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REDEFINING VALUE
THE MANUFACTURING REVOLUTION
Remanufacturing, refurbishment, repair and direct reuse in the circular economy

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About the international resource panel

This report was prepared by the Working Group on Circular Economy of the International Resource Panel (IRP). The IRP was established to provide independent, coherent and authoritative scientific assessments on the use of natural resources and its environmental impacts over the full life cycle and contribute to a better understanding of how to decouple economic growth from environmental degradation. Benefiting from the broad support of governments and scientific communities, the Panel is constituted of eminent scientists and experts from all parts of the world, bringing their multidisciplinary expertise to address resource management issues. The information contained in the International Resource Panel's reports is intended to be evidence based and policy relevant, informing policy framing and development and supporting evaluation and monitoring of policy effectiveness.

The Secretariat is hosted by the United Nations Environment Programme (UN Environment). Since the International Resource Panel's launch in 2007, twenty-five assessments have been published. Earlier reports covered biofuels; sustainable land management; priority economic sectors and materials for sustainable resource management; benefits, risks and trade-offs of Low-Carbon Technologies for electricity production; metals stocks in society, their environmental risks and challenges, their rates of recycling and recycling opportunities; water accounting and decoupling; city-level decoupling; REDD+ to support Green Economy; and the untapped potential for decoupling resource use and related environmental impacts from economic growth.

The assessments of the IRP to date demonstrate the numerous opportunities for governments and businesses to work together to create and implement policies to encourage sustainable resource management, including through better planning, more investment, technological innovation and strategic incentives.

Following its establishment, the Panel first devoted much of its research to issues related to the use, stocks and scarcities of individual resources, as well as to the development and application of the perspective of 'decoupling' economic growth from natural resource use and environmental degradation. Building upon this knowledge base, the Panel moved into examining systematic approaches to resource use. These include the direct and indirect (or embedded) impacts of trade on natural resource use and flows; the city as a societal 'node' in which much of the current unsustainable usage of natural resources is socially and institutionally embedded; the resource use and requirements of global food systems, green technology choices, material flows and resource productivity, resource efficiency and its potential and economic implications, and the assessment of global resource use. Upcoming work by the IRP will focus on governance of the extractive sectors, the impacts of land based activities into the marine and coastal resources, land restoration, scenario modelling of integrated natural resource use, resource efficiency and climate change.

REDEFINING VALUE
THE MANUFACTURING REVOLUTION

Remanufacturing, refurbishment, repair and direct reuse in the circular economy

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Preface

Circular Economy is at the forefront of current global discussions. This is due to the concerning pace by which natural resources are being used, and the consequent risk of scarcity of some resources, but also because of the environmental, social and economic benefits of a shift in the economy. Transformation from a linear economy, where products, once used, are discarded, to a circular one, where products and materials continue in the system for as long as possible, will contribute to a more sustainable future.

This report from the International Resource Panel, entitled *Redefining value – The manufacturing revolution. Remanufacturing, refurbishment, repair and direct reuse in the circular economy,* highlights processes that contribute to the Circular Economy shift by retaining the value of the products within the system, through the extension of their useful life.

The report calls for a revolution in the way of producing and consuming. A revolution where we move away from resource-intensive production and consumption models, towards low carbon, efficient processes, and where innovation will be the motor of change. This manufacturing revolution is essential for achieving the Sustainable Development Goals, specifically Goal 12 – Sustainable Consumption and Production – as well as the Paris Agreement, given the contributions of such processes to climate goals.

The report applies the value-retention processes to a series of products within three industrial sectors, so as to quantify the benefits relative to the original manufactured product. In this manner, the material requirement, the energy used, the waste, but also the costs and the generation of jobs are measured through first hand data from selected industries.

It also highlights the different barriers faced in the implementation of the processes, including regulatory, market, technology and infrastructure barriers, and how they can be overcome by a collaborative approach and by changing the mind-set of policy makers, industries and consumers.

We wish to thank the lead author Nabil Nasr and the rest of the team, for this very valuable contribution to advancing towards a Circular Economy and hope that it can influence the pace we are all making towards this transition.

Janez Potočnik
Co-Chair
International Resource Panel

Izabella Teixeira
Co-Chair
International Resource Panel

Foreword

If we want to change the world we live in, we will need to make big changes to the way we do things. Whether it's the way we build houses, produce electricity, or dispose of the waste, we need to re-think every aspect of what we do to make sure we are doing the best that we can with what we have.

For more equitable, sustainable development, we will need also to re-think the global economy, and how we value the resources supplied by nature. The traditional manufacturing model, where we make, use, and then dispose of a product is both wasteful and polluting. If we re-think this, and move towards a more circular model, where a product is used and then re-used, we retain the value of the materials and resources used to make that product.

Understanding the environmental and economic benefits of a circular economy, this report highlights important ways in which we can retain the value of products within the system by extending their life. And there are many examples of success. At repair cafes in 29 different countries all over the world, people come together to extend the life of their products through repair. The *REVISE-Network* in Flanders, uses a labelling system to guarantee the quality of electrical and electronic equipment which are sold by reuse shops. A social enterprise Fairphone designs products that last – both in their original design and in designing their repair to be as easy as possible.

It is clear that we need to scale up such initiatives that retain the value of products to preserve the planets resources, reduce greenhouse gas emissions and contribute to climate goals. I believe this report will inspire policymakers and the private sector to adopt a circular economy approach to production, thereby guiding us to a more sustainable world for all.

Erik Solheim
Under-Secretary General
of the United Nations and
Executive Director, UN Environment

Erik Solheim

Executive summary

Introduction and background

The circular economy proposes a framework in which outputs from every stage of the life cycle become inputs into another, offsetting the need for new materials and energy-intensive manufacturing activities, while also reducing waste. The circular economy has been positioned as an essential systemic perspective that can help to mitigate the loss of material, function, and embodied value created by traditional consumption (Ellen MacArthur Foundation 2013a). However, achieving these benefits requires engaging value-chain stakeholders in behavioral and social system transformation, and designing industrial economic and production systems to enable, accept, and support system circularity.

One of the objectives of a circular economy is the adoption of practices that seek to decouple the rate economic growth from the rate of growth of environ-

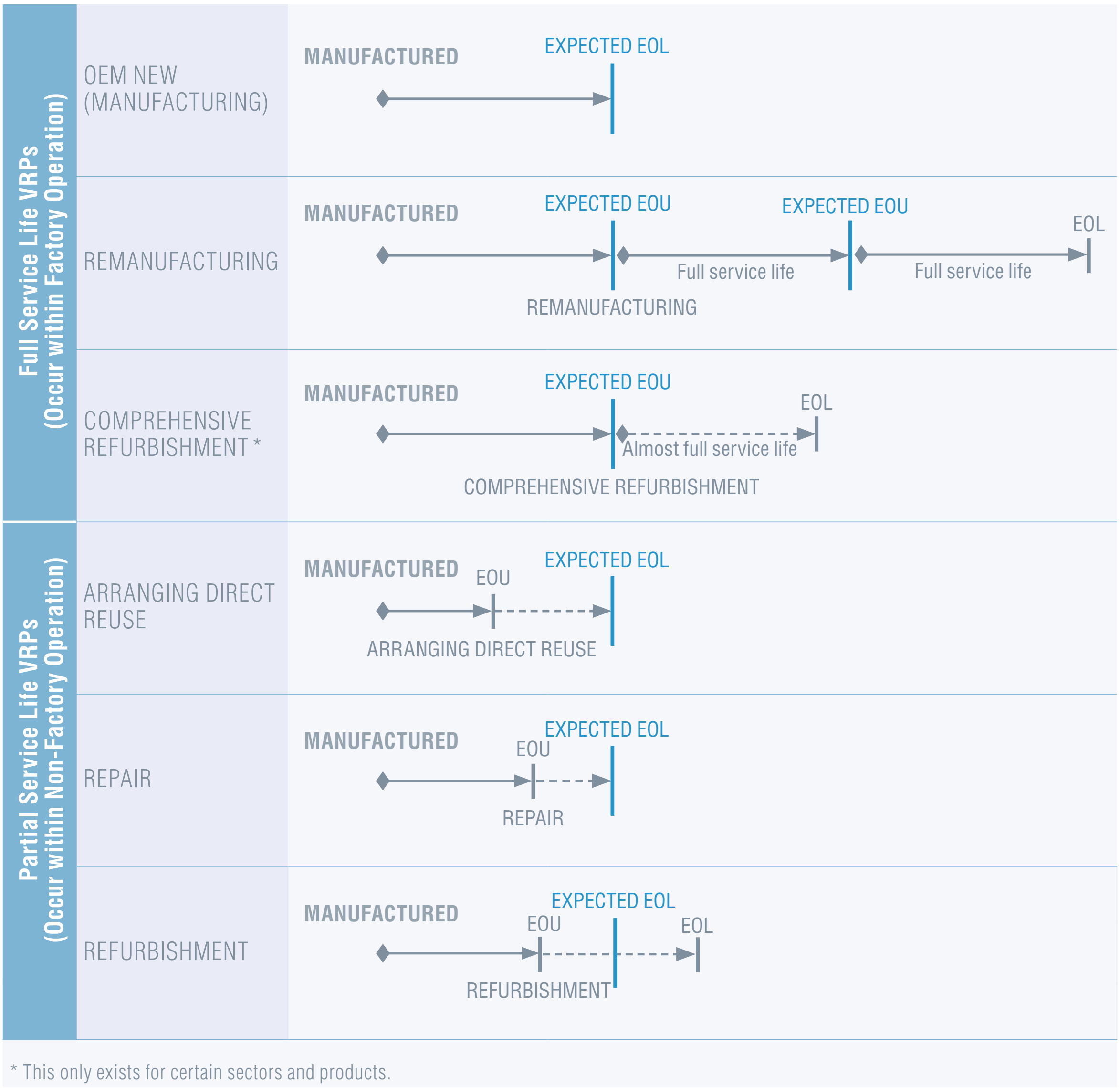


Figure A: Description of value-retention potential of VRPs mental impact. Many circular economy practices seek to retain value within the economic system (value-retention processes, or VRPs), and these processes include: arranging direct reuse, repair, refurbishment or comprehensive refurbishment, and remanufacturing. It is important to note that VRPs are not equal: the magnitude of impact avoided, economic opportunity created, and ultimately the value retained within the system, depends upon the specific VRP that is employed (refer to Figure A).

For many products and sectors, VRPs can offer benefits that include relative reduced environmental impact and reduced costs (vs. traditional new manufacturing). Despite these benefits, current adoption of VRPs remains low: Remanufacturing accounts for only ~2 per cent of US production, and only ~1.9 per cent of EU production (U.S. International Trade Commission 2012, European Remanufacturing Network 2015).

Opportunities and benefits of value-retention processes

There is often a perception that the pursuit of sustainability must come at an economic cost. However, this assessment reveals that circular economy, via VRPs, can offer an opportunity to achieve significant value-retention and environmental impact reduction, while also creating economic opportunities for cost-reduction and employment opportunity. Remanufacturing and comprehensive refurbishment VRPs offer full, or almost-full, new service lives to products, and offset significant environmental and economic costs associated with production. Arranging direct reuse, repair, and refurbishment VRPs offer additional options for customers to extend the service lives of products at relatively low environmental and economic costs (refer to Figure A).

This assessment examined specific environmental and economic impacts of each VRP for nine case study products, across three sectors (Industrial Digital Printers, Vehicle Parts, and Heavy-Duty and Off-Road (HDOR) Equipment Parts), and in four sample economies (Brazil, China, Germany, and US). In general, VRPs for the case study products in this report enabled the following benefits relative to the original equipment manufacturer (OEM) New product option:

- new material use (kg/unit);
- production waste generation (kg/unit);
- embodied material energy use (MJ/unit) and embodied material emissions generation (kgCO_2-eq./unit);
- process energy use (MJ/unit) and process emissions generation (kgCO_{2-}eq./unit); and
- costs associated with VRP product ($ USD/unit).

Product and system-design for VRPS and circular economy

Currently, product design specifications are ultimately responsible for ~75 per cent of a product's manufacturing costs, and ~80 per cent of the environmental and social impacts of a product: without an emphasis on overcoming waste and retaining value within production- and product-systems, the pursuit of circular economy can only be incremental, at-best.

The transition to circular economy relies on a new approach to product and system design, founded on three requirements: (1) The ability to create value; (2) The ability to protect and preserve value; and (3) The ability to easily and cost-effectively recover value. These three system requirements allude to essential circularity objectives that cut across product-, process-, facility-, and system-perspectives. These may include designing the product for long life, and/or keeping the product in the system (retaining value) for longer – in both cases, slowing the flows of materials into and out of the economic system. There are different design approaches that can be employed in pursuit of these objectives, organized according to circularity priorities and principles (refer to Figure B).

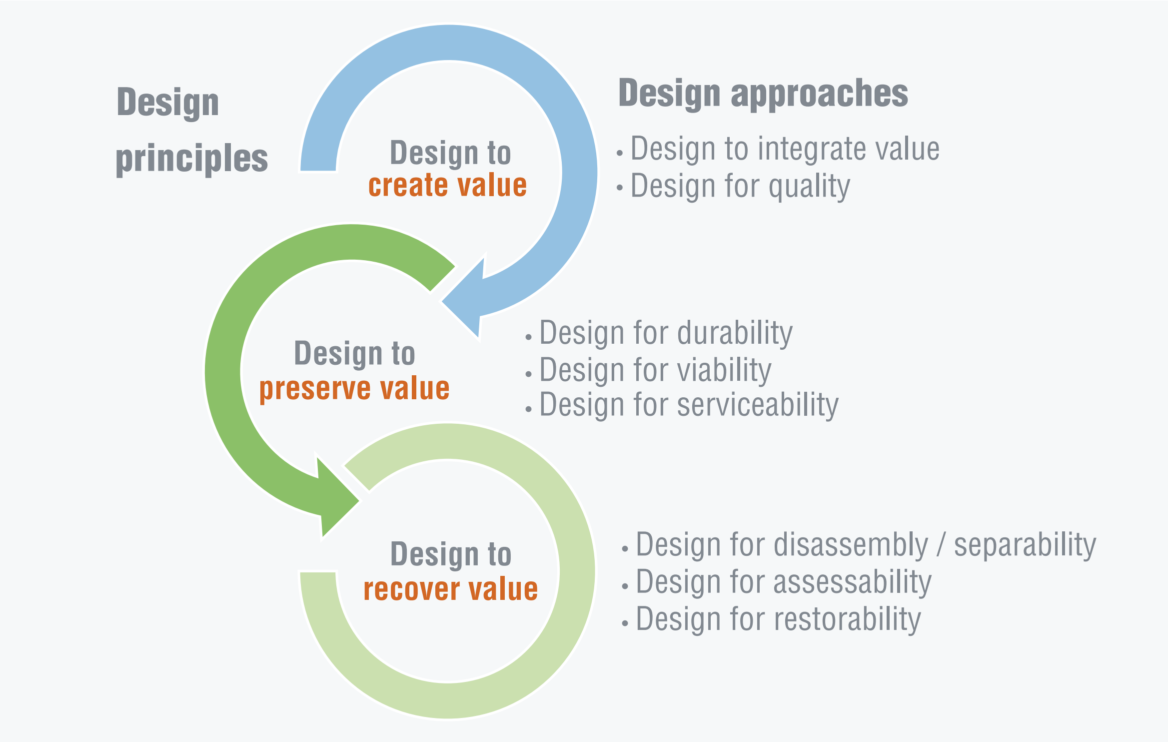


Figure B: Product development using VRP design principles

VRPs may not always be the optimal circular economy strategy for a firm to pursue, and the appropriateness of VRPs must be assessed on a product-by-product basis. Important product-level considerations for VRPs include: the nature of product and sub-system components; the use-phase energy requirement and energy efficiency of the product; the residual/remaining value that can be captured if VRPs were in-place; and the material composition of the product. In many markets, the availability of VRP product options creates targeted and differentiated opportunities to open new market segments, increase the economic participation of customers previously constrained where only OEM New options are available, and can even complement OEM New sales through innovative business and service models.

Innovative business models can complement design approaches by integrating the essential systems-perspective that seeks to reduce the loss of value to the system. In many cases, this may include improved and/or optimized product design and delivery, enhanced service contracts, and/or third-party operated reverse-logistics systems to facilitate VRPs at the product's End-of-Use (EOU)/End-of-Life (EOL). In other cases, creative business model approaches can facilitate the tracking of products throughout the distribution system, to improve maintenance, servicing, and take-back of the product from the user once it has reached a predetermined EOU or EOL (refer to Figure C).

VRPs are not intended as replacements for OEM New products, and if differentiated and positioned appropriately, VRPs may support growth opportunities for the entire product segment by targeting and engaging new, previously untapped, market segments that are underserved by OEM New products.

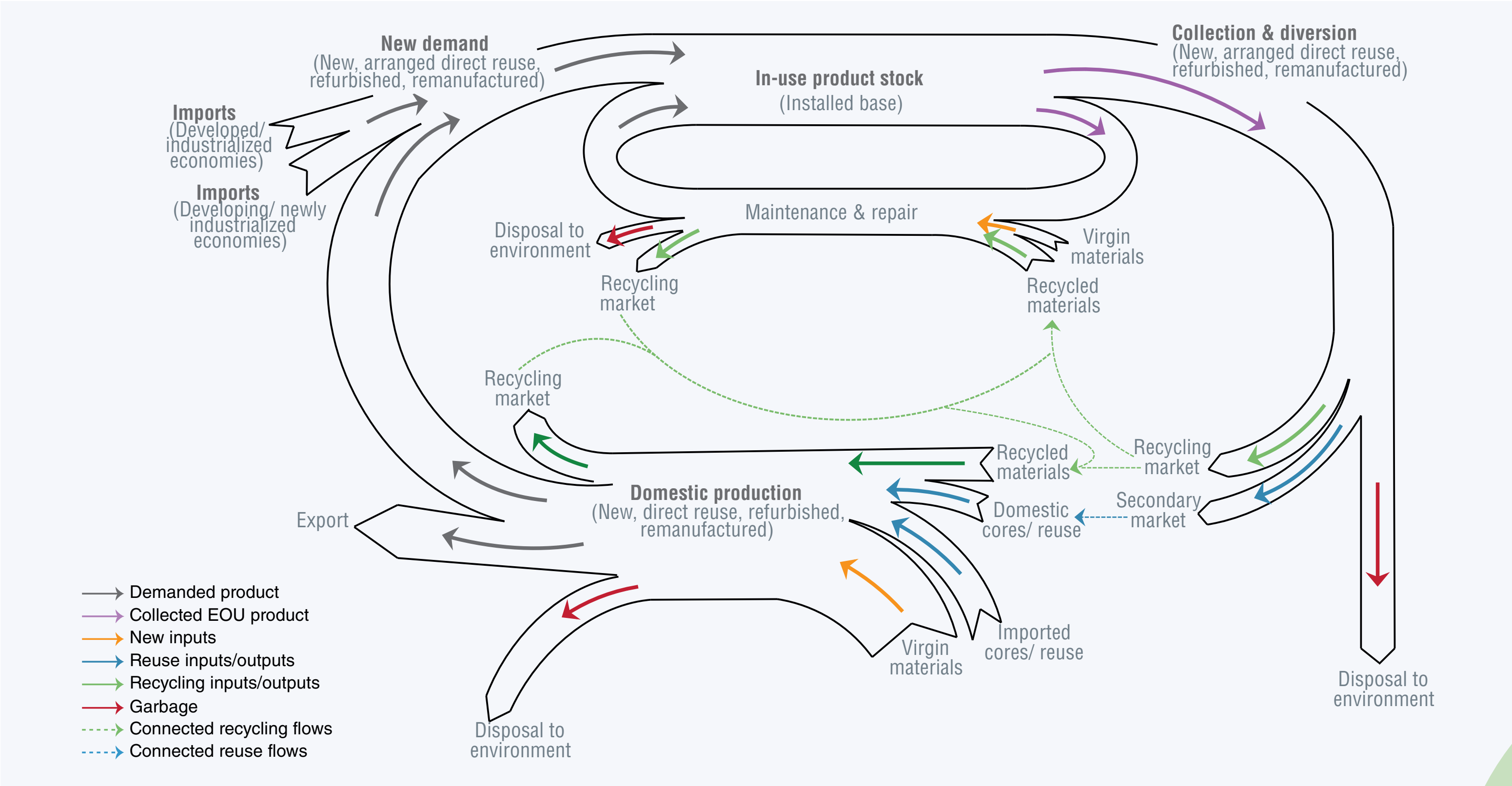


Figure C: Descriptive circular economy system model incorporating value-retention processes

VRPs and circular economy require differentiated approaches

Not all VRPs are appropriate for all products or all economies. Collaborative initiatives between domestic industry decision-makers and policy-makers to share information and to identify opportunities for improving circularity is needed: via closing loops and mitigating system losses; and via implementing the adoption of VRPs and VRP products in a manner that works within the existing production and collection infrastructure.

While every economy faces different challenges and barriers to VRPs, each also has an already established relationship with the key aspects of the VRP system that can inform a policy and implementation strategy.

- **Economies with current diversion, collection and recycling systems:** These systems can be adapted, formally or informally, to include diversion to secondary markets for reuse and VRP production.
- **Economies without recycling or reverse-logistics expertise:** Existing industry-led forward-logistics systems can be leveraged to improve overall logistics system utilization and productivity, alongside the application of Best Practices that may have already been established for collection programs in other jurisdictions.
- **Economies facing technological VRP producer capacity challenges:** Technology transfer enabled through improved access and trade in other products categories can be employed to the benefit of VRP production. Further, the vast body of knowledge about consumer behavior, innovation diffusion, and effective marketing that have been employed in the past to guide consumers away from less beneficial products (e.g. CFC-containing aerosols) can be utilized.

The mechanisms by which an industrialized economy pursues circular economy and VRPs may necessarily differ from those appropriate for a non-industrialized economy, largely because of varied technological, infrastructure, market, and regulatory conditions that can increase the cost and effort required to achieve the desired transformation. In industrialized economies, existing production, logistics and collection infrastructure are well entrenched, and the business case for overhauling these systems in pursuit of maximum VRP efficiency may be difficult, thus requiring an incremental approach. In contrast, many non-industrialized economies face the challenge of strategically building-up production, logistics and collection infrastructure where none currently exist.

While these types of systemic challenges face both industrialized and non-industrialized economies alike, the optimal strategies employed to overcome them likely differ. For example, where a non-industrialized economy has a strong reliance on informal repair activities and a low level of formal industrial capacity, the optimized circular economy strategy will not seek to displace repair with higher-impact VRPs in the short-term; instead it will focus on improving and enhancing the efficiency and value-retention ability within the existing repair system, and potentially expanding that system to achieve better outcomes for independent repair entities and customers alike.

Key actions for industry members and policy-makers

Government policy-makers have a central and pivotal role related to the presence and alleviation of regulatory, access and collection infrastructure barriers. Other stakeholders, including industry, may have an important role to play in the alleviation of barriers related to the customer market and technological capacity (refer to Figure D).

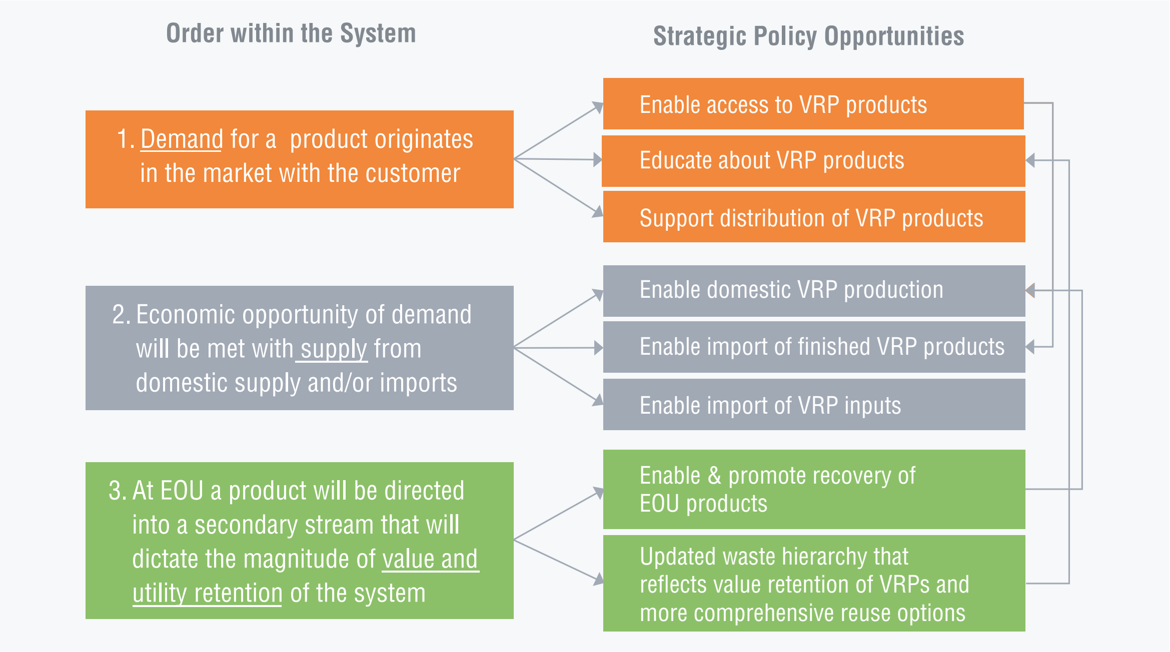
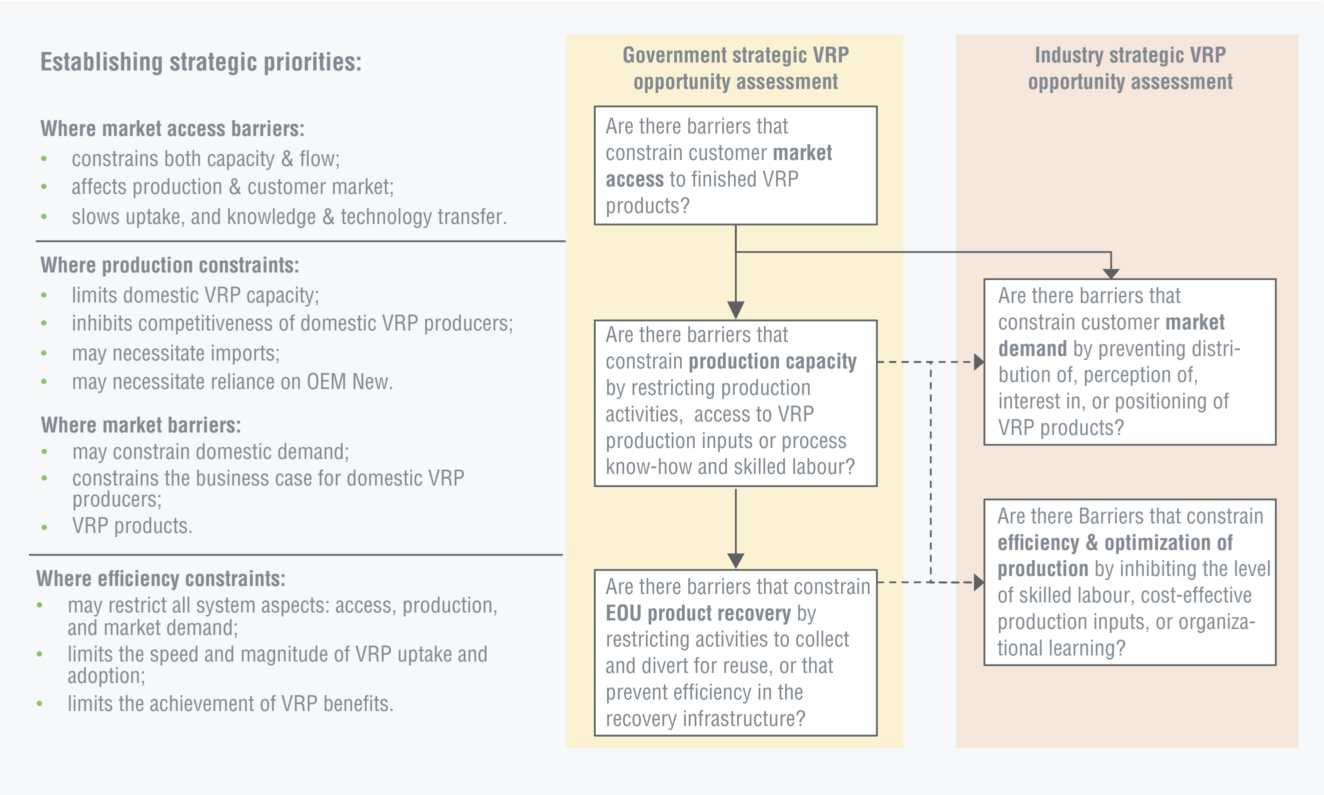


Figure D: Inherent system order enables strategic priorities for alleviation of barriers to VRPs

For VRPs to be part of an effective circular economy system, acknowledgement of the underlying order within the system can help to guide strategic policy opportunities. A simplified approach to barriers assessment and the role of government and industry members in developing strategic responses to barrier alleviation is outlined in Figure E.



Establishing strategic priorities:

Where market access barriers:
- constrains both capacity & flow;
- affects production & customer market;
- slows uptake, and knowledge & technology transfer.

Where production constraints:
- limits domestic VRP capacity;
- inhibits competitiveness of domestic VRP producers;
- may necessitate imports;
- may necessitate reliance on OEM New.

Where market barriers:
- may constrain domestic demand;
- constrains the business case for domestic VRP producers;
- VRP products.

Where efficiency constraints:
- may restrict all system aspects: access, production, and market demand;
- limits the speed and magnitude of VRP uptake and adoption;
- limits the achievement of VRP benefits.

Government strategic VRP opportunity assessment

Are there barriers that constrain customer **market access** to finished VRP products?

Are there barriers that constrain **production capacity** by restricting production activities, access to VRP production inputs or process know-how and skilled labour?

Are there barriers that constrain **EOU product recovery** by restricting activities to collect and divert for reuse, or that prevent efficiency in the recovery infrastructure?

Industry strategic VRP opportunity assessment

Are there barriers that constrain customer **market demand** by preventing distribution of, perception of, interest in, or positioning of VRP products?

Are there Barriers that constrain **efficiency & optimization of production** by inhibiting the level of skilled labour, cost-effective production inputs, or organizational learning?

Figure E: Role of government and industry decision-makers in assessment of VRP barriers and strategic priorities

Policy interventions to facilitate VRPs within a circular economy must target radical systemic change combined with the facilitation of incremental (process-level) innovations. In addition, policies need to combine sector-specific insights with cross-sectoral perspectives: many circular economy and VRP opportunities tend to be more aligned with and unique to product-type, but changes to the larger circular economy system can provide efficiency opportunities across sectors (e.g. shared reverse-logistics and/or collection system infrastructure). The style of regulation also needs to be innovation-friendly in order to appropriately engage stakeholders in dialogue and consensus via open, flexible, and reflective multi-stakeholder collaborations. A policy priority for the effective transition to circular economy must be to overcome the current passive throw-away culture exhibited by both consumers and producers in economic systems around the world, with a first step in establishing effective basic waste management and recycling infrastructure.

Effective policy approaches for VRPs must integrate the innovation and complexity of VRP processes and products within strategic initiatives, via collaboration with industry members, voluntary agreements, industry-developed standards, market-based instruments, and financial instruments. These approaches must also consider the integration of producer and consumer perspectives and should consider and incorporate: both technological and environmental focus; the important role of small-medium enterprises (SMEs); strategic niche management strategies and tools; and adoption forward-looking public procurement practices.

A top priority for industry decision-makers must be the adoption of a broad systems-perspective into business model and product design, and the prioritization of value-creation, value-preservation, and value-recovery as key objectives within a product-service system.

Conclusion

All economies have the potential to optimize the role of VRPs within their circular economy strategy. There is no evidence that the 'developing/newly industrialized' status of an economy affects the ability to fully engage in VRPs, and there is confirmation that this is not an issue of 'developed/ industrialized vs. developing/newly industrialized' economic standing. It is the presence and nature of the barriers to VRPs within the economic and production systems that determine the magnitude of, and speed at which the benefits of VRPs can be realized.

Regardless of how quickly, or to what extent VRPs increase within the production mix and/ or market demand, the potential to offset new material requirement, and retain value within the system is automatically increased with the alleviation of barriers to VRPs. While the absolute magnitudes of new material offset, energy requirement, and emissions generation are dependent upon the magnitude of the domestic industry and production level, the opening of markets and alleviation of barriers leads to net positive impact avoidance, and automatic improvements in material efficiency.

There are inherent systemic barriers to VRPs within an economy's production-consumption system that, if not appropriately addressed, can severely inhibit the adoption of VRPs, the achievement of associated environmental impact reduction, and the successful pursuit of circular economy. Based on the case study products and economies of this assessment, regulatory and access barriers presented the most significant constraint on the adoption of VRPs, preventing the flow of VRP products to potential customers, and eliminating the business-case for producers to engage in VRP practices. A top priority for policy-makers must be the enabling of VRP production and the consumption of VRP products if material efficiency and optimized environmental impact reduction are to be achieved.

There is an essential need for enhanced coordination and alignment between industry decision-makers and policy-makers. For industry, developing enhanced business models, extended circular consumption-production systems, voluntary standards, and engaging and educating the customer marketplace are essential functions. These efforts must be integrated with the efforts of policy-makers to protect economic and environmental interests, and to facilitate the transition to more resource-efficient circular economies in a manner that is informed by, aligns with, and reflects actual industry practices, needs, and requirements. The move towards international standards regarding the practices, processes, and qualifications of VRPs must include industry, government, and market stakeholder perspectives.

The adoption of VRP products around the world is low, but through the adoption of VRPs it has been shown that economic opportunity (e.g. via cost reduction and employment opportunity) and the reduction of important negative environmental impacts are possible. VRPs provide the most viable and proven approach to enabling industrial circular economies: It is essential that they form the foundation of circular economy strategies of companies, industries, and economies around the world. Despite very real implementation challenges that vary across each global economy, a bold and brave change is needed if the value of VRPs is to be realized, and the pursuit of circular economies mobilized. This change must entail and embrace product development that is for the entire product-system; flows of global forward-and reverse-logistics systems must be connected, and the efficiency of these systems maximized. To help spur new levels of interest and adoption, producers and customers alike must be able to have access to a greater range of value-retention process technology and products; and new and innovative business models must be developed, tested and deployed to support meaningful market transformation. The pursuit of circular economy is a vital and tangible strategy for overcoming the significant environmental and economic challenges that we are facing. It is time for all decision makers to engage in, and take conscious action that will enable, support and lead to the large-scale adoption of VRPs worldwide.

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Glossary of key terms

The following terms are intended for clarification purposes only. Accepted definitions were used when available. In this report, the following terms are used accordingly. Additional definition clarification is included in Section 2.

Arranging direct reuse: The collection, inspection and testing, cleaning and redistribution of a product back into the market under controlled conditions (e.g. a formal business undertaking).

Avoided environmental impacts: Refers to a scenario-based demonstration of the environmental impacts that are avoided by an economy due to the use of value-retention processes (VRPs) within the production mix. (Refer to terms Value-Retention Process, and Production Mix, below). This approach presents the differential environmental impacts between a scenario in which total supply comes from original equipment manufacturer (OEM) New units, and the scenario in which total supply incorporates the actual economy-specific production mix which includes value-retention processes (VRPs) to varying degrees. This impact differential, based on actual production volumes, presents the environmental impacts that are avoided because of economy-specific production mix.

Component: Refers to a constituent part of a broader defined system; an element of a larger whole object that could be a part and/or a product. For the purposes of this report, component is used to refer to the constituent parts of the defined case study products.

Comprehensive refurbishment: Refers to the refurbishment of used equipment that takes place within industrial or factory settings, with a high standard and level of refurbishment. Refurbishment increases or restores the product's performance and/or functionality and enables the product to meet applicable technical standards or regulatory requirements, with the result of making a fully functional product to be used for a purpose that is at least the one that was originally intended (Please refer to Refurbishment term below).

Core: A core is a previously sold, worn or non-functional product or module, intended for the remanufacturing process. During reverse-logistics, a core is protected, handled and identified for remanufacturing to avoid damage and to preserve its value. A core is usually not waste or scrap, and it is not intended to be reused for other purposes before comprehensive refurbishment or remanufacturing takes place.

Economic impacts: Refers to the economic impact metrics addressed within this study, specifically: cost advantage ($ USD); and employment opportunity (Full-time equivalent worker, or FTE).

Embodied material emissions: Refers to the carbon dioxide and greenhouse gas equivalent emissions emitted during the extraction and primary processing stages of materials later used as inputs to OEM New and value-retention process production activities; 'cradle-to-gate' up until entering the production facility 'gate'. Modeling of embodied material emissions uses a material-specific conversion ($kgCO_2$-eq./unit), based on the global average for each material type, in accordance with the Inventory of Carbon and Emissions (ICE) (Hammond and Jones 2011).

Embodied material energy: Refers to the energy consumed during the extraction and primary processes stages of materials later used as inputs to OEM New and value-retention process production activities; 'cradle-to-gate' up until entering the production facility 'gate'. Modeling of embodied material energy uses a material-specific conversion (MJ/kg), based on the global average for each material type, in accordance with the Inventory of Carbon and Emissions (ICE)(Hammond and Jones 2011).

End-of-life (EOL): Refers to the point in the product or object's service life at which the product or object is no longer able to function or perform as required, and for which there are no other options for the product but to be recycled or disposed into the environment.

End-of-use (EOU): Refers to the point in the product or object's service life at which the product may not be needed by the current owner/user, or able to function or perform as required, and for which there are other options available to keep the product and/or its components within the market, via value-retention processes (VRPs). It is important to note that EOU may occur without any product issue at all: The owner may simply no longer want or need the fully-functioning product, even though it has not yet fulfilled its entire expected service life. This includes various forms of obsolescence, which refers to the process of becoming obsolete, outdated or no longer used due to defects (material obsolescence), lack of interoperability or incompatibility of software (functional obsolescence), the desire for a new version (psychological obsolescence), or because repair/maintenance to maintain performance is expensive (economic obsolescence).

End-of-waste (EOW): Refers to conditions under which certain specified waste shall cease to be waste (per Directive 2008/98/EC), specifically: when it has undergone a recovery, including recycling; the substance or object is commonly used for specific purposes; a market or demand exists for such a substance or object; the substance or object fulfills the technical requirements for the specific purposes and meets the existing legislation and standard applicable to products; and the use of the substance or object will not lead to overall adverse environmental or human health impacts. (Directive 2008/98/EC)

Environmental impacts: Refers to the environmental impact metrics addressed within this study, specifically: new material offset (avoided) (kg); embodied material energy (MJ); embodied material emissions (kgCO_2-eq.); process energy (MJ); and process emissions (kgCO_2-eq.).

Expected service life: Refers to the manufacturer's expectations about the time-period for which a product can be used, usually specified as a median, and reflecting the time that the product can be expected to be serviceable and/or supported by its manufacturer.

Forward-logistics: Refers to the traditional flow of products from the point of production through to the consumer and reflects a traditional supply chain management perspective focused on product delivery.

Full service life: Refers to value-retention processes (VRPs) that enable the fulfillment of a complete new life for every usage cycle of the product, and includes manufacturing (OEM new), comprehensive refurbishment, and remanufacturing. These processes take place within factory settings and industrial operations.

In-use product stock: Refers to products in 'active use', including those being repaired for return to the original user. Different from traditional 'stock' terminology, In-Use Product Stock excludes end-of-use (EOU) products that have been removed from the marketplace to be used as input to direct reuse, refurbishment, comprehensive refurbishment, or remanufacturing. For purposes of clarity, In-Use Product Stock also excludes end-of-life (EOL) products that have entered recycling or disposal streams.

Life cycle assessment (LCA): As defined by the International Standards Organization (ISO), refers to a technique for the assessment of environmental aspects and potential impacts associated with a product by compiling an inventory of relevant inputs and outputs of a product system, evaluating the potential environmental impacts associated with those inputs and outputs, and interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study. (ISO 14040/44, 2006).

Module: Refers to a self-contained unit or item, such as an assembly or segment of a larger product, which itself performs a defined task and can be linked with other such units to form a larger system.

New material: Refers to the total 'new' (not reused via value-retention processes (VRPs)) material that is required as inputs to complete each OEM New and Value-Retention Process. New material can include a mixture of virgin (primary) and recycled (secondary) content, given that most of materials available for purchase in the global economy consist of some mixture thereof. The assumed ratio of virgin and recycled content used in modeling is based on the global average for each material type, in accordance with the Inventory of Carbon and Emissions (ICE)(Hammond and Jones 2011).

Original equipment manufacturer (OEM): Refers to the manufacturer of the original parts or equipment, including the items manufactured, assembled and installed during construction of a new product. The OEM may or may not be responsible for marketing and/or selling of the product.

OEM new: Refers to traditional linear manufacturing production process activities that rely on 100 per cent new material inputs, and which are performed by the original equipment manufacturer (OEM).

Part: Refers to a piece or segment of an object; may also be a component of a product. For the purposes of this report, part is used to acknowledge that the case study product may be a component of a larger defined product (e.g. vehicle parts, which are components of a vehicle).

Partial service life: Refers to value-retention processes (VRPs) that enable the completion of, and/or slight extension of, the expected product life, through arranging direct reuse of the product, repair, and refurbishment. These processes take place within maintenance or intermediate maintenance operations.

Potential reusability: Refers to the extent to which a product complies with End-of-Waste conditions, and thus qualifies as an input to value-retention processes.

Primary material: Also referred to as virgin material, refers to a material that has not been previously used or consumed, or subjected to processing other than for its original production. Primary material is assumed to contain no (zero) recycled content.

Process emissions: Refers to the carbon dioxide and greenhouse gas equivalent emissions emitted during the OEM New and/or value-retention process production activities. Modeling of process emissions is based on process energy (MJ/unit), converted using economy specific Global Warming Potential (GWP) 100a factors to account for grid mix of the producing economy (Ecoinvent 3.3 2016).

Process energy: Refers to direct at-the-meter energy consumed during the OEM New and/or value-retention process production activities, grossed-up to account for economy-specific electricity supply-chain efficiencies. Scaled process energy results include direct electricity consumption, as well as average electricity generation, transmission, and distribution losses specific to the producing economy (World Energy Council 2015).

Product: Refers to an article, object or substance that is manufactured or refined for sale, that is the final output of a process.

Product lifetime: Refers to the period that starts at the moment a product completes original manufacture and ends when the product is beyond any reuse or recovery at the product-level. (den Hollander, Bakker, and Hultink 2017)

Product platform: Refers to a set of common elements, including underlying technical components, parts or technology that are shared across a range of the company's products. New derivative products can be developed and launched by the company based on a common product platform.

Production mix: Refers to the equivalent production shares of OEM New and Value-Retention Processes that are adopted within a sample economy under different scenario conditions. Like 'market share', this refers to the percentage of total production that is accounted for by each production process.

Recycling: Refers to the relevant operations specified in Annex IV B to the Basel Convention. Recycling operations usually involves the reprocessing of waste into products, materials or substances, though not necessarily for the original purpose, and does not cover operations that recover energy from waste.

Refurbishment: Refers to the modification of an object that is a waste or a product that takes place within maintenance or intermediate maintenance operations to increase or restore performance and/or functionality or to meet applicable technical standards or regulatory requirements, with the result of making a fully functional product to be used for a purpose that is at least the one that was originally intended. The restoration of functionality, but not value, enables a partial new service life for the product.

Remanufacturing: Refers to a standardized industrial process that takes place within industrial or factory settings, in which cores are restored to original as-new condition and performance, or better. The remanufacturing process is in line with specific technical specifications, including engineering, quality, and testing standards, and typically yields fully warranted products. Firms that provide remanufacturing services to restore used goods to original working condition are considered producers of remanufactured goods.

Repair: Refers to the fixing of a specified fault in an object that is a waste or a product and/or replacing defective components, in order to make the waste or product a fully functional product to be used for its originally intended purpose.

Reuse: Refers to the using again of a product, object or substance that is not waste, for the same purpose for which it was conceived, without the necessity of repair or refurbishment.

Reverse-logistics: Refers to activities engaged to recapture the value of products, parts, and materials once they have reached end-of-use or end-of-life. All VRPs may be considered to be part of a reverse-logistics system, and in addition activities including collection, transportation, and secondary markets provide essential mechanisms for facilitating reverse-logistics.

Secondary market: Also referred to as the aftermarket, is a market for used goods or assets, or an alternative use for an existing product or asset where the customer base is a second, or derivative (related) market. Items on the secondary market may or may not be manufactured by the OEM.

Secondary material: Also referred to as recycled material, refers to any material that has been used at least once before, is not the primary product of a manufacturing or commercial process, and can include post-consumer material, post-industrial material, and scrap.

Service life: Refers to a product's total lifetime during which it can be used economically or the time during which it is used by one owner, from the point of sale to the point of diversion for reuse via VRPs, or to the point of disposal (Cooper 1994). This is differentiated from Expected Service Life as it refers to the actual service life and is not necessarily associated with manufacturer expectations or commitments.

Technical nutrients: Refers to non-toxic, highly-stable materials that have no negative effects on the natural environment, that are designed to be recovered and reused within production activities, that and can be used in continuous cycles without losing integrity or quality.

Upgrade: Refers to the act of raising a product to a higher standard with the objective to improve performance, efficiency, and/or functionality by adding or replacing components, including electronic and/or software. For the purposes of this report, an upgrade that is performed as the primary and/or sole objective of a VRP is categorized as a 'refurbishment'. Upgrades performed as one of several process steps of comprehensive refurbishment or remanufacturing are not distinguished.

Value-retention processes (VRPs): While recycling is also an integral part of circular economy, for the purposes of this study the expression Value-Retention Processes (VRPs) only refers to activities, typically production-type activities, that enable the completion of, and/or potentially extend a product's service life beyond traditional expected service life. These processes include arranging direct reuse, repair, refurbishment, comprehensive refurbishment, and remanufacturing. These processes help to retain value in the system via enhanced material efficiency, reduced environmental impacts, and may potentially offer economic opportunities associated with primary material production and traditional linear manufacturing.

Waste: Refers to any substance or object which the holder discards or intends or is required to discard (Directive 2008/98/EC).

1

Introduction

1.1 Introduction to this report

There is a growing awareness of the urgency to address the escalating resource use and environmental degradation associated with continued economic growth. The need to transition towards more sustainable economic systems, and improved material and resource efficiency through a circular economy is clear.

The International Resource Panel (IRP), an independent scientific panel operating under its parent organization, the United Nations Environment Programme (UNEP), has published several reports related to metals, assessing current available stocks, opportunities and issues with recycling, and the environmental and social risks associated with anthropogenic use patterns (UNEP 2017, 2014, 2011, 2016b). There is already recognition for the importance of considering alternative options for the management of products, their materials, and their components at the end-of-use (EOU) to further decouple economic growth from resource consumption and environmental degradation (UNEP 2017, 2014, 2011, 2016b). Among many proposed sustainability priorities, the circular economy has been proposed as a promising option for transitioning industrial economies towards longer-term sustainable economic systems.

The potential value of the circular economy goes well beyond the recycling of materials in their raw form; in the circular economy, value is ultimately embedded in our ability to retain the embodied and inherent value of product material, structural form, and ultimate function. Capturing, preserving, and re-employing this value not only serves to offset virgin material requirements, but also reduces required production activities and enables new value altogether by ensuring the completion of, and/or potentially extending a product's expected life.

However, to extend this knowledge and render it actionable in the contemporary industrial economy, there is a clear need to explore the strategies by which these benefits may be achieved. In this respect, an exploration of activities that serve to retain inherent value of a product through **arranging direct reuse, repair, refurbishment, and remanufacturing** (hereafter collectively referred to as value-retention processes or VRPs) is necessary for identifying the means to improve industrial system circularity. An exploration of each VRP, its role in the current industrial paradigm, and its potential to impact the future of the circular economy can thus shed light on the most effective ways to enhance resource efficiency and reduce environmental impacts associated with primary material production and traditional linear manufacturing.

Finding ways to achieve this 'decoupling' is a focus of the International Resource Panel in the pursuit of a worldwide system of resource use that is socially equitable, economically efficient, and environmentally healthy. Through the deployment and scaling of VRPs worldwide, the objectives of increased system circularity in the industrial economy, decoupling of economic growth from environmental degradation, and resource efficiency can be successfully pursued. It is critical, then, to understand the different ways in which these processes may interact within, and affect categorically, diverse economies.

A primary objective of this assessment is to evaluate whether innovation within the production process can enable reduced negative environmental impacts of production without compromising economic opportunity and the satisfaction of consumer needs. Quantification of the comparative benefits and impacts across VRPs, is determined for case study products and sectors, and sample economies. In addition, this study highlights that there are important distinctions between VRPs, both in terms of the actual activity undertaken, as well as the impact and value of that VRP activity in economic and environmental metrics. The increased understanding and education regarding the contribution of VRPs to circular economy and material efficiency are complementary outcomes that offer qualitative support for the transition to more circular economies and production processes.

This study is of benefit to a range of stakeholders, including Original Equipment Manufacturer's (OEMs), VRP entities, industry associations, policy analysts, policy-makers, members of the value-chain, and end-customers/users alike. The scaling of, and transition to more circular economies and improved resource efficiency requires initiative and coordination across sector, regional, national and international boundaries.

While some decoupling technologies and techniques (e.g. VRPs) are already commercially available and used in both developing/newly industrialized and developed/industrialized economies, increasing the dissemination, adoption, and economic viability of these approaches remains a challenge.

1.1.1 Scope of the study

This report acknowledges the urgency and magnitude of the sustainability challenge, and the complexity of responding appropriately. As described in Figure 1, this report focuses on a specific subset of concepts and applied options, necessarily differentiating circular economy motivations and interests from broader sustainability motivations and interests (refer to Section 1.2.1).

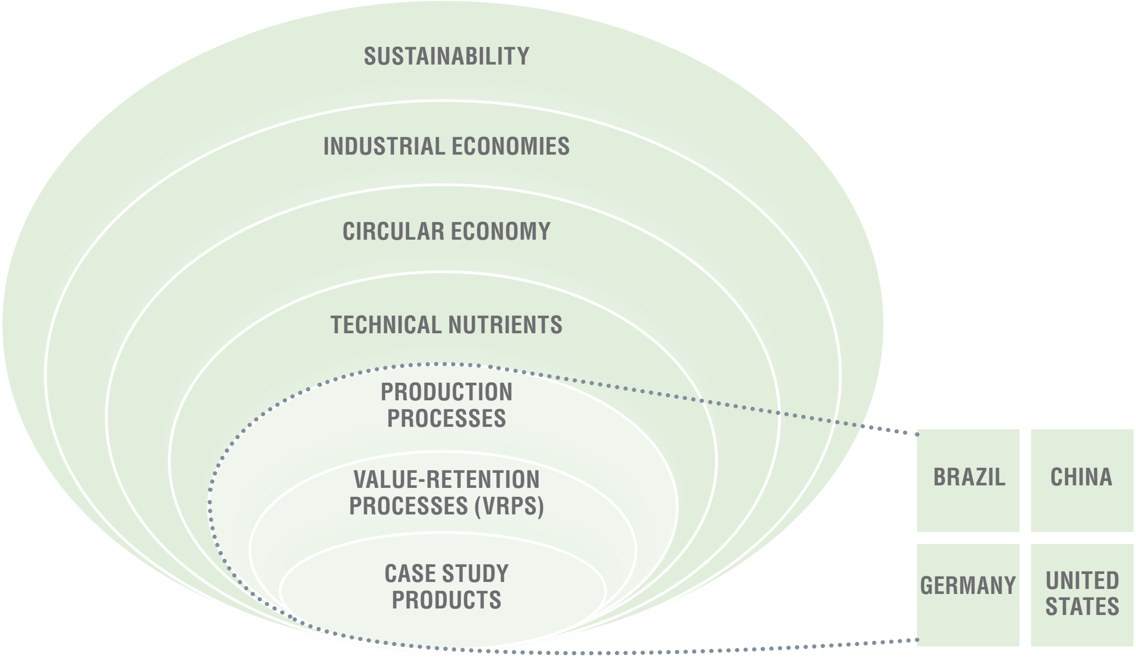

Figure 1: Scope of this report in broader context of sustainability and circular economy

While sustainability priorities are highly relevant and pertinent, circular economy is positioned as one of many potential mechanisms for pursuing broader sustainability objectives, particularly in the context of industrial economies (refer to Section 1.2.2). The perspectives, challenges, and opportunities for non-industrialized economies to engage in circular economy are also incorporated wherever possible. In addition, the nature of circular economy necessarily emphasizes primary stakeholders that include government, industry, and customers/users within production-consumption systems (refer to Section 1.2.3).

The circular economy differentiates between biological nutrient (organic) material flows and technological nutrient (inorganic or synthetic) material flows (McDonough and Braungart 2010, Ellen MacArthur Foundation 2013b). Unlike biological nutrients, technical nutrients can be cycled through a production system multiple times without a loss in quality, and as such are a relevant focus for this assessment of production and value-retention processes. This emphasis on technical nutrients guided the selection of case study sectors and products, which are predominately made of technical nutrients. Other sectors that are actively engaged in circular economy initiatives, such as the textile/apparel industry, produce products that are a mixture of biological and technical nutrients.

In addition to traditional 'OEM New' linear production, the VRPs that are specifically assessed in this study are:

- Arranging direct reuse;
- Repair;
- Refurbishment;
- Comprehensive refurbishment; and
- Remanufacturing.

The definitions and descriptions of these VRPs are further described in Section 2.

Reflecting geographical scope of sample economies Brazil, China, Germany, and the US, specific case study assessments were performed upon nine products that represented three sectors known to engage in VRPs (refer to Table 1). The rationale behind the selection of these sectors and products is further described in Section 4.2.

The environmental impacts of industrial activity can be measured extensively. Typical life cycle assessment (LCA) impact categories are often used to help avoid a narrow definition and understanding of environmental impacts, and these commonly consider: climate change; ozone depletion; human toxicity; photochemical oxidant formation; particulate matter formation; ionizing radiation, terrestrial acidification; freshwater eutrophication; marine eutrophication; terrestrial ecotoxicity; marine ecotoxicity; agricultural land occupation; urban land occupation; natural land transformation; water depletion; metal depletion; and fossil fuel depletion (Guinée 2002). The approach utilized by this assessment relies on measures and metrics that were available across the range of processes, facilities, and economies of interest, and as a result were necessarily limited. As such, the primary comparative environmental impact metrics (hereafter referred to as 'environmental impacts') assessed and reported in this study include:

- New material offset (avoided) (kg);
- Embodied material energy (MJ);
- Embodied material emissions (kgCO_2-eq.);
- Process energy (MJ); and
- Process emissions (kgCO_2-eq.).

While emissions impacts (kgCO_2-eq.) reflect *direct* environmental impacts, additional measures of new material use, and energy requirement, are included to account for *indirect* environmental and sustainability impacts. The environmental impacts of VRPs (measured as specified above) for the case study products at the product- and process-levels are presented in Section 5.2.

Similarly, the economic impacts of industrial activity can also be measured extensively: For the purposes of this report, the primary comparative economic impact metrics (hereafter referred to as 'economic impacts') assessed and reported in this study include:

- Cost advantage ($ USD); and
- Employment opportunity (Full-time equivalent worker, or FTE).

The economic impacts of VRPs (measured as specified above) for the case study products at the product- and process-levels are presented in Section 5.3.

Table 1: Case study products and sectors

Sector	Case Study Products	HS92 International Trade Code Reference
Vehicle Parts	1. Vehicle engine (Traditional, cast iron cylinder block)	840710-90
	2. Vehicle alternator	840991
	3. Vehicle starter motor	840991
	• Vehicle engine (Lightweight, aluminum cylinder block)[1]	n/a
Industrial Digital Printers	1. Production printer	844319
	2. Printing press (#1)	
	3. Printing press (#2)	
Heavy-Duty and Off-Road (HDOR) Equipment Parts	1. HDOR engine	840820
	2. HDOR alternator	840999
	3. HDOR turbocharger	841480

Specifically, this report will contribute to the literature across five key areas:

1. Increased understanding of the wide range of VRPs that are already prevalent around the world;
2. Estimated current and potential impacts and material efficiency that result from VRPs at the product, market and international levels;
3. Identified key barriers to increased market penetration and uptake of VRPs within domestic economies;
4. Assessed sensitivity of VRP impacts to the presence of key barriers, with the objective of informing corporate and government policy opportunities; and
5. Examined corporate (design and process) and government (trade, infrastructure, and incentives) policy options in support of accelerated transition to circular economy through VRPs.

The scoped focus of this report is not a commentary on broader and/or potentially conflicting sustainability motivations; instead this report offers a scoped assessment of a potential framework for evaluating and responding to sustainability challenges within the industrial economy. Further, this report focuses on a direct comparison of the traditional linear production system against alternative VRP options that may offer reduced negative environmental impacts of production. Given this emphasis on the process innovation within the production system, the report acknowledges, but does not go into extended depth on the consumption-side of the circular economy.

Expanding the use of VRP practices can offer substantial and verifiable benefits in terms of resource efficiency, circular economy, and protection of the global environment. However, their intensities and adoption globally have been limited due to significant technological, market, collection infrastructure, and regulatory/policy barriers. This study seeks to quantify the value of each different VRP across a range of metrics related to resource

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[1] The lightweight vehicle engine is not considered to one of the case study products. To reflect implications of alternate sustainable design approaches, this additional product example of a lightweight (versus traditional) vehicle engine was assessed at the material- and product-levels only (see Section 5.2.2.1) and is not included as a standard part of further analysis or results.

efficiency and the circular economy. In addition, barriers that have inhibited the growth and scale-up of VRP activities around the world are identified and discussed.

1.1.2 Report and Study Structure

The overarching objective of this study is to assess and identify some of the relative economic, and environmental impacts of each VRP from several different perspectives.

Subsequent to the necessary introduction and background sections describing context, approach and important considerations related to VRPs within a circular economy, as presented in Sections 2 and 3, it should be noted that discussion of the study is structured to align with the summarizing visual description in Figure 2:

- **Case study methodology** (Section 4): What is the conceptual framework for assessing and modeling product-level and economy-level insights about the impacts of VRPs? What are the limitations of these studies?

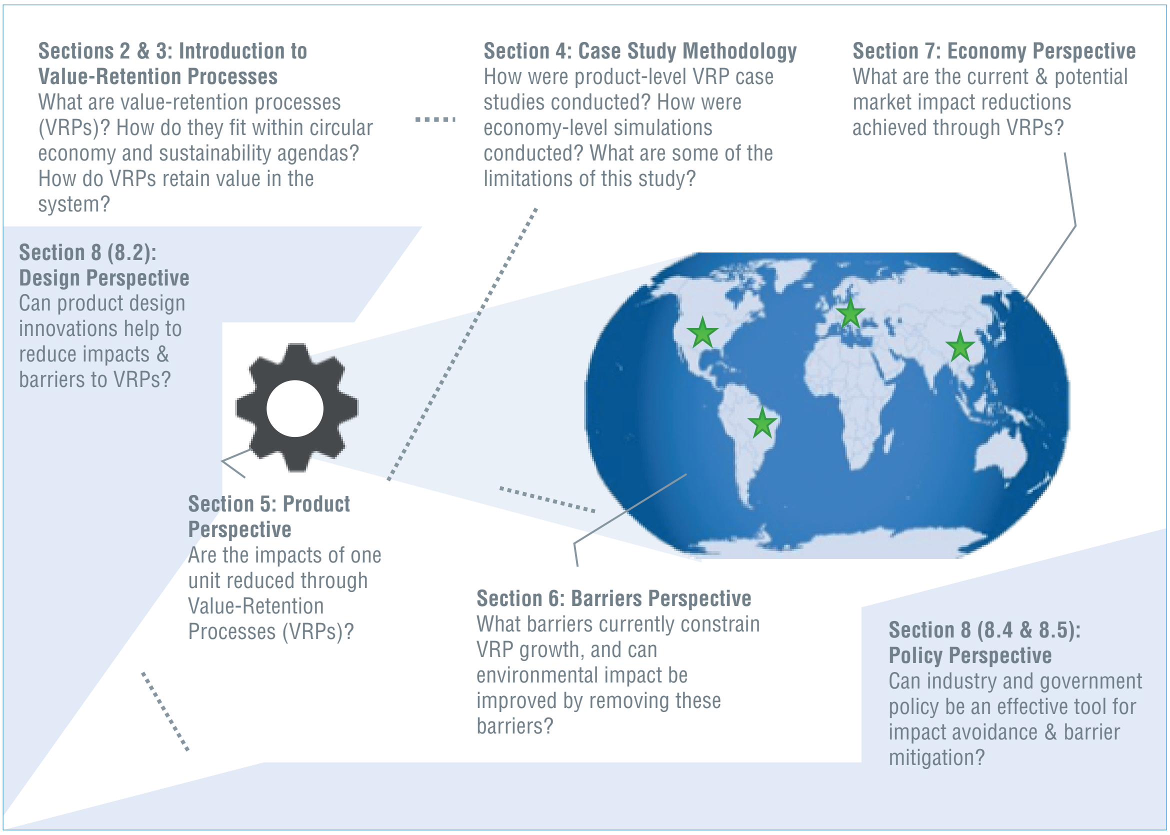

Figure 2: Overview of the report structure

- **Product perspective** (Section 5): What are the per-unit input requirements, by-products, and implications of traditional linear ('new') production, as compared to the same product brought back to the market through arranging direct reuse, repair, refurbishment, or remanufacturing processes. Could quantification of these VRP impact advantages/avoidances create new firm incentives to switch or diversify away from strictly linear production activities? The impacts and benefits of VRPs for the case study products of this assessment, at the product unit-level, are presented in Section 5 across each of the environmental and economic metrics of focus.

- **Barriers perspective** (Section 6): Looking within and across markets, how do current conditions and barriers impede the growth of VRPs? In this sense, how do these barriers contribute to reduced material efficiency and slow the transition to circular economy?
- **Economy perspective** (Section 7): Developed/industrialized and developing/newly industrialized economies alike are currently engaging in VRPs at varied levels for economic and environmental reasons; how do the aggregated benefits and impacts of VRPs compare across key markets, under different conditions? The impacts and benefits of VRPs for the case study products of this assessment, aggregated to the level of each sample economy, are presented in Section 7 across each of the environmental metrics of focus.

As part of a transition to circular economy, it is also essential that action be taken to improve the efficiency and ease of both VRP product production and exchange. To contribute to scaling of circular economy, firm-level and government-level responses must be deliberate and organized. While VRPs highlight essential process innovations that contribute to circular economy, there are two response perspectives derived from produce case study and sample economy-level analyses that deserve attention, as covered in Section 8:

- **Design perspective** (Section 8.2): What new efficiencies are possible through product design innovation (e.g. design for disassembly) that could increase the collection, application, and demand for VRP products in the market?
- **Policy- and decision-maker perspective** (Sections 8.4 and 8.5): How can government and industry decision-makers facilitate growth of VRPs while ensuring user/consumer protection, through innovative policy that facilitates safe presence of VRP products in the market?

Some key high-level insights, implications, and opportunities that may help inform higher-level policy-making and industry decision-making considerations beyond case study applications are discussed in extensive detail Section 8.

1.2 Introduction to the circular economy

In today's increasingly globalized and growing industrial economy, traditional linear models of production and consumption, often referred to as "take, make, use and dispose", are insufficient. They allow the materials, components, and embodied value of products to be lost from the industrial system, most notably at the end of life (Sundin and Lee 2012, McDonough and Braungart 2010, Bocken et al. 2016). As a result, these linear production models require continuously high levels of new (virgin- *and* recycled-sources) resource input and production activity to meet ongoing demand, and thus create negative environmental impacts—emissions, waste generation, and water consumption (Ellen MacArthur Foundation 2013a, World Economic Forum and Ellen MacArthur Foundation 2014). It is becoming increasingly clear that take-make-use-dispose models of industrial production are incompatible with the sustainable development to which global communities aspire.

In the absence of material and product collection and reuse, growing populations and incomes are expected to drive dramatically increasing demand for raw material inputs to production (UNEP 2011, 2014, 2016a). While increased production activity can offer economic growth and labor market advantages, it can also lead to increased consumption of raw materials and fuels, and increased environmental degradation from extraction activities and transportation, increased associated emissions and waste generation (UNEP 2011, 2016a). The pursuit of sustainable economic systems must be the long-term objective (United Nations 2018); however in the short term economic growth remains a central pillar of national objectives and strategies

Accepting the tension between these short-term and longer-term objectives, short-term efforts must seek out opportunities for increased material efficiency, resource efficiency and productivity, including marginal reduction in the environmental impacts of production (UNEP 2016b). This must occur in parallel with efforts focused on longer-term social and system transformation in pursuit of sustainable economic systems, including the ultimate decoupling of production from negative environmental impacts. The International Resource Panel (IRP), an independent scientific panel operating under the United Nations Environment Programme (UNEP) parent organization, has published extensively on the implications, challenges, and potential to achieve such decoupling, suggesting that decoupling strategies are necessary for meeting the United Nations' Sustainable Development Goals (UNEP 2016a, 2014, 2011).

In this pursuit, industrial researchers, policymakers, and economic experts alike are beginning to explore the concept of a Circular Economy—a framework in which outputs from every stage of the life cycle become inputs into another, partially offsetting the need for new materials and energy-intensive manufacturing activities, while reducing waste (Liu et al. 2018). Some examples of this increasing interest include the European Commission's Circular Economy Package (Bourguignon 2016), The Netherlands' Government-side Programme for a Circular Economy (Government of the Netherlands 2016), and China's 13th Five-Year Plan (Koleski 2017).

Current understanding of circular economy has evolved over time to incorporate a range of perspectives and concepts that relate to the closing of material and energy flow loops. Relevant theoretical influences originate in the concepts of performance economy (Stahel 2010), cradle-to-cradle (McDonough and Braungart 2010), industrial ecology (Graedel and Allenby 1995), and the laws of ecology (Commoner 2014). Additional key perspectives have contributed to the focusing of understanding about circular economy even further: Bocken et al. (2016) position the closing of resource loops via circular economy within *design and business model strategies*; Yuan, Bi, and Moriguichi (2006) focus on circular or closed flows of materials and energy, and the use of materials and energy over *multiple* phases in the context of China's implementation of the Chinese Circular Economy Promotion Law; and the Ellen MacArthur Foundation (Ellen MacArthur Foundation 2013b, World Economic Forum and Ellen MacArthur Foundation 2014) highlights and emphasizes the differences between *biological and technical systems*, and their role within the *industrial* economy.

Considering the range and scope of literature on circular economy, Geissdoerfer et al. (2017) propose a definition for the Circular Economy that is particularly relevant for this study: "*A regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling.*"

The circular economy has been positioned as an essential systemic perspective that can help to mitigate the loss of material, function, and embodied value created by traditional consumption (Ellen MacArthur Foundation 2013a). However, achieving these benefits requires engaging value-chain stakeholders in behavioral and social system transformation, and designing industrial economic and production systems to enable, accept, and support system circularity. In this pursuit, accepting the industrial economy focus of circular economy, three central needs are emerging as key strategies for enabling increased system circularity:

1. maximizing collection and capture of materials at the 'gaps' between lifecycle stages at which loss could occur;
2. retaining the highest possible value of materials, once recovered; and
3. remodeling the linear system through infrastructure development, process innovation, and product innovation to increase the use of high-value recovered materials as inputs into the production system, in place of raw inputs.

Inherent in these strategies is consideration of product design that can be employed to facilitate the pursue of collection, capture, value retention and recovery, and other aspects of the circular economy system. The collection of materials, and the methods used to re-employ those materials, thus become essential tactical decisions that must be considered at both policy and firm levels. A growing focus on innovation within existing traditional linear production systems can, to this end, be leveraged as a key driver of the transition to circular economy. Innovation in production processes, business models, product design strategies, and policy and trade frameworks can all be focused to allow adaptation towards system circularity, and therein the foundation for a comprehensively circular economy in the future can be laid. This is particularly relevant in the case of technical nutrients that must be cycled through a circular economy, where employing product life extension activities and circular recovery-production systems is critical to the economic viability of existing linear systems (while they exist, and in transition) and future circular economies.

In the absence of material and product collection and reuse, growing populations and incomes are expected to drive dramatically increasing demand for raw material inputs to production. While increased production activity can offer economic growth and labor market advantages, it can also lead to increased environmental degradation from extraction activities and transportation, increased associated emissions and waste generation, and increased consumption of raw materials and fuels. To succeed at sustainable and equitable economic development across all corners of the planet, we must figure out how to decouple production from these impacts.

1.2.1 The intersection of sustainability and circular economy

Despite its many varied definitions, sustainability in the context of environmental systems and ecology generally refers to the ability of natural systems to maintain (or regenerate) themselves at a certain rate or level over time, given the presence of limitations and impacts of human activity (Geissdoerfer et al. 2017, Bruntland 1987, Ehrenfeld 2005). Extended, current understanding of sustainability includes the acknowledgement of interdependent and reinforcing social, economic, and environmental systems (UN General Assembly 2005), and the expectation of '… *the balanced and systemic integration of intra and intergenerational economic, social, and environmental performance*." (Geissdoerfer et al. 2017).

Discussion and concept-development around sustainability has occurred for far longer than has the discussion on circular economy, and the objectives of sustainability are far broader, aiming to benefit the interdependent stakeholders and systems of environment, economy, and society (Elkington 1997). Similarities between sustainability and circular economy include an emphasis of the implications of planetary-scale problems, a global perspective informed by awareness of the negative environmental impacts of human activity, and the need for the engagement of multiple stakeholders in responding to these challenges (Geissdoerfer et al. 2017, Bruntland 1987).

However, important to this study are some key differences between the concepts of sustainability and circular economy (refer to Table 2). Given its emphasis on industrial systems, circular economy tends to focus on the direct benefits accrued within the industrial economy and to economic stakeholders, acknowledging the secondary (and/or marginal) benefits that may also accrue to environmental and social systems and stakeholders (Geissdoerfer et al. 2017). This approach is similar to assumptions used by Cooper et al. (2017, 1358), in which behavior changes required by the consumer (e.g. reduced consumption) are not central to the models or the discussion, and consumer utility (e.g. expected demand levels) are maintained.

In addition, while sustainability acknowledges the important influence and role that all stakeholders need to play, the nature of circular economy particularly emphasizes the roles of government (policy-makers) and industry (business decision-makers) (Geissdoerfer et al. 2017).

As clarified in Table 2, in alignment with the current literature on circular economy, and based on the availability of resources, the scope of this assessment in the context of circular economy thus only covers some aspects of traditional sustainability perspective (refer to Figure 1).

The industrial economy context of the predominant circular economy interpretations has consequences: first, the allocation of primary responsibility for transition to circular economy to policy-makers and industry necessitates a focus on the financial and economic opportunities that can be enabled via circular economy; at the very least, the financial opportunities are highlighted alongside the opportunity to reduce negative environmental impacts. This emphasis may create tension between sustainability objectives focused on the reduction of negative environmental impacts, and circular economy objectives which may consider environmental impact reduction in the context of economic priorities and needs. This tension is accounted for in this report, wherein the assessment of environmental impacts accompanies, and are often discussed relative to, the assessment of economic opportunities (refer to Sections 3, 5, and 7).

Table 2: Contrasted scope, stakeholder roles, and impact emphasis of sustainability and circular economy

	Sustainability	Circular Economy
Scope emphasis	• Broad interconnected social, economic and environmental systems	• Industrial economic systems
Stakeholder role & responsibility emphasis	• All stakeholders to social, economic, and/or environmental systems • Differing, but equally important roles and responsibilities	• Government and industry • Other stakeholders as they may relate to the achievement of circular economy objectives
Impact emphasis	• Broad environmental: Views environmental systems as foundational and essential to sustainable social and economic systems • E.g. energy consumption; environmental footprint; waste generation	• Economic and environmental: the pursuit of negative environmental impact reduction, considered in context of the economic implications • E.g. resource efficiency; material efficiency; resource productivity

Modified from Geissdoerfer et al. 2017

It must be acknowledged that any discussion of circular economy emphasizing industrial systems and economies is at risk of excluding non-industrial economies, as well as stakeholders outside of government and industry roles. These topics, and their integration into this report, are discussed further in Sections 1.2.2 and 1.2.3, respectively.

1.2.2 Sustainability and circular economy in non-industrialized economies

In terms of global political economy, economies that fall under the term ‘non-industrial’ refer to those economies that do not have highly developed manufacturing infrastructure or enterprise, and in which the capital to pursue industrial activity may be in short supply. These economies are often referred to as the “majority south”, due to their relative geographic location, and are contrasted with the “industrialized north” (Cranston and Hammond 2012, Cranston and Hammond 2010, Hammond 2006, Allen and Thomas 2000). The ‘majority south’ accounts for the majority 80 per cent of the world’s population that resides in non-industrial economies (Cranston and Hammond 2012, Hammond 2006).

In the context of sustainability literature, it is more common to emphasize the socioeconomic and political conditions of non-industrialized economies. These topics are discussed as an assumed precursor to sustainability initiatives and practices, with industrial transition strategies often focused on economic development, and the need for support and technology transfer from richer, more industrialized economies. With the majority of the world’s population residing in non-industrialized economies, and the often extensive carbon footprints of these economies, it is clear that the adoption of more sustainable practices is critical (Cranston and Hammond 2012, Hammond 2006).

However, the applicability of circular economy and its industrial economy origins to non-industrialized economies raises several questions: first and foremost, the circular economy emphasizes the transformation of industrial systems; how then to construct circular industrial economies where industrial systems may not currently exist? In addition, the absence of industrial systems does not imply the absence of economic systems – instead, non-industrial economies may tend towards a greater agricultural base, with limited structure in manufacturing and non-farming sectors (Johnston and Kilby 1975, Allen and Thomas 2000).

At the very least, strategies for pursuing and implementing circular economy require emphasis, resource allocation, and priorities that are appropriate for the conditions of different economies; in other words, the mechanisms by which an industrialized economy pursues circular economy may necessarily differ from the mechanisms by which a non-industrialized economy pursues circular economy.

The case study products and sample economies assessed in greater detail in Sections 5, 6, 7, and 8.2 are most closely focused on commercial/industrial products and activities in industrialized economies. The limitations associated with the incorporation of non-industrialized economies into the case studies of this report are discussed in greater detail in Section 4.4, and relate primarily to issues of data availability and limitations of the models. However, additional discussion of the potential insights, learnings and opportunity for non-industrial economies to engage in circular economy practices can be found in throughout the discussion in Section 8.

The assessment and study of circular economy initiatives and opportunities is relatively recent; while there is great urgency for stakeholders of all nations to act quickly to mitigate environmental damage, discussion of appropriate scope, framework, approach, metrics and indicators, and relevance of circular economy are on-going. It is also clear that different approaches to circular economy may be needed depending on the unique conditions faced by specific sectors and economies, some of which are discussed in Section 6. While the emphasis of this assessment is necessarily upon commercial/industrial products, commercial/industrial processes, and industrialized economies, this report provides insights into the product-, process-, and economy-level implications of pursuing different circular economy strategies under a variety of socioeconomic development conditions.

1.2.3 Interests and innovation: stakeholders within a circular economy

The broad goal of sustainability requires extensive transformation, not just of the production systems that are the emphasis of this report; they also require transformation of consumption patterns, disposal behaviors, and society sub-systems including politics, social structures, and physical infrastructure. From this perspective, it is understandable that the transformation for sustainability requires the engagement of every stakeholder on the planet.

The term social innovation has been used to describe the innovative activities, behaviors, programs and organizations that arise to help society address some unmet need (Mulgan et al. 2007). In the context of sustainability, these innovations can include new ways of viewing and managing ecosystems and ecosystem services, new systems and institutions to help facilitate improved environmental performance of producers and consumers alike, and even stakeholder engagement and education (Center for Social Innovation 2018). A key example of such innovation is the evolution of the ‘collaborative’ or ‘sharing’ economy, in which users share resources with reduced interventions from industry, in the interests of increasing the productivity of resources and products (as measured by usage rate) (Richter, Kraus, and Syrjä 2015, Milios 2016). The emphasis of this social innovation is on utility achieved through renting or borrowing goods, rather than owning them, and places less emphasis on the traditional customer-business relationship (Milios 2016).

While the sharing economy may offer innovation that can lead to sustainability objectives of enhanced resource efficiency, the transition away from traditional markets may present concerns from traditionally-organized industry stakeholders and producers. Alongside social innovations, business model innovations are also being developed by industry stakeholders. These business model innovations offer a new way of integrating sustainability interests into the production-consumption system, without diminishing the role of industry (Milios 2016). The product-service system (PSS), discussed in greater detail in Section 8.2.1, presents a business model innovation that incorporates more integrated products and services that consider both customer needs and product life-cycle considerations (Mont 2002, Tan 2010). Although PSS can vary in type, some common approaches include product sales that entails additional maintenance services and take-back agreements, user-oriented approaches that focus on leasing, rental, sharing, or pooling, and results-oriented services that focus on the provision of a service rather than on the product (Tukker 2015a, Milios 2016).

Differentiated from sustainability, stakeholders to circular economy are theoretically broad, but practically constrained to three primary groups most directly engaged in either the production or consumption aspects of the industrial economy: government, industry (including designers), and customers/users. As highlighted by Zink and Geyer (2017), the additional influences and dynamics of various markets within a circular economy create complexity and unpredictability related to preferences, behaviors, and decisions. However, as discussed in Section 6.2, the unique nature and perspectives of key stakeholders to the industrial systems of circular economy are essential considerations of any strategy to pursue circular economy. Thus, although the spectrum of stakeholders is appropriately limited for circular economy, the responsibility for the necessary social and systems innovation needed to facilitate a transition to circular economy is highly relevant. While the limitations of the case studies in this report are outlined in Section 4.4, significant discussion related to stakeholder interests, perspectives, resulting barriers, and potential roles and responsibilities going-forward, are incorporated into Sections 6, 7.2 and 8. Especially pertinent to this report, the evolution of business model innovation evolving alongside social innovation is discussed in greater detail in Section 8.2.

1.3 Introduction to value-retention processes within a circular economy

Within the circular economy framework, the cycling of technical nutrients falls across several essential systems: recycling systems, refurbishment and remanufacturing systems, arranging direct reuse systems, and repair/maintenance systems. With the exclusion of recycling, in which all recovered items are reduced to material-level, Value-Retention Processes (VRPs) serve to maintain all, or part of the integrity of the original product or component by keeping the original structural form of the product or component. The VRPs specifically studied in this report are: remanufacturing, refurbishment (including comprehensive refurbishment), repair, and arranging direct reuse.

The preservation of product and/or component integrity serves to further increase the marginal benefits of VRPs: by maintaining the original product or component structural form, fewer resources are required for production (e.g. electricity), and fewer wastes are generated (e.g. emissions).

1.3.1 Value-retention processes as a gateway to material recycling

Recycling refers to the reprocessing of waste into products, materials or substances; specifically, the reference to recycling throughout this report refers to the reprocessing at the material-level (Annex IV B to the Basel Convention).

While material recycling (henceforth referred to simply as ‘recycling’) is not a focus of this study, it remains an integral and important aspect of any circular economy. There is a common misperception that VRPs may detract from, or compete against recycling; in fact, all VRPs and recycling are essential within the context of a circular economy[2]. From this perspective, and like accepted waste management hierarchies[3], where *value-retention processes* ensure that material value and functionality are retained within the product, once functionality has degraded it is the *recycling* system that ensures that material value is retained within the broader system.

As described in Figure 3, resources enter into a horizontal production loop in which they are used as inputs to materials and/or parts that are then incorporated, via manufacturing, into a product; after the product-stage (e.g. end-of-use or EOU) there is an opportunity for disassembly and reutilization of parts, components, and/or modules in cases where sufficient infrastructure and systems exist. In these cases, the opportunity to further direct parts/components/modules into a cascading loop and be integrated into new production and product-use phases is created via VRPs. However, when it is no longer possible to retain these items within the

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[2] For the purpose of this study, we have defined value-retention processes as those activities, typically production-type activities that enable the completion of, and/or potentially extend a product’s service life beyond traditional expected service life. We thus distinguish between value-retention processes and recycling, while in reality recycling is part of a circular economy. See also the glossary of key terms.

[3] According to the European Commission’s Waste Framework Directive (Directive 2008/98/EC, Article 4), the waste hierarchy is applied as a priority order in waste prevention and management legislation and policy: (a) prevention; (b) preparing for re-use; (c) recycling; (d) other recovery, e.g. energy recovery; and (e) disposal. The United States’ Environmental Protection Agency employs the Waste Management Hierarchy as a ranking approach for sustainable materials management strategies in decreasing order from most environmentally preferred: source reduction and reuse; recycling/composting; energy recovery; and treatment and disposal.

production system, for functional and/or economic reasons, they can flow out of the cascading loop into recycling processes that ensure the recapture and retention of associated material value within the system. Implicit in the cascading system is that a product can reach EOU several times successively before reaching end-of-life (EOL). This is discussed in greater detail in Section 3.1.

A complementary perspective is that all products will eventually reach a point at which they no longer qualify for arranging direct reuse, repair, refurbishment or remanufacturing – either because of the associated cost, or because their implicit quality and utility potential has been degraded. At that point, there is still an essential need for efficient and effective recycling systems to recover the value of the materials contained within the product, and to recirculate those materials back into circular materials economy.

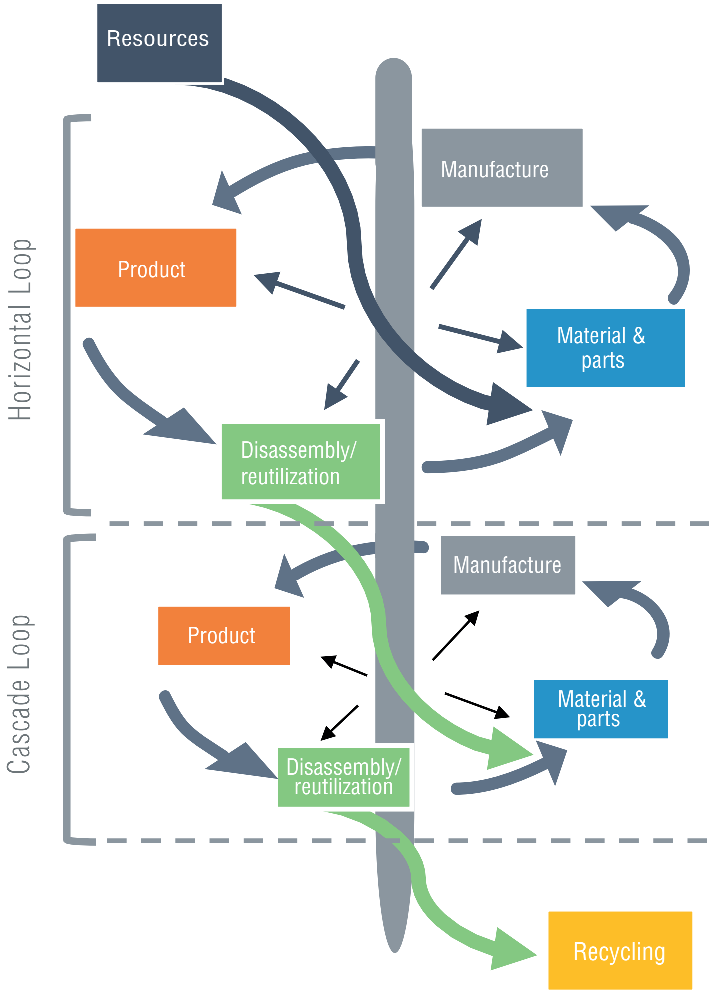

Figure 3: Recycling within a cascading material value-retention system

Recycling, alongside all the VRPs assessed within this report, is focused on the maximization of value retention under complex and varied product and infrastructure conditions. While recycling is not a focus of this study, this analysis has assumed the imperative presence of recycling systems as an important complementary function within the circular economy for recovering material value when a product has degraded below the requirements of VRPs.

2

Clarification and differentiation of value-retention processes

One of the main challenges facing VRPs around the world, as corroborated via international market access negotiations (World Trade Organization 2009) and the US International Trade Commission (USITC) (2012), is the wide range of definitions and interpretations of reuse and life extension processes. Much of the regulation of these governing definitions and interpretations originated out of concern for the protection of human health and the environment.

Gharfalkar, Ali, and Hillier (2016) show in their systematic analysis of peer reviewed literature the inconsistencies and lack of clarity that exist between the definitions or descriptions of repair, reconditioning, refurbishment and remanufacture. There are often multiple issues at stake, including common terminology differentiations made within and across sectors, as well as regulations focused on protecting consumer interests in certain countries. For example, while the VRP activity called '*reconditioning*' by those in the electronics industry (as preferred by the Professional Electrical Apparatus Recyclers League), '*rebuilding*' by the Federal Trade Commission, and '*remanufacturing*' under a definition as accepted by the World Trade Organization (WTO), the intent for each of these terms is the same: "*…the process of returning the electrical product to safe, reliable condition…*". Alternately, the medical sector typically uses the term '*refurbishment*' for the same VRP that the aerospace sector would use the term '*overhaul*'. In fact, both definitions are clearly describing what would be considered '*remanufacturing*' in other sectors.

The concept of waste, as defined in the Waste Framework Directive (Directive 2008/98/EC), offers an important starting point for this discussion. As "*… any substance or object which the holder discards or intends or is required to discard*", the term 'waste' may apply to both recovery and disposal activities, it may have neutral, positive or negative commercial value, and the act of discard can be intentional, unintentional, or can occur with or without knowledge of the holder (European Commission 2012). From this perspective, products undergoing one of the VRPs assessed in this study may, under certain conditions and in EU member states, meet the definition of 'waste' and fall under the regulatory purview of the Waste Framework Directive.

Also relevant to the definitions, practice, and oversight of VRPs is the concept of 'End-of-Waste' (EOW), which refers to the conditions under which certain specified waste shall cease to be waste under the Waste Framework Directive. These inclusive conditions require that the substance or object has undergone a recovery; that the substance or object is commonly used for specific purposes; that a market or demand exists for such a substance or object; that the substance or object fulfills the technical requirements for the specific purposes and meets the existing legislation and standard applicable to products; and that the use of the substance or object will not lead to overall adverse environmental or human health impacts (European Commission 2012). From this perspective, products undergoing one of several of the VRPs assessed in this study may, in EU member states, have EOW status under the Waste Framework Directive. Incompatibility of the definitions of what constitutes waste between economies engaged in VRPs and/or trade can create significant complications for industry members and policy-makers alike.

Given the potential confusion, for the purposes of this study it is essential to identify and retain consistent definitions to differentiate between each of the VRPs under examination. This study adopts VRP definitions and terminologies, consistent with internationally recognized sources (where they exist) that include, but are not limited to, the Basel Convention Glossary of Terms (Document UNEP/CHW.13/4/Add.2)[4] and the Waste Framework Directive.[5] These processes are distinguished, relative to one another in Figure 4 and discussed in the following sections.

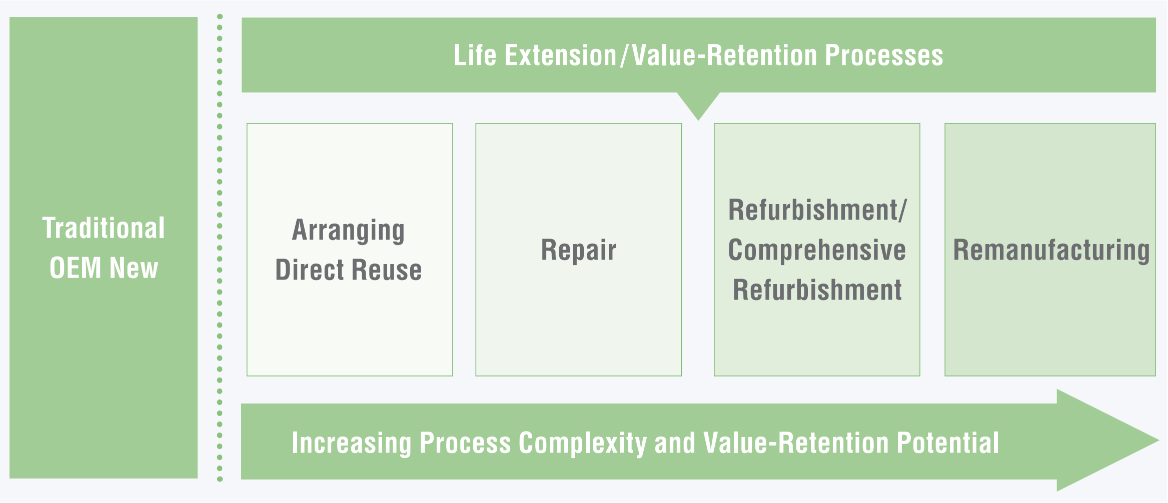

Figure 4: Definitions and structure of value-retention processes within this report

The following definitions for VRP's are derived largely from terminology contained in a glossary of terms that has been adopted at the Thirteenth meeting of the Conference of the Parties to the Basel Convention (COP 13) in May 2017 (Document UNEP/CHW.13/4/Add.2).

These definitions are included to demonstrate the complexity associated with clearly defining, and garnering agreement, on the appropriate definitions for different circular and life extension processes. While the Basel Convention is an international agreement, Parties choose to implement the terms of the agreement in their own way. Given the governance of the Basel Convention over a range of trade activities, where a circular or life extension process is defined for the Basel Convention as shown in Figure 5, it is accepted for the purposes of this report. It is noted that the "Technical guidelines on transboundary movements of electrical and electronic wastes and used electrical and electronic equipment, in particular regarding the distinction between waste and non-waste under the Basel Convention", as adopted by the Conference of the Parties to the Basel Convention at its twelfth meeting in May 2015 (Document UNEP/CHW.13/INF/7),[6] encompasses a terminology specific to electrical and electronic equipment. Please note that, as the Basel Convention definitions do not include remanufacturing, it is not included in Figure 5.

It should be noted that terminology and definitions for VRPs remain one of the most significant issues and challenges to increased scale and uptake of VRPs in economies around the world. There are numerous initiatives to help reduce the barriers created by legal definitions of VRPs, often initiated by industry to help educate and inform the markets they serve. Where appropriate and insightful, terminology and definitions from these non-official sources have also been included to demonstrate the range and significance of the definition challenge. This is discussed further in Section 6.

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[4] (Conference of the Parties to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal 2017).

[5] (European Commission 2008).

[6] (Conference of the Parties to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal 2014).

Reuse	Direct reuse	Repair	Refurbishment
The using again of a product, objective or substance that is not waste for the same purpose for which it was conceived, possibly after repair or refurbishment.	The using again of a product, object or substance that is not waste for the same purpose for which it was conceived without the necessity of repair or refurbishment.	Fixing of a specified fault in an object that is a waste or a product and/or replacing defective components, in order to make the waste or product a fully functional product to be used for its originally intended purpose.	Modification of an object that is a waste or a product to increase or restore its performance and/or functionality or to meet applicable technical standards or regulatory requirements, with the result of making a fully functional product to be used for a purpose that is at least the one that was originally intended.
(Document UNEP/CHW.13/4/Add.2)	(Document UNEP/CHW.13/4/Add.2)	(Document UNEP/CHW.13/4/Add.2)	(Document UNEP/CHW.13/4/Add.2)

Figure 5: Definitions relevant to VRP activities as adopted under the Basel Convention

2.1 Arranging direct reuse

As indicated, for the purposes of this study the definition of “Arranging direct reuse”, as set out in Document UNEP/CHW.13/4/Add.2 is utilized:

> **Arranging direct reuse:** The collection, inspection and testing, cleaning, and redistribution of a product back into the market under controlled conditions (e.g. a formal business undertaking).

Arranging direct reuse does not include reuse that occurs mostly through the undocumented transfer of a product from one customer to another. Under arranging direct reuse, no disassembly, removal of parts, or addition of parts occurs. The significance of this Value-Retention Process is that only those products that are in sufficient working condition, not requiring any component replacement or repair, and to which quick and easy aesthetic touch-ups can be performed, qualify as arranging direct reuse products. These products are not guaranteed to meet original specifications and are typically offered to the market at a significant price discount, with no, or at least a much-modified product warranty. Please refer to Figure 6 for a high-level description of key arranging direct reuse process stages.

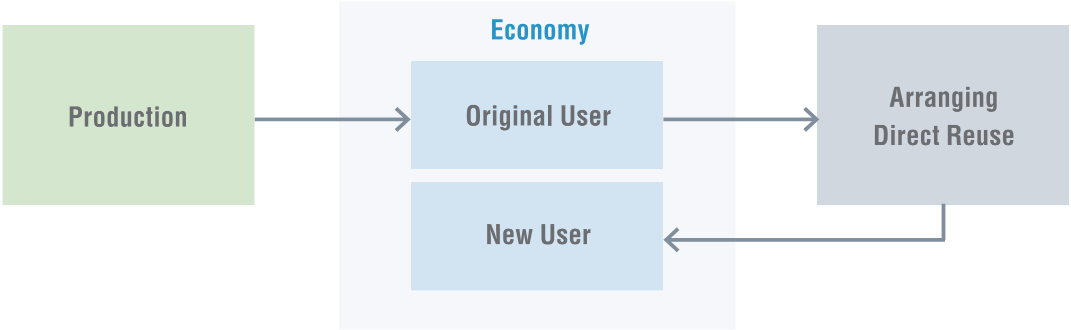

Figure 6: Descriptive summary of arranging direct reuse process


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Arranging direct reuse is often enabled when a product reaches its EOU prematurely: the owner may require an upgraded product, may no longer need the product, or may have a change in preferences. Alternately, the usage/service requirement rate may have been less than expected during the products service life, and as such it is able to surpass that expected life beyond scheduled EOL. In any case, although the product has reached EOU, it has not yet fulfilled its service life. Arranging direct reuse enables the product to continue to maintain productivity through use, instead of prematurely being discarded into a waste or recycling system.

2.1.1 Arranging direct reuse in case study sectors

In the case of the three sectors studied in this report, it is assumed that there is no direct reuse of HDOR parts given the nature of these products. Arranged direct reuse is undertaken for case study vehicle parts products and industrial digital printers.

2.2 Repair

Repair refers to the correction of specified faults in a product. The term encompasses the completion of the expected product technical life (King et al. 2006)

As indicated, for the purposes of this study the definition of “Repair”, as set out in Document UNEP/CHW.13/4/Add.2 is utilized:

> **Repair:** Fixing a specified fault in an object that is a waste or a product and/or replacing defective components, in order to make the waste or product a fully functional product to be used for its originally intended purpose.

It is important to note that, under the Basel Convention, repair is an activity that can be performed on both wastes and non-wastes, and therefore the *need* for repair is not sufficient for distinguishing between waste and non-waste.

For the purposes of this report, “Repair” activities also include those required for known product issues, which ultimately enables the product to complete its original expected life; and the maintenance of a product where, if left unmaintained, is known to constrain the product’s service life and utility to less than what is otherwise expected when recommended servicing is performed. Please refer to Figure 7 for a high-level process description of key repair process stages.

In common use of the term, there may be some confusion related to what constitutes ‘repair’, as there is generally no clear distinction between a ‘repair’ activity, and a ‘scheduled maintenance’ activity, depending on the product, sector and/or industry. For the purposes of this assessment, any repair activity which involves the object or product being returned to the original user is considered to be a “Repair” VRP.

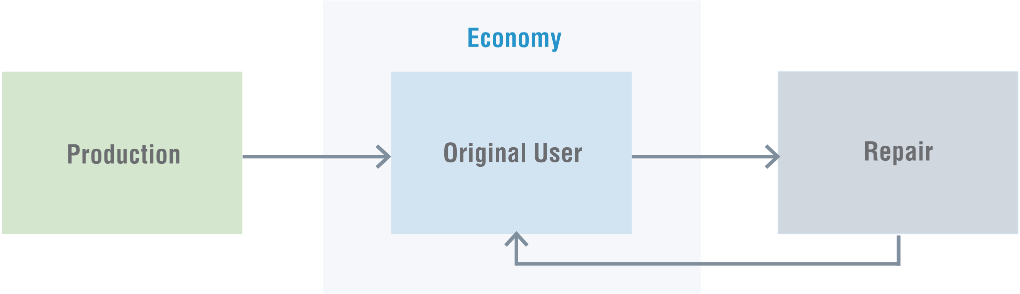

Figure 7: Descriptive summary of repair process

Unlike the other VRPs studied within this assessment, repair activities within the larger system occur elsewhere (Cooper et al. 2017) and they are considered as a separate flow: Most repair activities do not require established infrastructure (collection, diversion, inspection), production facilities (industrial disassembly and reassembly processes), or distribution infrastructure (transportation, distribution, sales). This characteristic differentiates repair activities from other VRP activities under a systems-perspective. In the case of non-industrialized economies, repair represents the vast majority of currently-used formal and informal value-retention activities due to technological, and industrial infrastructure limitations.

Repair activities are performed at the product-level, where a functioning product must have some worn or damaged parts removed and new parts added, in order for it to continue functioning for the duration of its expected life. Rather than the entire product being discarded into a waste or recycling stream due to a worn or damaged part, repair activities enable the continuance of the product's expected life. It is generally accepted that there is no warranty provided for repaired products, except for components that have been replaced in the process (Resource Conservative Manufacturing Consortium 2017).

2.2.1 Repair in case study sectors

In the case of the three sectors studied in this report, it is assumed that repair activities are undertaken for all case study products.


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2.3 Refurbishment

As indicated, for the purposes of this study the definition of "Refurbishment", as set out in Document UNEP/CHW.13/4/Add.2 is utilized:

> **Refurbishment:** Modification of an object that is waste or a product to increase or restore its performance and/or functionality or to meet applicable technical standards or regulatory requirements, with the result of making a fully functional product to be used for a purpose that is at least the one that was originally intended.

It is important to note that, under the Basel Convention, refurbishment is an activity that can be performed on both wastes and non-wastes, and therefore the *need* for refurbishment is not sufficient for distinguishing between waste and non-waste. In addition, the Resource Conservative Manufacturing (ResCoM) shared terminology supports that refurbishment can enable a new partial service life cycle for a product, but not a new full service life cycle, as discussed in more detail in Section 3.1 (Resource Conservative Manufacturing Consortium 2017).

For the purposes of this report, "Refurbishment" activities reflect those as contained in the definition cited above, and include activity terminologies specific to key industry sectors, such as 'minor overhauls' (heavy-duty engines and equipment), and 'upgrades' (electrical and electronic equipment). Relative to other VRPs, refurbishment requires sufficient modification of an EOU product such that its usable operating life could be extended beyond the original design expectation: This requires material replacement and renewal activity that far exceeds 'repair' activity, but which is less structured, industrialized, and quality-focused than 'remanufacturing' activity. A warranty may be provided for major wearing parts of the refurbished product, but it generally covers less than the warranty for a newly manufactured or remanufactured version (Resource Conservative Manufacturing Consortium 2017). The refurbishment process is performed *within repair and/or maintenance facilities* to increase or restore performance and/or functionality or to meet applicable technical standards or regulatory requirements. Please refer to Figure 8 for a high-level process description of key refurbishment process activities.

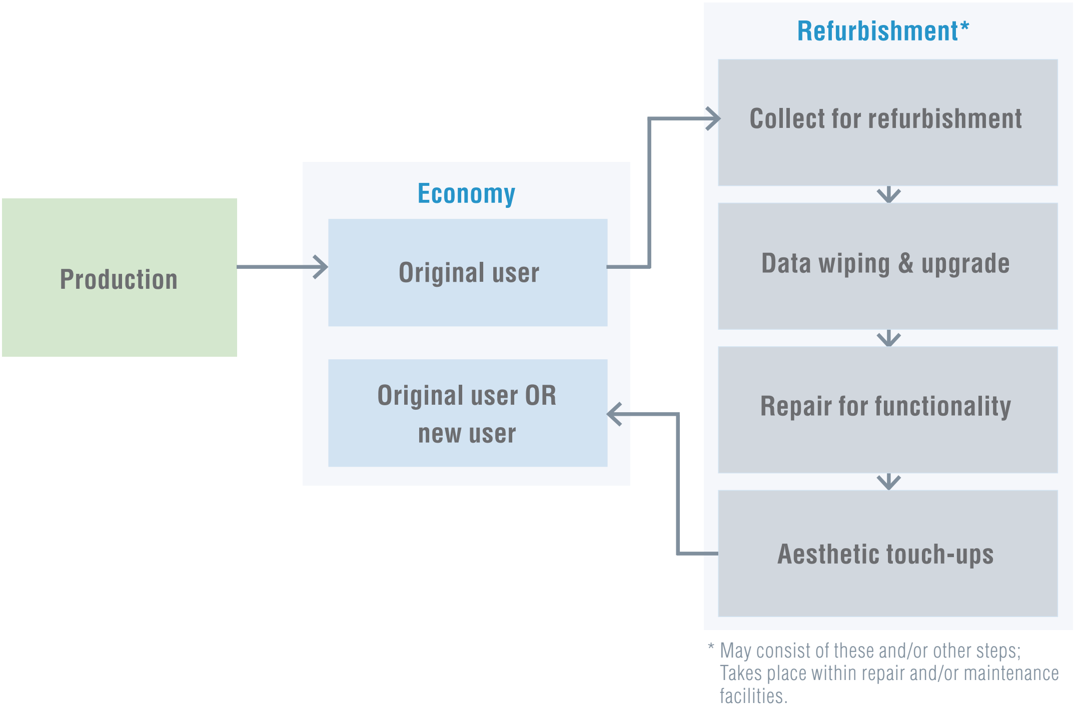

Figure 8: Descriptive summary of refurbishment process

2.3.1 Refurbishment in case study sectors

In the case of the three sectors studied in this report, refurbishment practices are only typically utilized for vehicle parts as outlined below:

1. **Vehicle parts:** *Refurbishment* activities for vehicle parts occur at the component (versus vehicle product) level, and primarily occur under repair or maintenance settings, outside of industrial factory processes. As such, for the purposes of this study it is assumed that vehicle parts undergo more generic standard *refurbishment* activities that restore functionality, and which are therefore categorized within Group 2 as a partial service life process (refer to Section 3.1.2).

It must be noted that despite the general refurbishment practices described above, refurbishment is generally not undertaken for the case study products, and this is reflected in the results presented in Section 5.2.2.

2.4 Comprehensive refurbishment

Importantly, a key insight from this assessment is that there are differing degrees of refurbishment activity that yield differing levels of material value retention and product utility. For the purposes of this report, “Comprehensive Refurbishment” activities are further differentiated from other “Refurbishment” activities as follows:

> **Comprehensive refurbishment:**
> Refurbishment that takes place within industrial or factory settings, with a high standard and level of refurbishment.

Comprehensive refurbishment differs from standard refurbishment in that it involves a more rigorous process within a factory setting, and is only undertaken by certain sectors including, but not limited to industrial digital printers, medical equipment, and HDOR equipment parts. The addition of value during comprehensive refurbishment enables an almost full new service life for the product.

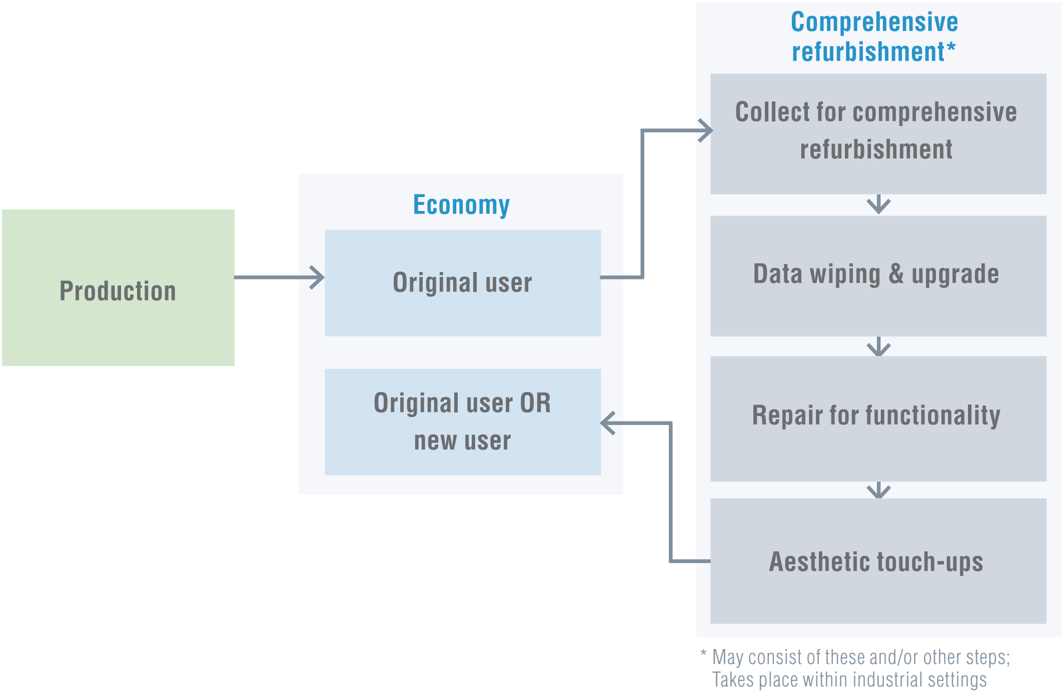

Figure 9: Descriptive summary of comprehensive refurbishment process

Figure 9 describes the complete comprehensive refurbishment process that would take place within industrial or factory settings; accordingly, standard refurbishment activities utilize only some of these steps, at a lesser intensity, and take place within repair or maintenance facilities.

2.4.2 Comprehensive refurbishment in case study sectors

In the case of the three sectors studied in this report, the following comprehensive refurbishment practices are typically utilized for industrial digital printers and HDOR equipment parts as outlined below

2. **Industrial digital printers:** Industrial digital printers have high value even at EOU, and at EOU they are typically managed as an entire product (versus multiple components). This enables more enhanced and sophisticated VRPs to take place: producers are better able to recover the entire industrial digital printer unit, and to undertake comprehensive refurbishment in an industrialized factory setting. As such, for the purposes of this study it is assumed that industrial digital printers undergo comprehensive refurbishment processes that restore value, utility and functionality to the product, and which are therefore categorized within Group 1 as an almost full service life process (refer to Section 3.1.1). The comprehensive


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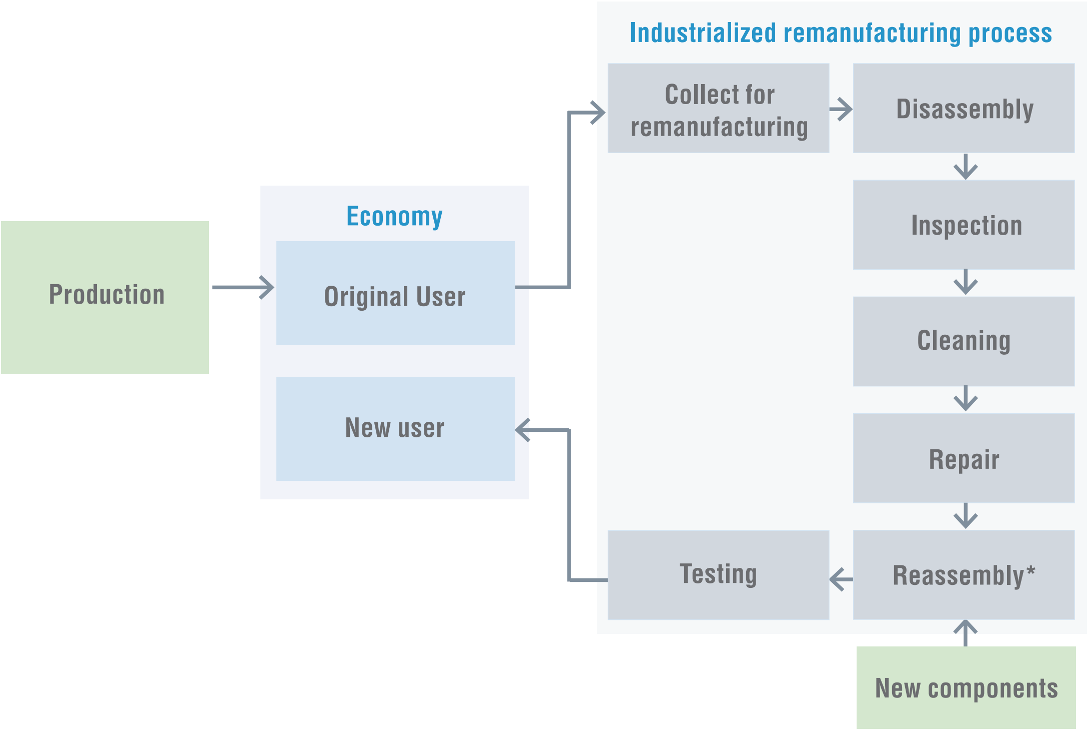
refurbishment processes that are undertaken for industrial digital printers are similar in complexity and rigor to those undertaken for remanufacturing.

3. **HDOR equipment parts:** Like industrial digital printers, HDOR equipment parts have high value even at EOU, and are often designed to require scheduled overhauls to bring functionality and performance back to the promised standard. The HDOR equipment industry has a well-established infrastructure, including design for VRPs and scheduled overhauls, that enables comprehensive refurbishment processes to be undertaken with efficiency. As such, for the purposes of this study it is assumed that HDOR equipment parts undergo comprehensive refurbishment processes that restore value, utility and functionality to the product, and which are therefore categorized within Group 1 as an almost full service life process (refer to Section 3.1.10). The comprehensive refurbishment processes undertaken for HDOR equipment parts are similar in complexity and rigor to those undertaken for remanufacturing.

It must be noted that despite the comprehensive refurbishment practices described above, comprehensive refurbishment is generally not undertaken for two of the case study HDOR equipment part products (HDOR alternator; HDOR turbocharger). This is reflected in the results presented in Section 5.2.3.

2.5 Remanufacturing

The Basel Convention does not specifically address remanufacturing, and as such there is a wide range of definitions and descriptions utilized worldwide. The WTO (2009) has determined remanufactured goods to be: *"…non-agricultural goods that are entirely or partially comprised of parts that (i) have been obtained from the disassembly of used goods; and (ii) have been processed, cleaned, inspected, and tested to the extent necessary to ensure they have been restored to original working condition or better; and for which the remanufacturer has issued a warranty*". Nasr and Thurston (2006) and the ResCoM project (2017) further refine the definition of remanufacturing: where remanufacturing is a specific industrial process of disassembling, cleaning, inspecting, repairing, replacing, and reassembling the components of a part or product in order to return it to "as-new" condition. Upgrades to electronic systems and/or software can also be performed during the remanufacturing process, if appropriate. Please refer to Figure 10 for a high-level process description of key remanufacturing process activities.



* May include upgrade if appropriate

Figure 10: Descriptive summary of remanufacturing process

Similarly, the USITC (2012) defines remanufacturing as: "*An industrial process that takes place in an industrial setting that restores the end-of-life goods to original working condition or better. Firms that provide remanufacturing services to restore end-of-life goods to original working condition are considered producers of remanufactured goods*".

In September 2016, six global automotive remanufacturing associations[7] came to an international agreement on an (automotive sector-specific) remanufacturing definition to enable support and increased awareness of remanufacturing (Motor & Equipment Remanufacturing Association 2016).

> "Remanufacturing is a standardized industrial process[8] by which cores are returned to same-as-new, or better, condition and performance. The process is in line with specific technical specifications, including engineering, quality, and testing standards. The process yields fully warranted products. A core is a previously sold, worn or non-functional product or part, intended for the remanufacturing process. During reverse- logistics, a core is protected, handled and identified for remanufacturing to avoid damage and to preserve its value. A core is not waste or scrap and is not intended to be reused before remanufacturing."

An early and essential priority of this assessment was to effectively bridge these varied definitions and interpretations, and to ensure that this assessment reflected the realistic industry practice. As such, for the purposes of this report, to create alignment, and to ensure a process description appropriately reflective of reality, the following definition of "Remanufacturing" is used for the purposes of this report.

> **Remanufacturing:** A standardized industrial process[8] that takes place within industrial or factory settings, in which cores are restored to original as-new condition and performance or better. The remanufacturing process is in line with specific technical specifications, including engineering, quality, and testing standards, and typically yields fully warranted products. Firms that provide remanufacturing services to restore used goods to original working condition are considered producers of remanufactured goods.

This includes the minimum expectation of an industrial process in an industrial setting, consisting of specific activities including disassembly and cleaning, the requirement for testing and documentation, and the assurance of 'as-new or better-than-new' performance and quality of the remanufactured product. Given the nature of remanufacturing, there may be potential for remanufactured parts or components to be integrated into a different, but related, product such as a more current model. This requires more comprehensive design considerations, which are discussed in greater detail in Section 8.2.

2.5.3 Remanufacturing in case study sectors

The exact process and activity undertaken by remanufacturers necessarily differs by product type: in most cases, remanufacturing includes the complete disassembly of all component parts for inspection and cleaning, however in the case of some products (e.g. industrial digital printers), disassembly only down to the module-level may be appropriate. This is especially true when the module itself has been designed for remanufacturing, in which case, by design, the module may have a longer expected technical life than the product into which it is incorporated. Similarly, different sectors may utilize different reassembly procedures: in the case of medical devices, every disassembled part has an identifying serial number, and must be reassembled into the same remanufactured product; this differs from other sectors where disassembled parts may go directly

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[7] European Association of Automotive Suppliers (CLEPA) (EU), and European Organization for the Engine Remanufacture (FIRM)(EU), Motor & Equipment Remanufacturers Association (MERA) (US), and Automotive Parts Remanufacturers Association (APRA)(US), Automotive Parts Remanufacturers National Association (ANRAP) (Brazil), Remanufacture Committee of China Association of Automobile Manufactures (VRPRA) (China).

[8] An industrial process is an established process, which is fully documented, and capable to fulfill the requirements established by the remanufacturer.

into a general inventory and utilized as needed in the remanufacturing of completely different product units. Design strategies for VRPs are covered in significantly greater detail in Section 8.2.

In the case of the three sectors studied in this report, the following unique remanufacturing processes are utilized:

1. **Vehicle parts:** The vehicle engine, alternator and starter are treated as products themselves. Full disassembly and cleaning activities are performed on each component, which then typically go into a general inventory to be used in the reassembly of a different remanufactured vehicle parts product.

2. **Industrial digital printers:** The production printer and printing presses are treated as products themselves but consist of many internal parts and components as well. Remanufacturing includes disassembly to the primary modular-level (e.g. frame, electronics, cartridges), and full cleaning. Disassembled parts and components may go into a general inventory; however, all parts and components have identifiable serial numbers that are tracked and recorded as they are utilized in the remanufacturing of a different industrial digital printer product.

3. **HDOR equipment parts:** The HDOR engine, alternator and turbocharger are treated as products themselves; full disassembly and cleaning activities are performed, however, given that many HDOR parts have high value and durability, they are often designed for remanufacturing. Thus, it is typical that the HDOR parts core remains together during the remanufacturing process, with only a few newly manufactured parts being integrated during reassembly.

3

Retaining value through circular production models

Product markets around the world have begun to shift in recent years, moving away from a focus on sales volume, and focusing increasingly on value creation and value retention, often through the extension of useful product life (Saelens 2016, Weiland 2014). There are several market forces behind this transition including, but not limited to, the increasing importance of revenue-driving customer relationships and retention, increasingly volatile input material prices, design capability and innovations in modularization, and increasingly efficient collection infrastructure opportunities (Saelens 2016, Weiland 2014). From the industry perspective, value creation in this context includes three aspects (Saelens 2016):

1. Using VRPs to enable greater value realization through repairs, refurbishment or remanufacturing (including upgrades);
2. Reforming product design approaches towards extended value creation; and
3. Shifting customer engagement away from passive transactions to proactive relationships.

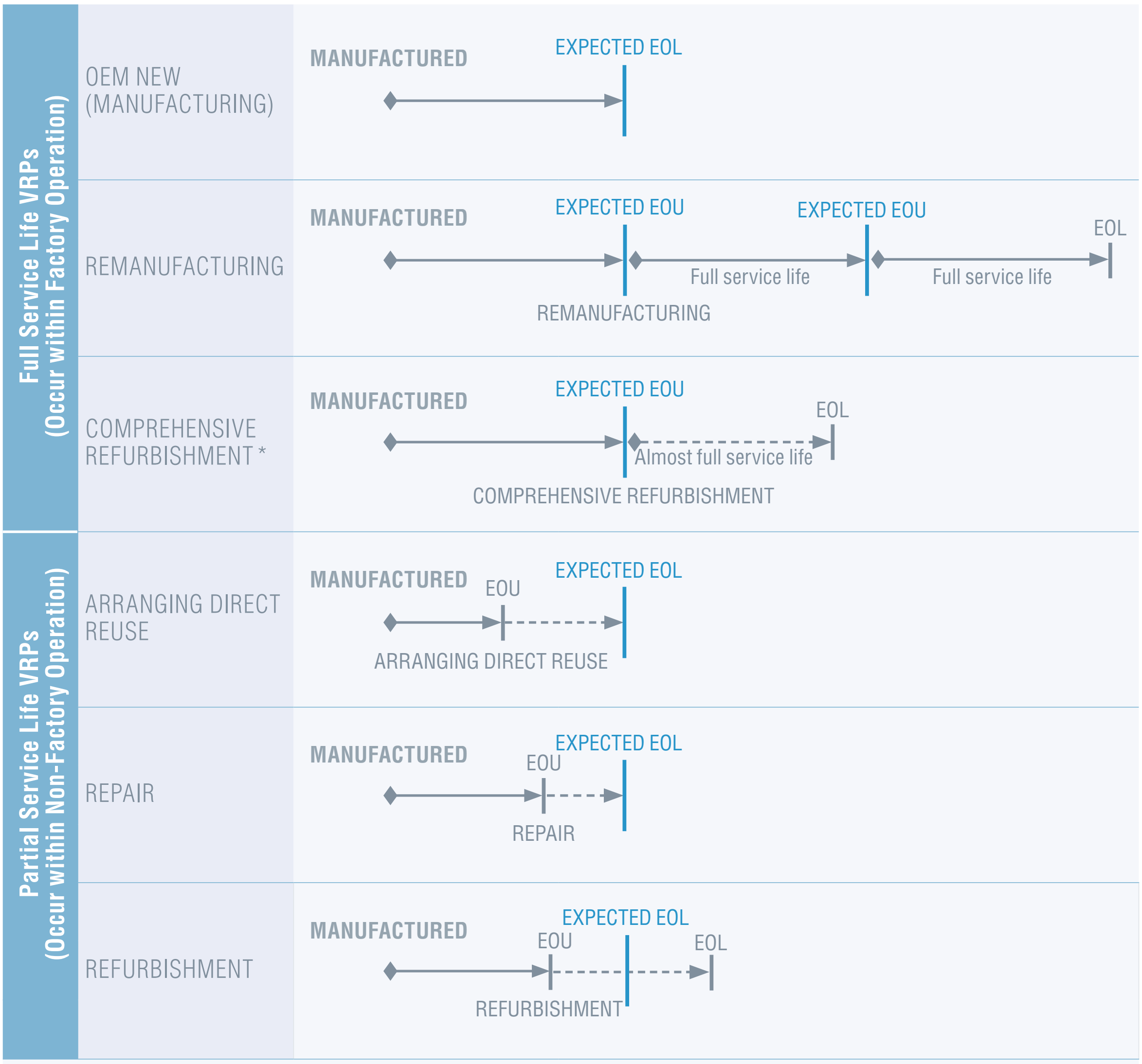
While this study focuses on the actual relative impacts of different VRPs (per item #1), this lens also highlights the important role of industry in ensuring broad consideration of product design (e.g. design for disassembly) as an enabler of VRPs (item #2), as well as the important role of the educated and empowered customer relationship (item #3). For efficiency, definitions for VRPs and other relevant processes/mechanisms are recalled in the following sections.

3.1 End-of-use and end-of-life in the context of value-retention processes

In the context of VRPs, end-of-use (EOU) must be differentiated from end-of-life (EOL), as these critical terms clarify where opportunity for VRPs exist. In the design of new products, specifications for 'expected life' of the product are established. The expected life determines the designed durability and duration of the product: how many cycles, runs, miles, hours, etc. it should perform before maintenance interventions are required to ensure performance (e.g. repair, refurbishment), and how many of these can be performed before the product will degrade beyond use, or reach EOL. Product EOL signifies that there are no other options for the product, but to be recycled or disposed of into the environment. However, if any other option exists to keep the product, and/or its components, within the market – via VRPs – then the product has only reached EOU. As a reminder, EOU may occur without any product issue at all: The owner may simply no longer want or need the fully-functioning product, even though it has not yet fulfilled its entire expected service life, creating an opportunity for arranging direct reuse or another VRP. The opportunity for VRPs lies in determining and understanding how a seeming product *EOL* may actually only be product *EOU*. In other words, once a product or components has reached EOU, it may be directed into EOL options of recycling or disposal – it may also, where infrastructure exists, be directed into a secondary market for repair, arranging direct reuse, refurbishment or comprehensive refurbishment, or remanufacturing instead.

For the purposes of this study, VRPs were organized into two categories (refer to Figure 11): equivalent full service life processes refer to processes that enable the fulfillment of a complete new life for every usage cycle of the product, and includes manufacturing (OEM new), comprehensive refurbishment, and remanufacturing. These processes take place within factory settings and industrial operations. In contrast, partial service life processes refer to processes that enable the completion of, and/or slight extension of, the expected product life, through arranging direct reuse of the product, repair, and refurbishment. These processes take place within maintenance or intermediate maintenance operations. These categories and VRPs are more clearly described in the following sections and are illustrated in Figure 11.

Please note that the length of the lines in Figure 11 are only intended to reflect relative service life duration enabled by different VRPs, and do not suggest quantified actual service life duration. The dotted lines reflect *potential* service life extension enabled by each VRP, as compared to the service life *guarantees* indicated by the solid lines.



* This only exists for certain sectors and products.

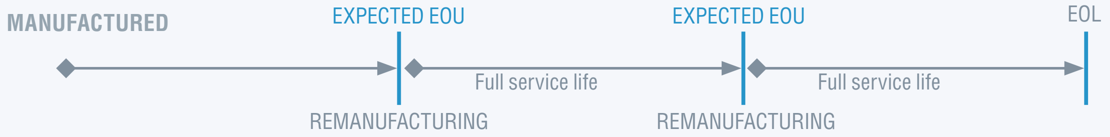
Figure 11: Summary of value-retention processes differentiation within the context of EOU and EOL

3.1.1 Equivalent full service-life processes

Equivalent Full Service-Life Processes
Enable the completion of a full, new service life for every usage cycle of the product.

Manufacturing (OEM New): Manufacturing is the value-added to production of merchandise for use or sale, from using labor and machines, tools, chemical and biological processing, or formulation. Manufacturing processes are the steps through which raw materials are transformed into a final product. The manufacturing process begins with the product design, and materials specification from which the product is made. These materials are then modified through manufacturing processes to become the required part. Newly manufactured products are designed to have an expected useful lifetime, at the end of which they will reach and expected end-of-life (EOL).

Remanufacturing: Remanufacturing is a standardized industrial process, occurring within industrial factory settings, by which cores are returned to same-as-new, or better, condition and performance; and therefore, enabled to complete multiple new usage cycles in the market. Depending on the specific product, remanufacturing can be performed multiple times before final EOL is reached, with value and utility being restored each time, enabling the additional full service life.

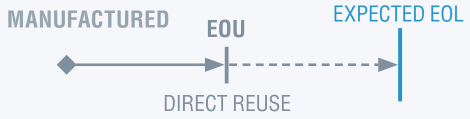


Comprehensive Refurbishment: Comprehensive refurbishment takes place within industrial or factory settings, by which cores are returned fully-functioning, restored performance condition. As such, while comprehensive refurbishment restores original performance, value retention and utility are less than would be achieved through remanufacturing, and an *almost*, but not *full* new service life of the product is enabled.

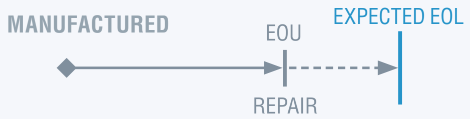
3.1.2 Partial service life processes

Partial Service Life Processes
Enable the continuation of the product to the completion of its expected service life, and may partially, but not fully, extend the original expected service life of the product.

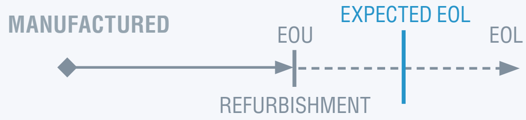
Arranging direct reuse: Arranging direct reuse within this study refers to the collection, inspection and testing, superficial cleaning, and redistribution of a product back into the market under controlled conditions. The significance of this VRP is that only those products that are in sufficient working condition, not as far into their service life, not requiring any component replacement or repair, and to which quick and easy aesthetic touch-ups can be performed, qualify as arranging direct reuse products. These products are not tested for, or returned to original specifications, and are typically offered to the market at a significant price discount, with no, or at least a much-modified product warranty.



Repair: Repair activities are performed at the product-level, where a functioning product must have some worn or damaged parts removed to be restored or replaced, for it to continue functioning for the duration of its expected life. Rather than the entire product being discarded into a waste or recycling stream due to a worn or damaged part, repair activities bring the entire product back to its original functioning capacity for the continuation of the product's expected life.



Refurbishment: Relative to other VRPs, refurbishment requires sufficient modification of an EOU product such that its usable service life is extended beyond the original design expectation: this requires material replacement and renewal activity that far exceeds 'repair' activity, but which is significantly less structured, industrialized, and quality-focused than remanufacturing.



Although is it common to consider and discuss VRPs as 'equivalent' under a broad terminology of 'reuse', to do so would be problematic and misrepresentative. This is because each VRP is distinct in how exactly it affects the product lifecycle, retains material value, and generates utility for the user.

This perspective also presents the implication that full service life and partial service life VRPs may be pursued for different reasons beyond their value-retention potential. For example, where product design necessitates partial life VRP interventions during the product's first service life, partial service life VRPs may be utilized to discourage and/or prevent premature EOL.

3.1.3 Full service life versus partial service life value retention

As identified above, remanufacturing is the only VRP that offers a full new life to the product. Thus, the material and energy intensity of remanufacturing activities—and their associated economic and environmental impacts—must be considered in a context that reflects the value of at least another full new life for the product that is created as a result.

In contrast, repair and standard (non-comprehensive) refurbishment processes are different: repair activities do not truly "extend" the product life, because repair is typically only applied when a product fails or reaches EOU *before* it has completed its expected EOL; standard (non-comprehensive) refurbishment activities may enable an extension of the product life to some degree, but not by a full new product life. In other words, repair and standard refurbishment allow a product to *fulfill*, and potentially *slightly extend*, the original, single, expected life cycle at the expense of requiring additional material and energy inputs beyond original manufacturing process. As such, while the respective impacts of these processes appear to offer significant benefits when compared to original equipment manufacturer (OEM) New and remanufacturing processes, as demonstrated throughout Section 7.3, their impacts must be considered *in addition to* the impacts of the product's original production process.

Similarly, the impacts of arranging direct reuse are typically believed to be effectively negligible. However, it is essential to clarify that arranging direct reuse only extends the initial product life by some finite time, and that product utility and value necessarily diminish over time through use and depreciation. This is demonstrated for example products from the relevant case study sectors in Figure 12 and Figure 13, and is also demonstrated in the product-level analysis, in Section 5.2.[9] As shown, the value of the life extension enabled via arranging direct reuse is not equal to, but rather less than, the complete value of the initial product life cycle.

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[9] For the purposes of this assessment it is assumed that there is no formal arranging direct reuse (undertaken by OEMs) occurring within the HDOR equipment parts system. There may be gray-market and informal arranging direct reuse occurring, in which case a similar depreciation of value and utility over arranging direct reuse cycles should be assumed.

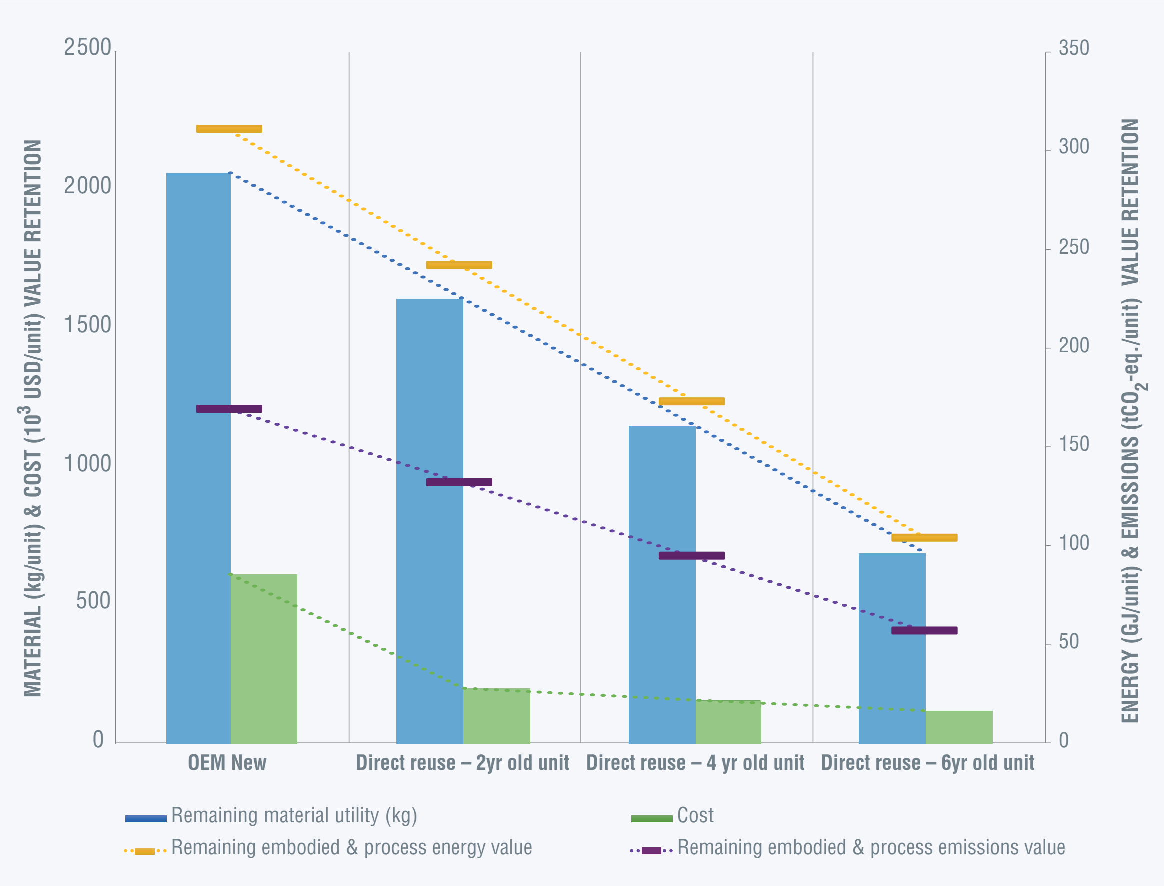

Figure 12: US industrial digital printing press (#2) utility and per-unit value via arranging direct reuse over time

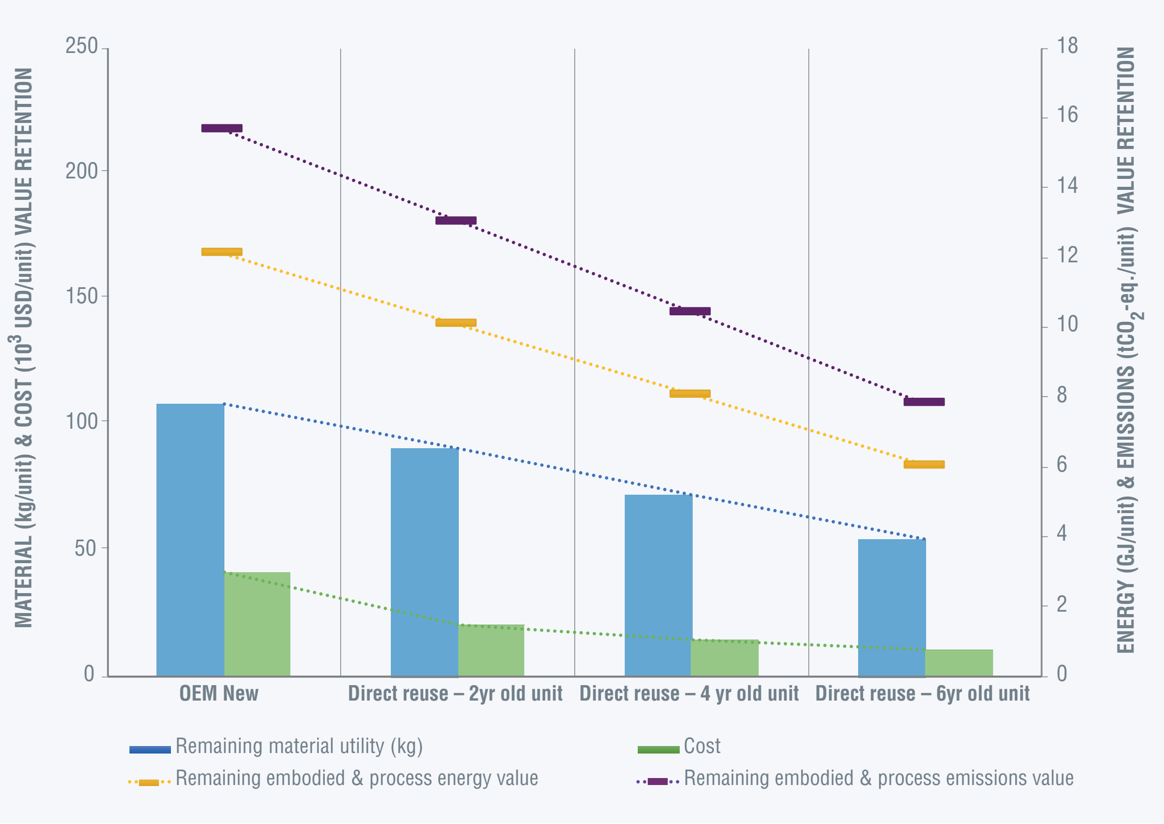

Figure 13: US Traditional vehicle engine utility and per-unit value via arranging direct reuse over time

Please note that remaining material utility (as referenced in Figure 12 and Figure 13) reflects a proxy-approach to describing the material-level degeneration and degradation over time. The OEM New category reflects the cost and material requirement (economic metrics), and the embodied and process energy inputs and the embodied and process emissions (environmental metrics) associated with the brand-new product. Subsequent arranged direct reuse categories (2 year-old unit; 4 year-old unit; and 6 year-old unit) reflect the declining sale price (asset value) achieved through arranged direct reuse. Utilizing common straight-line depreciation accounting of asset value, a linear decline is applied to the material, energy, and emissions values: the negative impact of declining remaining material utility reflects inherent material-level degradation that occurs throughout the course of regular use. In contrast, the declining remaining energy value and emissions values represent the positive marginal environmental impact offsets that are enabled because of the direct reuse of the product. Additional details regarding the product-level results can be found in Section 5.2. Implicit in this is that once materials have fully-degraded, the product is no longer able to function, and has lost all utility for both user and VRP opportunity.

Thus, comparing VRPs solely based on their immediate process impacts does not accurately reflect the value and potential of each in the context of achieving circular economy.

In virtually all cases, contextualizing each VRP in terms of how it is utilized and applied across different sectors is necessary to provide a more complete picture of the potential efficiency gain, impact avoidance, and value retention.

To address this inherent complexity, it is necessary to consider product-level impacts at a more aggregate macro-level, considering the broader economic and environmental impacts that VRPs may have under different circumstances of socioeconomic development and systemic barriers. In this pursuit, Section 7.3 of this report leverages and incorporates the product-level perspective to model the representative impacts of each VRP across a range of economic contexts and scenarios. These models are subsequently used to suggest different states of technical, regulatory, market, and infrastructural barrier conditions, from which the possible trajectory of VRP adoption and the associated impacts at those levels can be estimated. Ultimately, these projections can inform both industrial strategies and policy initiatives in a way that best suits the cost-effective and low-risk transition towards greater VRP adoption, and thus ultimately a more rapid transition to a circular economy.

3.2 Differentiating value-retention processes from traditional recycling and reuse

In addition to defining each VRP clearly, it is also important to distinguish VRPs from other technical material circular economy activities that include reuse and recycling.

Recycling remains a central activity in the reduction of material waste, and decreased dependence on virgin material. As part of the circular economy, recycling recovers base materials at EOU and cycles them at the material-level back into component or materials production. Recycling is: *The series of activities, including collection, separation, and processing, by which products or other materials are recovered from the solid waste stream for use in the form of raw materials in the manufacture of new products, other than fuel for producing heat or power by combustion* (from Document UNEP/CHW.13/4/Add.2 and Document UNEP/CHW/OEWG.10/INF/10 under the Basel Convention).

VRPs, as production process innovations, can contribute to increased use of non-new components in the production process, without losing the value inherent in the structural form of the component. Compared to other circular economy mechanisms like recycling, VRPs can retain the embodied value-added (cost of labor, energy and manufacturing activities) of a component, and thus have the potential to make a greater economic contribution per unit of production when compared to traditional recycling (Hauser and Lund 2008, Klein 1993, Sundin and Lee 2012). VRPs and recycling go hand-in-hand as essential aspects of a cascading material value-retention system, as depicted in Figure 3.

A few specific and key factors differentiate VRPs from other technical processes of a circular economy, which include:

1. the product- and/or component-level perspective of the activity (as opposed to material-level perspective);
2. that the structural form of the product or component is maintained;
3. that the embodied value-added (cost of labor, energy and manufacturing activities) of the product or component is retained; and
4. that the product or component is used again for its original intended purpose.

Despite all efforts to develop and enhance VRP systems within a circular economy, all products will eventually reach EOL. As such, although not the focus of this study, effective and efficient diversion systems and recycling technologies remain an essential part of a circular economy, and an important consideration in addition to the insights presented in this report.

3.3 Repair in the context of circular economy

As discussed in Section 2.2, repair is somewhat different from the other VRPs, as it does not typically take place within industrial settings and is often conducted informally. For these reasons, a more detailed discussion of repair is covered in the following sections.

3.3.1 Envisioned effect and relevant sectors for repair

Defective products can be repaired during one use cycle (same ownership) or between two cycles of use (changed ownership). A number of companies, social enterprises and initiatives are in place:

- to provide the service of repair (e.g. by repair workshops, retailers, manufacturers);
- to help citizens repair or fix products (e.g. community-centered workshops); and/or
- to repair and sell products between two cycles of use (e.g. reuse and repair networks).

Repair of broken and faulty products that would otherwise have been lost as waste is one important element in the strategies of the circular economy model. King and Burgess (2005) concluded that from an environmental point of view repair is the most preferable option to keep a defect product in use, since it uses less energy and material than other VRPs. The volume flow of energy and primary raw materials used for the life-cycle of products for certain services determines the bundle of environmental impacts on the extraction and disposal side (Schmidt-Bleek 1993, Bringezu, Schütz, and Moll 2003, Steinmann et al. 2016).

Longer usage of materials already contained in products avoids waste and mitigates the depletion of natural resources (Bakker et al. 2014, Bobba, Ardente, and Mathieux 2016, Prakash et al. 2012, Kagawa et al. 2008). In terms of energy-using products the benefits achieved are variable and depend on the selected impact category, the extension of the lifetime, the impacts of repair and the efficiency of the replacement product (Ardente and Mathieux 2014, Devoldere et al. 2009, Steiner et al. 2008).

Considering the repair activities of household goods in France, the automotive repair sector represents 60per cent of the repair companies in all sectors; the second most strongly represented sector is the repair of electrical and electronic equipment (ADEME 2014). ADEME, the French environmental agency, states that from 2010 to 2012 the whole sector decreased in terms of employees and enterprises as the turnover of the automotive sector decreased by 3 per cent, while the turnover of the other subsectors increased.

While repair in the automotive sectors seems rather well established, it is still at its infancy for electric and electronic appliances.

3.3.2 Current good practice, obstacles and ways of improvement

There are good practice examples on the emerging repair sector (refer to Box 1 and Box 2). In Germany, a study conducted by Prakash et al. (2016) demonstrates that technical failures are among the main reasons (56 per cent) for product replacements of large household appliances. With regard to electronic notebooks, only 25 per cent of replacements were the result of technical defect.

In the UK, the potential of reusable and repairable items in the waste stream was investigated, and it was found that 23 per cent of all waste electrical and electronic equipment (WEEE) separately collected at the local household recycling centres could be re-used with a small amount of repair (Waste and Resources Action Programme 2011). About 40 per cent of waste collected at the curbside and 51 per cent of the items taken to the local household recycling centers of disposed bulky waste were estimated to be reusable with some minor repaired (Waste and Resources Action Programme 2012).

Product design, and transparency regarding material use and assembly, can critically determine whether product repair activities can be pursued. For instance, product design can complicate the replacement of components, as is illustrated by the IFIXIT smartphone repair-ability scores[10], which show several examples of where the replacement of components is very difficult or not possible without damaging other components. This notably decreases the technical life cycles of products.

A best-practice example is that of Fairphone, for which 'design for reparability' plays a central role[11]. The founder of Fairphone, Bas van Abel, has been awarded the most prestigious environmental prize in Germany in 2016.

The circumstance of high repair costs in relation to cheap new products, missing guidance and lacking tools also constitute difficulties for the consumer to consider repair (Cooper 2004, McCollough 2010).

Moreover, there are life-style issues associated with whether repair activities are undertaken. For many people, having the latest version of a product is strongly associated with personal identity and feelings of success in life (Cox et al. 2013). In order to improve the possibilities of extending product lives "*new cognitive framings, institutional frameworks and social practices that engage with used products in order to save them from ending up as material streams*" will be required (Lauridsen and Jørgensen 2010).

Recently, the European Commission (European Commission 2016) analyzed the environmental effects of a possible increase of the current repair rate by establishing product-related requirements to increase the reparability of products in Europe. The results of the study showed that measures to ensure availability of spare parts for at least a certain amount of years and measures to enable an easier dismantling of products seem to provide the highest benefits in terms of resource savings.

In addition, policies may provide incentives for repair. In Flanders and in Sweden, value-added tax (VAT) on repaired second-hand products including bicycles, clothing, household linen, and leather goods and shoes has been reduced.

3.3.3 Getting data on repair of household goods

There is very little published data on repair, especially related to the case study products and sectors focused on within this report. Thus, it is not surprising that monitoring and measuring the effect of waste prevention measures such as repair activities is still in its very infancy (Sharp, Giorgi, and Wilson 2010).

Important repair-related data for the impact assessment of the repair of products include the current number and quality of repairs, as well as the repaired stock. The European Commission (2016) collected this data based on existing studies and expert opinions to estimate stock and sales of selected products in Europe (refer to Table 3).

This research considered, for example, an average extended lifetime for any type of repair, although different types of repair activities might have differing effects on the actual service lifetime of products. Because of these limitations, the authors arrived at the conclusion that "the size of the repair sector in the past was not significant enough to be studied at the EU level" (European Commission 2016).

Further approaches to provide some evidence on the scale of repair relies on gathering bottom-up data from companies and initiatives. For example, the REPAIR CAFÉS (refer to Box 1: Good Practice Example – Community-Centered Workshops) maintain repair records. In 2016, a (second) global survey of volunteers at REPAIR CAFÉS undertaken by The Centre for Sustainable Design (CfSD) at the

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[10] https://www.ifixit.com/smartphone-repairability
[11] https://www.fairphone.com/

Box 1: **Good Practice Example – Community-Centered Workshops**

REPAIR CAFÉ

REPAIR CAFÉS are free meeting places, where people come together to collaborate with others to extending the life of their products through repair. Visitors can find tools and materials to repair their broken items (e.g. clothes, furniture, electrical appliances) with the help of expert volunteers with repair skills in all kinds of fields.

Martine Postma initiated the REPAIR CAFÉS and the first REPAIR CAFÉ-meeting was in Amsterdam in 2009. Since 2011, the non-profit organization REPAIR CAFÉ-Foundation has provided professional support to local groups in the Netherlands and other countries wishing to start their own REPAIR CAFÉS.

Today, there are over 1100 REPAIR CAFÉS -groups in 29 different countries all over the world. (https://repaircafe.org).

Box 2: **Good Practice Example – Reuse and Repair Networks**

REVISIE-NETWORK IN FLANDERS (BELGIUM)

REVISIE is a quality label to guarantee the quality of electrical and electronic equipment, which is sold by the reuse shops De Kringwinkel in Flanders. De Kringwinkel is a federation of shops selling used goods. They operate as an exclusive franchise and are served by reuse centers (a hub where collected goods are sorted, tested and stored). The reuse centers are embedded legally in the Flemish waste and material management policy. The legal framework is the basis for the accreditation and the subsidizing of the reuse centers by the Public Waste Agency of Flanders, OVAM. The reuse centers derive 39 per cent of their income from the sale of second-hand products, 14 per cent from the tonnage fees for collections and the sale of recyclable materials, 1 per cent from OVAM's environmental subsidy, and 46 per cent from employment subsidies.

Komosie, which stands for Federation of Environmental Entrepreneurs in the Social Economy, is the umbrella organization of all accredited reuse centers in Flanders. Komosie has a quality policy for its members on different levels. REVISIE is one of the quality labels, which can be used by members meeting the accredited quality management standards of the label for electrical and electronic equipment.

In 1999, the Komosie Federation started to develop REVISIE as a quality label for repaired waste electrical and electronic equipment (WEEE), financially supported by the Flemish waste agency OVAM until the end of 2008. The objective was to create a region-wide network with repair workplaces that would be collecting and repairing WEEE for sale in the reuse shops.

Today, REVISIE has become a strong embedded quality label within the sector. The label assures the customer that an electrical and electronic device from the reuse shop De Kringwinkel will work properly and safely. In specialized repair workplaces (in the reuse centers), every device is subject to a thorough technical inspection, professionally repaired (if necessary), tested and fully cleaned. Quality, safety and energy consumption are paramount criteria in this operation. The reuse centers are collecting WEEE via own collecting channels (customers that deliver WEEE or have it picked up at home) and they get access to reusable WEEE via both the inter-municipal partnerships and via distribution channels from Recupel (the Producer Responsibility Organization for the implementation of the legal take-back obligation of WEEE in Belgium).

In 2015, there were 31 centers, of which ten have special repair workplaces/reuse centers for WEEE which mainly involves controlling, testing and making large electronics suitable for sale. WEEE which cannot be repaired or made suitable for sale are distributed to the recycling sector.

Approximately 250 people in the sector are employed in the collection, treatment and repair of WEEE. Some reuse centers undertake limited repair and revision for some of the electronics collected. In 2015 there were 128 shops that offered large and/or small WEEE. Not all shops sell WEEE, but all centers do.

University for the Creative Arts (UCA) in Farnham in the UK, in collaboration with the REPAIR CAFÉ-Foundation, showed that the majority keep records on the overall number of repairs undertaken, repairs by item category and the types of fault or repair carried out (Charter and Keiller 2016).

Table 3: Estimated life and stock of household products in Europe

Parameter	Unit	Washing machines	Dishwashers	Vacuum cleaners	Coffee machines
Technical lifetime without repair	Years	13	13	6	8
Lifetime extension thanks to repair activities during the mid-life of products	Years	6	6	4	4
Lifetime extension thanks to refurbishment at the EOL of products	Years	6	6	4	4
Current mid-life repair rate	% of sales	30%	37%	20%	32%
Current EOL refurbishment rate	% of products reaching EOL	3%	3%	2%	2%

Source: (European Commission 2016)

A small proportion of REPAIR CAFÉS even record the weight of products repaired, i.e. Farnham REPAIR CAFÉS in the UK, as a means of estimating total mass of products from the waste stream as a result of their interventions. According to the survey, on average, 63 per cent of the broken products brought to REPAIR CAFÉS are repaired (Charter and Keiller 2016). Since 2014, there has been an increase in the proportion of REPAIR CAFÉS that frequently receive electrical and electronic equipment for repair while there has been a decrease in non-electrical items (ibid.).

Another example for improved data provision and monitoring is the mandatory recording by members of the KOMOSIE network (refer to Box 2: Good Practice Example – Reuse and Repair Networks). All members must fulfill standards for record keeping (OVAM 2015). Members with specialized workplaces where the inspection, testing and repair of discarded electrical and electronic equipment and devices are carried out on a larger scale (REVISIE-Network), must record each appliance being checked, cleaned and repaired, including the manufacturing year and a detailed description of all the operations carried out and the results (Vandeputte 2014). Collectively, in 2014, the KOMOSIE members prepared 12 of all incoming electrical and electronic equipment for reuse (considering both: products which required a repair and those, which were not faulty) (OVAM 2015).

Another approach to monitor and measure waste prevention via repair is the use of more process-oriented indicators (Wilts 2012), such as the turnover of repair shows, which is possible indicator that complements some of the other output indicators already mentioned. The French environmental agency (ADEME) produces regular country-level reports with such data on the repair sector in order to assess the impact of national waste prevention measures, and in particular to promote repair (ADEME 2014). Over time, these reports are gaining in completeness and reliability; ADEME argues that the quantification of actors and structures involved in the repair sector proved to be a complex exercise and the definition of the methodology represents a major challenge.

The latest review study on the economic repair sector presents statistical data on the number of enterprises, establishments, employment and turnover per household good. Activities of retailers and other actors within the social economy or self-repair are not quantified, but trends of development are being qualitatively assessed

4

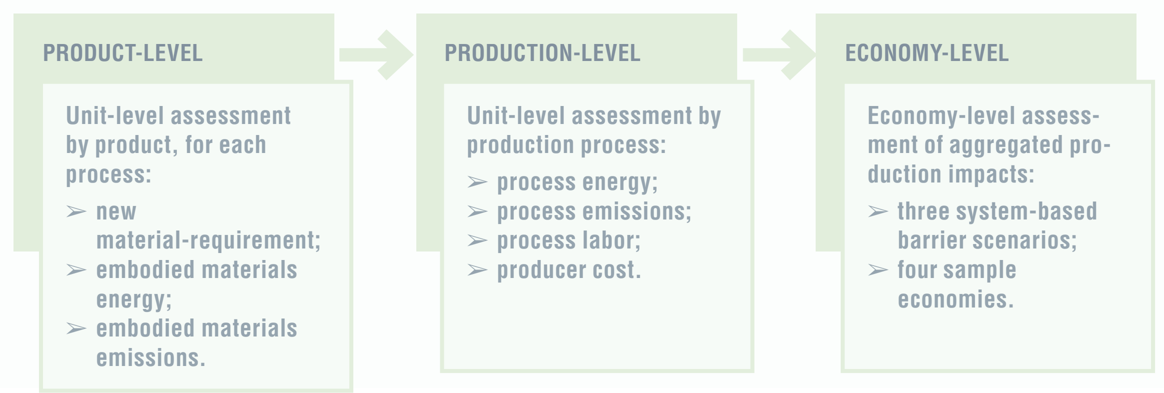
Context and methodology for the study

4.1 Conceptual framework

To help facilitate and support more circular economies, it is important to understand the impacts that different types of innovation can have upon products, businesses, sectors, and economic systems. Given the broad range of innovations that can influence, and are essential to circular economies, a hybrid approach utilizing bottom-up (product and process-level) and top-down (economy-level) perspectives enables appropriate reflection different VRP impacts across product systems.

The analysis presented in this report utilizes a hybrid of bottom-up and top-down evaluations to capture some of the more significant economic and environmental impacts of both innovation, and barriers to broad applications in the circular economy. This approach does not undertake a life-cycle analysis (LCA) method, however it does incorporate an attributional approach that identifies and accounts for specific states and impacts of the relevant processes at the product-level (refer to Section 5) and at the aggregated economy-level (refer to Section 7). Per Figure 14, an overview of these approaches is provided below, and expanded on in more detail in Sections 4.2 and 4.3, respectively.

The comprehensive study methodology, models, and data are included in Appendix B.



Unit-level assessment by product, for each process:
- new material-requirement;
- embodied materials energy;
- embodied materials emissions.

Unit-level assessment by production process:
- process energy;
- process emissions;
- process labor;
- producer cost.

Economy-level assessment of aggregated production impacts:
- three system-based barrier scenarios;
- four sample economies.

Figure 14: Overview of conceptual assessment framework

Product: At the product-level, a bottom-up approach is used to assess production requirements and life cycle implications for a single individual product, across each VRP. For example, this includes new material requirement (kg/unit), embodied materials energy requirement (MJ/unit), and embodied materials emissions impact (kgCO$_2$-eq./unit) for every unit produced. Comprehensive empirical data collection for a sample of ten products, representing three different sectors is used to highlight the product-level economic and environmental impacts of VRPs within the circular economy (refer to Table 1). Appendix A describes these case study products and sectors in greater detail (refer also to Section 4.2).

Production: Production-level impacts (or factors) layer on the process-specific impacts of production for OEM New and each VRP on a per-unit basis. These impacts include process energy requirement (MJ/unit), associated process emissions (kgCO$_2$-eq./unit), the labor requirement (full-time worker/unit), and the cost advantage (per cent $ USD/unit). Production impacts are reflected in a per-unit basis to support and enable subsequent aggregation at the macro-sector and economy scales. Given the differing nature of production across global economies, production impacts are reflected in economy-specific impact factors for each of the example production regions: Brazil, China, Germany, and the United States of America (US) (refer to 4.3.3).

Economy: Product- and production-level impacts per unit are aggregated to the macro-sector and economy scales differently, depending on production mix, production facility performance, as well as the country of origin. Product-level impact data are incorporated into a top-down aggregation approach, based on estimated production volumes for each case-study product and sector in an economy.

To assess the magnitude of impact that current common barriers to VRPs may have upon economic and environmental impact measurements, the top-down approach normalizes production levels across four sample economies (US, Germany, Brazil and China) under a Status Quo (current state) scenario. Barriers to VRPs are well documented; this analysis extends, through sensitivity analysis, understanding of which barriers to VRPs most significantly constrains the transition to circular economy. Where the impacts of barriers cause inefficiency and/or negative impacts for different stakeholders and/or to the environment, policy approaches may then be used to appropriately and effectively target specific barriers for alleviation/mediation of both the barrier, and the resulting impact.

Two additional barriers-based scenarios are utilized to examine the impact of different barrier alleviation initiatives upon each of the four sample economies: these include a Standard Open Market for VRP Products scenario, and a Theoretical High for VRP Products scenario. The methodology for this approach is further clarified in Section 4.3, and details regarding barrier alleviation scenarios are further described in Figure 15, and further analyzed in Section 7.

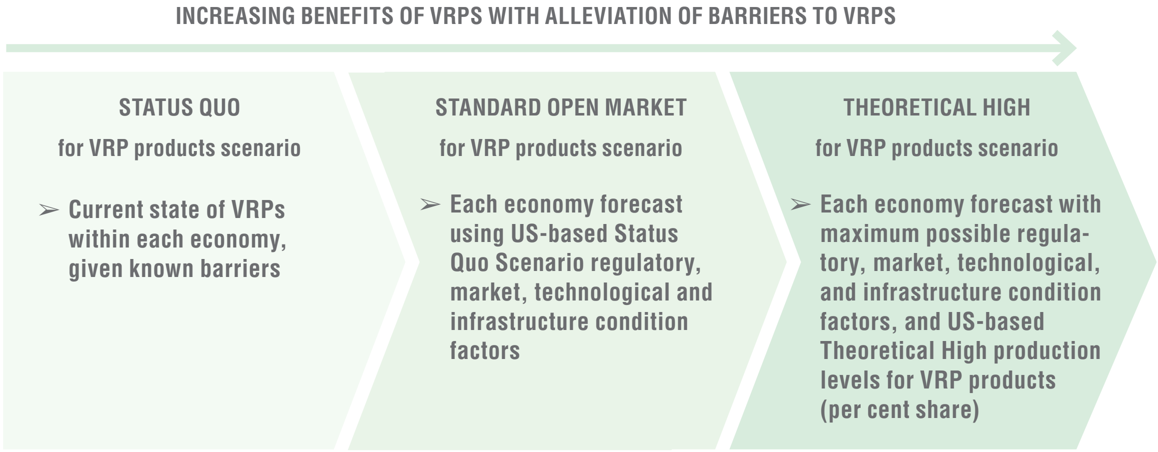


Figure 15: Overview of barrier alleviation scenarios

A systems-view of the economy, including production of OEM New and VRP products is essential: understanding the interconnectedness and complexity of relationships between a range of system variables and conditions (factors) ensures a better appreciation of current-state impacts, and implications of future decision-making and policy direction. At a minimum, this study accounts for some of the primary system factors that must be considered in the context of VRP production, as described in Figure 16.

STATE OF ECONOMY

☐ Growth rate for product market

OPENNESS TO PRODUCTION & TRADE OF VRP PRODUCTS

☐ Import & export rates of finished reuse products
☐ Import & export of cores
☐ Regulatory constraints on production, distribution, and/or sale

MARKET READINESS & MARKET PENETRATION

☐ Demand share (of market)
☐ Production share (of market)
☐ Customer/consumer access

STATE OF DIVERSION CUSTOMER & RECOVERY INFRASTRUCTURE

☐ Product expected life & EOU fall-out rate
☐ EOU diversion to secondary market rate
☐ EOL diversion to recycling rate
☐ EOL disposal to environment rate

STATE OF PRODUCTION EXPERTISE & INFRASTRUCTURE

☐ Share of new material inputs
☐ Share of reuse inputs
☐ Production waste diverted to recycling
☐ Production waste disposed to environment

Figure 16: Key factors affecting value-retention processes and production systems

Extensive effort was undertaken to ensure a rigorous empirical approach. The following sections describe the model development and methodology for both the bottom-up (product- and production-level) analysis (Section 4.2), and the top-down (aggregated economy) analysis (Section 4.3). Included are data collection methods, key product/component characteristics used in the model, assumptions used between the various VRPs included, and description of the modeling program.

4.2 Bottom-up modeling: empirical data collection and product-level analysis

To ensure that the results obtained from this analysis could be properly applied to industry-wide conclusions, preliminary product selection considerations were discussed thoroughly with industry experts, reviewed in literature, and considered in the context of current market conditions. The resulting case study sector and products were selected largely because these sectors are known to engage in VRPs, interested collaborating industry members were willing to provide access for on-site data collection and interviews, and these products represented sufficient scale within potential sample economies to enable meaningful modeling approaches.

4.2.1 Collection of data on case study products and processes

Where much of the current literature on circular economy and material efficiency relies on assumptions and secondary data, of primary interest to this assessment was the collection of first-hand data about case study products and production processes. Researchers were engaged in the complete disassembly and classification of constituent components and materials, as well as numerous on-site visits with industry collaborators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to conduct careful observation of each production process and common practices for each case study product, wherever possible. Where on-site assessments were not possible due to proprietary concerns, industry collaborators provided detailed Bill of Materials (BOM) data sets for product-level materials analysis, as well as comprehensive utilities reports to support and enable process energy and labor requirements, for OEM New and each VRP production. Each on-site assessment involved multiple visits, and direct interaction with all levels of the organization, from front-line operators, through to business unit managers and vice-presidents; it also involved support from across the organization, including operations teams, finance, and facility management. Given the substantial scope of this assessment, in some cases process-based data could not be collected directly due to the dynamic nature of the process (e.g. repair of traditional vehicle engines). In these cases, secondary data from recent LCA and engineering literature were utilized, and additional validation was provided through review by supporting industry experts.

The data collection methodology first required an assessment of the product and product-platform key characteristics of average length of first service life (e.g. up to EOU), and actual useful life of the product-platform (e.g. up to EOL). In addition, it involved, the collection of primary product and component characteristics (e.g. weight, material types, causes of fall-out/failure), types of VRPs available for that product, production waste generation, and the potential reusability (or salvage rate, e.g. 96 per cent) of each product component, under each different VRP. This also included material requirement gross-up estimates to account for production byproduct waste and recycling, substantiated by data from relevant LCA literature.

4.2.2 Product-level model development and approach

Product-level analysis was primarily performed at the component-level for two reasons. First, in the case of remanufacturing and comprehensive refurbishment, different product components can have different reuse-potential. In other words, within the same product, some components can be reused for multiple service lives (e.g. chassis or frame), whereas others may be limited to only a single service life (e.g. software, electronic systems). This differentiation is discussed further in Section 8.2.4. The component-level approach utilized in the product-level model ensured that total material circulation for each component, via the VRP, could be appropriately captured relative to other components and the product-platform overall. In addition, this approach enabled a more detailed assessment of value-retention and reuse-potential across each of the different VRPs. Comparison is assessed on a single unit process basis: One product, unit going through a single cycle of an OEM New or VRP process.

Essential component-level data and information, derived largely from the BOM, included material type, weight (by material), as well as the associated embodied material energy and embodied material emissions of each, using the material-based global averages from the Inventory of Carbon and Energy (Hammond and Jones 2011, Circular Ecology 2017). The presence of recycled-content at the materials-level is accounted for upfront, at the input stage: for example, the embodied materials energy and emissions values are reflective of global average recycled-content for each material, and therefore include the additional energy and emissions associated with that recycled content, on a per-kg basis.

An objective of the product-level assessment was to generalize the impacts of OEM New and VRP production of nine case study products, across facilities and economies. As such, it was not possible to meaningfully assume the origin of each material-input, for each component within each product: Instead, global average values for embodied material energy (MJ/kg) and emissions ($kgCO_2$-eq./unit) impact data points were used (Hammond and Jones 2011, Circular Ecology 2017). It is important to note, however, that for the *process*-level analysis, it was crucial to reflect process energy and process emissions, for the economy where that production activity was occurring in. Thus, for production activities in each respective case study economy, process-related energy and emissions impacts were based on economy-specific aspects of efficiency (generation, as well as transmission and distribution efficiencies) as well as the implications of electricity grid mixture in terms of Global Warming Potential (GWP, $kgCO_2$-eq.). Process-related energy and emissions data were taken directly from the Ecoinvent 3.3 database, utilizing the average value for each case study economy (additional details on the study methodology are included in Appendix B).

An important aspect, when considering circular economy and VRPs, is to understand what events or mechanisms may trigger the opportunity to engage in VRPs. There are a range of reasons that a product may reach EOU and fall-out of the market, thus becoming eligible for another service life through VRPs, as discussed in greater detail in Section 3.1. Specific to the case study products assessed in this study, the product-level analysis incorporated three appropriate reusability mechanisms:

Fatigue/Failure: The fatigue/failure mechanism applies to components that typically fail due to wear-and-tear, over time. These components have an appropriate durability (or loss-probability) curve that is applied to the products' service life, using a Weibull distribution.

Hazard: The hazard mechanism applies to components that generally do not tend to fail from use, but rather from unforeseen ('hazard') issues, such as misuse by the user or damages that occur during transit. This type of mechanism would be appropriate for structural components such as housings or frames. In modeling, hazard is represented using a cumulative exponential distribution over all the component's service life cycles.

Predetermined: The 'predetermined' mechanism applies to components that are replaced based on a time-schedule or other external indicators determined by the OEM, and not as a result of direct measurement of component performance or failure. These components can include bushings, bearings, and other wear components that will be replaced as predetermined by the manufacturer. This mechanism uses a step-distribution over multiple service life cycles, where the component will be used/reused until it reaches its predetermined end-of-life, after which it is diverted into waste or recycling streams.

The simulation program uses MATLAB to perform a Monte Carlo simulation on the stochastic model, which enables output results of average new material requirements (inversely, the required component replacement), by material type, for each production process. Due to the analysis being a stochastic model, Monte Carlo is necessary to obtain average results, as well as to address and minimize uncertainty within the model. The program takes the component-level data and simulates multiple service life cycles for the component using randomly-generated probabilities. In other words, this process determines whether the component will be reused in the VRP for an additional service life cycle. The reusability mechanisms are also applied to simulate the probability and implications of that additional VRP service life cycle.

Using the MATLAB program procedure, the product BOM is uploaded into the model, and the number of simulations, *n*, is defined. This can also be conceptualized as the number of *products* the model will run. From there, each component, *m,* is run through multiple service life cycles, *i*, until it ultimately fails through the assigned reusability mechanism, thus reaching EOL. This procedure is run for every component of the BOM, until all components have been assessed for each OEM New and VRP simulation.

This analysis estimates the average material that reaches EOL through one of the fall-out mechanisms and, inversely, the average new material required to replace that failed component in a VRP, for each consecutive service life cycle. Each product starts out as an OEM New product with original product and material composition necessary to complete a single original service life. After the initial service life, the product then becomes eligible for VRPs; however, it will only undergo a VRP based on what is appropriate for that product and based on the relevant conditions of the sector. For example, in the case of remanufacturing, some components may not be eligible for an additional service life cycle: relative to the whole product, these components may not have retained sufficient overall value to justify remanufacturing them; alternately, there may be an intolerable risk of product failure if certain components were to be reused in the process. This rigorous approach to the product-level analysis enables a more realistic understanding of: (1) the reusability of product components from an original product design standpoint; and (2) the inefficiencies that can exist within VRPs that are related to the design and nature of product components.

4.3 Top-down modeling: macro data and economy-level analysis

The dynamics of a system model that represents an entire economy are complex and have been reasonably simplified to allow for generalization within this model. While the calculation of product-level stocks and flows is largely linear, there are calls in the literature highlighting the importance of accounting for some of the key factors that influence and affect consumer behavior upon the growth and transformation of product markets. (c.f. Peres, Muller, and Mahajan 2010, Subramanian and Subramanyam 2012, York and Paulos 1999, Mylan 2015, Weitzel, Wendt, and Westarp 2000).

In this case, all model simulation begins with the product market: the total quantity and representative shares of a product, by each production process type, including OEM New, arranging direct reuse, repair, refurbishment or comprehensive refurbishment, and remanufacturing. Because the objective is to simulate the influence of different conditions (often barriers) upon the various product stocks and flows within a market, all markets are assumed to start with a stock/quantity, or installed base for the specific case study product, that reflects the actual size of the reference economy. The conditions of each economy affect how that installed base is shared by OEMs (New) and VRP producers, as well as how those market shares are expected to evolve over a period of time.

A simplified descriptive representation of the top-down model is presented in Figure 17, below. To reflect growth, market evolution, and compounding complexity in a realistic and meaningful way, these scenario projections are simulated over a seven-year period. This simulation period does not reflect a suggested or optimal circular economy transformation timeline, as such a comprehensive

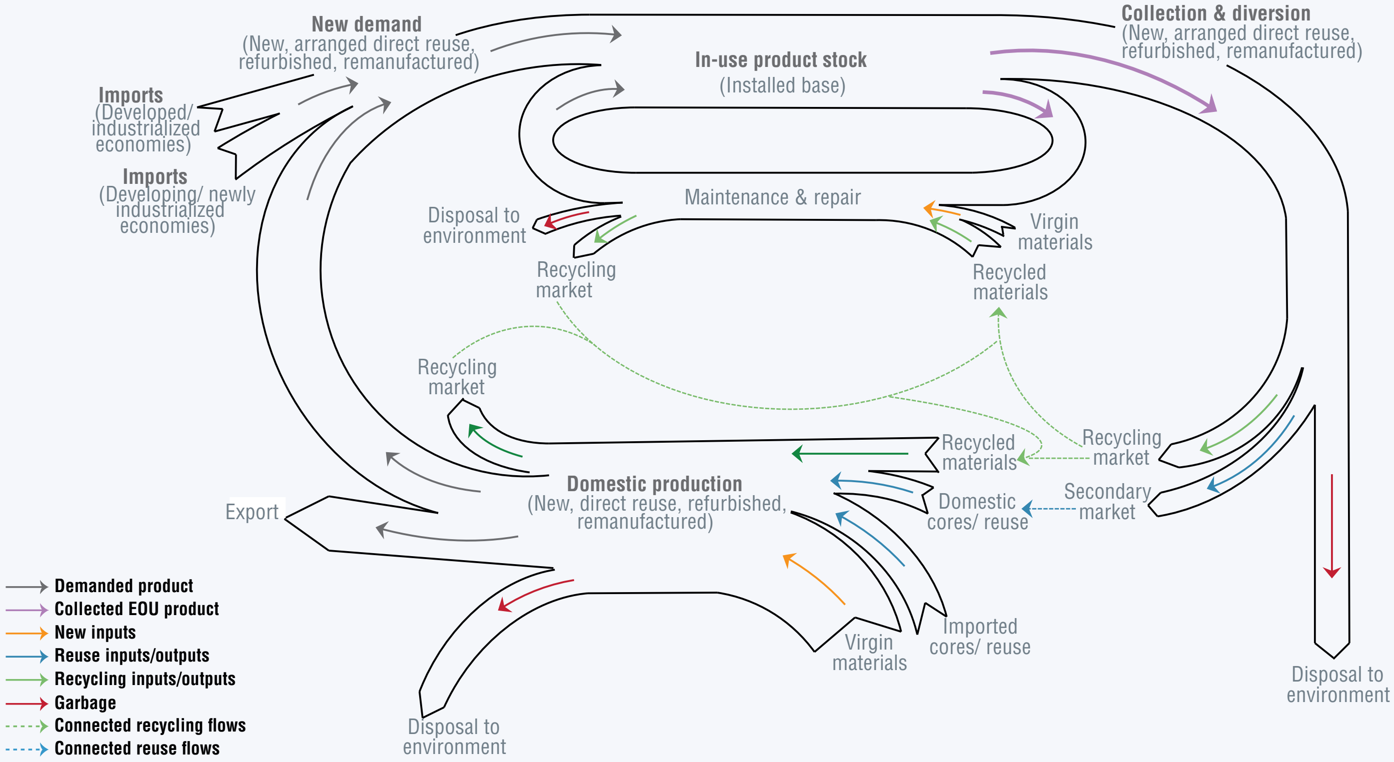

Figure 17: Descriptive economic system model utilized for top-down analysis

transformation must be grounded in the actual conditions of each individual economy, and must reflect the priorities of each individual initiative, some of which may require significantly more (less) time to accomplish.

Based on expected demand, OEM New and VRP versions of a product are supplied either by domestic producers, or via imports (top-center and top-left of Figure 17). Domestic producers rely on a variety of inputs to production, including recycled and virgin materials, as well as domestically- or imported-reuse inputs (cores). In addition to the finished product, other production outputs may include materials directed into a recycling market, or materials that are disposed into the environment (bottom-center and bottom-left of Figure 17). As described previously, repair activities can take place within the service life of a product and return the product to its original owner. The repair process may require virgin and/or recycled material inputs (via parts replaced), and results in product waste materials that may be directed into recycling markets or disposed into the environment (top-center of Figure 17). Alternately, EOU/EOL products may fall-out of the in-use product stock (market) becoming available for collection and diversion (top-right of Figure 17). These products may be diverted into a secondary market for VRPs, into a recycling market, or disposed into the environment (bottom-right of Figure 17).

Please note that the arrows within the diagram, reflect presence and directionality of system factors and flows only, and do not suggest the magnitude in any way. For example, materials directed into the recycling market may later be used in production, however these flows are not quantified by the model.

An overview of the comprehensive analytical model that was developed for the economy-level assessment is provided in Figure 18. As depicted, modeling calculations started with the installed base (stock) of the product in the market (top-left orange box) and the estimated market share of product by OEM New and VRP process (top-center blue box). From these starting points, other values within the model were derived; as impacts of production were assessed on a per-unit basis, the aggregated economy-level results presented in Section 7 are largely based on the Total Finished Domestic Production (center green box), Imports from Developed and Developing Economies (center green boxes), and Production Levels of Repair (center-right green box). A complete description of the model, including formulas is included in Appendix B.

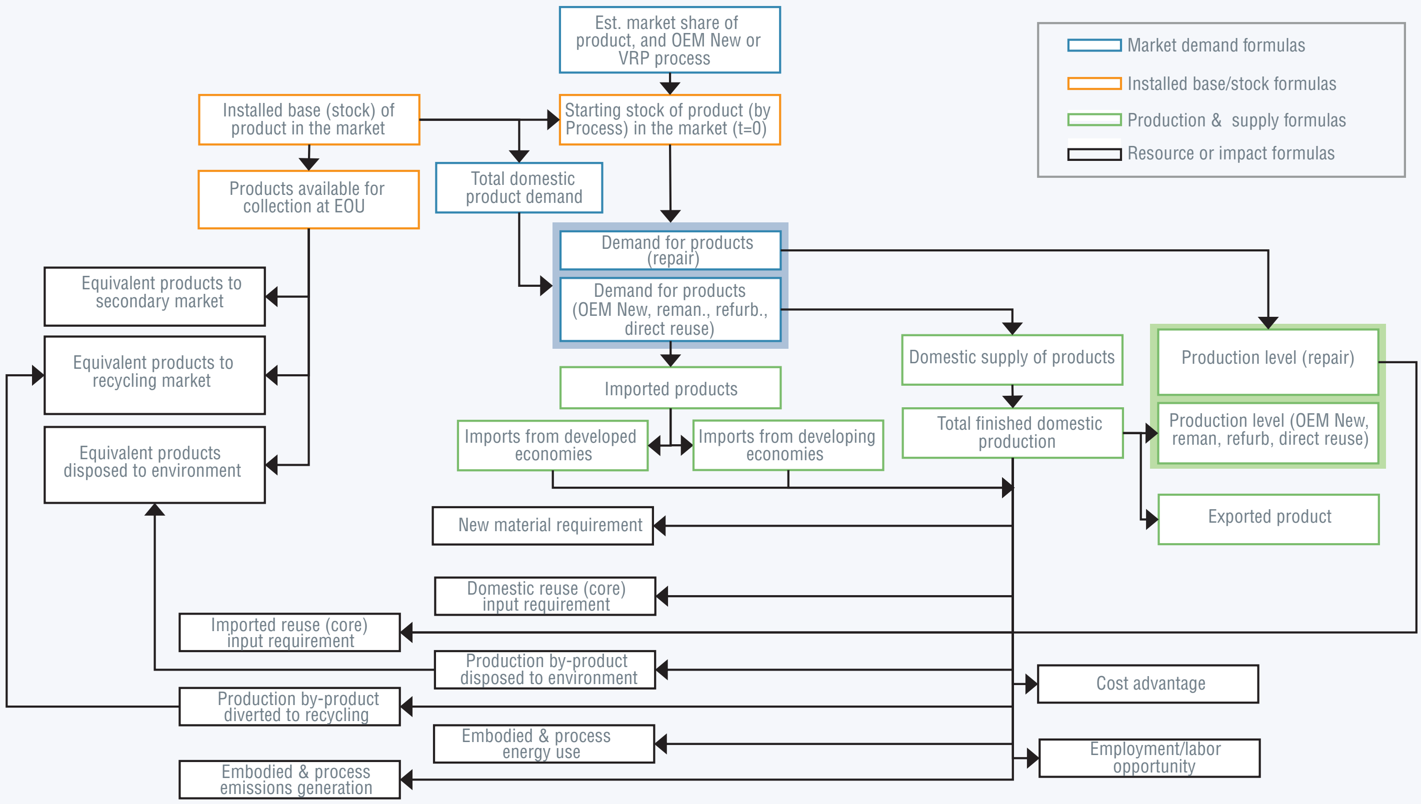

Figure 18: Overview of comprehenive analytical systems-model mechanics for economy-level assessment

4.3.1 Demand and market share modeling

In the absence of comprehensive micro-data for each economy, a simplified approach was used to model the evolution of market share for each product, by OEM New and VRP production. Projected market demand for each case study product was based on two key parameters. First, demand was partially estimated using the expected implicit growth of the market, based on the historic (2010 – 2015) five-year compound annual growth rate (CAGR) performance of the product category, for each respective economy. Second, the evolving market share of each product, by process type, was an important consideration that enabled the reflection of two different types of demand: new demand, which originates from customers that previously had not participated in the product market; and replacement demand, which originates from the fall-out of an EOU OEM New or VRP product from the market, for which the customer now requires a replacement. This approach enabled the reflection of differentiated value-retention enabled by each VRP.

The model assumes that the total 'installed base' or 'in-stock' market for the case study product can be divided into relevant 'market shares' that reflect each of the available production processes: OEM New, arranging direct reuse, repair, refurbishment or comprehensive refurbishment, and remanufacturing. In most economies, the practices of traditional OEM New production and repair are commonly accepted and understood: as such, it is assumed that the market share percentage for repair is constant. In contrast, the dynamic nature of the model ensures that an increase in demand for VRP products will offset the equivalent demand for OEM New. In other words, and especially in the case of new demand, it is assumed that any new demand not satisfied by a VRP product will instead be satisfied by an OEM New product, and as such the quantity of OEM New product demanded is determined via net-subtraction of VRP demand from total case study product demand.

It is important to note that the model accounts for repair activities differently than other OEM New and VRP activities. OEM New, arranged direct reuse, refurbished and comprehensively-refurbished, and remanufactured products require a complex supply chain with extensive infrastructure and stakeholders; in contrast, repaired products follow a more simplistic flow (refer to Figure 17). It is assumed that the repair process only temporarily removes a product from the economy and that the repaired product is returned to its original owner once the repair process is completed. As such, demand for, and associated requirements of the repair process are modeled separate from demand for the other VRP products that enter the economy via a more complex supply chain. The model assumes that once all repair cycles have been completed, the product will fail and be removed from the in-use product stock, to be replaced in the next cycle.

In this economy-level model, the influence of network effect is reflected in a simplified manner: as the number of VRP products in that market increases, it becomes relatively more significant within the mathematical function, and can demonstrate some degree of 'acceleration'. In other words, the larger the size of the starting market, the larger the relative market share, and the more significant the absolute impact of the growth rate upon actual product volume. While there are many more complex and comprehensive ways to model the diffusion of innovation, this approach enables a generalized, but realistic reflection of market transformation projections.

Within each single-year period of the seven-year simulation, demand is estimated based on real product sector growth projections and market-level conditions. Data from the previous period (year) informs calculations for the next period (e.g. products that reach EOU and fall-out in period 1, are replacement demand in period 2), and the implications of these dynamics are compounded to demonstrate the evolution of each product economy over the total seven-year simulation period.

This form of market share modeling ensures that the sum of all shares does not exceed 100 per cent, and accomplishes the need to balance the impact of increasing (decreasing) demand for OEM New or VRP, as competing production process options become relatively less (more) attractive in the economy (Sterman 2000). The model assumes constant parameter values over time, with the exception of the size of the installed base, or in-use stock of the product, which is determined endogenously by the model, as a function of the starting in-use product stock in the economy, plus the addition of new product (demand), minus those

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products that fall-out of the economy due to failure or reaching EOU. Products that fall-out of the in-use product stock of the economy are directed to VRPs (EOU), or to recycling or disposal (EOL).

4.3.2 Modeling the supply chain

All market size and demand estimates within the model reflect conditions of each actual economy, determined through economic reports and market research data sets. In the interests of accounting for consumption behaviors, the model thus also accounts for the extent to which demand is supplied by domestic production, or by imports. A primary implication of imports is that, while they enable the satisfaction of domestic demand, they also result in the allocation of both impacts and benefits (as measured in this assessment) to the producing economy, or economy of origin. In other words, increased uptake of VRP products in an economy only accomplishes domestic impact reduction if at least some of those VRP products are produced domestically. From a global perspective, it is important to note that increased adoption of VRP products, regardless of origin, can contribute to overall impact reduction, however this may not contribute to the accomplishment of domestic objectives, such as carbon emissions reduction.

Assumptions regarding the split between domestic production and import are determined exogenous to the model, based upon current trade balance conditions for each economy. Import and export rates are held constant over the modeling period and are incorporated to reflect the inherent trade-related policies that would enable or hinder import of cores and finished VRP products to supply domestic demand and enable or hinder export of cores and finished VRP products as a mechanism for increased domestic production capacity. It is assumed that domestic supply accounts for the remaining balance of demand (1 – Import Rate), that there is no stockpiling in the economy, and that there is no trade of arranged direct reuse or repaired products.

4.3.3 Modeling production and production impacts

Through the derivation of total domestic production levels, the model approximates production requirements (inputs), as well as the generation of by-product materials that are either directed into a recycling stream or disposed of into the environment. Although the OEM New and VRP production activities can differ significantly, the model simplifies production inputs into three categories: new material inputs (inclusive of average recycled content), imported core inputs, and domestically-sourced core inputs. The relative shares (per cent of a single unit) of each of these inputs should vary by product and production process, as well as the economy in which the activity is occurring. As one of the primary objectives of this assessment is to quantify the relative impacts of different production processes under different market conditions, this generalization is necessary and sufficient.

To understand the aggregate implications of cumulative economic production, a mass-balance approach is utilized. Given that inputs are presented as shares of the finished product, a constraint within the model requires that the sum of all production input materials (per cent) is equal to 1. All material input share parameters are exogenous to the model and were derived from the component-level and product-level analyses described previously in Section 4.2.

Similarly, specific environmental and economic impact metrics are calculated using impact factors that were determined per unit for each different production process. These impact metrics contribute to greater understanding of relative environmental impacts (positive and negative) across OEM New and VRP production activities. As described previously, the impact factors of interest to this study include: new material offset, production waste generation, embodied material energy, embodied material emissions, process energy requirement, process emissions generation, cost advantage, and employment opportunity.

4.3.4 Modeling end-of-use and collection

The premise of circular economy is the cycling of materials (technical and biological) through a system to retain value and mitigate loss. As such, modeling the management of products and materials once they reach the end-of-use (EOU) stage is an essential aspect of a circular system model. In this case, the model once again starts with the actual installed base of the case study product, by process type, and applies a discard or fall-out rate to estimate how many of that particular product (via process type) will reach the EOU stage in that period. The fall-out rate and quantity of product reaching EOU is estimated as a fraction of the installed base, in accordance with the methodology of Elshkaki and Graedel (2013). In this case, the fall-out rate, reflected as 1/L in which L is the expected lifetime of the product, is multiplied by the total size of the installed base of the market for each product and process type.

It is important to note that EOU may refer to a point at which the product can no longer be used due to performance degradation, or that the current owner no longer wishes to retain the product for a variety of reasons.

When the product becomes 'available for collection' the model assumes that it leaves the economic market (no EOU product stockpiling[12] or storage) and will enter one of three possible flows: (1) routing to secondary market for reuse via a VRP application; (2) routing to recycling market; or (3) disposal to the environment. The route the product will take is based on collection probabilities which are estimated as a function of product- and economy-level factors that are reflective of, but are not limited to: ease of collection, state of collection and collection infrastructure, cost of collection and diversion in the market, presence of supporting diversion regulations, social norms and attitudes towards diversion, presence of related return incentives (e.g. core deposit), and other barriers to diversion such as the prohibition of reuse. The model utilizes collection probabilities and a mass-balance approach to determine the quantities of EOU products that follow different flows. For simplicity, it is assumed that there is no loss that is not 'captured' within the model: the 'disposal to environment' flow reflects those products that are deliberately directed into the garbage stream, as well as those that are 'lost' to the system because they do not enter either the secondary market or the recycling market. It is also important to note that there is a necessary quality discount that is applied to EOU products directed into the secondary market. This discount reflects the common condition that some recovered products do not meet the necessary quality standards for VRPs, with the low-quality differential being routed into the waste stream instead.

4.4 Limitations of the study

The objectives of this study are ambitious, and the scope necessarily extensive. The discussion and insights presented herein offer new perspective on the pursuit of circular economy through the adoption of VRPs; however, there are some limitations to the study that require attention and consideration as future research initiatives.

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[12] Stockpiling refers to the accumulation of goods or materials, potentially for intended future use. Although stockpiling is a common practice, it was not possible to adequately reflect the diverse range of stockpiling practices and implications within this assessment.

4.4.1 Impact constraints resulting from case study data availability

From an impact perspective, the case studies products and sectors, and the sample economies studied are not fully representative or reflective of the global marketplace. The availability of sufficient and reliable data was a primary driver of case study sector and sample economy selection.

Regarding product selection, the comprehensive across-process assessment of environmental and economic impacts required the selection of sectors and products that met three criteria: (1) the product must be known to undergo all (or most) of the VRPs being assessed, in sufficient volumes; (2) VRPs must be undertaken for case study products in each sample economy; and (3) researchers must have access to material-, component-, and product-level impact data for each of the relevant VRPs. Realistically, much of this data is traditionally considered proprietary and confidential, and as such, selection of case study products heavily relied upon the willingness of industry collaborators around the world. While many VRPs are undertaken for traditional business-to-consumer (B2C) products (e.g. clothing, bicycles, mobile phones), these products were often deemed unsuitable because they could not be studied to the necessary extent: many of these undergo a few, but not all VRPs, and as such the necessary across-process comparison would be limited; the practice of VRPs on these products occurs in some, but not all economies; detailed material-, component-, and process-level impact data was not available and/or is not tracked; and/or VRPs for these processes occur in very low volumes, inhibiting sufficient macro-level analysis.

To mitigate some of the limitations of case study product representativeness, additional discussion on an extended selection of less industrial products has been incorporated in Section 5.4 to broaden process-level insights alongside market-level representativeness.

The selection of sample economies was similarly challenging: while care was taken to ensure a reflection of both developed (Germany, US) and developing (Brazil, China) economies, each of these case study economies is considered to be industrialized. Regarding sample economy selection, modeling needs required that three criteria be met: (1) VRPs must be undertaken for case study products in each sample economy; (2) researchers must have access to industry collaborators based in, or with sufficient knowledge of the sample economy; and (3) researchers must have access to material-, component-, and product-level impact data for each of the relevant VRPs. The omission of non-industrialized economies was largely due to the lack of required data for case study products, studied VRPs, and economic activity.

To mitigate some of the limitations of the industrialized economy focus on the case studies, additional discussion on the conditions and perspectives of non-industrialized economies as they relate to circular economy, sustainability, and VRPs has been incorporated throughout Section 8 to highlight insights and opportunities that apply across all economies.

The study of repair processes across each sample economy presented many challenges, as repair activities by nature do not typically occur within standardized or industrial processes. Repair activities can be incredibly diverse in nature, typically take place in smaller establishments and/or are undertaken informally, and the volumes of these activities are typically not tracked in a manner that allows for macro-level analysis. To account for the uniqueness of repair in the context of other VRPs, and to provide for extended insight in how repair is being incorporated into circular economy in distinct ways around the world, a separate section focused on repair has been included in Section 3.3

Although stockpiling (deliberate accumulation) of EOU products and materials likely occurs in the sample economies, the absence of reliable data on stockpiling behaviors and quantities required that an assumption of zero stockpiling be used within the model. An implication of this assumption is that there is no time-delay in the cycling of materials and/or products through the modeled system, and therefore no reflection of the real economic implications of material or product ('core') shortages (or abundance) in the secondary markets being modeled.

4.4.2 Limitations of the models

As described in the preceding sections, the case studies incorporate two models to appropriately account for bottom-up (product- and process-level) and top-down (economy-level) considerations and variables.

While the product-level modeling is extensive, comprehensive, and incorporates data from relevant life-cycle assessments (LCAs) in the literature, the extensive scope of this study prohibited full LCA's from being conducted for each case study product. The use of LCA data from the literature was limited to process-level requirements where they could not be empirically collected: typical energy type utilized by the facility (e.g. electricity); hours of work per unit per process; and work process variations between VRPs. To mitigate some uncertainty, researchers ensured that LCA-data used in the product-level models were based on LCA studies that utilized a common methodology and approach. Given the process-emphasis and the extensive scope of the undertaking, the assessment excludes impacts resulting from forward- and reverse-logistics (including disposal) transportation within the system; these were deemed to be relatively equivalent across each process. In addition, use-phase impacts were also excluded on the basis that the products and processes are commensurable: the same product was assessed for each process, and no product performance efficiency-gain was enabled. In other words, the processes were assessed against the exact same product, not across upgraded and/or more efficient versions of the product. This was done to ensure an appropriate and valid comparison that limited situational uncertainty. It should be noted that many VRPs are performed on older versions of products that may not meet current levels of performance efficiency, and the implications of these practices are discussed in greater detail in Sections 8.2.4 and 8.3.2.

The economy-level modeling for this study accounts for a broad systems-perspective, necessarily simplified to facilitate the inclusion of all case study products, sectors, and sample economies. Given the range of technological capabilities and capacity that exist across organizations, sectors, and economies, the economy-level model was unable to account for the implications of advances in robotics, other forms of artificial intelligence (AI), and new technologies such as additive manufacturing. However, the role of additive manufacturing in VRPs is discussed further in Section 8.2.3.3.3. In addition, technological and social innovations have potentially significant roles to play in accelerating the rate of VRP adoption, and the potential benefits therein. However, due to the dynamic and diverse nature of system conditions and barriers, the dynamic simulations of the economy-level models do not reflect barrier-alleviation pathways over time, and do not incorporate transformative pathways of innovation. Instead, the impacts of barrier alleviation are assessed via the Status Quo, Standard Open Market, and Theoretical High scenarios which reflect varying degrees of barrier presence/absence.

Finally, although the essential role of customer/consumer awareness, attitudes, and behavior are emphasized throughout the discussion in subsequent sections, many of the intricacies of consumer psychology and behavioral economies modeling were not possible due to a dearth of required micro-data on consumer/customer response to VRP products across each sample economy. While this assessment accounts for current attitudes and acceptance via the proxy measure of demand share and production mix, there is opportunity to further enhance these models through the incorporation of additional behavioral economic data and modeling approaches, with a focus on VRP products.

This report presents sound insights and perspectives and is among the first studies to present quantified estimates of the contribution that VRPs can make towards greater resource efficiency and circular economy. However, it must be emphasized that there is urgent need for continued research efforts to further investigate highly relevant issues, including: current practices and barriers to VRPs, including material-flows, within non-industrialized and otherwise constrained economies (e.g. Small-Island Developing States); data collection and analysis on the use of VRPs in consumer products and B2C markets; comprehensive economic modeling that incorporates both behavioral aspects of VRP product demand, and technological innovation capacity aspects of VRP production; and data collection and analysis on the magnitude of less formal/informal repair and direct reuse activities, as contribution to circular economy within national economies.

As previously mentioned, a comprehensive discussion of study methodology is included in Appendix B.

5

Product-level benefits of value-retention processes

5.1 Modeling the product-level impacts of value-retention processes

As described previously, a selection of products from key sectors that already engage in VRPs to some degree were selected for the product-level study. These case study products are described in Table 4.

A more detailed description of model methodology, data collection and validation procedures is included in Sections 4.2 and 4.3.

Table 4: Summary of case study products and processes assessed

Sector	Case study products	Standard processes
Industrial digital printers	• Production printer • Printing press (#1) • Printing press (#2)	• All; comprehensive refurbishment • All; comprehensive refurbishment • All; comprehensive refurbishment
Vehicle parts	• Traditional vehicle engine • Lightweight vehicle engine • Alternator • Starter motor	• No significant refurbishment • No significant refurbishment • No significant refurbishment • No significant refurbishment
Heavy-duty and off-road equipment parts (HDOR)	• Engine • Alternator • Turbocharger	• All; comprehensive refurbishment • No significant refurbishment • No significant refurbishment

The boundaries of the modeled VRPs versus the traditional linear manufacturing system are illustrated in Figure 19, and comparison is on the basis of a single unit process cycle. As discussed previously, the way in which a VRP extends the life of the product or components will vary: where comprehensive refurbishment and remanufacturing can provide a complete new service life to the product (or almost complete new service life, in the case of comprehensive refurbishment), arranging direct reuse, repair and refurbishment are typically used to enable the completion of the original life of the product.

To capture these relative differentiations, Figure 20 illustrates the product life of a population of each of the case study products (assumes normal distribution), in which the products fall-out of the system over the typical life span due to a range of reasons, where VRPs may be introduced, and the resulting

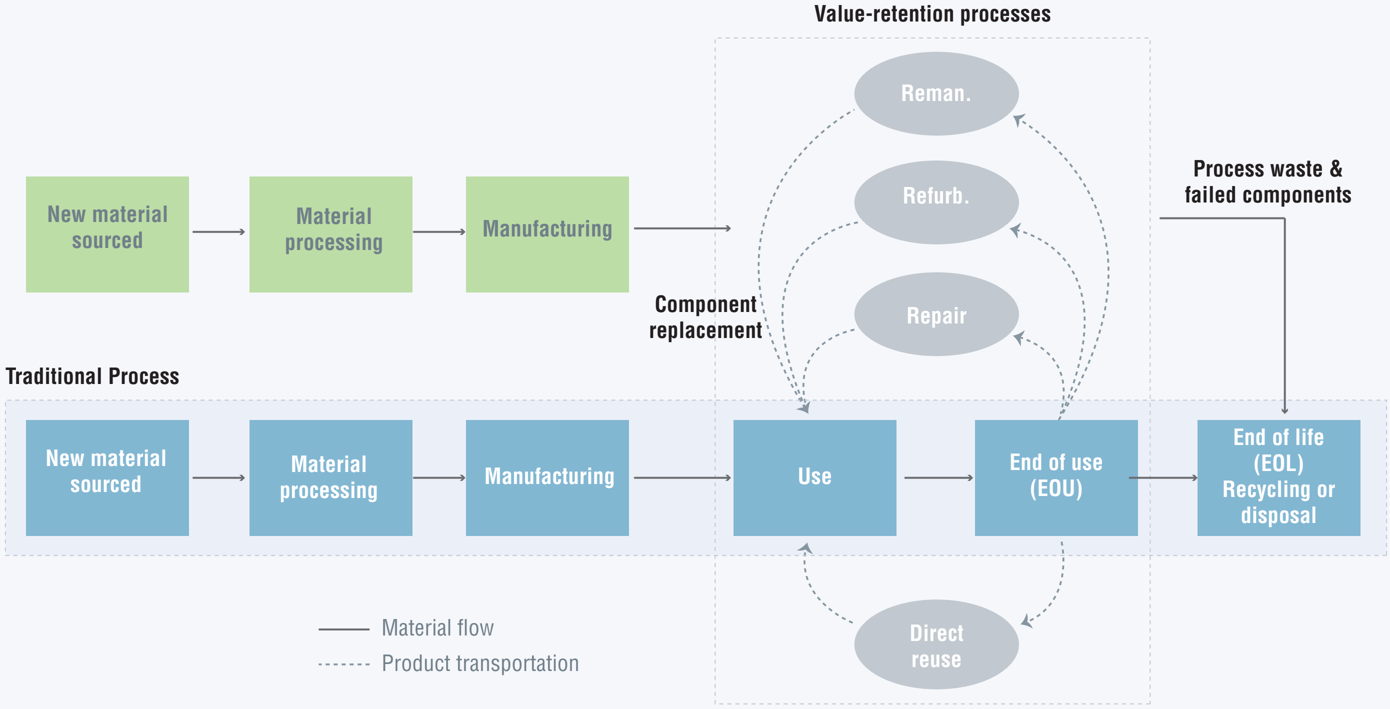

Figure 19: Product-level system and flows for value-retention processes

product life implications of each VRP. For example, reuse and repair activities enable the EOU product to complete the original expected service life (hence, shorter usage cycle overlapping with the original OEM New product's expected service life curve); in the case of remanufacturing, the EOU product is typically recovered in the later phase of the expected service life (curve) and restored to like-new condition where it will experience, at minimum, an additional fully functional service life. Refurbishment and comprehensive refurbishment activities might take place anytime in the range between the start of the OEM New average service life cycle and the start of the average remanufacturing service life cycle (based on the representation in Figure 20 below).

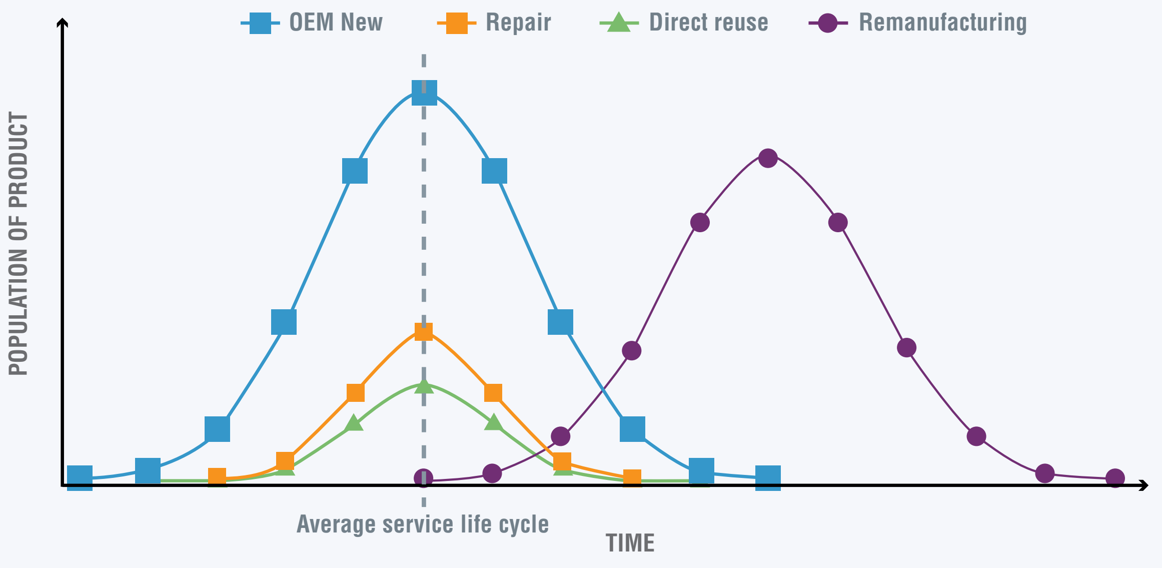

Figure 20: Example model for reutilization of vehicle parts products at EOU through value-retention processes

The parameters affecting product service life and EOU opportunity for VRPs necessarily varies by product type, country, and market in several ways: the complexity and designed durability of the product or component may affect the length of its technical life and its condition at the typical EOU; depending on the economy, and potentially other consumer preferences and norms in different regions, some products may be kept 'in-use' through repair and reuse activities beyond the original expected life that they were designed for, as a result of income and/or other constraints that affect access to OEM New and other VRP products.

At the material level, a primary advantage of VRPs is the direct related reduction in new material requirement[13]. In other words, rather than meeting one unit of market demand by using 100 new materials (OEM New), that market demand may be met via a VRP product that requires as much as 90 per cent less new material input, without constraining demand. This effectively reflects the 'new material offset' amount that is enabled by material reuse in VRPs; this material reuse results in greater material value-retention and material-use efficiency within the system.

For these case studies, the lifespan characteristics of each component were assessed differently for each VRP. For remanufacturing and refurbishment, industry collaborators participating in the study supported the estimation of the following key data points:

1) probability of salvage at EOU (salvage rate);
2) maximum number of times a component could be effectively reused;
3) additional new material inputs to the process (e.g. replacement);
4) destination of materials removed during the process (e.g. landfill or recycling);
5) the cause of component EOU, which could consist of:

- mechanical fatigue or failure;
- hazard losses; or
- predetermined failure (intentional replacement); and

6) maximum potential service life of the product, after which no extension would be possible.

Additional information related to potential process impacts were requested from collaborating companies for each of the relevant products and processes, including: total process energy requirement; labor hours per unit; and average cost advantage created (versus OEM New production) via the VRP. These data points reflect the product-level requirements and impacts of production via linear and VRPs.

5.2 Environmental impacts of value-retention processes at the product-level

The environmental impacts of VRPs differ by product, material, and market as a result of complexity within the system. Material requirement and other impacts were primarily determined based on data from US-based industry collaborators, and in some cases existing literature, and were estimated for other sample economies based on relevant data and impact factors in subsequent market-level modeling.

Based on this research and analysis, the material efficiency, embodied and process energy requirement, and embodied and process emissions generation associated with US-based production of case study products, by OEM New and VRPs are presented in the following sections. Please note that the unit of comparison is a single unit process cycle: as such, the results presented in the following sections reflect the requirements and environmental impacts of a single unit going through an OEM New, remanufacturing, comprehensive refurbishment, refurbishment, repair, or direct reuse process.

It is important to note that this analysis differentiates embodied material energy of all relevant materials – *the energy associated with the extraction and processing of raw materials prior to production* – from the energy required by the actual production process itself. Similarly, embodied material emissions – *the CO_2-eq. emissions associated with the extraction and processing of raw materials prior to production* – is differentiated from emissions associated with the actual production process.

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[13] Please refer to Glossary of Key Terms. New material includes a mixture of virgin (primary) and recycled (secondary) content. Given that the vast majority of materials available for purchase in the global economy consists of some mixture of virgin and recycled materials, the assumed ratio of virgin and recycled content used in modeling is based on the global average for each material type, in accordance with the Inventory of Carbon and Emissions (ICE) (Hammond and Jones 2011).

5.2.1 Industrial digital printers

Material-level analysis results for industrial digital printer sector case study products are reflected in Table 5 through Table 7. Given the complexity and comprehensive nature of the Bill of Materials associated with these case study products, a minimum of 80 per cent of the product's weight is represented in the analysis; in many cases greater than 80 per cent by weight is reflected. The differential between represented product weight and the weight of total new material inputs reflects production process waste and recycling; in other words, material inputs which are not part of the finished product.

Table 5: US production printer product-level material efficiency, energy and emissions impacts

Production printer								Represented product weight (kg):		891.8 kg
	New material inputs by process and material (kg/unit)								Embodied material energy (MJ/kg)	Embodied material emissions (kgCO$_2$-eq./unit)
	Steel	Stainless steel	Cast iron	Copper	Aluminum	Brass	PCB	TOTAL	TOTAL	TOTAL
OEM New	962.6	5.9	-	3.3	1.8	1.2	6.4	981.0	95 580.0	12 413.3
Reman	15.4	0.1	-	0.1	0.0	0.0	0.0	15.6	605.9	64.7
Comp. refurb	7.2	0.0	-	0.0	0.0	0.0	0.0	7.3	293.1	31.6
Repair	1.0	0.0	-	0.0	0.0	0.0	0.0	1.1	260.9	36.2
Arranging direct reuse	0.0	0.0	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 6: US industrial digital printing press (#1) product-level material efficiency, energy and emissions impacts

Industrial digital printing press #1								Represented product weight (kg):		3 707.3 kg
	New material inputs by process and material (kg/unit)								Embodied material energy (MJ/kg)	Embodied material emissions (kgCO$_2$-eq./unit)
	Steel	Stainless steel	Cast iron	Copper	Aluminum	Brass	PCB	TOTAL	TOTAL	TOTAL
OEM New	3 577.9	28.2	-	123.2	317.8	-	29.9	4 077.1	483 605.4	60 236.6
Reman	279.5	5.1	-	12.6	36.2	-	4.4	337.9	63 873.5	8 323.2
Comp.refurb	155.1	3.6	-	11.5	18.6	-	2.5	191.3	36 189.4	4 729.5
Repair	34.5	0.0	-	0.0	0.0	-	0.0	0.0	694.0	50.4
Arranging direct reuse	0.0	0.0	-	0.0	0.0	-	0.0	0.0	0.0	0.0

Table 7: US industrial digital printing press (#2) product-level material efficiency, energy and emissions impacts

Industrial digital printing press #2					Represented product weight (kg):					2 075.8 kg
	New material inputs by process and material (kg/unit)								Embodied material energy (MJ/kg)	Embodied material emissions ($kgCO_2$-eq./unit)
	Steel	Stainless steel	Cast iron	Copper	Aluminum	Brass	PCB	TOTAL	TOTAL	TOTAL
OEM New	2 088.1	4.4	44.0	17.2	113.4	-	16.3	2 283.4	253 924.8	32 307.7
Reman	93.5	0.1	6.0	5.7	17.7	-	0.3	123.3	8 517.3	834.9
Comp. refurb	28.8	0.0	5.4	0.0	27.1	-	0.1	61.5	6 184.9	485.7
Repair	20.2	0.0	7.5	0.0	0.0	-	0.0	27.6	592.2	44.6
Arranging direct reuse	0.0	0.0	0.0	0.0	0.0	-	0.0	0.0	0.0	0.0

Based on the averages for these case study products for the industrial digital printer sector, weighted impact reduction potential for each process ranges as shown in Figure 21. Please note that process energy and process emissions results are inclusive of the electricity generation supply chain, including efficiency and losses.

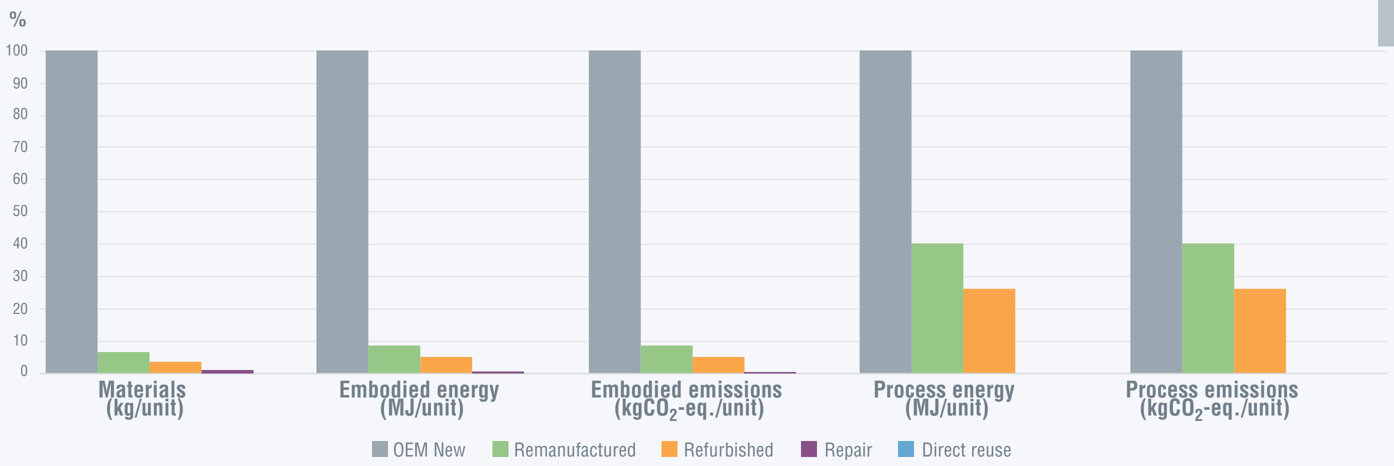

Figure 21: Comparative weighted average impacts per unit for US via value-retention processes for industrial digital printers

5.2.2 Vehicle parts

Material-level analysis results for case study products representing the vehicle parts sector are reflected in Table 8 through Table 11, with results for the traditional vehicle engine and lightweight vehicle engine discussed in greater detail in Section 5.2.2.1. Given the complexity and comprehensive nature of the Bill of Materials associated with these case study products, a minimum of 80 per cent of the product's weight is represented in the analysis; in many cases greater than 80 per cent by weight is reflected. The differential between represented product weight and the weight of total new material inputs reflects production process waste and recycling; in other words, material inputs which are not part of the finished product.

Table 8: US vehicle alternator product-level material efficiency, energy and emissions impacts

Vehicle alternator						**Represented product weight (kg):**	**4.9 kg**
	New material inputs by process and material (kg/unit)					**Embodied material energy (MJ/kg)**	**Embodied material emissions ($kgCO_2$-eq./unit)**
	Steel	Cast iron	Copper	Aluminum	TOTAL	TOTAL	TOTAL
OEM New	1.8	1.2	1.3	1.1	5.4	286.1	18.4
Reman	0.3	0.2	0.3	0.2	1.0	12.7	3.6
Refurb	–	–	–	–	-	-	-
Repair	0.0	0.0	0.1	0.0	0.1	4.8	0.3
Arranging direct reuse	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 9: US vehicle starter motor product-level material efficiency, energy and emissions impacts

Vehicle starter motor						**Represented product weight (kg):**	**3.3 kg**
	New material inputs by process and material (kg/unit)					**Embodied material energy (MJ/kg)**	**Embodied material emissions ($kgCO_2$-eq./unit)**
	Steel	Cast iron	Copper	Aluminum	TOTAL	TOTAL	TOTAL
OEM New	0.3	1.9	0.9	0.5	3.6	168.4	11.3
Reman	0.0	0.1	0.2	0.0	0.4	8.9	0.9
Refurb	–	–	–	–	-	-	-
Repair	0.0	0.0	0.1	0.0	0.1	4.8	0.3
Arranging direct reuse	0.0	0.0	0.0	0.0	0.0	0.0	0.0

5.2.2.1 Vehicle parts design tradeoffs in the context of value-retention processes

Particularly in the case of vehicles, there has been a design emphasis in recent years on reducing the weight of the vehicle in pursuit of greater fuel efficiency. Some economies have progressed further than others in terms of market adoption of lightweight options. Of interest to this study is the significant potential difference in *material-level* environmental impacts a lightweight vehicle engine that utilizes a cylinder block of cast aluminum, as compared to the *material-level* environmental impacts of a traditional vehicle engine that uses a cast iron cylinder block. Although both are part of the vehicle engine product category, this example is used to help demonstrate the substantial impact differential that results from design decisions, as discussed further in Section 8.2. It should be noted that this assessment does not include the entire life-cycle of the vehicle parts, and therefore does not reflect production-level impacts or fuel-efficiency related advantages of the cast aluminum engine cylinder block that are further documented in life-cycle analysis literature (Lewis, Kelly, and Keoleian 2014, Kim et al. 2010).

Table 10: US traditional vehicle engine product-level material efficiency, energy and emissions impacts

Traditional vehicle engine (Cast iron cylinder block)					Represented product weight (kg):		108.5 kg
	New material inputs by process and material (kg/unit)					Embodied material energy (MJ/kg)	Embodied material emissions ($kgCO_2$-eq./unit)
	Steel	Cast iron	Copper	Aluminum	TOTAL	TOTAL	TOTAL
OEM New	11.2	93.5	-	20.0	124.8	5,669.8	389.8
Reman	1.8	1.8	-	1.8	5.4	353.7	22.4
Refurb	–	–	-	–	-	-	-
Repair	0.0	0.2	-	0.3	0.5	50.4	3.1
Arranging direct reuse	0.0	0.0	-	0.0	0.0	0.0	0.0

Table 11: US lightweight vehicle engine product-level material efficiency, energy and emissions impacts

Lightweight vehicle engine (Aluminum cylinder block)					Represented product weight (kg):		89.9 kg
	New material inputs by process and material (kg/unit)					Embodied material energy (MJ/kg)	Embodied material emissions ($kgCO_2$-eq./unit)
	Steel	Cast iron	Copper	Aluminum	TOTAL	TOTAL	TOTAL
OEM New	11.2	30.7	-	61.4	103.3	10 516.0	641.5
Reman	1.7	0.7	-	2.4	4.8	417.6	25.5
Refurb	–	–	-	–	-	-	-
Repair	0.0	0.2	-	0.3	0.5	50.4	3.1
Arranging direct reuse	0.0	0.0	-	0.0	0.0	0.0	0.0

Based on the averages for the aggregated case study products for the vehicle parts sector, weighted impact reduction potential assuming 100 per cent traditional engines (cast iron cylinder blocks) for each process ranges as shown in Figure 22. In comparison, Figure 23 reflects the weighted average material-level impacts for case study vehicle parts, assuming 100 per cent lightweight engine (aluminum cylinder blocks). As mentioned previously, rigorous life cycle data for production processes and use-phases were not completed for the lightweight vehicle engine, and instead the focus is on the material-level impacts of the use of an aluminum cylinder block versus a traditional cast iron cylinder block. Please note that process energy and process emissions results are inclusive of the electricity generation supply chain, including efficiency and losses.

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14 The lightweight vehicle engine BOM is assumed to be consistent with that of the traditional vehicle engine BOM, with the exception of the cylinder block, which was exchanged for an aluminum one (lesser component weight) for this illustrative analysis.

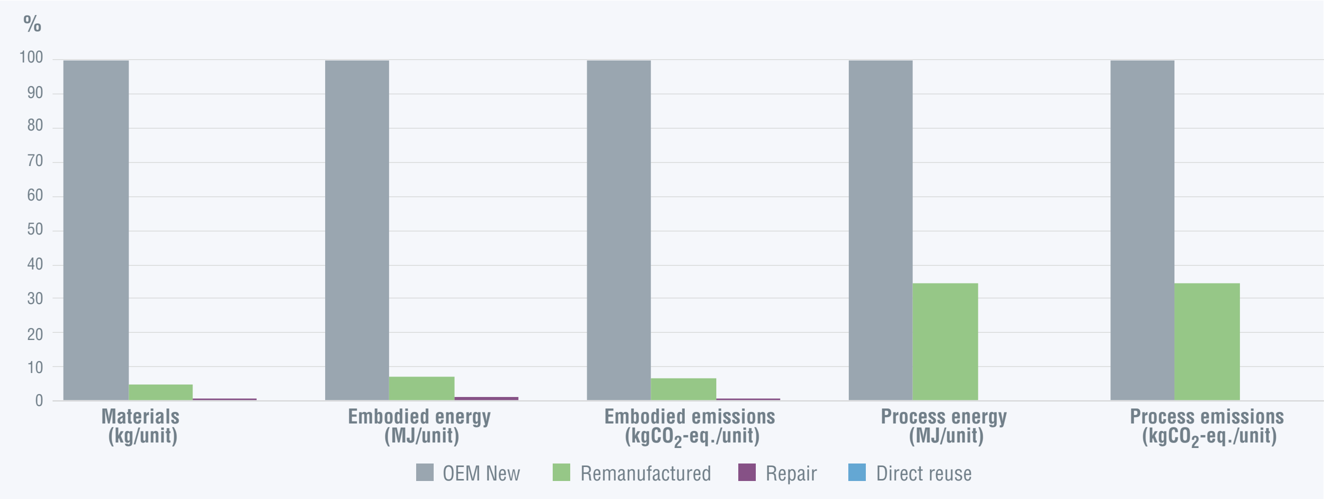

Figure 22: Comparative weighted average impacts per unit for US via value-retention processes for vehicle parts production with 100 per cent cast iron engines

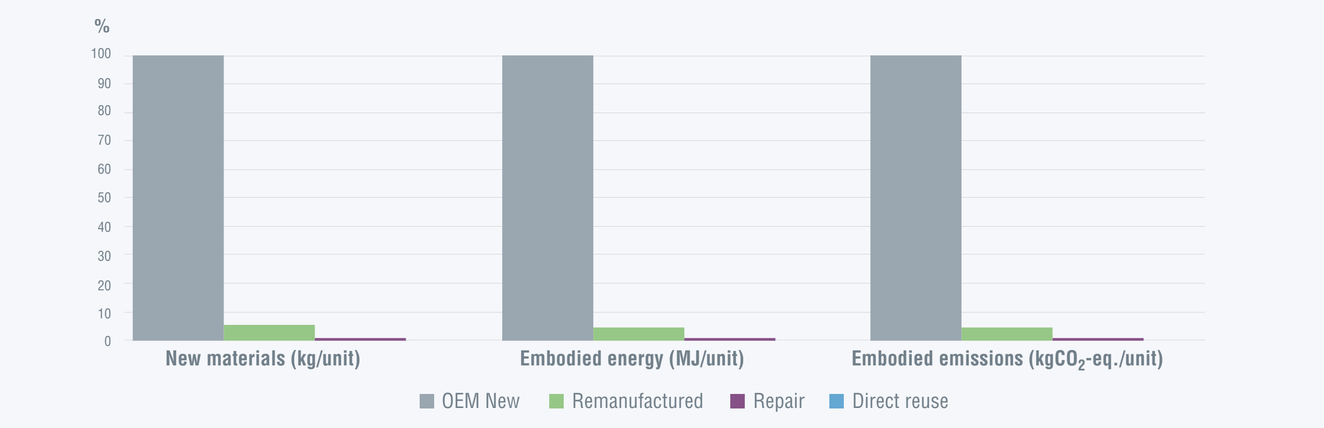

Figure 23: Material-level Comparative weighted average impacts per unit for US via value-retention process for vehicle parts with 100 per cent lightweight engines

5.2.5 Heavy-duty and off-road (HDOR) equipment parts

Results for HDOR parts sector case study products are reflected in Table 12 through Table 14. The complexity and comprehensive nature of the Bill of Materials associated with these case study products, a minimum of 80 per cent of the product's weight is represented in the analysis; in many cases greater than 80 per cent by weight is reflected. The differential between represented product weight and the weight of total new material inputs reflects production process waste and recycling; in other words, material inputs which are not part of the finished product.

Table 12: US HDOR engine product-level material efficiency, energy and emissions impacts

HDOR engine							Represented product weight (kg):	11 787.0 kg
	New material inputs by process and material (kg/unit)						Embodied material energy (MJ/kg)	Embodied material emissions ($kgCO_2$-eq./unit)
	Steel	Cast iron	Copper	Aluminum	Brass	TOTAL	TOTAL	TOTAL
OEM New	3 539.2	7 304.8	-	-	-	10 844.1	253 759.2	19 996.1
Reman	641.9	1 563.4	-	-	-	2 205.3	51 988.2	4 110.9
Comp. refurb	332.8	1 746.8	-	-	-	2 079.6	50 359.9	4 031.9
Repair	83.9	626.5	-	-	-	710.4	17 349.5	1 394.3
Arranging direct reuse	0.0	0.0	-	-	-	0.0	0.0	0.0

Table 13: US HDOR alternator product-level material efficiency, energy and emissions impacts

HDOR alternator							Represented product weight (kg):	41.4 kg
	New material inputs by process and material (kg/unit)						Embodied material energy (MJ/kg)	Embodied material emissions ($kgCO_2$-eq./unit)
	Steel	Cast iron	Copper	Aluminum	Brass	TOTAL	TOTAL	TOTAL
OEM New	9.9	19.9	6.6	0.0	-	36.4	976.7	72.9
Reman	1.0	2.0	0.7	0.0	-	3.7	99.1	7.4
Comp. refurb	-	-	-	-	-	0.0	0.0	0.0
Repair	0.5	0.0	0.6	0.0	-	1.1	35.0	2.3
Arranging direct reuse	0.0	0.0	0.0	0.0	-	0.0	0.0	0.0

Table 14: US HDOR turbocharger product-level material efficiency, energy and emissions impacts

HDOR turbocharger					Represented product weight (kg):		57.8 kg
	New material inputs by process and material (kg/unit)					Embodied material energy (MJ/kg)	Embodied material emissions (kgCO$_2$-eq./unit)
	Steel	Cast iron	Copper	Aluminum	Brass	TOTAL	TOTAL	TOTAL
OEM New	2.6	47.7	-	-	0.6	50.9	1,269.4	102.1
Reman	0.5	5.0	-	-	0.1	5.5	138.2	11.0
Comp. refurb	-	-	-	-	-	0.0	0.0	0.0
Repair	0.0	0.0	-	-	0.6	0.6	24.2	1.5
Arranging direct reuse	0.0	0.0	-	-	0.0	0.0	0.0	0.0

Based on the averages for these case study products for the heavy-duty and off-road equipment parts sector, weighted impact reduction potential for each process ranges as shown in Figure 24. Please note that process energy and process emissions results are inclusive of the electricity generation supply chain, including efficiency and losses.

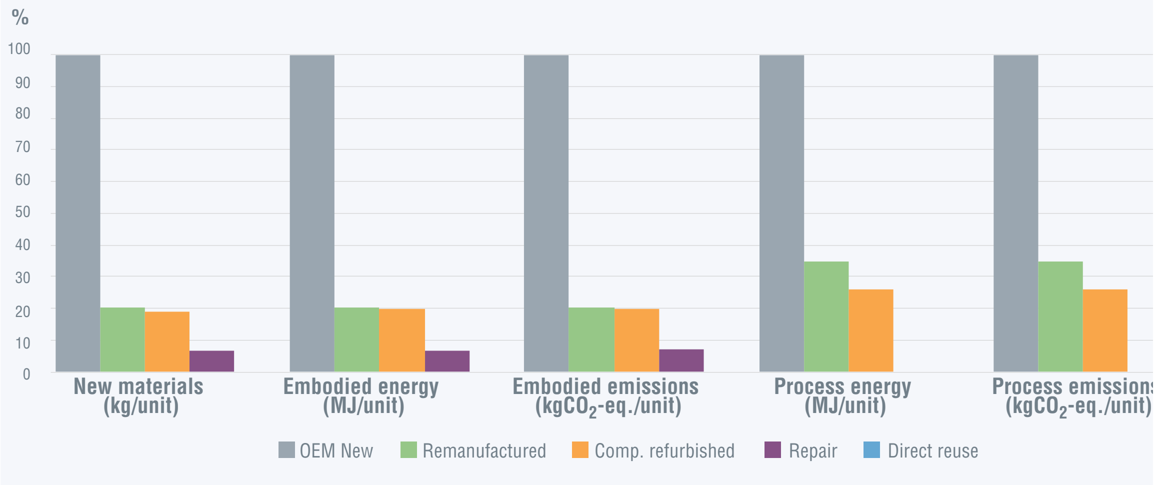

Figure 24: Comparative weighted average impacts per unit for US via value-retention processes for HDOR parts production

As discussed in Section 3, the absolute product-level benefits achieved through circular production models, although clearly demonstrative of the value of VRPs relative to OEM New production, must be considered in the context of the value and utility created. The case study product results presented in the preceding sections reflect quantified per-unit process benefits in terms of material and energy use, as well as emissions generation.

In absolute terms, VRPs enable reduction in environmental impacts from 60 per cent to 99 per cent of OEM New when looking at a single process cycle. The economic considerations of VRPs at the product level are also highly relevant to the discussion of impacts and benefits that become possible through the use of VRPs in the pursuit of circular economy.

5.3 Economic advantages of value-retention processes at the product-level

As emphasized before, full service life and partial service life VRPs are undertaken for different reasons and enable different impact opportunities. As such, the product-level labor opportunity, production waste (includes scrap recyclable process byproduct), and cost advantages for select case study products were assessed and evaluated for case study industrial digital printing press #2 (Figure 25 and Figure 26) case study vehicle engine (Figure 27, and Figure 28), and case study HDOR engine (Figure 29 and Figure 30). Please note the change in scale in the vertical axes across each of these figures.

These product-level results are presented relative to the OEM New version of the same product. As such, the higher relative values for employment opportunity observed for remanufactured, comprehensive refurbishment, and refurbishment in Figure 25, Figure 27, and Figure 29 reflect the greater number of labor hours, and therefore full-time labor requirement of these VRP processes relative to the OEM New process. In contrast, relative cost for VRPs is lower than for OEM New across Figure 25 through Figure 30, reflecting the cost reduction (discount) for the customer.

More detailed discussion and reflection on these product-level findings are presented subsequently in Sections 5.3.1, 5.3.2, and 5.3.3.

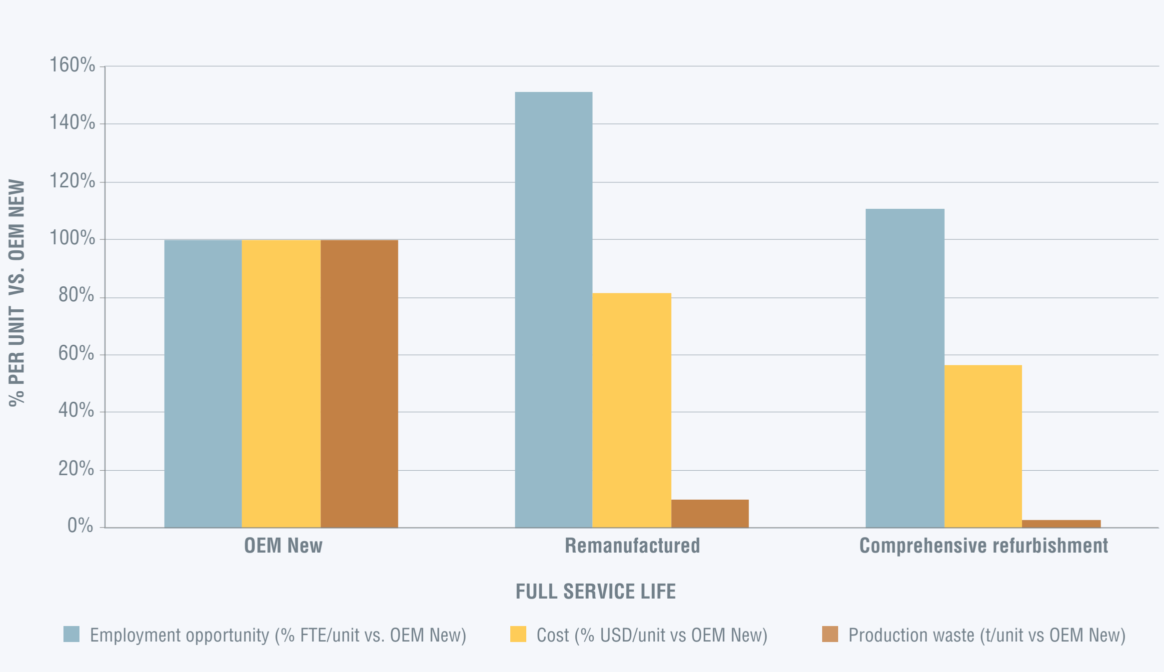

Figure 25: Employment opportunity, cost advantage, and production waste reduction via full service life VRPs for case study industrial digital printers

As shown in Figure 25, relative to a single-unit of the OEM New industrial digital printing press #2, the full service life VRPs of remanufacturing and comprehensive refurbishment offer a reduced cost to the customer, significantly reduced production waste, and an increased requirement for skilled labor which may create a relative employment opportunity.

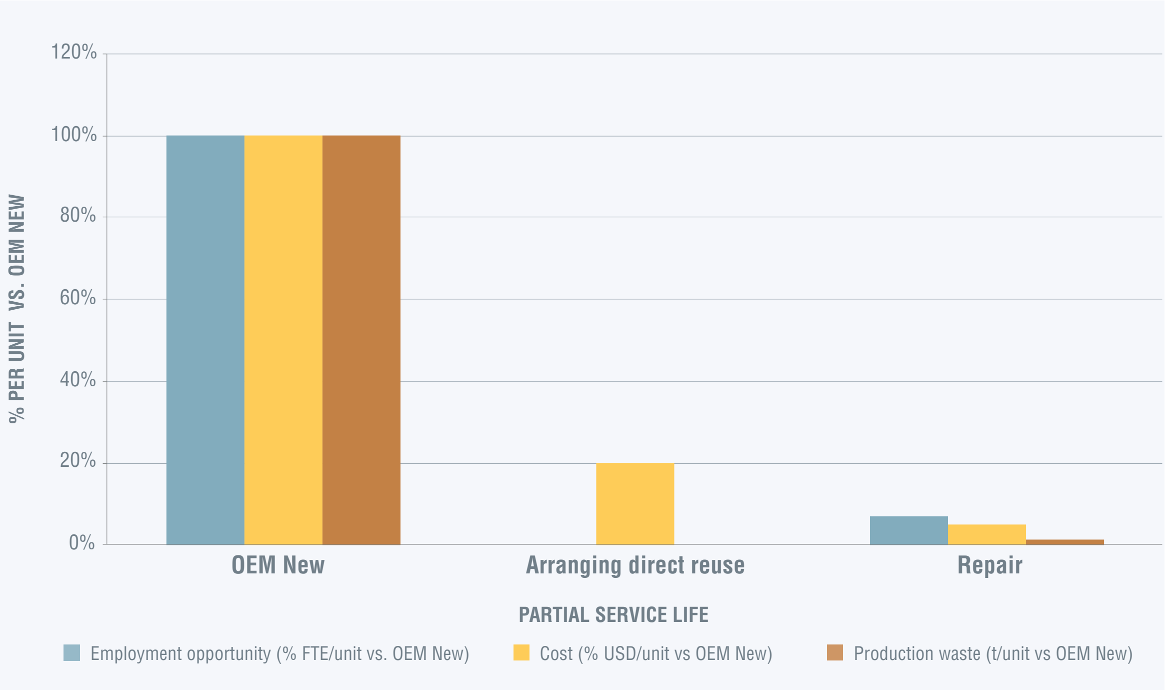

Figure 26: Employment opportunity, cost advantage, and production waste reduction via partial service life VRPs for case study industrial digital printers

Partial service life VRPs offer an alternative set of value-retention options for the customer that emphasize a significantly reduced cost, and almost no production waste generation (Figure 26). As expected, these less-intensive processes require fewer labor hours. Repair activities do generate a positive employment opportunity; however, it is significantly less than the labor required to produce an OEM New version of the product. Arranging direct reuse activities require labor to facilitate the reverse-logistics of the product, however as the actual process of direct reuse does not require labor, it is not reflected in this assessment. As a reminder, requirements of collection infrastructure were beyond the scope of this study (refer to Section 4.4 for a more comprehensive discussion on limitations).

Figure 27: Employment opportunity, cost advantage, and production waste reduction via full service life VRPs for case study vehicle parts

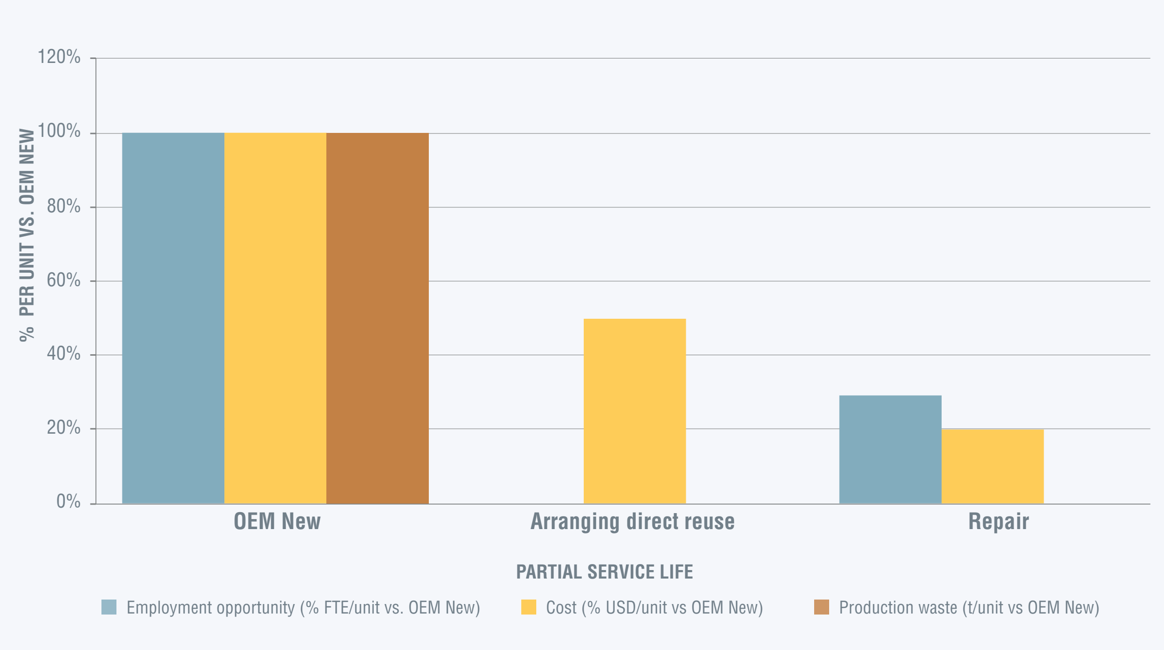

Figure 28: Employment opportunity, cost advantage, and production waste reduction via full service life VRPs for case study vehicle parts

As shown in Figure 27 and Figure 28, the relative product-level economic opportunities of full service life and partial service life VRPs for case study vehicle engines are similar to what was observed for industrial digital printers: cost reduction across all VRPs relative to OEM New; production waste reduction across all VRPs relative to OEM New; and a significant increase in employment opportunity resulting from remanufacturing (a full service life VRP). These findings were also replicated for case study HDOR engines, as shown in Figure 29 and Figure 30.

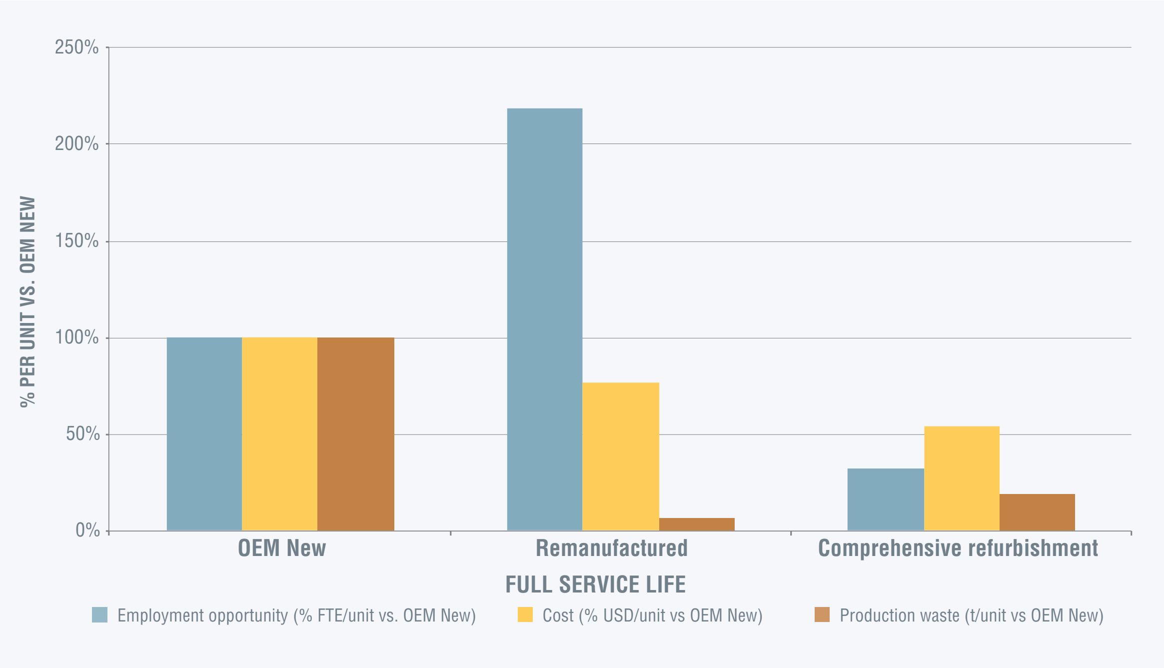

Figure 29: Employment opportunity, cost advantage, and production waste reduction via full service life VRPs for case study HDOR equipment parts

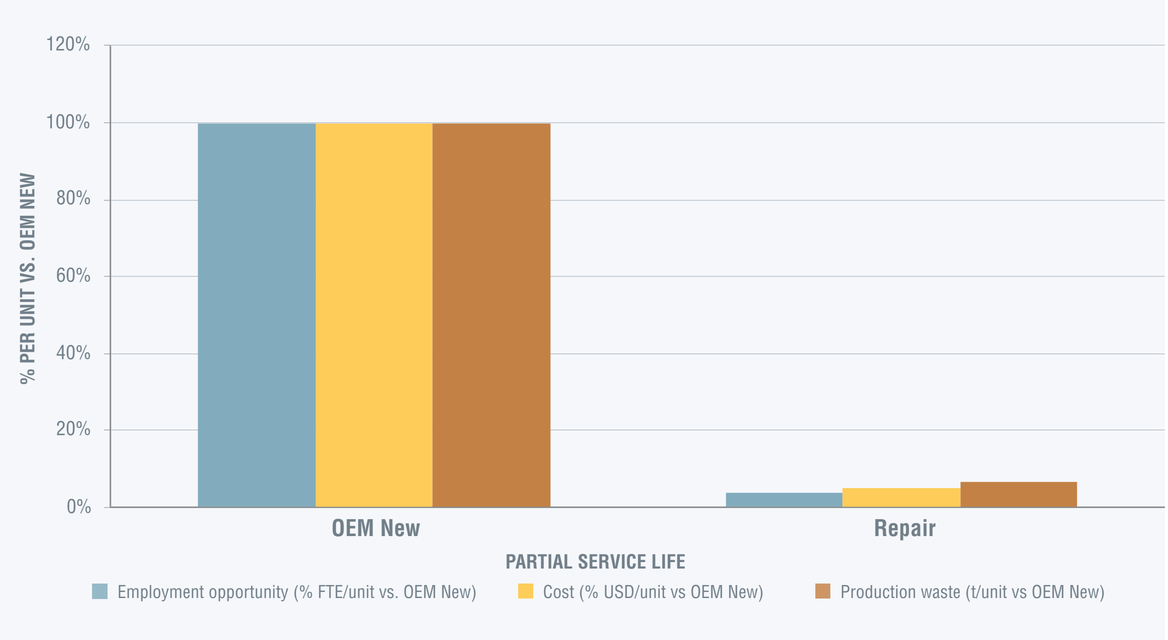

Figure 30: Employment opportunity, cost advantage, and production waste reduction via partial service life VRPs for case study HDOR equipment parts

5.3.1 Production cost advantages of value-retention processes

Significant cost advantages (reductions) are made possible through VRPs, as a large share of costs to the producer are offset by the reduced requirement for new input materials and associated processing costs. In addition, for some products and sectors, process energy-related costs can be significantly reduced through a reduction in the number of processing stages and activities, which may be offset by more manual activities, such as the disassembly and product quality-testing stages required in a remanufacturing process. Cost advantages of VRPs range, conservatively, between 15 per cent and 80 per cent of the cost of an OEM New version of the product, with the lowest cost option enabled via repair for partial service life VRPs, and comprehensive refurbishment for full service life VRPs. Once again, while every VRP offers a cost advantage (reduction) in comparison to the OEM New option, the preferred VRP option may depend on the priorities and economic situation of the customer or user.

The cost advantages shown in these figures reflects commercial pricing, and as such represent the most conservative cost advantage: inherent to these prices is additional profit margin that may be built into the price by the VRP producer based on their own objectives. Given this, the actual cost advantage to the producer may be significantly more than what is passed on to the customer; however, at the very least, price discounting remains an effective competitive strategy for VRP producers, as discussed in Section 6.1.3.

5.3.2 Employment opportunities through value-retention processes

The requirement for potentially more manual VRP production processes, and a necessary level of labor force skills, highlights the employment opportunity inherent in VRPs. While the cost of labor remains a significant share of total production costs in all manufacturing activity, in the case of VRP labor the additional cost is typically more than offset by the relative reduction in materials, utilities, and other overhead and operating costs. In the case of remanufactured products, a significant increase in full-time labor requirement is observed, and at the same time, remanufacturers are typically able to offer a consistent cost advantage to potential customers. In other words, while the cost of labor for remanufacturing may be a relatively higher share of the remanufacturer's total production costs versus the traditional OEM, the other production cost advantages that are created typically more than cover the potential increase in associated labor costs.

It is important to note that the employment opportunity is not equal across all VRPs: in fact, only remanufacturing, and to some degree comprehensive refurbishment, offer greater full-time employment opportunity relative to traditional OEM New production. In economies with a relatively higher share of arranging direct reuse, and repair activities, there may be a relative reduction in employment opportunity.

From the perspective of policy-makers, it is essential to note that, in addition to the per-unit environmental benefits described in Section 5.2, and the economic advantages described in Figure 25, Figure 27, and Figure 29, full service life VRPs including remanufacturing and comprehensive refurbishment offer significantly higher opportunity to increase employment levels, creating additional direct and secondary economic benefits within an economy. Thus, as the production share of remanufacturing and refurbishment are increased, a corresponding increase in full-time employment opportunities is possible.

5.3.3 Production waste reduction through value-retention processes

A corollary to the reduction in new material requirement that can be achieved by VRPs' is the reduction in production wastes and recyclable by-products materials. As can be seen in Figure 25 through Figure 30, every VRP offers some degree of reduced production waste for which there is little diversion or collection potential: where arranging direct reuse requires no new material inputs, and therefore no additional production wastes, even remanufacturing – a process which serves to increases value-retention and product utility through a full additional new life – creates production waste reduction potential that ranges between 90 per cent (industrial digital printers) and 95 per cent (vehicle parts) for these case study sectors.

The decrease in the volume of production waste and recyclables is first and foremost an economic opportunity associated with increased adoption of VRPs: not only do high quantities of production waste indicate that there is value within the system that is currently being lost (e.g. not being utilized at its highest potential) through design, technological and/or other forms of process inefficiency; but there are also operating costs associated with that waste production that must be borne by the producer, including storage, hauling and tipping fees.

While the product-level analysis and insights provide essential information and context for the discussion of circular economy potential and implementation, the context of the economies in which these activities are undertaken is also significant and integral to the development of strategies for circular economy. The following section continues this effort, applying these product-level insights to the aggregate context and conditions of actual economies.

5.4 Assessing product-level opportunities in other sectors

As discussed, the intersection of circular economy and VRPs necessitates a focus on case study products that consisted predominately of technical (inorganic and synthetic material) nutrients, and for which multiple types of VRPs are undertaken. These scope requirements suggest a bias towards industrial products that are sold into business-to-business (B2B) marketplaces. However, VRPs can offer marginal product-level benefits across other products and sectors that are less industrial in nature, and/or that are more consumer-facing (e.g. business-to-consumer, or B2C).

The following sections discuss the VRP implications for several additional products. It is important to note that the products presented here do not represent the entirety of all products; they have been included to reflect on a broader range of product types, primary users, markets, as they relate to the potential for adopting VRPs.

These assessments highlight the importance of considering the nature and design of both product and product-system prior to engaging in VRPs, as discussed in more detail in Section 8.2.4.

5.4.1 Inkjet printer cartridges

When products reach EOU some consumers/users/customers may be motivated to pursue options for extending the service life of a product. Especially in the case of consumer products, consumers may lack the necessary information to know which option to pursue, and the consumer's behavior can influence the magnitude of any environmental savings that might be achieved. (Krystofik, Babbitt, and Gaustad 2014) This is particularly true in the case of inkjet printer cartridges, where customer attitudes can affect whether an OEM New or remanufactured product is purchased in the first instance; and at EOU, consumer behaviors can affect whether cartridge refills are undertaken, and the implications of the subsequent refill transportation requirements.

Although there are several life cycle assessments for printer cartridges in the literature (Four Elements Consulting LLC 2008, Pollock and Coulon 1996, Krystofik, Babbitt, and Gaustad 2014, Gutowski et al. 2011), very few focus on the life cycle impact differential enabled by alternative EOU options.

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In the case of inkjet printer cartridges two VRP options are commonly available in industrialized economies: cartridge refilling (arranging direct reuse), and remanufacturing (Pollock and Coulon 1996, Krystofik, Babbitt, and Gaustad 2014, International Imaging Technology Council 2006).

Krystofik, Babbitt, and Gaustad (2014) observed impact at the service life level rather than the number of printed pages, finding that satisfying five service lives (including use-phase energy) using remanufactured printer cartridges (versus five OEM New cartridges) offered a 37 per cent reduction in global warming potential (GWP) impact (kgCO_2-eq.) and ~50 per cent reduction in cumulative energy demand (CED, MJ). In contrast, one OEM New cartridge, refilled four times offered a 76 per cent reduction in GWP impact (kgCO_2-eq.) and ~48 per cent reduction in CED for the first refill (Krystofik, Babbitt, and Gaustad 2014, 1139 and 1143). In these assessments, uncertainties related to consumer refill transportation requirements and practices were considered and incorporated.

Findings by Four Elements Consulting LLC (2008) presented a slightly different perspective. Looking specifically at the production phase of the life cycle, remanufacturing presented a 7 per cent reduction in GWP impacts, a 4 per cent reduction in primary energy, and a 7 per cent reduction in total waste when compared to OEM New production. However, when incorporated with use-phase performance efficiency changes and EOL, these results inverted: the remanufactured printer cartridge incurred a GWP impact increase of 6 per cent, a primary energy increase of 9 per cent, and total waste increase of 37.5 per cent compared to the OEM New product (Four Elements Consulting LLC 2008, 13). Findings by Gutowski et al. (2011, 4545) identified similar use-phase implications: a refilled toner cartridge offered a 6 per cent energy savings over the OEM New option, assuming that the refilled cartridge performed as new; however, accounting for performance changes, this savings would be offset, potentially incurring an increase in energy requirements.


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5.4.2 Office furniture systems

Although the purchase transaction of office furniture systems (e.g. interconnected cubicle panels, work surface, and cabinet components) typically occurs at the B2B-level, it is the everyday user who interacts with the office furniture system. As such, performance expectations of VRP office furniture systems is necessarily high. In practice, repair and maintenance of office furniture systems is typically included under the OEM warranty; arranging direct reuse is not formally undertaken; however remanufacturing of office furniture systems is becoming increasingly common (Technavio Research 2016, Next Manufacturing Revolution 2014).

Similar to printer cartridges, there are several life cycle assessments for office furniture systems in the literature (Dietz 2005), with some of these specifically focused on the comparative environmental impact differences between the OEM New and remanufactured options (Sahni et al. 2010, Krystofik et al. 2017, Center of Excellence in Advanced & Sustainable Manufacturing 2016, National Center for Remanufacturing and Resource Recovery 2005).

Given the high-share of technical nutrients and low use-phase energy requirement of office furniture systems, it is logical that each of these studies found varying degrees of environmental impact reduction tied to the remanufacture of office furniture systems: aligned with findings by Sahni et al. (2010), Krystofik et al. (2017) found an 82 per cent reduction in GWP impacts ($kgCO_2$-eq.) and an 83 per cent reduction in CED (MJ) in each of the two remanufacturing service lives assessed, relative to the OEM New product. The National Center for Remanufacturing and Resource Recovery (2005) found a 40 per cent reduction in waste generation enabled via office furniture remanufacturing.

5.4.3 Mobile (cellular) phones

Increasingly, consumer electronic products are the focus of environmental impact discussions: not only do these products contain toxic, and valuable materials that should be appropriately managed; global demand for internet-connected devices, including mobile phones, is increasing dramatically each year (Waring 2014, IDC 2016). Given wide-spread consensus that landfill is not an acceptable form of EOU management for mobile phones, as evidenced by e-waste recycling programs around the world, the importance of enabling improved EOU options for mobile phones is logical (Ontario Electronic Stewardship 2009, King and Burgess 2005, Conference of the Parties to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal 2014, Geyer and Blass 2010).

Some environmental impact and life cycle assessments of mobile phones exist in the literature (Yu, Williams, and Ju 2010, Fehske et al. 2011, Moberg et al. 2014), with the most typical VRP option of refurbishment assessed comparative to an OEM New option (Zink et al. 2014). Zink et al. (2014, 1106) found that in direct comparison (excluding a break-even analysis), the refurbished mobile phone presented the potential for a 55 per cent reduction in GWP impact ($kgCO_2$-eq.) relative to the OEM New product.

6

Analysis of value-retention processes at the systems-level

6.1 Market and system conditions affecting current state of value-retention processes

One of the most significant challenges to increasing the scale of VRPs in economies around the world is the complex nature of the system, which—beyond the traditional supply-chain perspective of production—must consider massive and complex aspects. These include collection infrastructure and incentives, regulatory classifications and terminology that can interfere with access and trade, markets and social norms that associate 'new' with status and quality, and well-entrenched technological and production systems oriented towards linear flows and producer responsibility. For ease of reference, the economy-level systems-model previously discussed in greater detail in Section 4.3 and originally presented in Figure 17 is shown below (Figure 31).

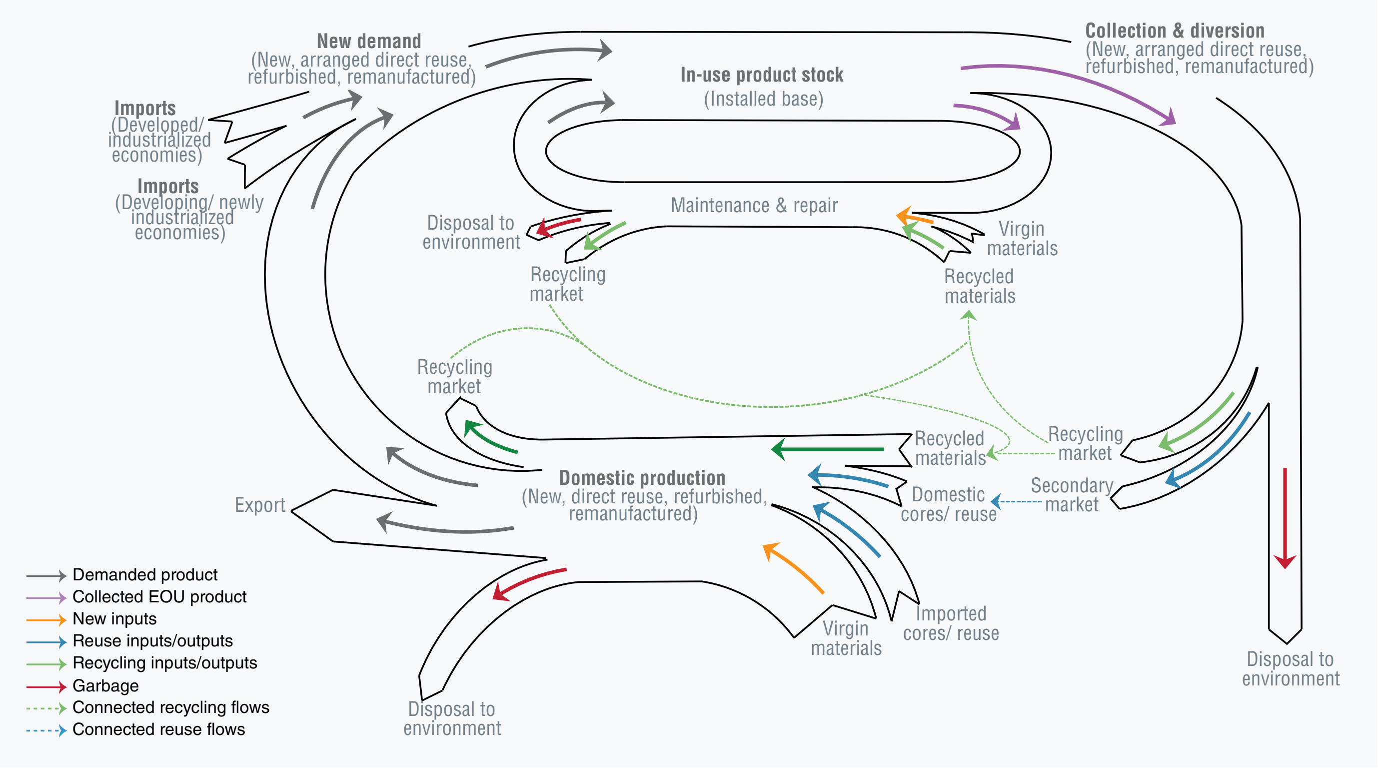

Figure 31: Description of the complex economic system required to support value-retention processes

The objective of increasing the scale and prevalence of VRPs and products within an economy requires a holistic approach that considers the magnitude and cause of barriers throughout the entire system, as well as how those barriers may interact to compound or negate one another. To simplify the nature of key known barriers to VRPs, Figure 31 enables the organization of the occurrence of the barriers:

- **Regulatory and access barriers**: Refers to barriers that restrict the movement of, and/or access to VRP products or cores. In many cases these barriers may manifest as prohibitions of the production and/or sale of VRP products into a domestic market; they may also manifest as increased fees, tariffs or other transactional costs associated with bringing finished VRP products or components (cores) for VRP production into the domestic economy. At a high level, these barriers either constrain the customer market from accessing VRP products (production, import, and/or sales restrictions), or they constrain VRP producers from accessing essential production inputs (domestic collection and reuse, and/or import restrictions).

- **Collection infrastructure barriers**: Refers to constraints on the VRP system related to the ability to recover EOU products or components from the market and redirect them into appropriate end-of-life materials management streams. Of importance to this study is the presence of, and efficiency of the secondary market system that recovers EOU products and components for use as inputs to VRP production. VRP production is dependent on the ability to access EOU products and components; the vast majority of economic and environmental benefits created via VRPs are tied to the offset of original production materials and processes through the reuse of viable parts, components, and/or modules (in the case of remanufacturing and refurbishment, these may be referred to as 'cores'). If collection infrastructure is inadequate or inefficient, the reuse input requirements of VRP producers cannot be met. There are implications for producer, industry and economy: in the absence of VRP input materials, producers are likely to revert to OEM New traditional production practices – using greater material inputs, energy, and emissions levels to meet demand.

- **Technological barriers**: Refers to the constraints on the VRP system related to the VRP producer's ability to access the necessary technology, product knowledge and know-how, and skilled labor necessary to maximize the benefits of VRP production, as identified more specifically in Table 15. Where technology, product knowledge, process know-how and/or skilled labor are insufficient, the capacity of the VRP producer is relatively constrained, and the associated potential economic and environmental benefits are limited. In addition to being limited in the current state, the VRP producer's ability to build capacity over-time – whether demand opportunity exists or not – is likely stunted. This ensures that, even under barrier-alleviation scenarios and strategies, growth, uptake, and gains from increased VRP production occur more slowly, and with lesser impact avoidance.

- **Market barriers**: Refers to the range of barriers which may present in the customer market, and which may include access to distribution and sales channels in the logistical context, or to a pre-existing market preference for 'new' products. The complexity of customer (consumer) attitudes, preferences, willingness-to-pay, and actual purchasing behavior creates significant additional challenges for VRPs, even in markets where no other barriers are present. Where a strategic approach for many VRP producers is to offer a discounted price as a way to incentivize the purchase of the VRP product, this price discount is directly tied to the VRP producer's ability to find cost advantage in the production process. As mentioned above, the presence of technological, collection, and/or access constraints can directly affect the VRP producer's ability to offer a price discount, and therefore to respond to potential customer market barriers.

A more comprehensive discussion and list of these barriers are reflected in the subsequent sections and summarized in Table 15.

The legacy of past policy decisions and technological, behavioral, organizational and institutional conditions efficiency present significant barriers to progress in this area. At the same time, the economics and relative attractiveness of different circular production models vary significantly for different products and markets, with each facing

Table 15: Summary of key barriers inhibiting practice and scale-up of value-retention processes

Type	Examples of systemic barriers to VRPs
Regulatory and access barriers	• Lack of legally and internationally-agreed and/or accepted definitions of remanufacturing, refurbishment, and repair activities[15] • Legal classification of 'used' goods as 'waste', which may restrict consideration of 'used' goods as valuable inputs to VRP production activities[11] • Bans and/or restrictions on the imports of 'cores'[11] • Requirements for special classification and/or import treatment of finished VRP products, including extensive documentation and packaging conditions[11] • Micro-level behavior of firms and customers can be affected by macro-level factors such as taxes and regulations[16]
Technological barriers	• Lack of third-party access to original product specifications to support VRP production and testing[11] • Lack of third-party access to core location, impeding collection efficiency and effectiveness[11] • OE design that inhibits VRP options for the product[11] • R&D and core quality testing technical capabilities[11] • Capital requirement to extend/add VRP production capacity to existing manufacturing operations[17] • Cost and overhead burden of core collection infrastructure and logistics[11] • Long-standing organizational systems oriented towards linear production activities[11] • Non-traditional labor force skill requirements[18] • Lack of industry standardization and defined standards, which creates an unleveled playing field even between VRP producers[11] (refer to Section 8.4.3 for extended discussion of voluntary standards opportunities)
Market barriers	• Increasing presence of new but low-quality imported product options competing against domestically-produced VRP products[11] • Lack of customer awareness and understanding of VRP product options[11] • Lack of 'demand' or 'pull' for VRP products into the marketplace[11] • Complex market signals and indicators, and inconsistent market strategies of VRP producers which can lead to customer confusion and misunderstanding[19] • OEM concern for potential cannibalization of new product sales by VRP products[14] • Customer perception of value related to the concept of 'reuse' and VRP products[11] • Presence of prohibitive policy that restricts market access to VRP products[11] • Pre-existing market preference for new products (e.g. as status symbol) [11] • Complex customer preferences for product attributes related to sustainability: sometimes attractive, sometimes deterrent[12]
Collection barriers	• Presence and quality of diversion and collection infrastructure, which may prevent VRP producers from accessing cores/reuse inputs[11] • Centralized versus decentralized collection systems (e.g. third-party) which increase complexity and magnitude of reverse-logistics system costs[11] • Regulated diversion programs enable shared collection cost burden (e.g. Germany), versus firm-initiated collection systems for which the entire cost burden falls upon the firm[11] • Customer diversion behavior and convenience of diversion versus disposal options[11]

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[15] (U.S. International Trade Commission 2012, Hopkinson and Spicer 2013, Nasr et al. 2016, UNEP IRP Beijing Workshop and Nasr 2016, UNEP IRP Berlin Workshop and Nasr 2016).

[16] (Organisation for Economic Co-operation and Development 2009).

[17] (European Commission 2004).

[18] (Ashford 1993).

[19] (Guide and Li 2010, Atasu, Guide Jr, and Van Wassenhove 2010)

its own challenges in terms of adoption and market access potential. A systems-level perspective enables the identification of conditions that act as barriers to improved adoption of and engagement with circular production processes, and which may inhibit the realization of the resource-saving potentials of these different circular models.

While the firms that engage in VRPs are increasingly innovative and creative in their processes, VRP activity remains low relative to traditional production and manufacturing. According to the US International Trade Commission (2012), remanufacturing has an estimated intensity of only ~2 per cent of all manufacturing occurring in the United States, and European Remanufacturing Network (2015) study results reveal a remanufacturing intensity of only 1.9 per cent of all manufacturing occurring in Europe. Additional details about the relative share of other VRPs (production mix and market share) were estimated via interviews with collaborating industry experts.

The collection infrastructure (including programming and/or landfill bans) that help to facilitate the collection of EOU products from customers and users for the secondary market are also important for circular economy models. Regional infrastructure often exists to allow for materials recycling. However, remanufacturing, and refurbishment, in many countries, lack local or regional level infrastructure and/or programming that may help to facilitate the direction of EOU products into appropriate secondary markets. In many cases, these collection activities occur between commercial or industrial entities, however without supportive collection infrastructure/systems a significant, and potentially prohibitive cost burden of collection is placed upon independent entities.

From the perspective of production capacity, the availability of, and access to equipment, expertise, programming, and facilities can lower logistics costs and allow market players to access local labor and engineering skills thus creating local jobs. Each of these product life extension practices is accompanied by opportunities and constraints, some of which are sector-specific, and some are linked to the scale of reverse-logistics operations, which can be strongly dependent on economies of scale and on the level of economic development.

Like most businesses, those engaging in VRPs must manage complex systems of agents throughout their supply chains: customers and wholesalers, core suppliers and distributors, OEM's and competitors (Atasu, Guide Jr, and Van Wassenhove 2010). However, there is evidence that producers of VRP-products are competitively disadvantaged relative to producers of the 'new' version of the product in three distinct forms: production and supply chain complexity, regulatory and system complexity, and market complexity.

6.1.1 Production and supply chain complexity

Unlike traditional manufacturers, producers engaged in VRPs face additional infrastructure cost requirements in the sourcing of inputs. These costs manifest through the additional labor, transportation, and communication that are required to recover cores from customers located around the world in some cases and return them to the appropriate VRP facility for processing. Where the producer has access to the original sales destination (e.g. the OEM), the locating of cores can be simpler, and collection infrastructure can be piggybacked on top of existing distribution networks via reverse-logistics. These still incur additional costs but are far simpler to undertake as compared to the many cases where the VRP producer is not affiliated with the original sale and is not privy to information about the location of cores, for collection purposes. The asymmetrical information regarding the location of cores creates a cost advantage for OEMs engaging in VRP; regardless of this advantage, the requirement for reverse-logistics within the supply chain puts any VRP producer at a distinct disadvantage to traditional linear production activities.

6.1.2 Regulatory and system complexity

Significant and unique policy-related barriers to VRPs exist in certain markets. These policy-related barriers often, either directly or indirectly, create disadvantage for a variety of reasons that range from consumer protection interests (e.g. import restrictions) to environmental protection interests (e.g. product recycling targets). As discussed, often these barriers originate in the understanding of, and regulated definition of VRPs and VRP inputs, such as cores. Where policy language fails to recognize the embodied value of a core, and/or requires cores to be treated as waste materials, the collection and movement of cores to support VRP production becomes prohibitively constrained.

Significant factors affecting the competitiveness of VRP producers include: the availability of low-cost new products; customer preferences for new products; shrinking relative demand for VRP products; lack of knowledge of foreign markets; transportation costs; availability of cores; and lack of distribution or marketing channels (U.S. International Trade Commission 2012, European Remanufacturing Network 2015).

6.1.3 Market complexity

In traditional market competition, producers can use distinct and complex strategies to signal quality and value to their target customer, using mechanisms of brand, price, advertising, appearance, functionality, and other product characteristics (Atasu, Guide Jr, and Van Wassenhove 2010). In the context of VRP products, these traditional signals can become convoluted, as described in a few examples below.

> **Brand:** Given the requirement for a 'core', VRP producers must walk a fine line of using original OEM-branded cores in a branded VRP product, and appropriately differentiating them from the 'new' version of that same product. There is often significant concern from OEMs that remanufacturing, and refurbishment can not only cannibalize sales of the new product but can also erode the reputation and confidence that the market may have in the brand. Where a strong brand may signal positively to the market about the new product, using the same brand for VRP products may have a different outcome (Guide and Li 2010). For example, where the new and VRP product are indistinguishable from one another, the VRP product can become a perfect substitute for the new product; whether this creates an advantage or disadvantage to the producer depends on whether they are the OEM or the VRP producer (Atasu, Guide Jr, and Van Wassenhove 2010). As VRPs can be performed by an OEM, contracted out to a third party, or independently undertaken, the role of branding can have both positive and negative implications. While the role of brand may be different in the context of B2C versus B2B products, the service reputation and reliability associated with brand is particularly important for B2B transactions, particularly those occurring at higher price points (refer to Section 8.2.1) (Brown, Sichtmann, and Musante 2011, Tukker 2015b).

> **Price:** Price has often been used to signal 'quality', with higher prices suggesting higher quality, higher-priced inputs, and lower prices suggesting lower quality, lower-priced inputs. In this case, VRP producers may be motivated to price the VRP product at a discount – because they have higher margins, and because they may attract customers with a lower willingness-to-pay for the product. However, the practice of price discounting also sends a signal that the market may interpret as indicating a lower-quality product. In the case of remanufacturing, where the finished remanufactured product meets or exceeds the same performance and quality specifications as the new product, this price signal can actually undermine the technological and process investment behind remanufacturing and can misrepresent the product in the market place. In the absence of other information, customers must interpret whether the lower-priced VRP product is discounted to attract their business or discounted because of lower product quality.

A visual organization of these barriers, including barrier interrelationships, is presented in Figure 32.

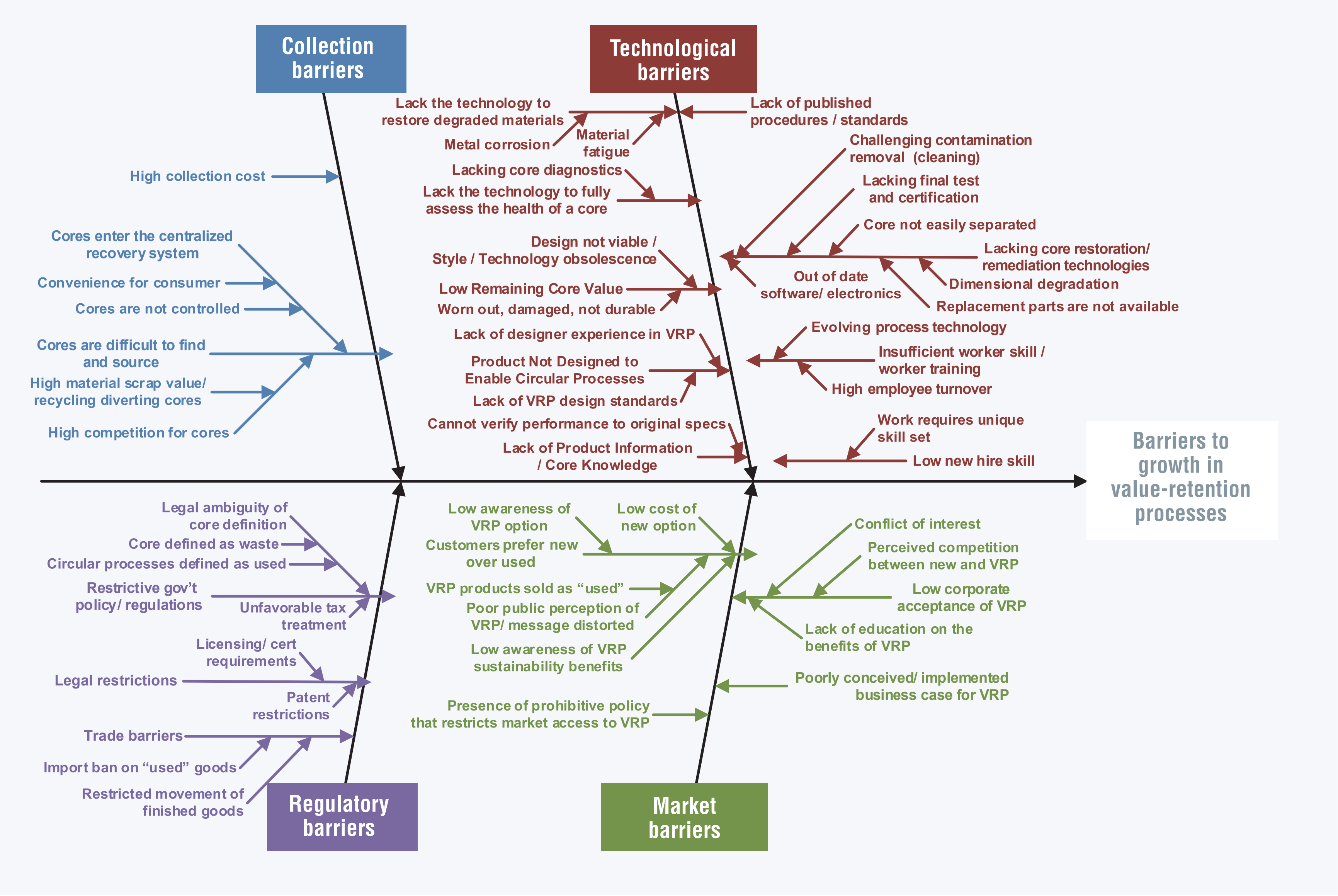


Figure 32: Classification of barriers to value-retention processes

6.2 Key stakeholders

Despite its logical appeal, there are significant challenges that inhibit the growth of VRPs alongside traditional production activities. These challenges and barriers are presented across a range of key stakeholders from essential system perspectives: market, production, and diversion and collection/recovery.

6.2.1 Producers

OEM refurbishers and remanufacturers

While the margin advantage attracts some OEM's to engage in the side-business activity of VRPs, for certain products or product lines, predominant challenges from the perspective of OEM's include the perceived threat of cannibalization and market share loss, and the technical challenge of changing established systems and processes. Some firms that have embraced VRPs, such as Caterpillar Inc., argue that the lower price remanufactured option actually creates new markets for customers who are able to subsequently participate in the market, given the lower price point opportunity. This may be particularly true in economies in which VRP products are not accessible, and where the higher price of OEM New products may prevent customers from purchasing a product they may need.

Firms that have effectively differentiated their markets for 'new' product and 'VRP' product have demonstrated the potential to grow overall market share through VRP product lines (U.S. International Trade Commission 2012). OEM's hold the greatest power within the full service life VRP system; they are the owners of the intellectual property, product design specifications, and locational information for core collection. Competitive OEMs wishing to limit third-party activity in the market have been known to withhold these important types of information, ultimately preventing more comprehensive VRPs from happening. The desire by OEM's to prevent competition from VRP products and third-party VRP producers is one of several key factors impacting the growth of VRPs within industry (UNEP IRP Beijing Workshop and Nasr 2016, UNEP IRP Berlin Workshop and Nasr 2016, Nasr et al. 2016). The lack of OEM engagement in VRP activities is also a constraint on growth of VRPs in pursuit of improved resource efficiency.

Third-party value-retention process entities

Third-party repair, refurbishers, and remanufacturers are independent firms that collect available product components for the purposes of VRPs in some form, either in collaboration with, or, without the knowledge of the OEM. For many products, full service life VRPs cannot be adequately completed without the necessary product design specifications; in many cases the third-party VRP producer also faces challenges trying to locate and recover product cores as part of a separate reverse-logistics. In cases of OEM reluctance to engage in VRPs, some view third-party VRP producers as the primary driver of potential growth of VRPs in the industry; however, without access to product specifications from OEM's and some OEM designs that purposefully prevent VRPs or upgradability (e.g. printer cartridges), the production potential of third-party VRP producers remains quite constrained. Overcoming the lack of OEM collaboration and engagement is key to expansion of VRP products contributing to much greater resource efficiency and circularity.

6.2.2 Market-level stakeholders

Domestic customers

Market demand is always a defining factor for the growth of any industry. The decision by OEM's and third-party producers to engage in VRPs is often dictated by market dynamics: Is there a market for VRP versions of a product, and at what price point is the VRP product viable? OEM's and third-party producers typically offer discounted price points for the VRP product, simply to account for the discounted market perception: that 'used' is equivalent to a higher-risk and lower-quality product. At the right discount, however, customers will accept different VRP products. The cost advantage that may exist across VRP products is described further as part of the product level advantages of VRPs in Section 5.3.1. Customers may be more open to VRP products under a service business model, in which the customer only leases the product, and receives a full-service-for-fee offering from the leasing company. A significant barrier to VRP industry growth, is that customers do not seem to be aware and/or sufficiently educated about VRP products and their value. Overcoming the perception that 'VRPs possess higher risk and lesser quality than 'new' versions of the product through education and awareness and promoting the cost and resource use advantages of VRPs must be strategic priorities in the pursuit of resource efficiency within production systems. Transitioning the marketplace away from product-oriented offerings, and towards service-oriented offerings could significantly impact the acceptability and proliferation of VRPs goods in the marketplace. All of these factors are discussed in greater detail in Sections 8.2 and 8.3.

International trade partners

Export opportunities for VRP goods are significant for many economies. For the United States, with remanufacturing industries accounting for approximately $11.7B USD in 2011, and especially for foreign markets that require lower price points, and/or that have accessibility challenges within their domestic markets (U.S. International Trade Commission 2012). Export opportunities create growth potential for VRP producers, however these opportunities are often constrained by regulatory barriers in foreign markets. The primary barrier facing international trade and exchange of VRP products and components relates to the lack of accepted definitions of what these processes entail, and how VRP are (or are not) differentiated from wastes. Many developing/newly industrialized economies, concerned about the risk of becoming a dumping ground for the waste by-products of first-world nations, restrict the movement of non-new products and cores (e.g. India, Brazil), and often completely prohibit the import of VRP products or cores for remanufacturing (e.g. China) (U.S. International Trade Commission 2012). While the mitigation of dumping practices must be a priority, and these measures might be helpful in some situations, they may also inadvertently impede legitimate trade opportunities for VRP products, and therefore impede the pursuit of resource efficiency, globally.

6.2.3 Collection and recovery networks

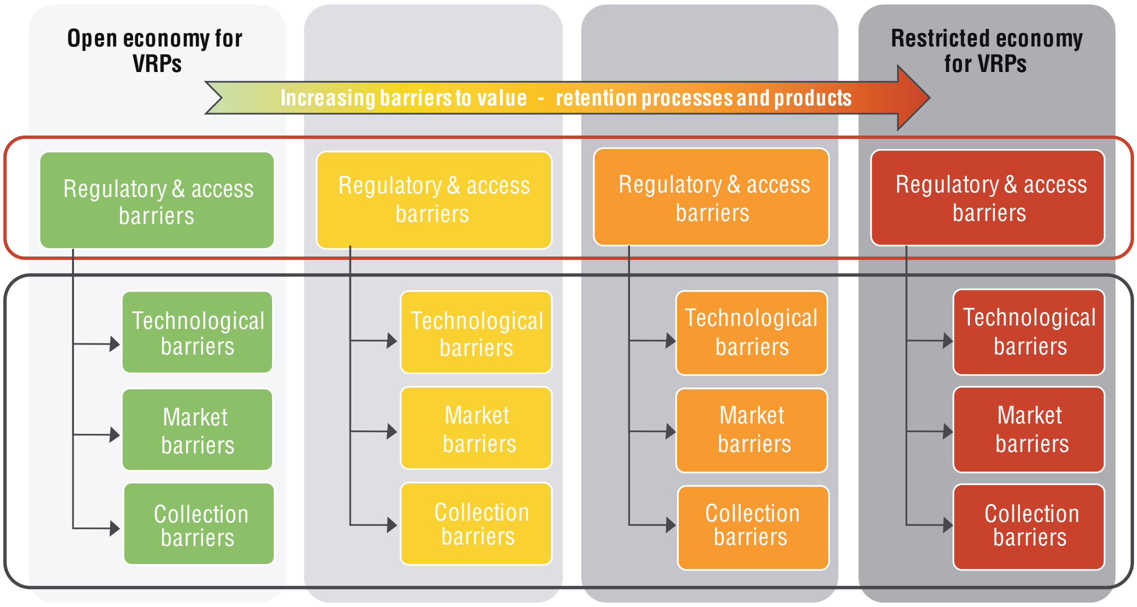
The size of the VRP industry, and the ability to improve resource efficiency is entirely dependent upon the VRP producer's ability recover product cores from the market in the first place. The logistics of collection are well studied, and an unavoidable fact of reverse-logistics and collection is that there is an increased cost to the system that must be borne by someone. In the absence of diversion regulations, there is often little incentive for OEMs or municipal governments to assume the cost burden of collection. For some VRP producers, typically larger OEM's engaging in remanufacturing, that can justify the business case for recovering cores (e.g. where there is a secondary market incentive payment for the core that would be paid to the collector), the collection system can be effective, as demonstrated by the high collection rates for HDOR equipment parts for remanufacturing, globally (~93 per cent). However, collectors must educate and incentivize the user to ensure that the product gets back into the collection system instead of going to landfill. In the case of remanufacturing, producers often attempt to accomplish this by offering an incentive payment for the return of the product or charging a deposit fee on the product at the time of purchase. With the appropriate education and incentives in place, users and agents throughout the system are better positioned to increase collection rates and improve the efficiency of reverse-logistics systems to get cores back into the VRP system.

7

Value-retention processes within markets

7.1 Modeling framework

To reflect the range of conditions that exist in economies around the world, four representative sample economies — Brazil, China, Germany and the US — were identified, each with differing conditions and barriers that affect the adoption and growth of VRPs. Primary barrier categories focus on challenges in regulatory policy, technological capability, market conditions, and collection system (reverse-logistics) infrastructure.



Modified from (UNEP IRP Beijing Workshop and Nasr 2016, UNEP IRP Berlin Workshop and Nasr 2016)

Figure 33: Spectrum of barrier-conditions and barrier-alleviation scenarios

The overarching approach to modeling and accounting for different systemic barriers to VRPs is described in Figure 33, which reflects the range from no barriers to VRPs (green), increasingly through to many barriers to VRPs (red). For the purposes of this assessment, each representative economy was then considered in terms of the policy, technological, and economic literature surrounding its industrial systems, and rated on a spectrum of barrier presence and severity.

Considered in conjunction with the product-level impacts discussed in Section 4, these baseline economic models provide the socioeconomic contexts in which the impacts of barrier alleviation on Value-Retention Process performance and adoption potential were projected. Additional details about the assessment of VRP barriers can be found in Appendix B.

The potential for arranging direct reuse, repair, refurbishing and remanufacturing is dependent largely on product type and design, material composition, and the presence of appropriate technical knowledge and infrastructure to support these activities. As such, the potential material efficiency, or 'reusable share' of a single unit of the product is unlikely to change across markets; and as such, these per-unit material efficiency values are held constant across the market economies represented in this report. What may change from one economy to another relates to technical production efficiency: the magnitude of production waste and associated requirement for new material inputs; the labor required to complete the process for a single unit; the associated energy requirement of the production process, reflective of the efficiency of infrastructure in that economy; and the emissions associated with that energy consumption. These factors are presented in greater detail in Appendix B.

7.2 Barrier alleviation scenarios

As with any form of innovation, a significant determinant of success in Value-Retention Process adoption is the degree to which the barriers precluding the growth of these process innovations (VRPs) are alleviated. To predict how the circular economy might be enabled, considering the myriad interactions of inhibiting factors, baseline economic models were combined with product level VRP models to subsequently project the evolution of the industrial economy over a seven-year period under three different scenarios for barrier alleviation. As such, the results of this scenario analysis reflect the cumulative values over the simulated seven-year period These scenarios are modeled as follows:

Status quo for VRP products: Industrial economies in all representative markets continue to grow and adopt VRPs at their current rate, with all inhibiting factors held constant, ultimately maintaining current rate of economic and environmental performance.

Standard open market for VRP products: Each representative economy is forecasted to grow under regulatory, trade, economic, and technological conditions that are equivalent to those of the Status Quo United States assessment.[20] Moderate existing barrier intensity is met with similarly moderate interventions toward alleviation.

Theoretical high for VRP products: Barrier alleviation is projected as a priority in all representative markets, reflecting widespread acceptance of and investment in a transition to the circular economy. Research and development of technologies, business models, and policy initiatives to support VRPs proceed at an increased rate and intensity relative to the contemporary US baseline case, and the share of production activity across each VRP is set to reflect the Theoretical High US production share. This scenario is deliberately set to establish an extreme, positive, scenario for VRPs.

For ease of reference, this approach was originally discussed in Section 4.3, and presented in Figure 15 (refer now to Figure 34). It is important to note that the use of a seven-year simulation period does not suggest that this is a sufficient or optimate transformation period for industrialized or non-industrialized economies. The transformation to circular economy is complex and requires comprehensive and integrated engagement of government, industry, and value-chain stakeholders, and as such expectations of the transformation timeline must be firmly grounded in the individual conditions and priorities of every respective economy.

These scenarios reflect the range of market evolution possibilities that may result from different levels of conceptual acceptance of and investment in the circular economy concept, as both the

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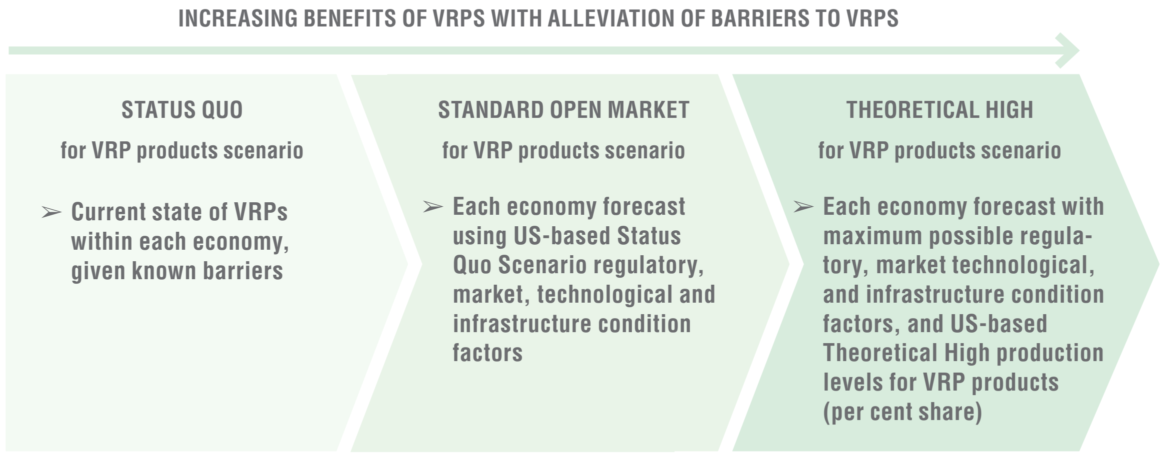
[20] The use of the US example as Standard Open Market is not a reflection on the reputation and performance of other progressive countries, but rather a necessary condition for the some of the required modeling. This decision was due to the Industrial Digital Production Printer case study sector, which is affected by Basel Convention rules that constrain (if not volume, then the ease of) the exchange of these units for use in VRPs at the international level. While not a commentary on the value of the Basel Convention, the absence of similar constraints made the US the least-constrained sample economy within the study.

industry and the demands upon it continue to grow. The results of these projections are thus intended to provide insights into how to address barrier factor interactions in pursuit of greater VRP adoption. As previously mentioned, to reflect growth, market evolution, and compounding complexity in a realistic and meaningful way, these scenario projections are simulated over a seven-year period. This duration period was selected because it ensured that systemic changes could be observed over time, without an unrealistic assumption that there would be no other significant endogenous changes in an economy.



- ➢ Current state of VRPs within each economy, given known barriers
- ➢ Each economy forecast using US-based Status Quo Scenario regulatory, market, technological and infrastructure condition factors
- ➢ Each economy forecast with maximum possible regulatory, market technological, and infrastructure condition factors, and US-based Theoretical High production levels for VRP products (per cent share)

Figure 34: Overview of barrier alleviation scenarios

As with any strategic initiative, there are three critical stages: first, establish a baseline to understand the reality of the 'current state'; second, clearly define the objective or target, so that the vision can be articulated; and finally, establish an implementation plan with clearly defined steps and milestones that enable progress from the current state toward the desired future.

In the case of VRPs, the Status Quo and Theoretical High scenarios reflect the first and second stages, respectively. The Standard Open Market for VRP products scenario offers some insight into potential implementation plans – via policy decisions and system interventions – that may guide policy makers and industry decision makers in the development of appropriate strategies for their country's specific conditions and needs.

Within each of these barrier alleviation scenarios several system-based factors were determined and applied: (1) Regulatory factors, which reflect the presence and relative extent of regulatory-based differentiation and/or discrimination against case study products produced via VRPs, which also differ across case study sectors within each of the represented economies; (2) Market factors, which reflect relative customer-based differentiation and/or discrimination against refurbished and remanufactured products across represented economies; and (3) Technological factors, which reflect the relative degree of systemic technological barriers across each of the represented economies. Collection infrastructure factors were held constant in each economy, across each scenario.

7.2.1 Regulatory and access factors

Regulatory and access factors are differentiated by case study sector, as a range of regulatory barriers exist specific to different sectors, product types and/or materials. For example, the Basel Convention applies to case study industrial digital printers, thus potentially requiring additional procedural requirements for the movement of affected repaired, refurbished, and remanufactured industrial digital printers between Signatory countries (e.g. US) and countries that are both Signatory and Party (e.g. ermany)[21]. Regulatory factors are determined quantitatively based on a combination of the OECD's Trade Facilitation Indicators[22] for each represented economy, and the World Bank's 2015 Ease of Doing Business Index[23]. The OECD Trade Facilitation Indicators were developed to help countries alleviate problematic border procedures and reduce trade costs and reflect relative ease of trade across OECD countries across a range of trade factors. The World Bank Ease of Doing Business Index ranks economies, relative to each other, on the basis and presence of business-friendly regulations: countries are ranked out of a possible 190, with a score of '1' reflecting the most business-friendly conditions. These metrics were normalized and multiplied to determine appropriate regulatory and access factors for each represented country, by appropriate case study sectors (please refer to Table B-30 in Appendix B).

7.2.2 Market factors

Market factors within the economy-level model reflect a qualitative average 'discount' that might be applied by customers and businesses to refurbished and remanufactured goods within an economy, and which therefore constrains demand for these VRP options. This discount references expectations and perceptions about product quality (e.g. products via VRPs as having lesser quality than that of an OEM New option), as well as market-based preferences for 'new' products as status symbols and indicators of affluence or prestige. Economies that have had greater exposure to VRPs and options are assumed to 'discount' refurbished and remanufactured products to a relative lesser degree than would be in economies with little to no exposure to VRPs. In other words, market factors are greater for those economies that currently face the greatest market constraints. The influence of social norms, consumer preferences, information asymmetry are important considerations within the VRP market, and are discussed in greater detail in Sections 6.1, 6.2, and 8.3.2.

7.2.3 Technological factors

Technological factors reflect the relative benchmarking scores from the OECD's Science, Technology and Innovation Outlook 2016 report, which reflects the degree to which national-level science, technology and innovation (STI) policies, instruments, and systems are contributing to growth[24]. For the represented economies, relative scores from the STI Outlook 2016 report are aggregated into five categories describing the current status of the relative STI system (please refer to Table B-29 in Appendix B).

7.2.4 Import share

Finally, trade conditions, specifically import ratio assumptions were required to simulate Standard Open Market and Theoretical High scenarios, particularly for economies that currently enforce some degree of import restrictions against VRPs. For these scenarios the import share for OEM New products for each economy was held constant; in the Standard Open Market for VRP products scenario, import ratios for VRPs were set equal to that of the equivalent product for the US; in the Theoretical High scenario, import shares were either maintained (developed/industrialized economies), or set to an assumed 20 per cent share (developing/newly industrialized economies) (please refer to Tables B-31 and B-32 in Appendix B).

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[21] A multilateral agreement under Art. 11 of the Basel Convention (OECD Decision C(2001)107/Final) allows for such movements; however, certain procedural requirements, such as a PIC procedure, apply.

[22] OECD. 2015 Trade Facilitation Indicators. http://www.oecd.org/trade/facilitation/indicators.htm

[23] World Bank. 2015 Ease of Doing Business Index. http://data.worldbank.org/indicator/IC.BUS.EASE.XQ.

[24] OECD. Science, Technology and Innovation Outlook 2016. http://www.oecd.org/sti/oecd-science-technology-and-innovation-outlook-25186167.htm

7.3 Analysis and opportunities via value-retention processes

7.3.1 Overview of analysis approach

A primary objective of this study is to understand the benefits, through impacts avoided, of increasing the adoption of VRPs within economic production activities. As such, results and analysis are presented for the most part, in aggregate format contrasting the impacts (and impacts avoided) between OEM New production, and the cumulative VRP activity level for each case study sector within each studied economy. Where appropriate, and to provide an understanding of the approach, additional clarifying examples of simulation over time (e.g. over seven years), and the substantiating data behind aggregated results are provided.

It should be noted that production levels reflect the aggregated production volume in an economy, which may be supplied into the domestic market, or may be exported. Total domestic production may be different from domestic market demand levels: in some cases, domestic production may be lower than domestic demand, with the differential supply requirement being met by imported units. In cases where domestic production exceeds domestic demand, the implication is that there is a substantial quantity of finished units being exported to other markets (refer to Figure 31).

The calculation of total environmental impacts includes the direct environmental production impacts that result from domestic production levels, including exported units; it also includes the indirect environmental production impacts that are associated with the production of OEM New and VRP products in other economies. This approach ensures that the environmental impacts are appropriately allocated to the consuming economy alongside the direct environmental impacts that contribute to the domestic economy.

In addition to presenting analysis of the current state impacts (via Status Quo scenario), the additional Standard Open Market for VRP Products and Theoretical High for VRP Products scenarios data are included to highlight the opportunity and implications of alleviating barriers to VRPs. As each of the represented economies face differing conditions and constraints, the opportunities and implications for both policy makers and corporate decision-makers will necessarily differ.

As previously described, the Theoretical High scenario reflects ideal conditions in which adoption of VRPs reflects the production shares and market adoption observed for the optimized Theoretical High US scenario. The purpose for this ideal scenario is to demonstrate what might be possible if, through joint-effort and collaboration, stakeholders in an economy were able to immediately alleviate the primary barriers constraining VRP adoption.

The following sections illustrate this analysis, organized by case study sector: industrial digital printers; vehicle parts; and HDOR equipment parts. It is important to note that some observations, for example, those driven by an overarching condition of an economy, may be applicable across all sectors; other observations may be sector-specific, and/or even process specific.

7.3.2 Context of analysis

An unavoidable consequence of economic growth is the increased consumption, to some degree, of materials and resources. As production levels rise within an economy – either to meet domestic or international demand—the requirement for energy, labor, and material inputs, and the generation of emissions and solid waste will also rise. The projected growth rates for the represented sectors are based on compound annual growth rates (CAGR) of actual past five-year performance within each economy.

The primary objective of increasing the scale of VRPs within an economy’s production system is to enable an increasing rate of economic growth and prosperity, alongside a relatively decreasing rate of materials and resource consumption. In the absence of any improvements to material or production process efficiency, the rate of input consumption and the rate of waste and emissions generations will parallel the rate of change to the production level. Logically, in this way growing customer demand within a specific market will require greater quantities of material and energy inputs to production; a shrinking or stagnating product market will likewise reduce the quantity of material and energy inputs and wastes generated. However, given economic and human prosperity objectives tied heavily to economic growth, the pursuit of more sustainable production systems cannot rely on de-growth strategies. This is particularly meaningful in the context of developing/newly industrialized markets in which middle class population and associated consumption patterns are increasing.

The pursuit of material efficiency and production efficiency can be achieved by decreasing the per-unit requirements and impacts of production where the rate of increase in materials and energy consumption, and waste and emissions generation is decoupled from production growth. A key strategy in the pursuit of reduced per-unit impacts of production is the increased scale and adoption of VRPs that effectively offset input requirement and waste generation, without compromising the ability of the economy to grow.

The barriers to VRPs discussed in Section Erreur ! Nous n'avons pas trouvé la source du renvoi. are complex, interconnected, and vary from one country to another. Despite this complexity, it must be acknowledged that the alleviation of these barriers represents the proverbial 'low-hanging fruit' opportunities when considered in the context of the more massive global system overhaul and redesign that will be needed to more fully respond to the reality of finite resources and fast-approaching maximum carrying capacity of the planet. Even if all known barriers to VRPs were alleviated tomorrow, more substantial changes related to consumption behavior, product design, collection infrastructure, financial market and corporate rewards systems are required to sufficiently respond to the planet's constrained systems.

In the meantime, insights and strategic options are needed to support and enable policy makers and industry decision-makers to begin planning and implementing towards the desired future state. There are key differences in the priorities, opportunities, and ideal strategies for developed/industrialized versus developing/newly industrialized economies.

7.4 Analysis of Industrial digital printers sectors

The industrial digital printing subsector (high-volume commercial digital printers) consists of companies that produce imaging technology systems, part modules, replaceable components, and consumable colorant cartridges. These companies primarily focus on imaging products that use toner or ink as the print material. There is a significant subsector encompassing independent, contract, and OEM organizations that provide alternatives to new products. Industrial digital printers are unique among the case study products because they are designed with VRPs in mind, as discussed further in Section 8.2.

Although there are only a few producers of industrial digital printers worldwide that engage in VRPs including arranging direct reuse, refurbishment and remanufacturing, these producers represent a significant share of the global market and have well established global infrastructure to support the growth of demand for VRP industrial digital printers.

7.4.1 Industrial digital printer production levels

Production levels refer to the output volume of domestic producers and includes the total number of units supplied into the domestic market, as well as the total units exported to other markets. The estimated production levels of industrial digital printers, by OEM New and VRP production types, and by economy, are presented in Figure 35 through Figure 38. Also shown are estimated total domestic market demand levels for each economy, which are indicative of the relative levels of imported products to supply domestic demand.

The industrial digital printer sector in the US has progressed dramatically in terms of adoption of VRPs within the production mix (Figure 35). Led by a few key market leaders that are based in the US, there is great opportunity for material efficiency and impact reduction through VRPs. Please note that, since the Standard Open Market for VRP Products scenario is reflective of US conditions, there is no change to US production levels and associated production impacts between the Status Quo and Standard Open Market for VRP Products scenarios.

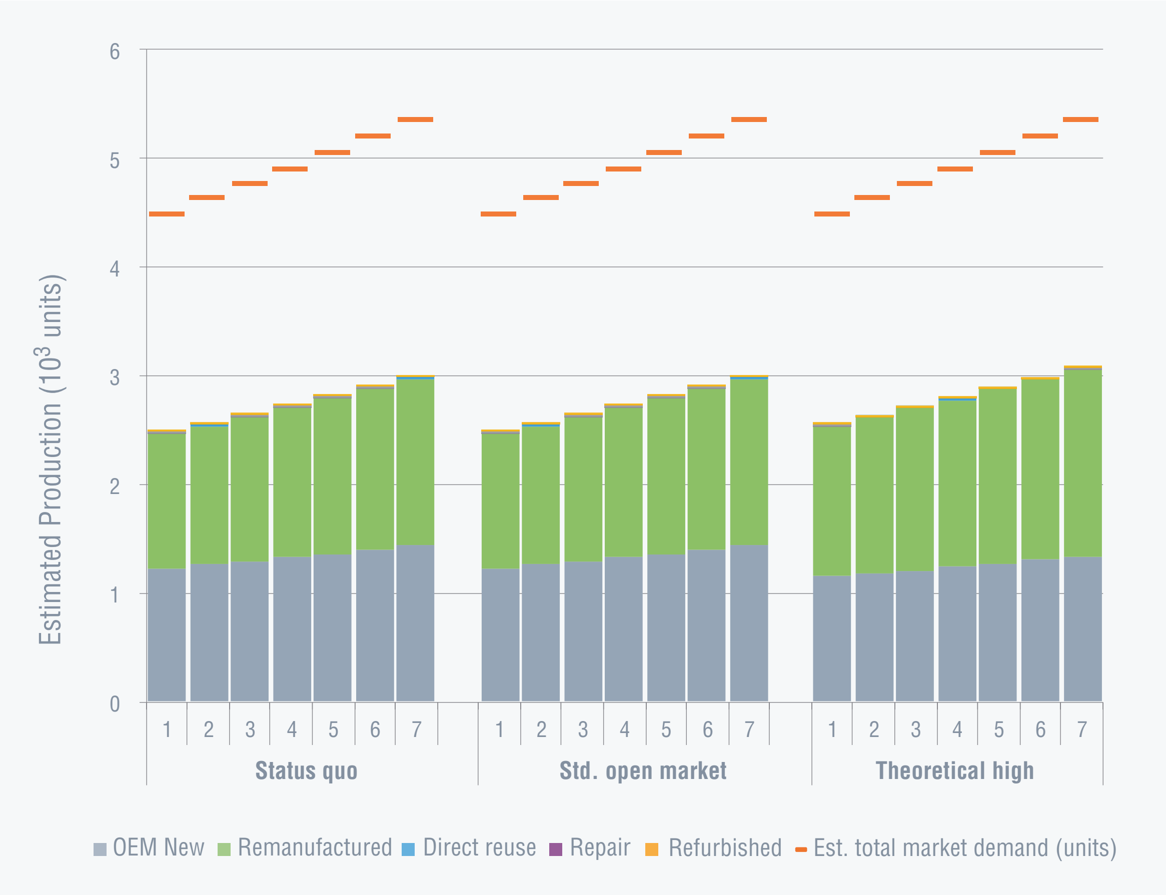


Figure 35: Estimated US production of industrial digital printers relative to estimated demand in US simulated over 7 year scenarios

Germany also shows a meaningful share of remanufacturing activity in the Status Quo scenario, although production activities currently emphasize OEM New production (Figure 36). In contrast, Brazil and China each have a lesser share of VRP production for these products in the Status Quo scenario. In Brazil, regulatory barriers constrain the movement of industrial digital printer cores into the country for remanufacturing or comprehensive refurbishment (Figure 37). In China, this lower VRP share is largely due to regulatory conditions that do not allow for unconstrained remanufacturing and refurbishment of industrial digital printers (Figure 38) (U.S. International Trade Commission 2012).

Production levels are a very important aspect of this analysis, as it is the production level that significantly informs the associated impacts of production, including process-based material requirement, process energy requirement, and associated process emissions. These process-based impacts are importantly differentiated from materials-based impacts. While the embodied materials energy and emissions associated with all case study products, based on their material composition, reflects a global average, the process-based energy and emissions are reflective of the economy, and corresponding energy-production grid, in which production takes place.

The alleviation of some of the regulatory, technological and market-based barriers under the Standard Open Market suggest that the uptake of VRP production may lead to increased share of the production mix, over time, for industrial economies facing significant regulatory and other barriers (Figure 37 and Figure 38). However, adoption rates can be constrained by the starting share of VRPs: where relatively low (high), growth of the VRP production mix share occurs more slowly (quickly).

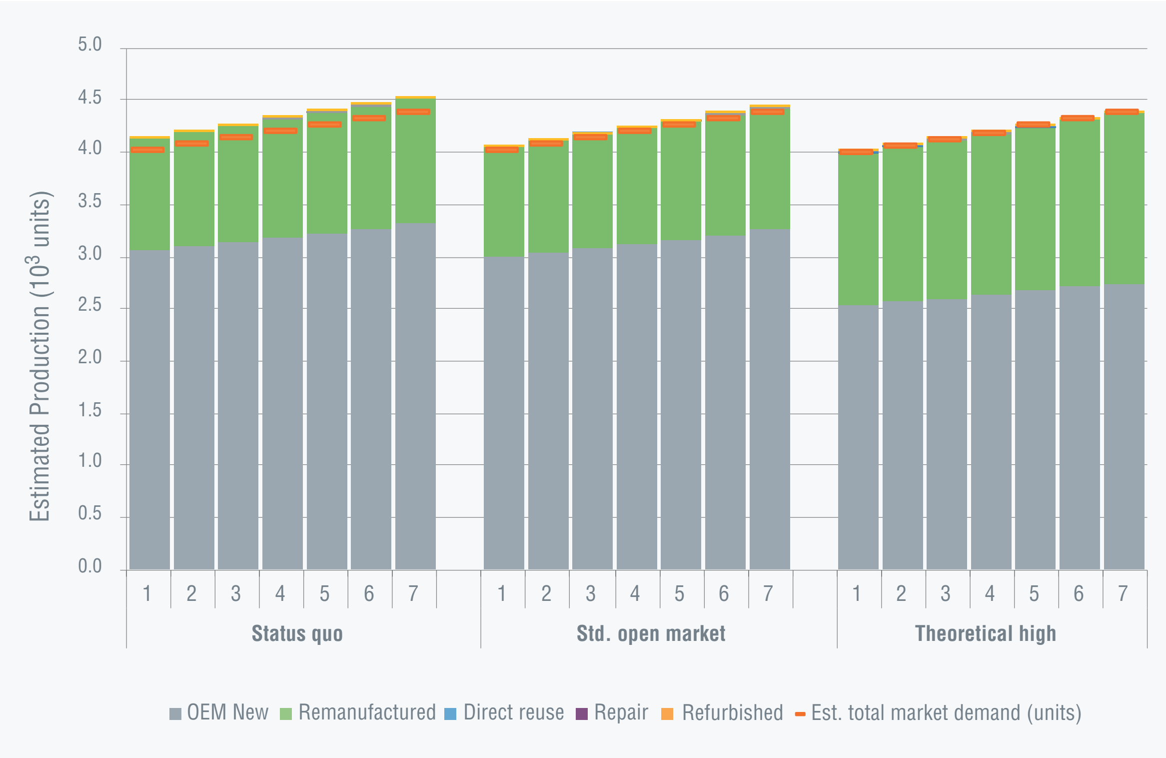


Figure 36: Estimated Germany production of industrial digital printers relative to estimated demand in Germany simulated over 7 year scenarios

This is further evidenced by the impact of an imposed higher production share via the Theoretical High scenario, where combined with the alleviation of other systemic barriers, VRP production levels increase significantly in previously constrained economies (Figure 37 and Figure 38).

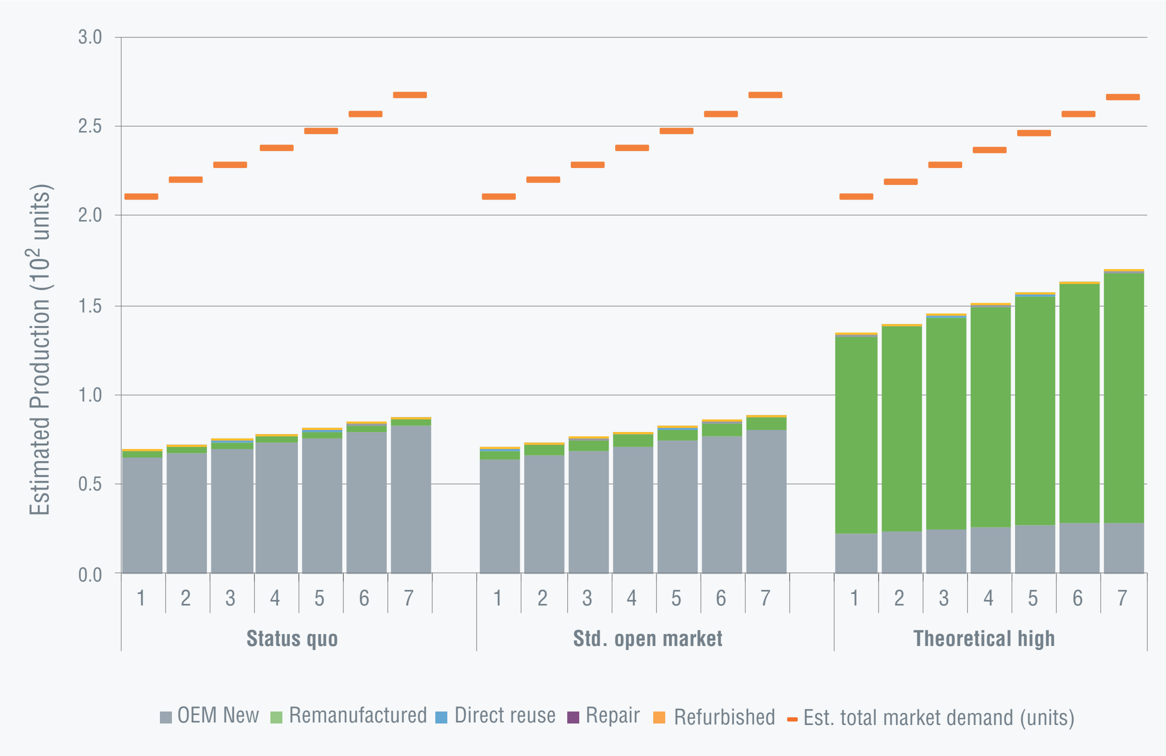


Figure 37: Estimated Brazil production of industrial digital printers relative to estimated demand in Brazil simulated over 7 year scenarios

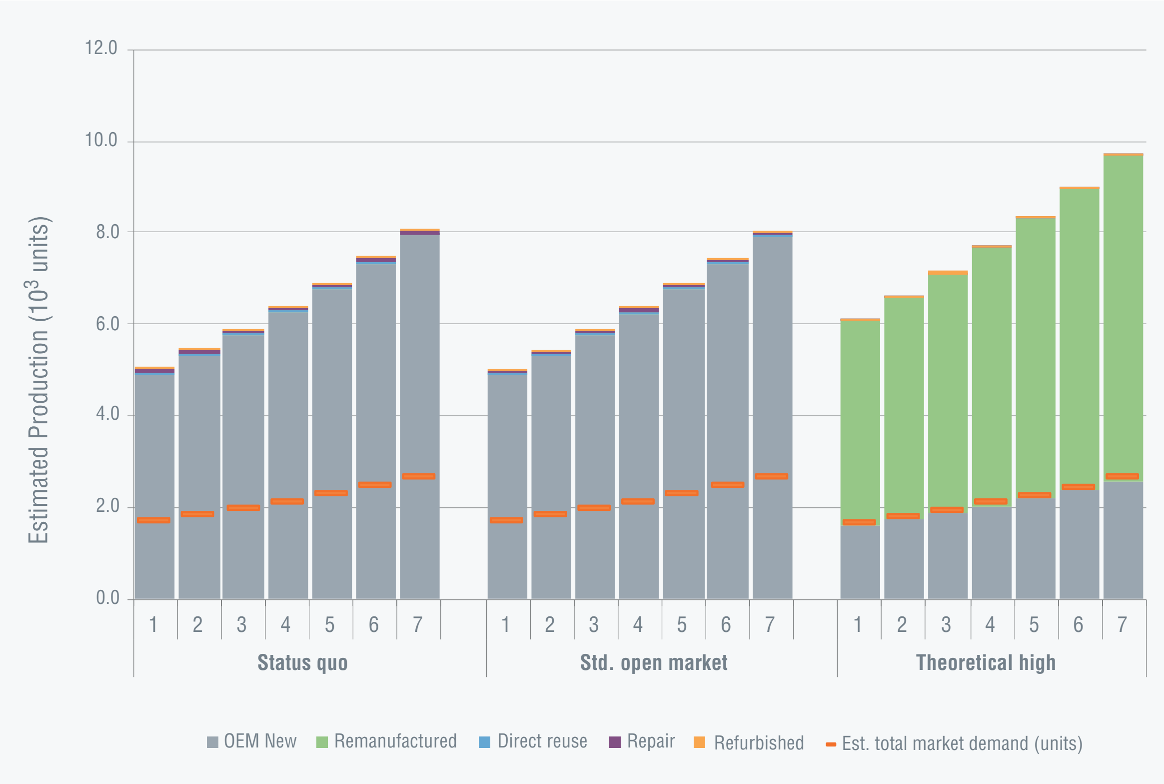


Figure 38: Estimated China production of industrial digital printers relative to estimated demand in China simulated over 7 year scenarios

7.4.2 Analysis of material-level impacts from industrial digital printer production

The production level and growth rates of production in each economy and scenario both inform and affect the associated impacts that are of interest to this study. The material impacts of production are presented in Figure 44 through Figure 47, however a demonstrative example of the aggregation approach is provided first, in this section, and in Section 1.4.3.

Aggregated production is simulated over a seven-year period, and the associated impacts are calculated accordingly. New materials both used and avoided through the incorporation of industrial digital printer remanufacturing for each of the seven-years, across all three scenarios is depicted in Figure 39, while Figure 40 highlights just the quantity of new materials avoided over the same period and scenarios.

New material avoided is a representation of material offset that is enabled through VRPs: in other words, the reuse of materials and components (sometimes referred to as 'cores') as part of VRP production activities inherently reduces the need for the equivalent quantity of new materials. This 'new material avoided' measure reflects the difference in the quantity of new material that would have been required if 100 per cent of an economy's production was via linear OEM New processes. This can also be considered as the quantity of 'material saved' because of VRP production activities within an economy.

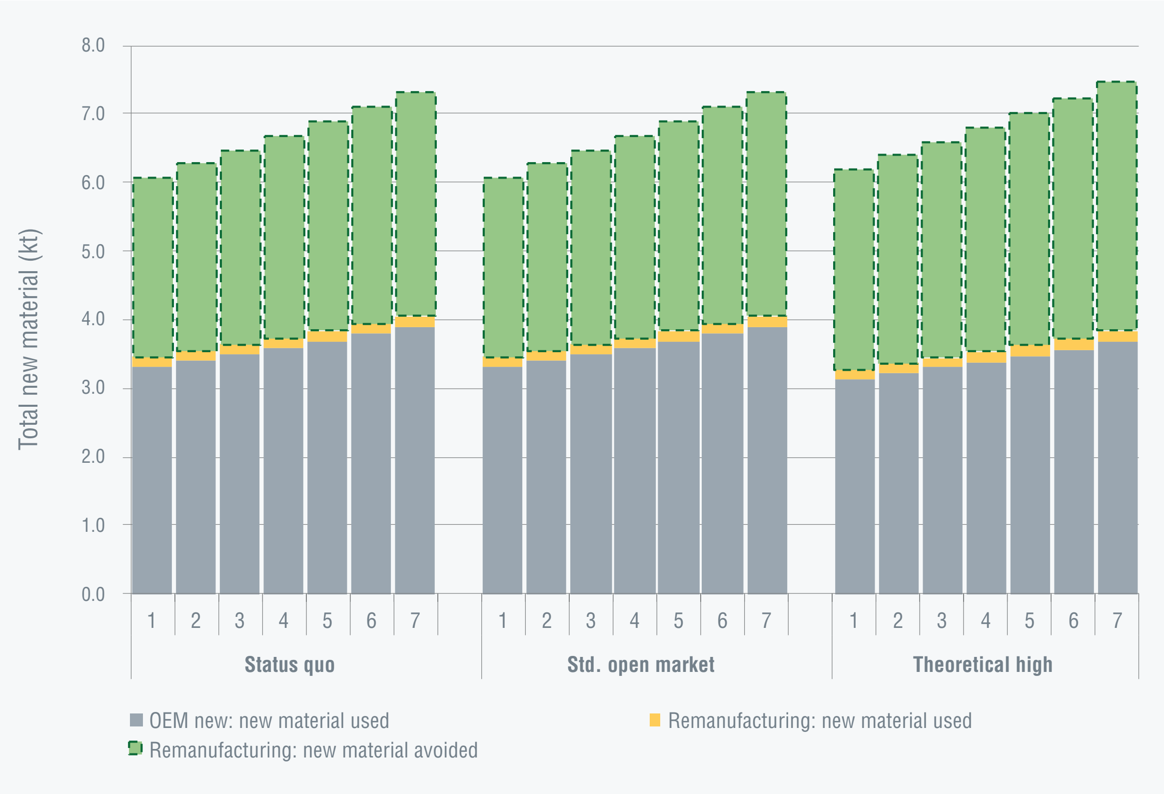


Figure 39: Estimated aggregated new material used and avoided via US remanufacturing of industrial digital printers simulated over 7 year scenarios

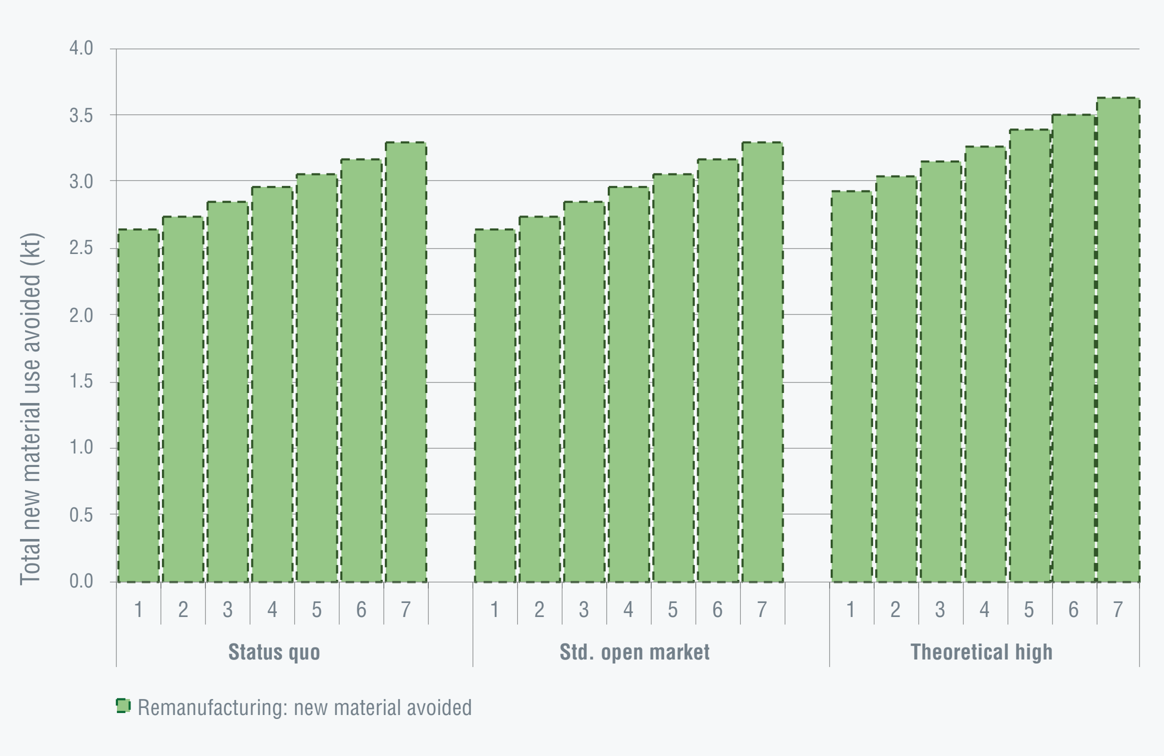


Figure 40: Estimated aggregated new material avoided via US remanufacturing of industrial digital printers simulated over 7 year scenarios

As seen from Figure 39 and Figure 40, the remanufacturing of industrial digital printers taking place in the US is responsible for significant reduction in new material requirements, which are offset by the reuse of product cores in the remanufacturing process.

7.4.3 Aggregation of impacts from industrial digital printer production

From the absolute material, energy and emissions data generated over the seven-year simulation, an aggregate value for the entire period is calculated. Figure 41 describes, as an example, the cumulative new material (aggregate 7 years) that is both used and avoided, when comparing US industrial digital printer production via OEM New versus remanufacturing processes. Given the significant presence of VRP production in the US marketplace, the material-avoided through remanufacturing is significant. It is also important to note that remanufacturing does require the use of some new material inputs as part of the process described in the previous sections. Under each of the scenarios, it can be seen that through remanufacturing (as only one example of VRPs), production-level growth (and the economic growth and prosperity inherent to such growth) can occur, without parallel growth in new material requirement.

Similarly, the aggregated energy and emissions impacts of US industrial printer production are reflected in Figure 42 and Figure 43. These values were determined utilizing the same approach as was used to assess new material requirement and new material avoided.

From the aggregate results presented in Figure 42 (energy impact) and Figure 43 (emissions impact), for industrial digital printers, the most significant impacts derive from the embodied material energy and embodied material emissions associated with the extraction and primary processing of production-input materials. Both of these figures compare the aggregate impacts of OEM New production and aggregate impacts of VRP production in each scenario for the US.

It is worth noting that the high value for aggregated embodied materials energy for industrial digital printers (and potentially other electronic equipment) is largely driven by the presence of printed circuit boards in the product, which significantly affects the aggregate embodied energy use reflected in Figure 42 (refer to Table 5, Table 6, and Table 7 for detailed unit-level impacts; additional details on the embodied energy implications of printed circuit boards can be found in Appendix B, Table B - 2).

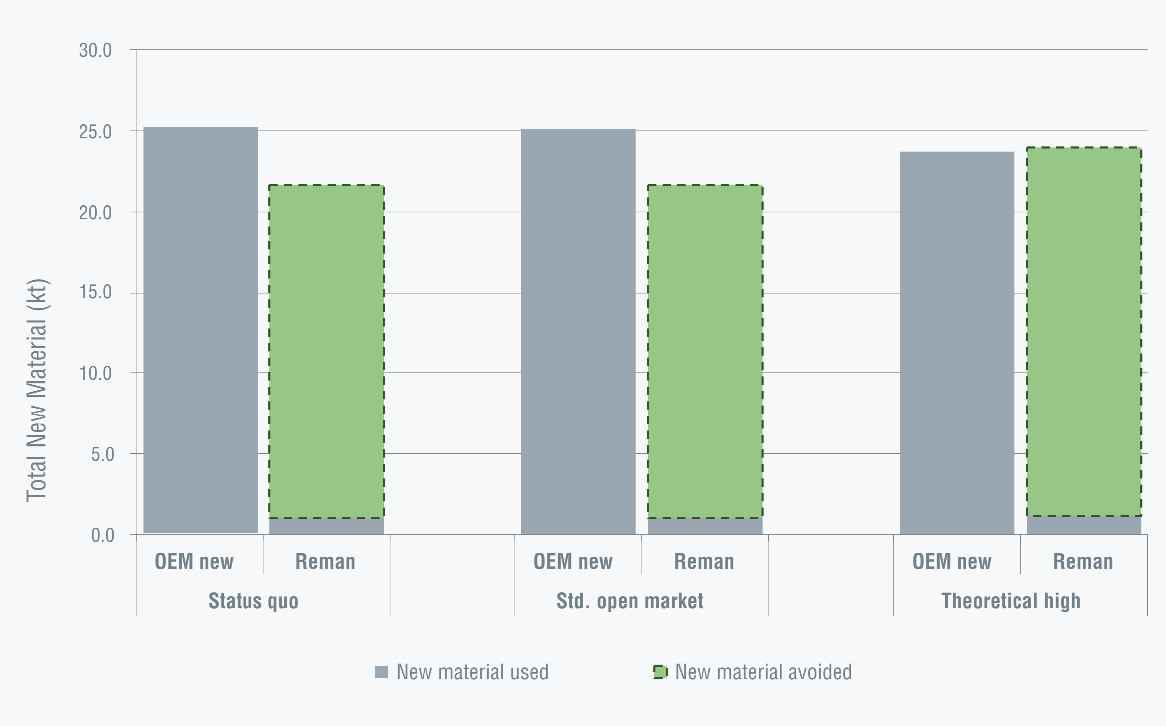


Figure 41: Comparison of new material used and avoided via US remanufacturing of industrial digital printers

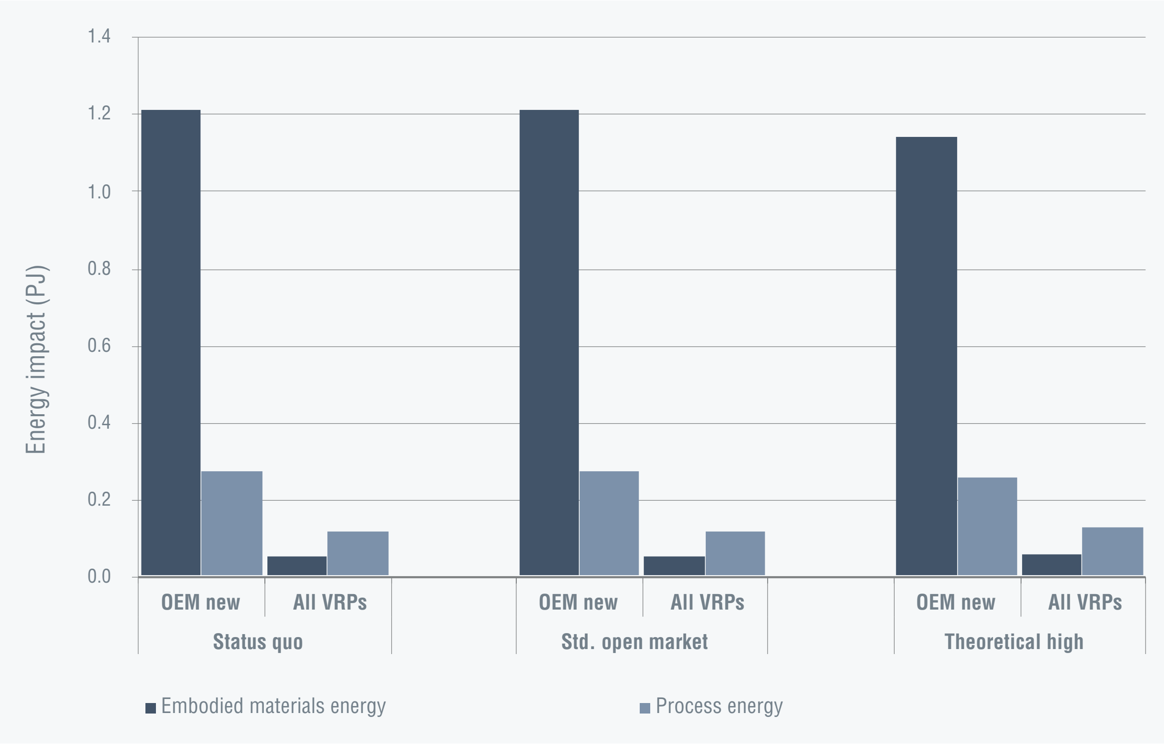


Figure 42: Estimated aggregate 7-year embodied and process-based energy for US production of industrial digital printers

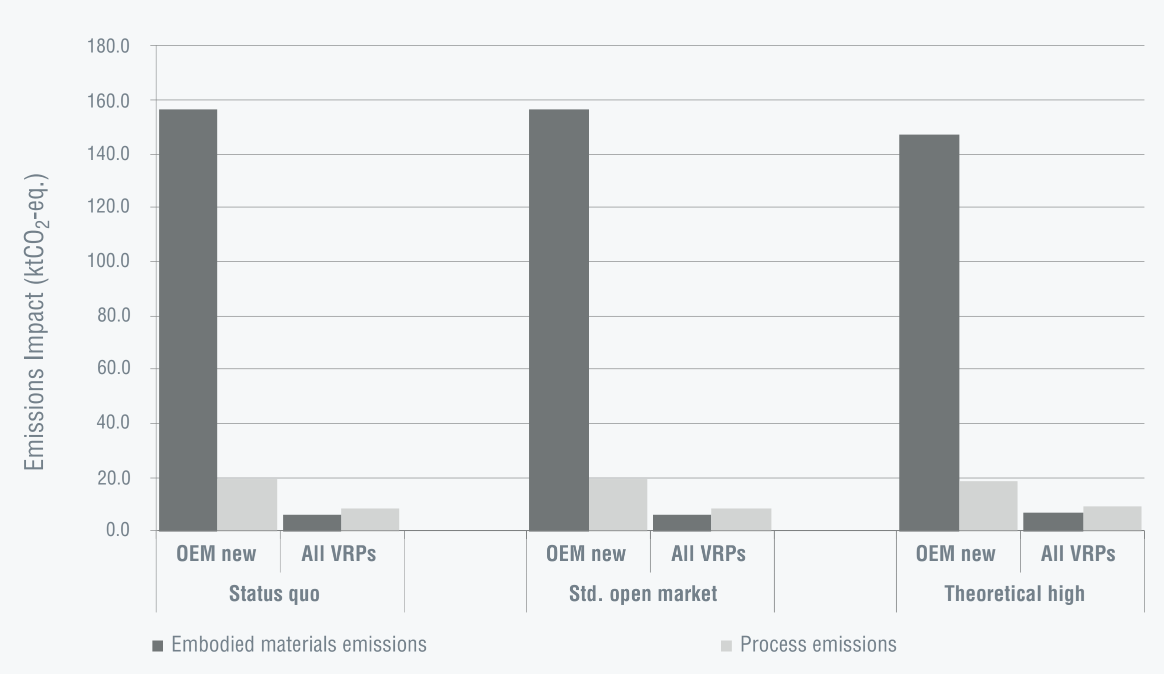


Figure 43: Estimated aggregate 7-year embodied and process-based emissions for US production of industrial digital printers

Given this, potentially the greatest benefit created via VRPs for industrial digital printers is the offset of new material requirement, and the reduction in associated embodied material energy and embodied material emissions. This insight is further observed across all sample economies, as presented in the next section.

7.4.4 Industrial digital printers sector: impacts avoided through value-retention processes

Using the approach described in Sections 7.4.2 and 7.4.3, the aggregated impacts that are avoided in each economy as a result of VRP industrial digital printers produced domestically and imported are estimated and presented in Figure 44 (US), Figure 45 (Germany), Figure 46 (Brazil), and Figure 47 (China). For each of these figures, estimated production and import levels of VRP industrial digital printers are depicted in panel (a); estimated material use avoided as a result of VRP production are depicted in panel (b); estimated embodied and process energy use avoided as a result of VRP production are depicted in panel (c); and estimated embodied and process emissions avoided as a result of VRP production are depicted in panel (d).

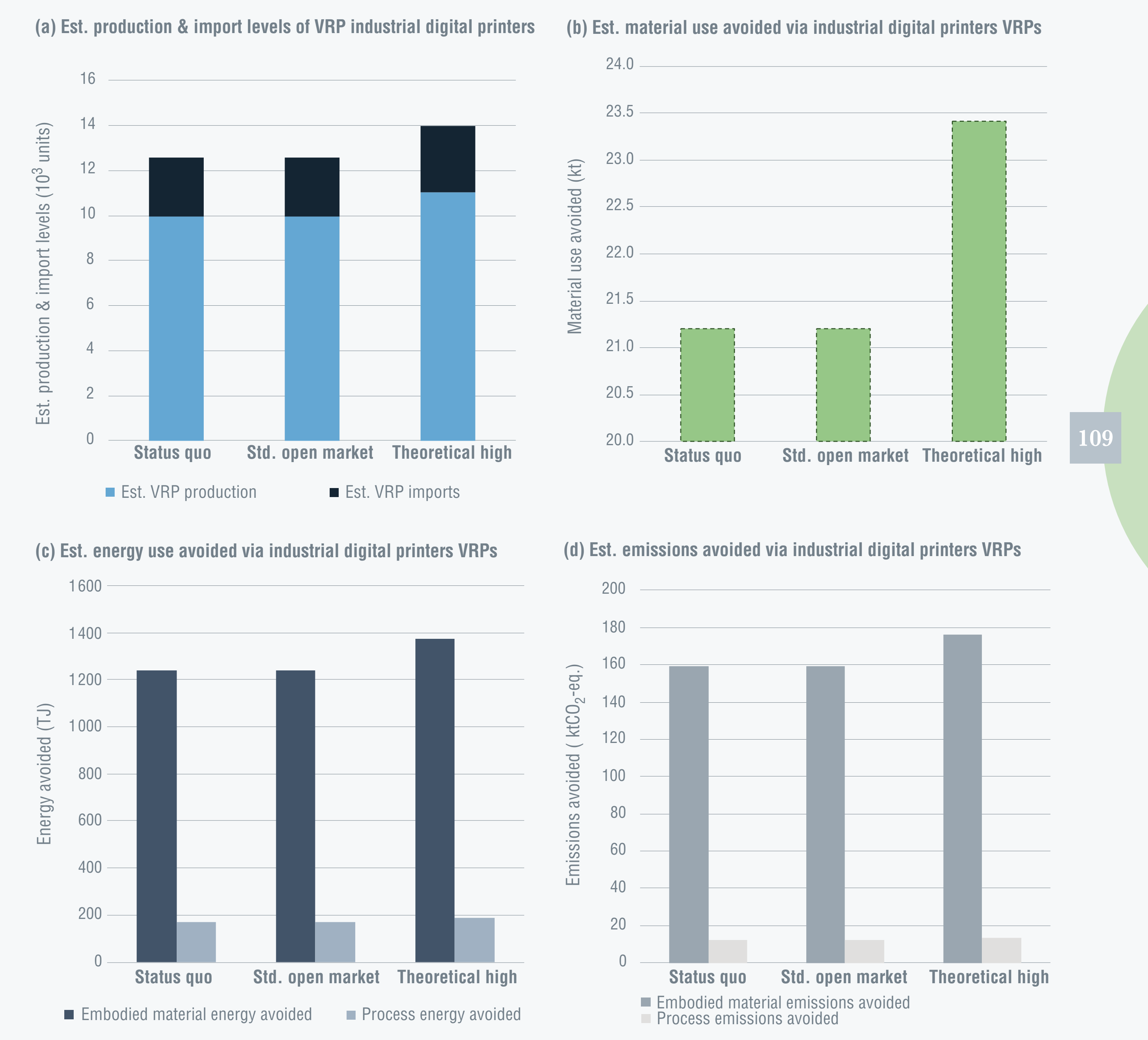


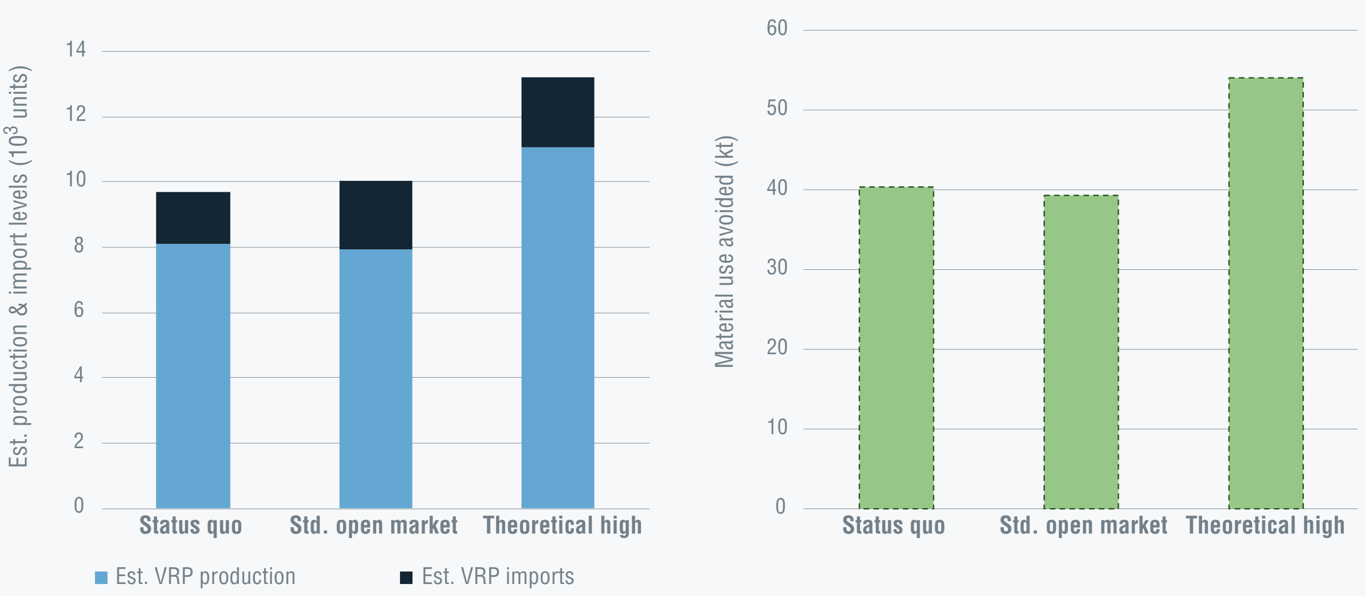
Figure 44: Estimated aggregate 7-year impacts avoided via US industrial digital printer production with value-retention processes

In review of these results, it is important to note the differing scales: not only do production levels vary significantly across these economies, but the factors influencing the associated impacts of production (e.g. the efficiency of energy production, transmission and distribution, and the energy production grid-mix) also vary significantly.

As demonstrated at the product-level, the high levels of embodied material energy avoided in every economy, relative to process energy avoided (Figure 44 through Figure 47), is largely driven by the significant impact of reuse of printed circuit boards.

(a) Est. production & import levels of VRP industrial digital printers

(b) Est. Material use avoided via industrial digital printers VRPs



(c) Est. energy use avoided via industrial digital printers VRPs

(d) Est. emissions avoided via industrial digital printers VRPs

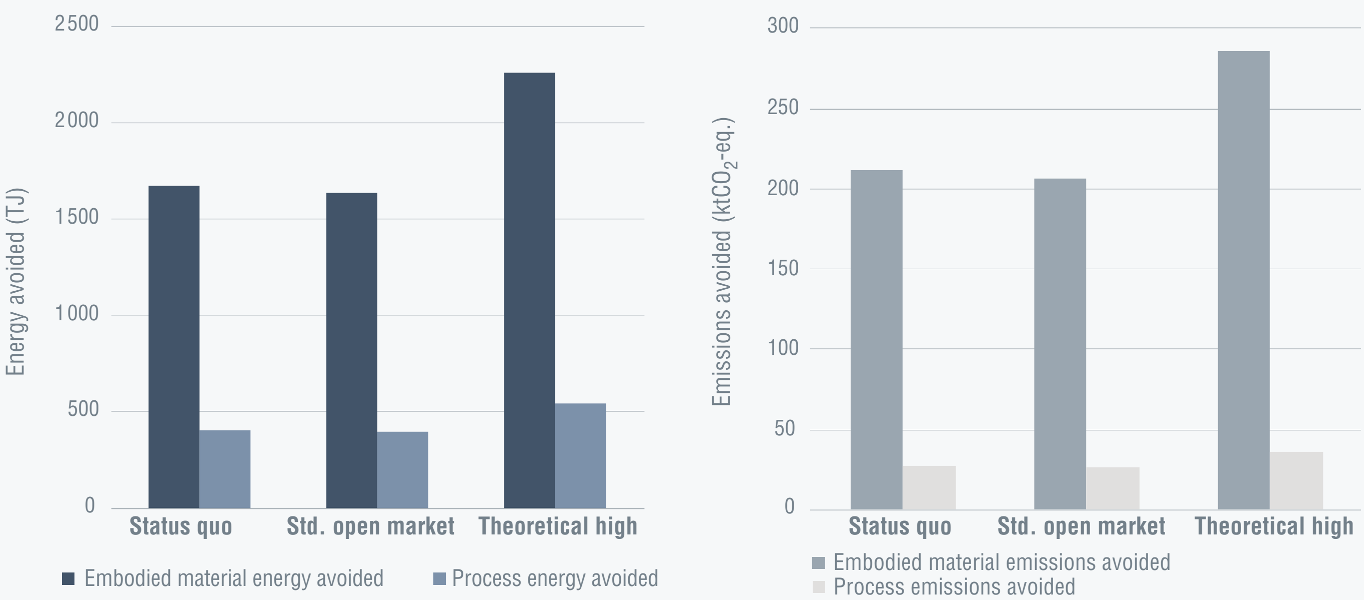
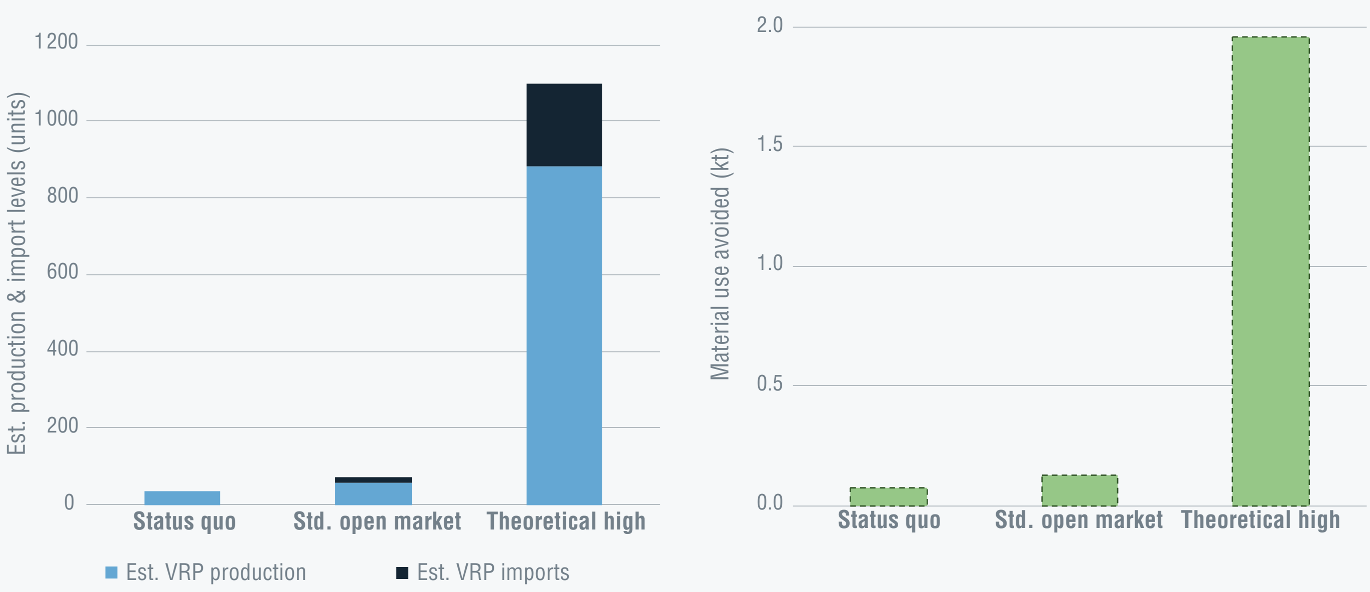


Figure 45: Estimated aggregate 7-year impacts avoided via Germany industrial digital printer production with value-retention process

It is also important to note the conditions of the Standard Open Market scenario and the Theoretical High scenario. The slight reduction in impact avoidance observed for Germany (Figure 45, panels b, c, and d) and China (Figure 47, panels b, c, and d) between the Status Quo and the Standard Open Market scenarios is attributed to two primary causes: The effect of modified import shares which may reduce the domestic production requirement, and thus the impacts of domestic production, and the effect of a changing production process mix, wherein the displacement of lower-impact partial service life VRPs by higher-impact full service life VRPs may actually marginally increase the new material requirement, and associated material and process impacts (refer to Theoretical High scenarios for Germany and China, in Figure 45 and Figure 47, respectively).


(a) Est. production & import levels of VRP industrial digital printers **(b) Est. material use avoided via industrial digital printers VRPs**

(c) Est. energy use avoided via industrial digital printers VRPs **(d) Est. emissions avoided via industrial digital printers VRPs**

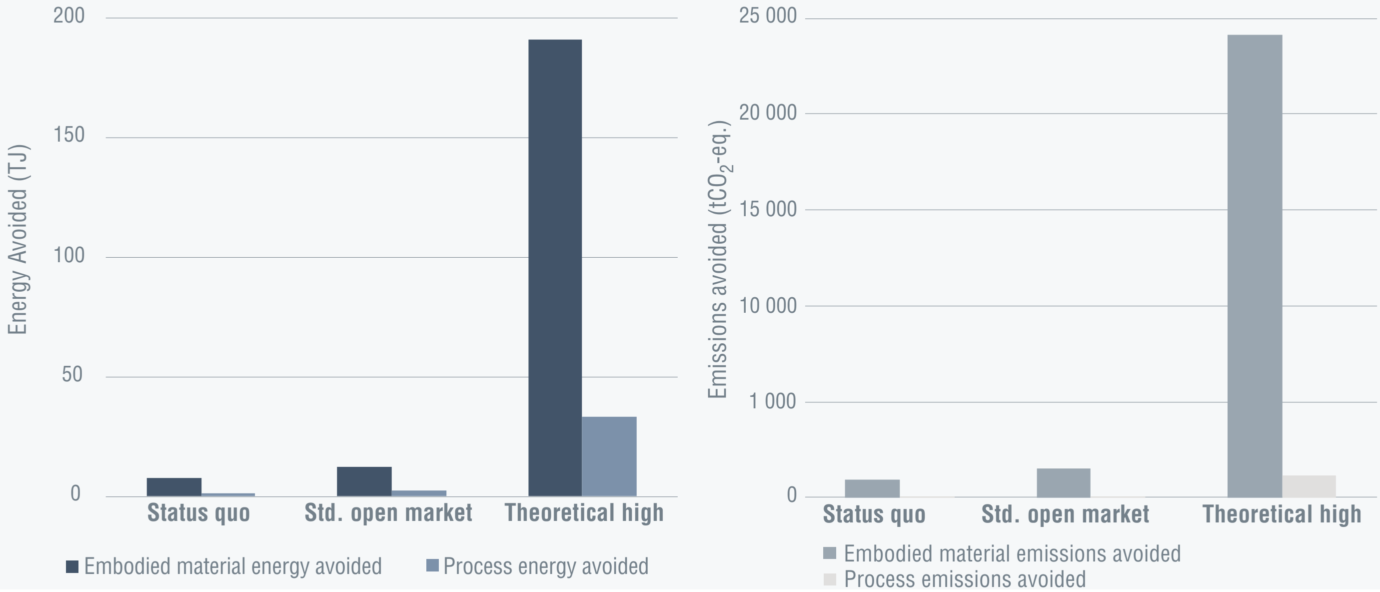
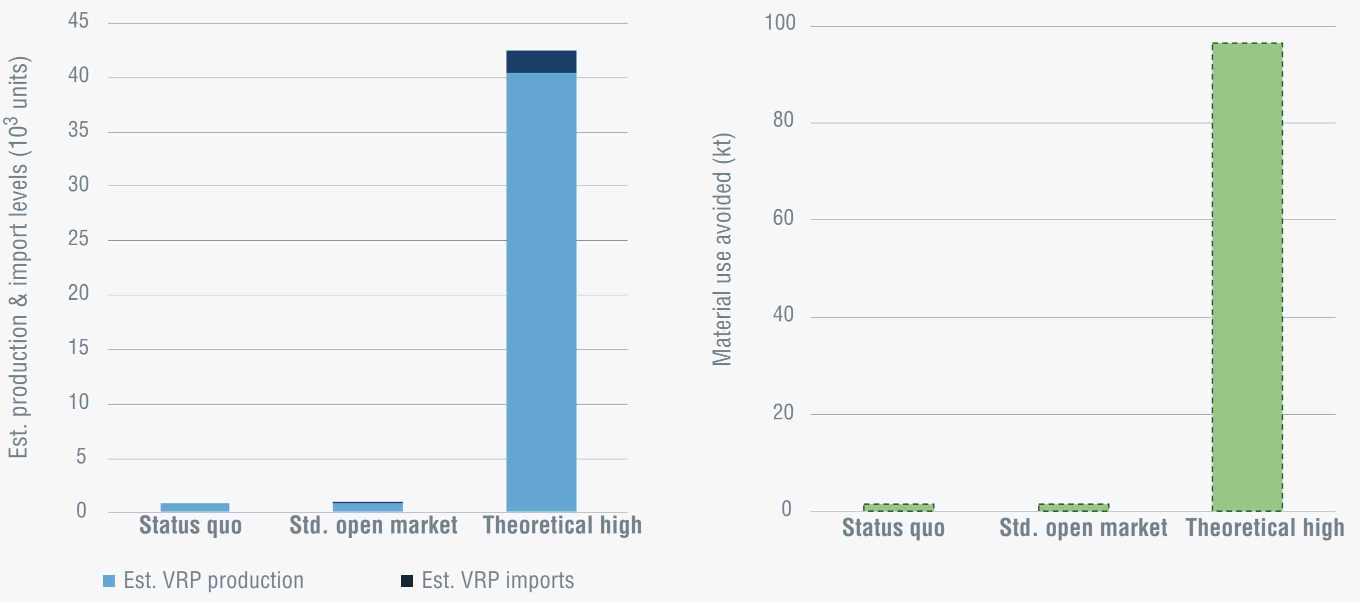
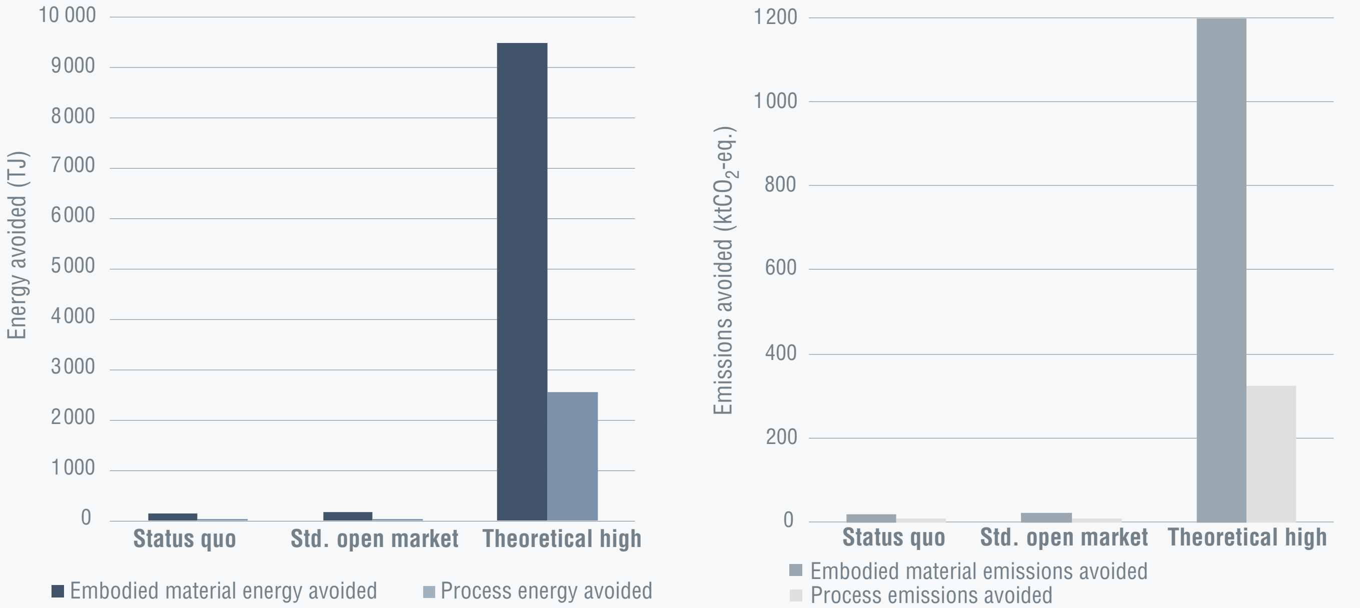


Figure 46: Estimated aggregate 7-year impacts avoided via Brazil industrial digital printer production with value-retention processes


(a) Est. production & import levels of VRP industrial digital printers

(b) Est. material use avoided via industrial digital printers VRPs


(c) Est. energy use avoided via industrial digital printers VRPs

(d) Est. emissions avoided via industrial digital printers VRPs

Figure 47: Estimated aggregate 7-year impacts avoided via China industrial digital printer production with value-retention process

From this analysis, there are significant opportunities to reduce the environmental burden and impacts associated with the growth of the market for VRP industrial digital printers across all economies. While the greatest benefits stem from the avoided embodied material energy and embodied material emissions associated with raw material extraction and processing, there is also a significant reduction in the per-unit requirements and impacts, on average, when demand can be partially met through VRP production. While the results of the Theoretical High for VRP Products scenario are unrealistic in the short-term, decisive and strategic action to alleviate barriers to VRPs in the industrial digital printer sector can only enhance the contribution of VRPs towards the circular economy.

It should be noted that the imposed presence of full service life VRPs in the Theoretical High scenarios for Brazil (Figure 46) and China (Figure 47) effectively displace the current high adoption levels of formal and informal lower-impact partial service life VRPs of repair and direct reuse. For less- and non-industrialized economies where partial service life VRPs (namely, repair) are the dominant form of value-retention within the economy, the adoption of higher-impact full service life VRPs may be unrealistic in the short-term and may also lead to unintended negative environmental consequences in the mid- to long-term, as discussed further in Section 8.3.2.

It must also be acknowledged that the potential for negative environmental impact reduction between the Status Quo and Standard Open Market Scenarios across the sample economies appears to be minimal: this is the result of the scenario assumptions for which barriers to VRPs are alleviated, but adoption rates of VRPs reflect actual current state conditions of the economy. This insight is particularly important, as it firmly highlights that the passive alleviation of barriers can only achieve marginal improvements in impact reduction: increasing adoption rates of VRPs within an economy's production mix through policy and market-based instruments remains a critical element of any circular economy strategy that seeks negative environmental impact reduction (refer to Section 8.4).

7.5 Analysis of vehicle parts sector

The automotive parts industry is one of the world's largest markets for VRPs. This sector includes companies that process components for production light duty cars and trucks, and for medium and heavy commercial vehicles. The sector encompasses independent, contract, and OEM organizations, as well as the supply chain that provides the reverse-logistics of cores from EOL vehicles. The products for which VRPs are currently employed include engines, transmissions, starters, alternators, steering racks, and clutches (U.S. International Trade Commission 2012).

VRP production of vehicle parts has been occurring in markets around the world for decades; as such, remanufacturing is a more familiar VRP opportunity for the vehicle parts industry and their customers. Particularly for heavily mechanical (versus electrical) vehicle parts, such as those included as case study products, remanufacturing is a familiar option in markets where VRP products are permitted.

7.5.1 Vehicle parts production levels

The estimated production levels of vehicle parts, by OEM New and VRP production types, and by economy, are presented in Figure 48 through Figure 51. Also shown are estimated total domestic market demand levels for each economy, which are indicative of the relative levels of imported products to supply domestic demand, and/or exported products.

The vehicle parts sector in the US has progressed dramatically in terms of adoption of VRPs within the production mix (Figure 48). Although currently at a relatively low production share in the US, there is great opportunity for material efficiency and impact reduction through VRPs. In the US, a primary barrier to growth of VRPs for vehicle parts is the competition presented by low-priced imports from other economies. In general, the US's high import level of vehicle parts significantly constrains the growth of domestic VRP activity. This study does not consider changes to the import ratios for the US market; so, while VRP production of vehicle parts remains fairly consistent, even under the Theoretical High for VRP Products scenario, it should be assumed that an increasing presence of competitively-priced domestically-remanufactured options may disrupt the current competitive market and may lead to increased domestic VRP production as a result.

In contrast to the US, Germany, Brazil and China have a lesser share of VRP production in the current state due to the presence of some constraining conditions. In the case of Brazil, market growth (Compound Annual Growth Rate (CAGR) 2012 – 2014) in the relevant Status Quo scenario period was negative.

Please note that, since the Standard Open Market for VRP Products scenario is reflective of some of the US conditions, there is no change to US production levels and associated production impacts between the Status Quo and Standard Open Market scenarios.

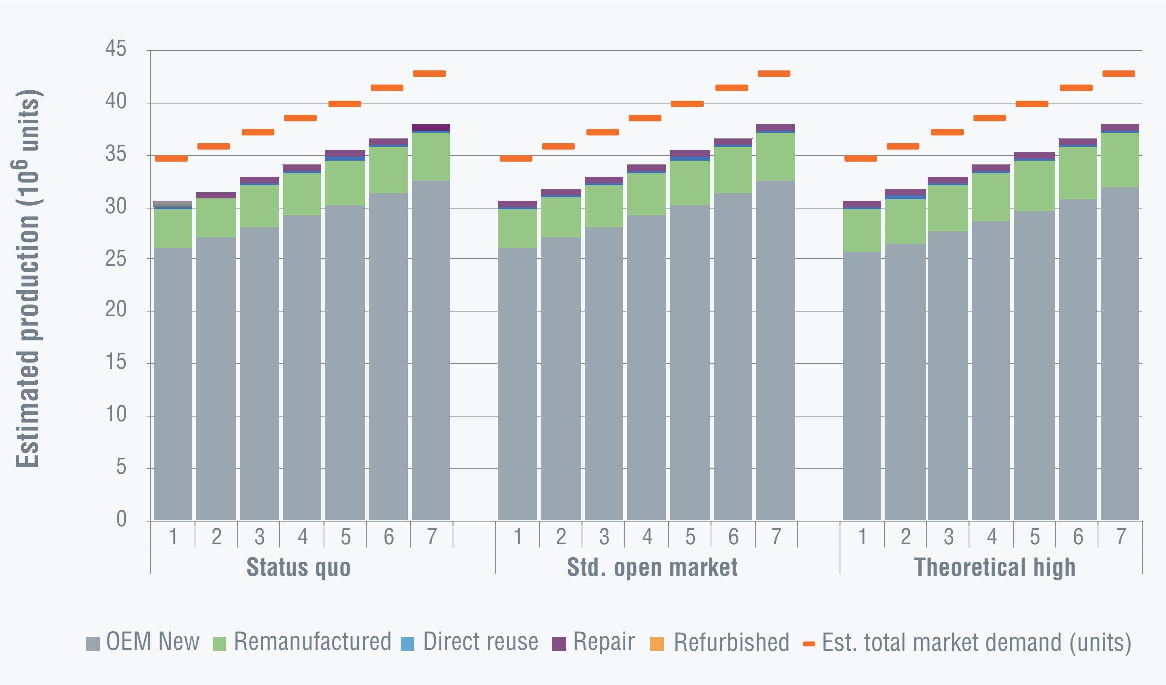


Figure 48: Estimated US production of vehicle parts relative to estimated demand in US simulated over 7 year scenario

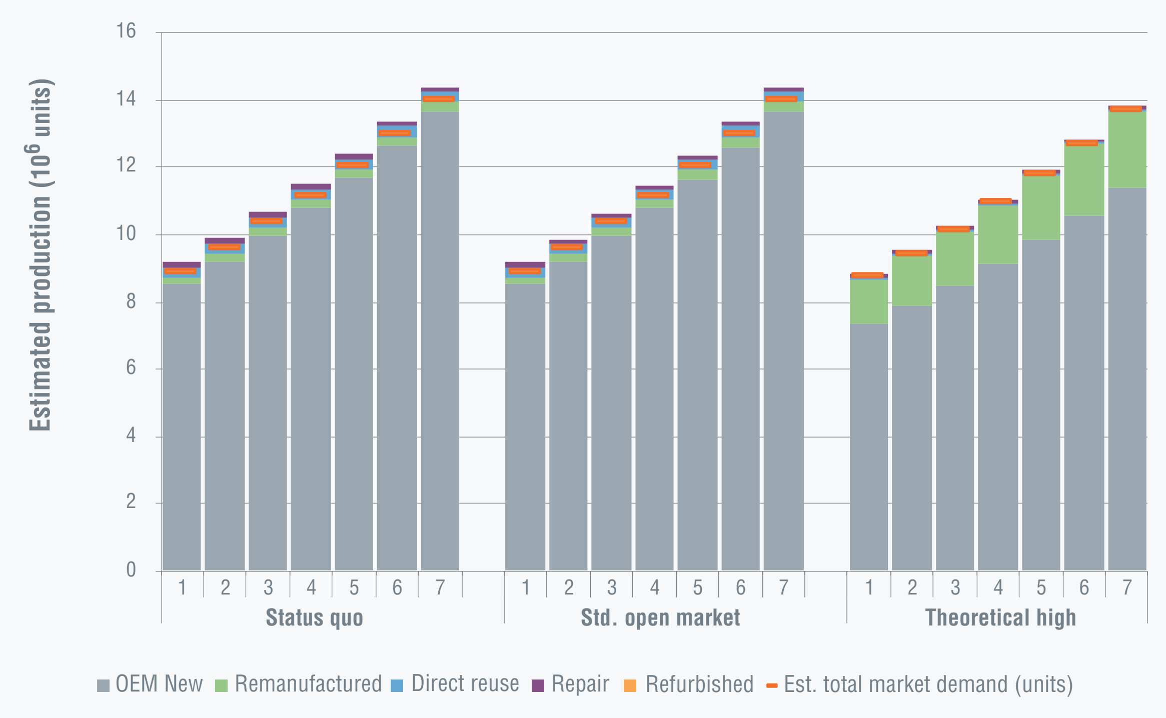


Figure 49: Estimated Germany production of vehicle parts relative to estimated demand in Germany over 7 year scenario

As shown in Figure 50, the model assumes the current (declining) market growth rates in case study vehicle parts production occurring in Brazil. Declining total production levels over time also contributes the adoption of VRPs within the production mix, and the absolute reduction of negative environmental impacts, as presented in Figure 62.

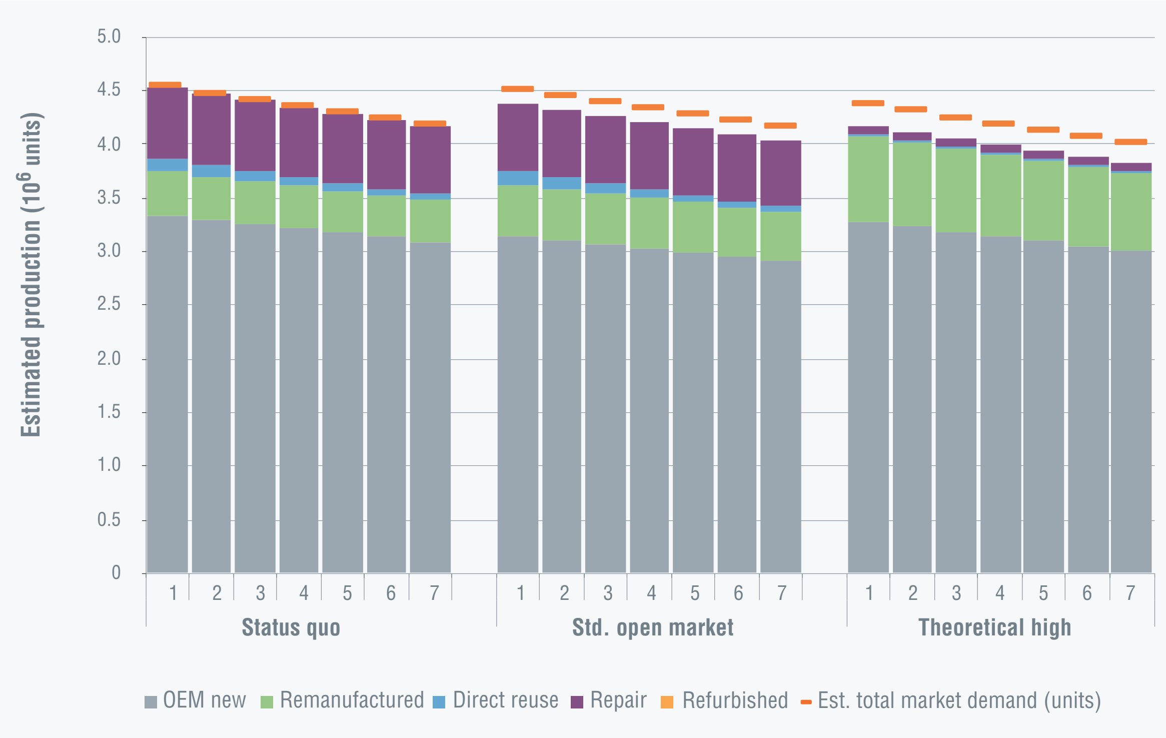


Figure 50: Estimated Brazil production of vehicle parts relative to estimated demand in Brazil over 7 year scenario

It is important to note that the displacement of lower-impact partial service life VRPs with higher-impact full service life VRPs in the Theoretical High scenarios for Brazil (Figure 50) and China (Figure 51) reflects an unrealistic transition away from more common repair and direct reuse activities. The decrease in potentially avoided impacts that result from such a transition are demonstrated in Figure 62 and Figure 63, and discussed in greater detail in Section 7.5.5.

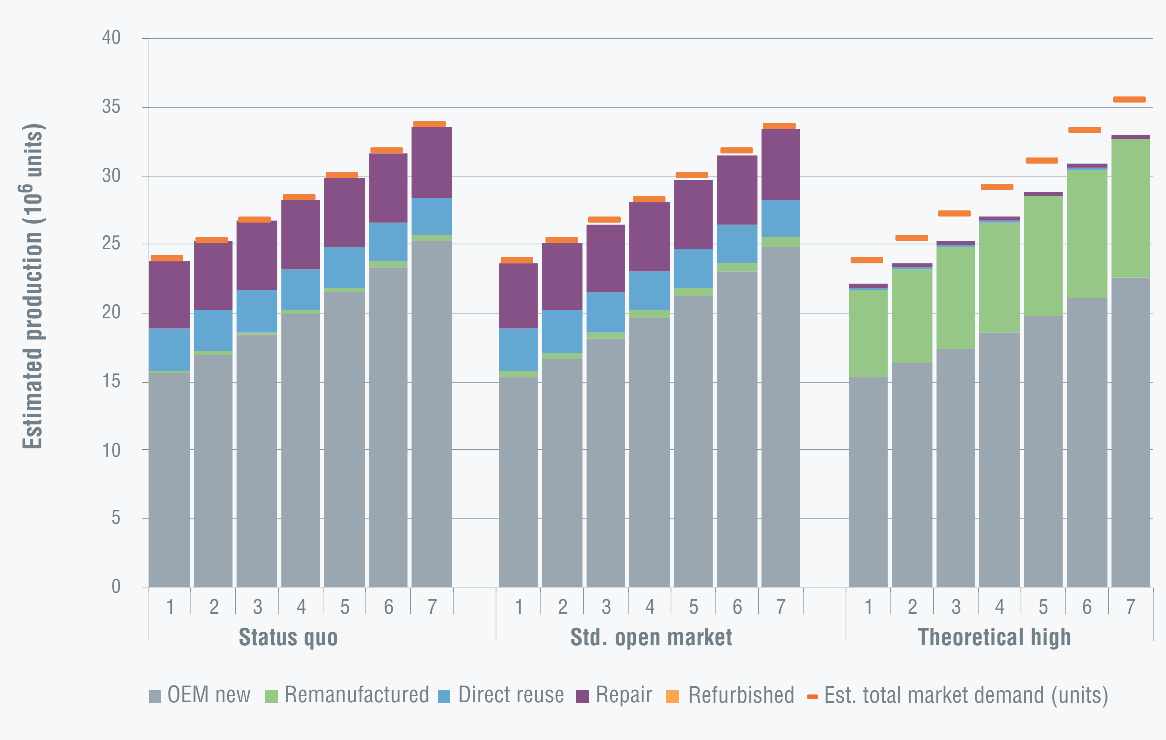


Figure 51: Estimated China production of vehicle parts relative to estimated demand in China over 7 year scenario

7.5.2 Analysis of material-level impacts from vehicle parts production

The production level and growth rates of production in each economy and scenario both inform and affect the associated impacts that are of interest to this study. The impacts of production are presented in Figure 52 through Figure 70, however a demonstrative example of the aggregation approach is provided in this section, and in Section 7.5.3. These results assume that 100 per cent of vehicle engines in an economy are traditional, utilizing cast iron cylinder blocks.

Once again, aggregated production is simulated over a seven-year period, and the associated impacts are calculated accordingly. Figure 52 depicts the new materials both used and avoided through the incorporation of vehicle parts remanufacturing for each of the seven-years, across all three scenarios, while Figure 53 highlights just the quantity of new materials avoided over the same period and scenarios.

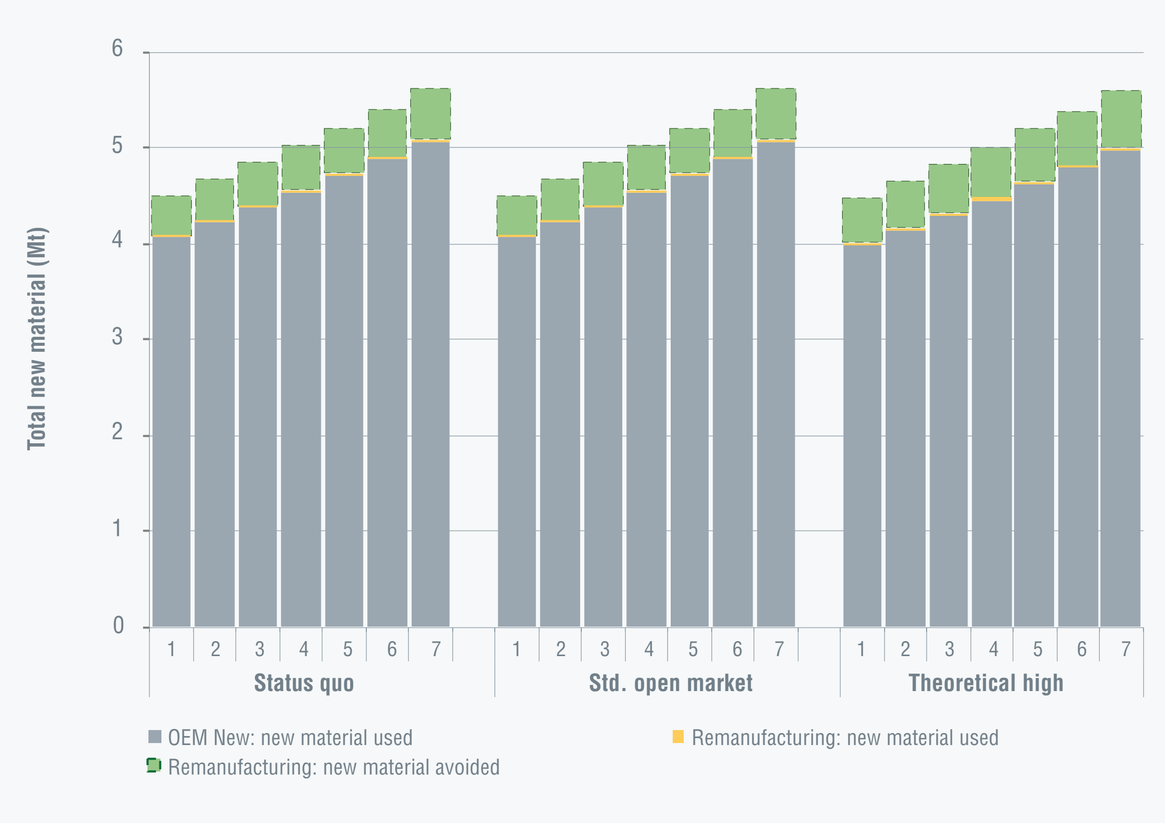


Figure 52: Estimated aggregated new material used and avoided via US remanufacturing of vehicle parts over 7 year scenario

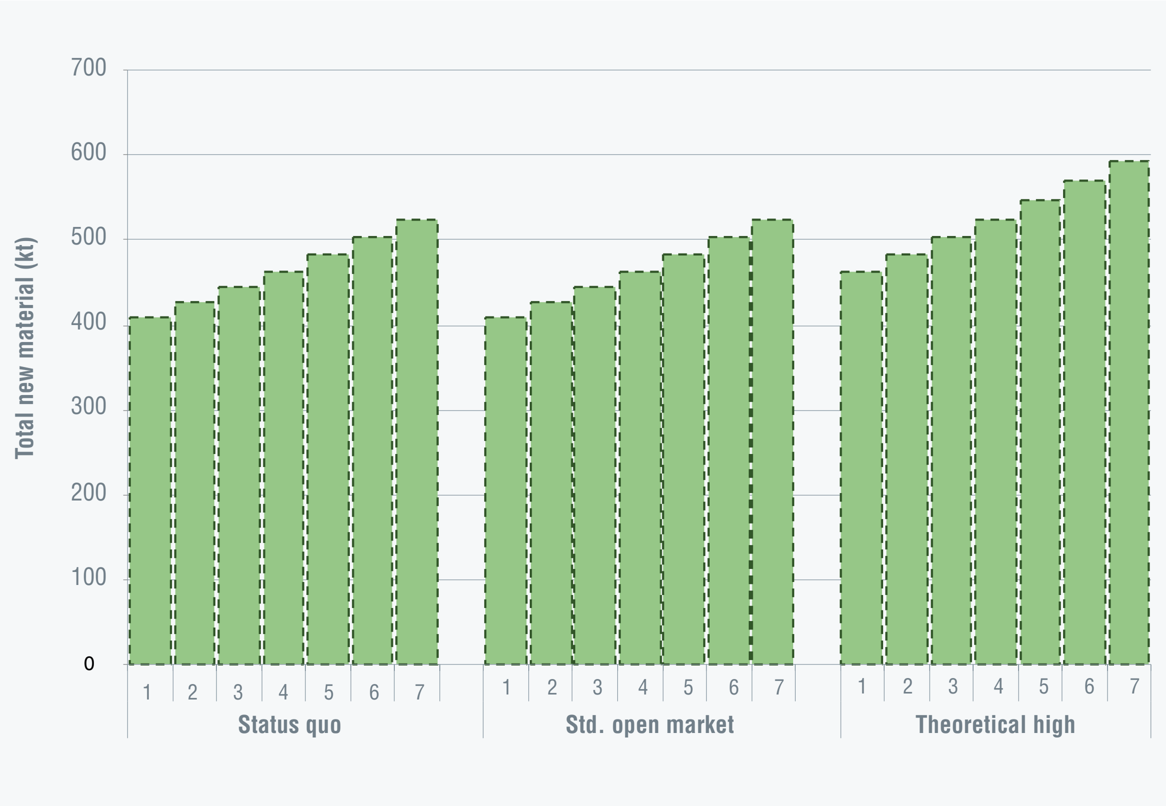


Figure 53: Estimated aggregated new material avoided via US remanufacturing of vehicle parts over 7 year scenario

7.5.3 Aggregation of impacts from vehicle parts production

From the absolute material, energy and emissions data generated over the seven-year simulation, an aggregate value for the entire period is calculated. Figure 54 describes, as an example, the cumulative new material that is both used and avoided, when comparing US vehicle parts production via OEM New versus remanufacturing processes.

In contrast to the significant material avoidance demonstrated in the case study of industrial digital printer products, the relatively smaller production share of VRPs in the vehicle parts sector is highlighted. It is important to note, however, that despite the apparently 'smaller' magnitude of material avoided, there is still a significant benefit created in terms of absolute quantity of new material that is offset through the application of VRP production.

While Figure 54, Figure 55 and Figure 56 reflect aggregated impacts assuming 100 per cent cast iron engine block, a brief comparative analysis of the tradeoffs associated with utilizing 100 per cent lightweight aluminum engine block (versus traditional cast iron) is provided in Section 7.5.4.

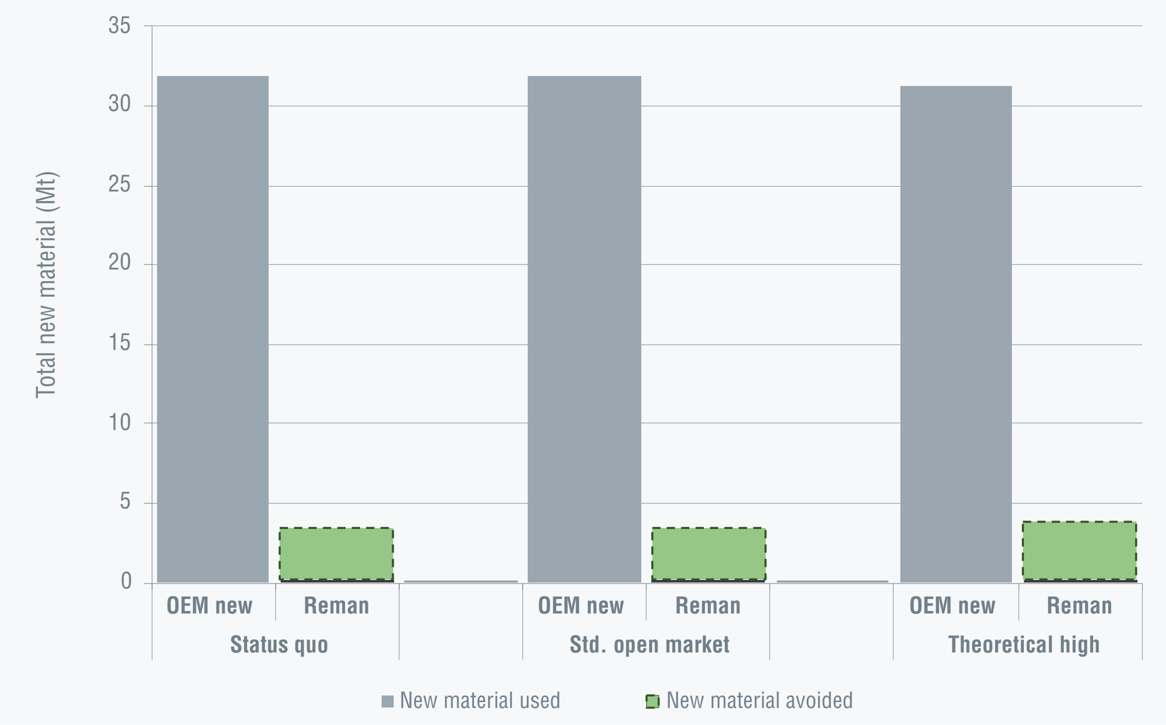


Figure 54: Comparison of aggregate 7-year new material used and avoided via US remanufacturing of vehicle parts

As mentioned, the relative level of VRPs in the vehicle parts production mix is smaller than that of industrial digital printers, and as such material currently avoided via remanufacturing appears small (Figure 54). The currently high levels of embodied material and process energy (Figure 55), and embodied material emissions (Figure 56) highlight the potential to reduce environmental impacts through adoption of VRPs.

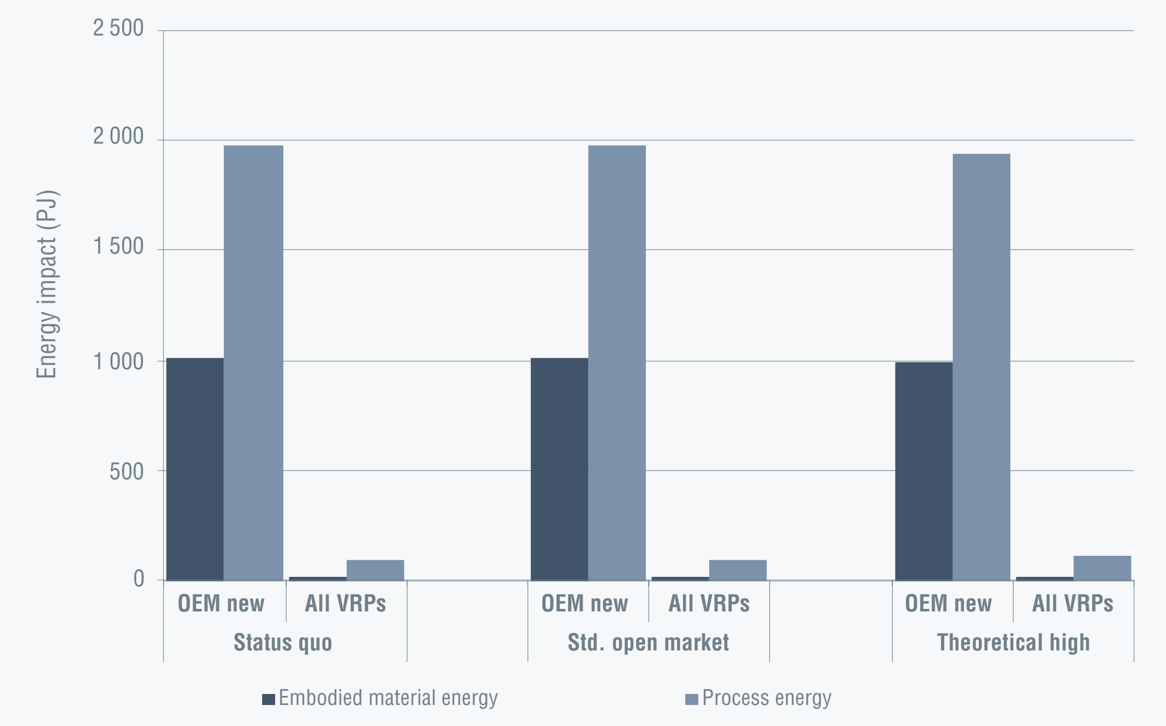


Figure 55: Estimated aggregate 7-year embodied material energy and process energy use, US case study of vehicle parts with traditional engine

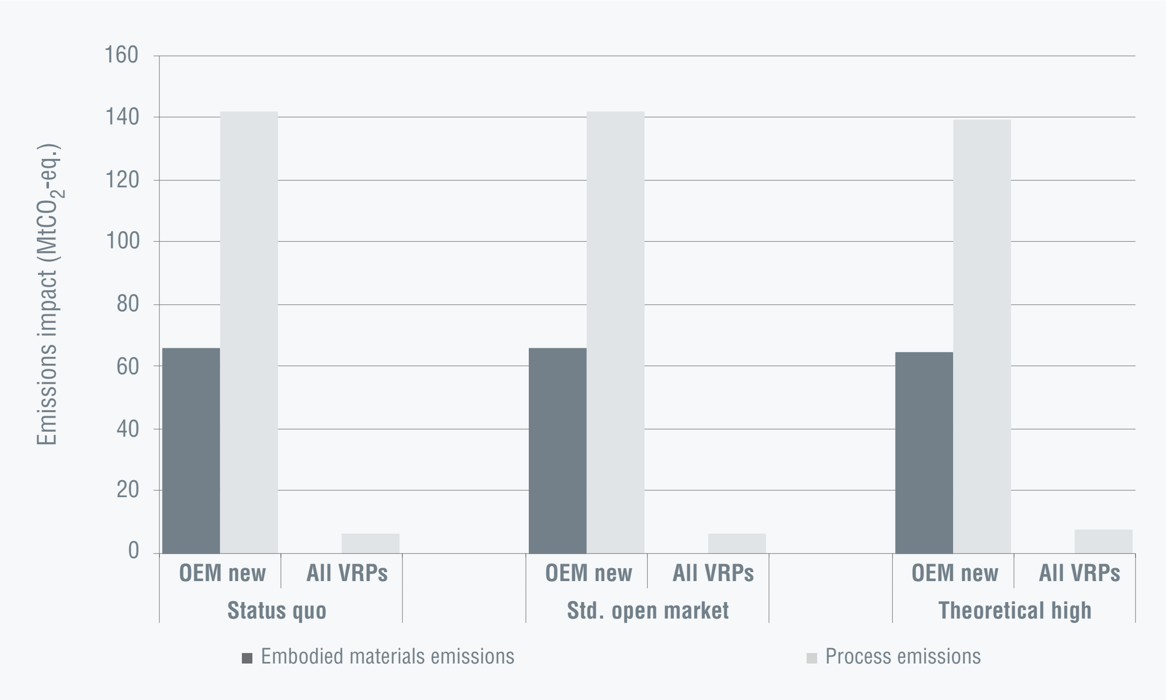


Figure 56: Estimated aggregate 7-year embodied material emissions and process emissions, US case study of vehicle parts with traditional engine

7.5.4 Impact tradeoffs of lightweight design in vehicle parts sector

As presented in Section Erreur ! Nous n'avons pas trouvé la source du renvoi., there are impacts of a product that may differ due to design decisions as basic as what material to use. For illustrative example, a simplified assessment of the impact differential at the product-level was presented for traditional engines utilizing cast iron cylinder blocks and lightweight engines utilizing aluminum cylinder blocks. To clarify the implications of the lightweight material decision at an economy-level, Figure 57 reflects the comparative new material use and avoidance enabled by production and remanufacturing of lightweight engines instead of traditional engines in the combined case study vehicle parts under Status Quo and Theoretical High scenarios. Despite the reduction in material use, however, the use of a more energy-intensive material creates negative environmental implications in terms of embodied energy and embodied emissions, as shown in Figure 58 and Figure 59.

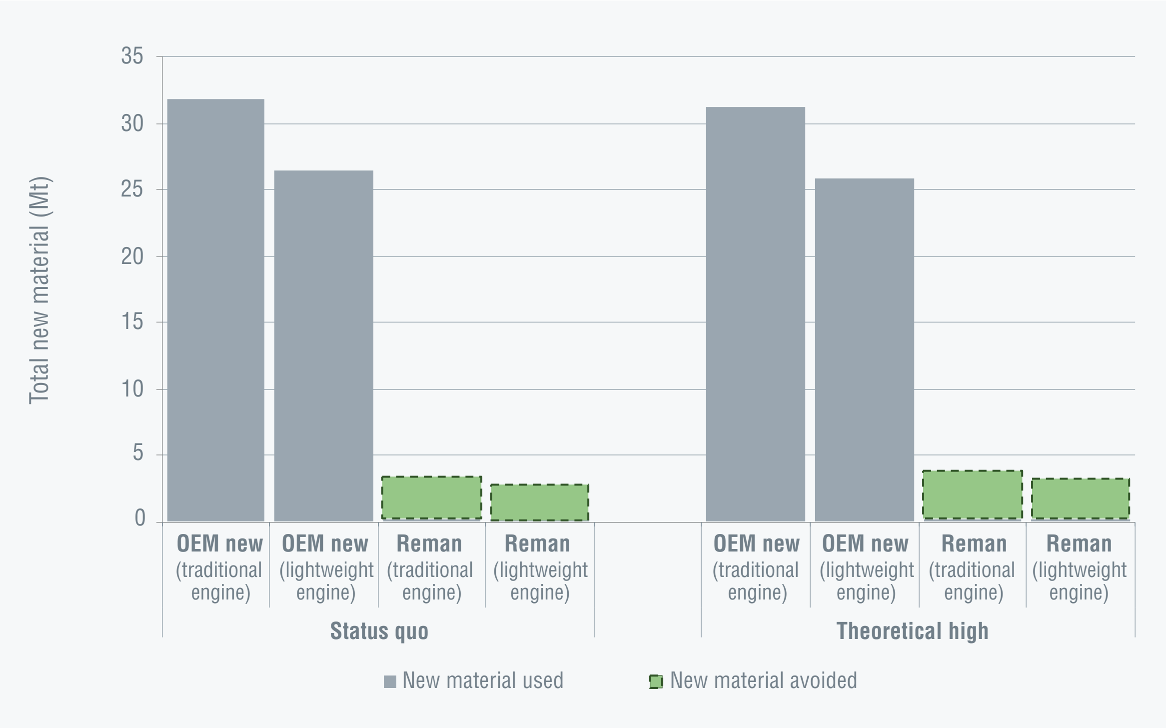


Figure 57: US aggregate 7-year material use and avoidance comparison of traditional vs. lightweight engine mix

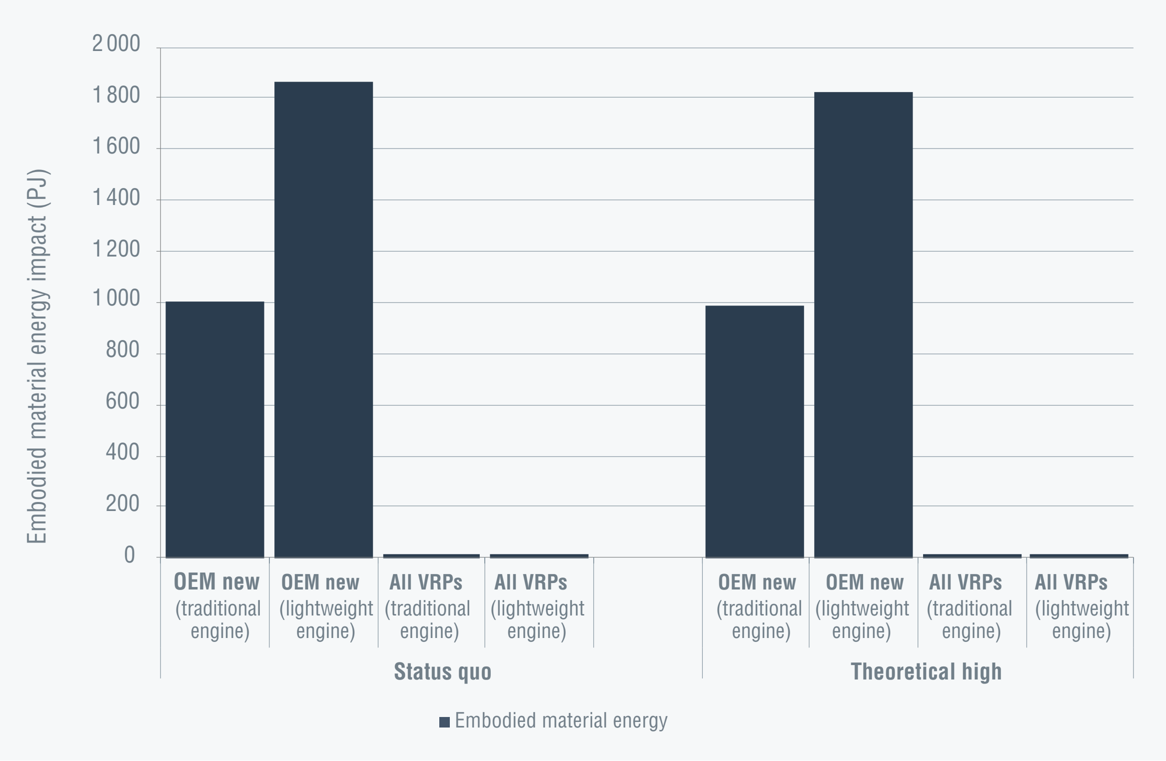


Figure 58: US aggregate 7-year embodied material energy comparison of traditional vs. lightweight engine mix

New material use is reduced when all vehicle engines are produced with aluminum cylinder blocks (Figure 57) however, embodied energy and emissions are higher (Figure 58). Under either the traditional or lightweight vehicle engine design, the Theoretical High scenario with maximized VRP production offers impact reduction in material use, embodied energy, and embodied emissions relative to the Status Quo state.

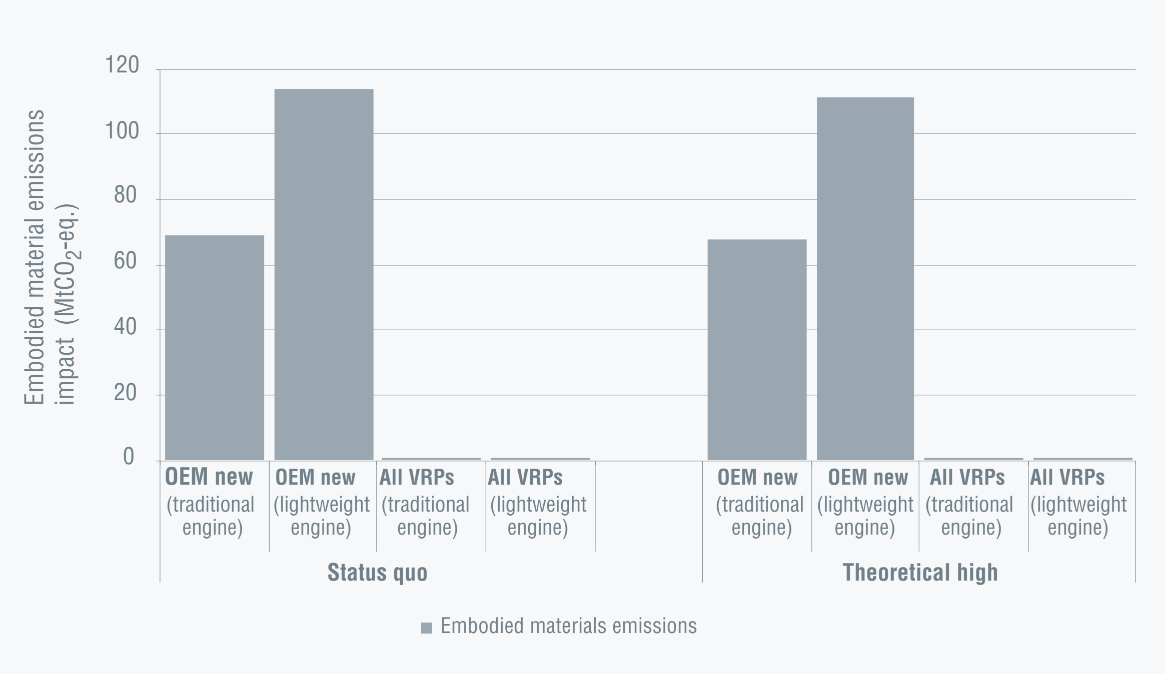
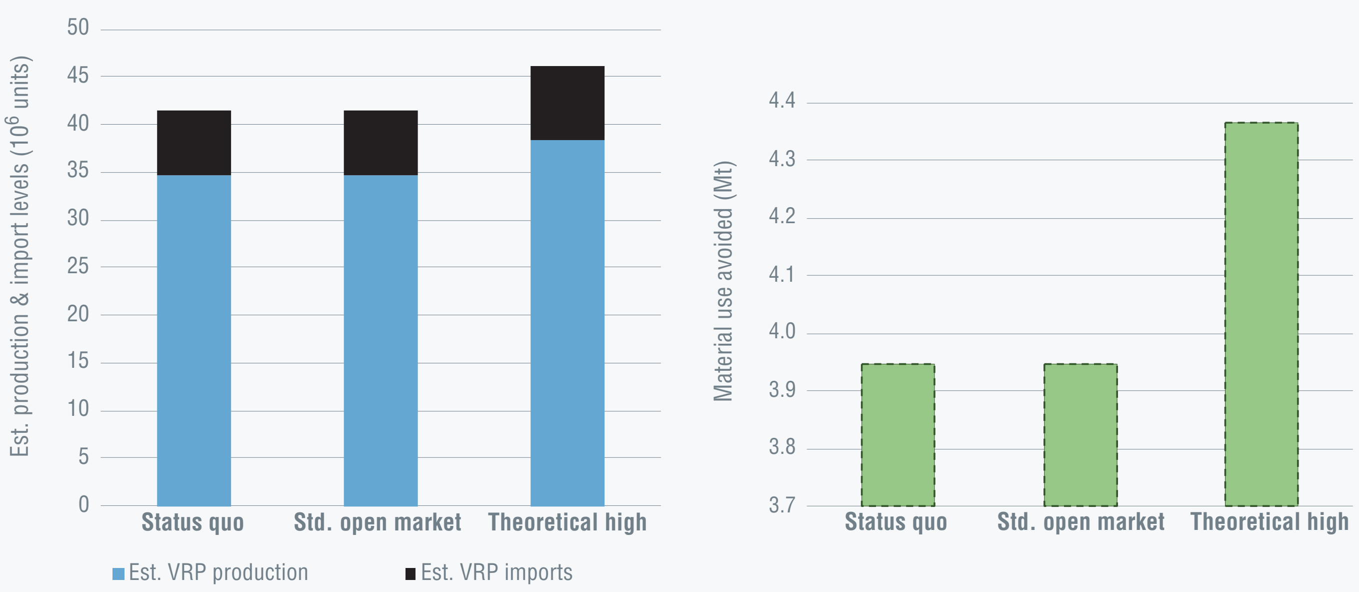


Figure 59: US aggregate 7-year embodied material emissions comparison of traditional vs. lightweight engine mix

7.5.5 Vehicle parts sector: impacts avoided through value-retention processes

Using the approach described in Sections 7.5.2 and 7.5.3, the aggregated impacts that are avoided in each economy as a result of VRP vehicle parts produced domestically and imported are estimated and presented in Figure 60 (US), Figure 61 (Germany), Figure 62 (Brazil), and Figure 63 (China). For each of these figures, estimated production and import levels of VRP vehicle parts are depicted in panel (a); estimated material use avoided because of VRP production are depicted in panel (b); estimated embodied and process energy use avoided as a result of VRP production are depicted in panel (c); and estimated embodied and process emissions avoided as a result of VRP production are depicted in panel (d).

In review of these results, it is important to note the differing scales: not only do production levels vary significantly across these economies, but the factors influencing the associated impacts of production (e.g. the efficiency of energy production, transmission and distribution, and the energy production grid-mix) also vary significantly.



(a) Est. production & import levels of VRP vehicle parts

(b) Est. material use avoided via vehicle parts VRPs

(c) Est. energy use avoided via vehicle parts VRPs

(d) Est. emissions avoided via vehicle parts VRPs

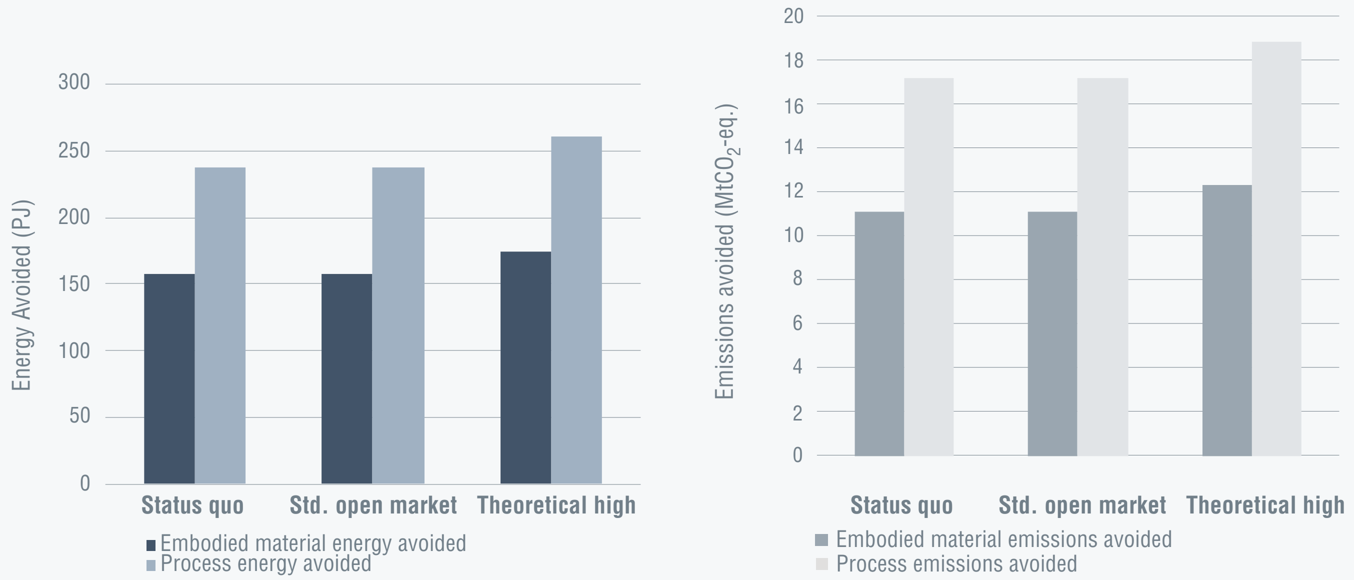
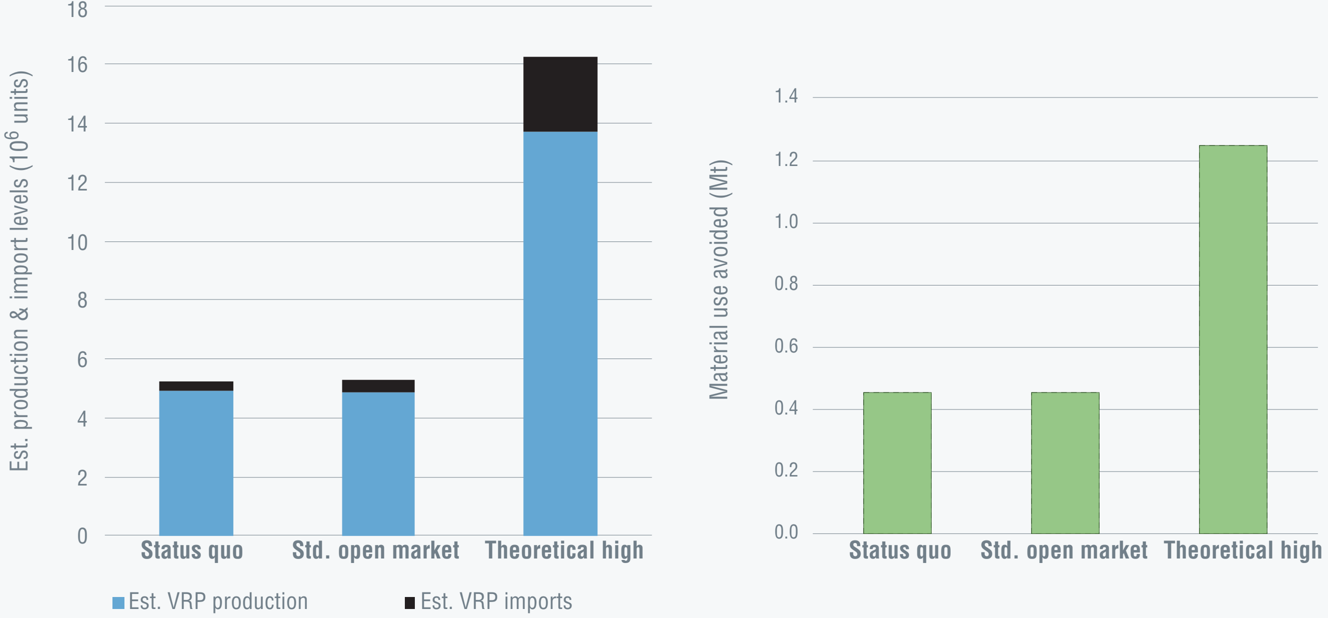


Figure 60: Estimated aggregate impacts avoided via US vehicle parts production with value-retention processes

For economies in which the increase in full service life VRPs in the Theoretical High scenario does not come at the cost of lower impact partial service life VRPs (refer to US in Figure 60 and Germany in Figure 61), there is potential for reduced environmental impacts through increased adoption of VRPs. However, as observed in Brazil (Figure 62) and China (Figure 63), the increase in imports and/or the offset of partial service life VRPs highlights that strategies for incorporating VRPs to support circular economy must be considered carefully in the context of each economy.

(a) Est. production & import levels of VRP vehicle parts

(b) Est. material use avoided via vehicle parts VRPs



(c) Est. energy use avoided via vehicle parts VRPs

(d) Est. emissions avoided via vehicle parts VRPs

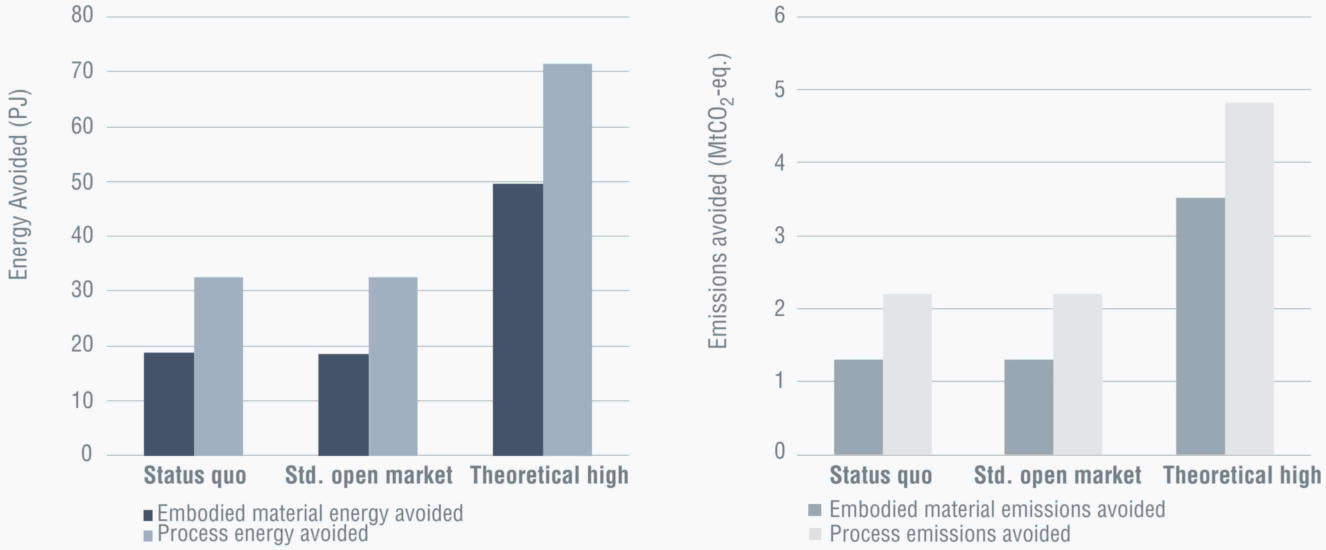
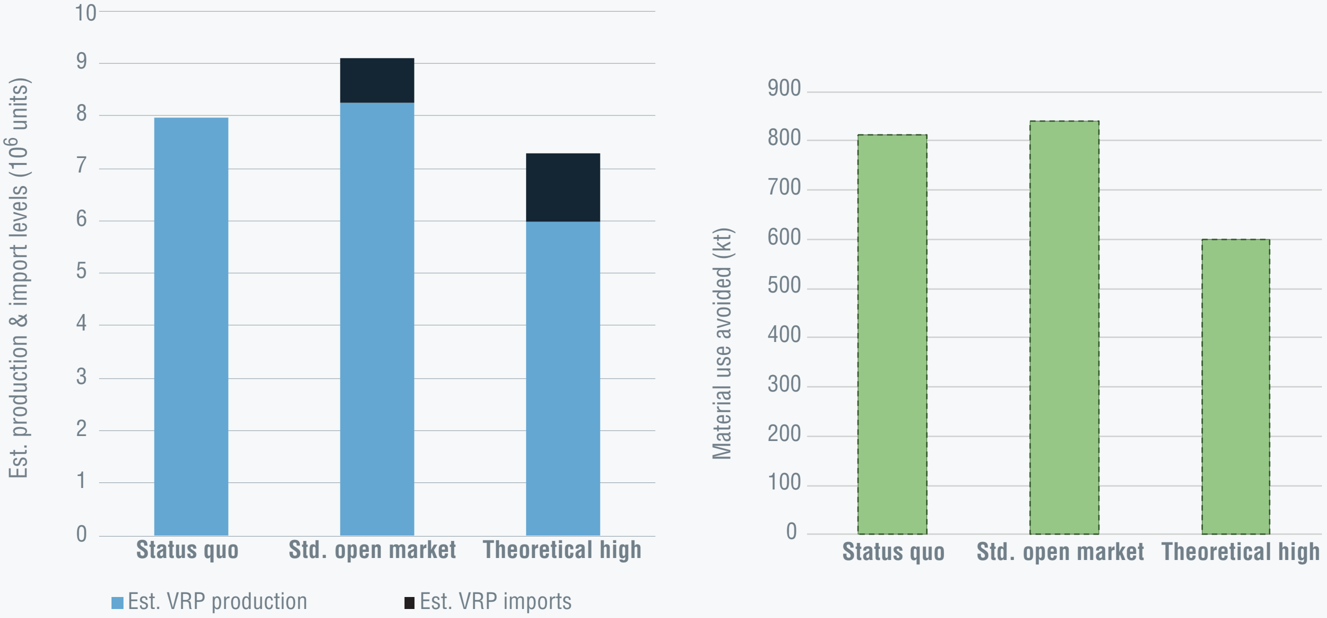


Figure 61: Estimated aggregate 7-year impacts avoided via Germany vehicle parts production with value-retention processes

As observed in the Theoretical High scenario for Brazil (Figure 62), the reduction in the repair share of the production mix results in a net decrease in avoided embodied material energy, embodied material emissions, and process energy and emissions, when compared to the Standard Open Market scenario. In other words, while there is still a very large net-positive absolute reduction in impacts, the very high share of repair activities in the Brazil economy does allow for relatively greater offset of embodied materials energy and emissions. These outcomes are observed in the case of China as well (Figure 63).

(a) Est. production & import levels of VRP vehicle parts

(b) Est. material use avoided via vehicle parts VRPs



(c) Est. energy use avoided via vehicle parts VRPs

(d) Est. emissions avoided via vehicle parts VRPs

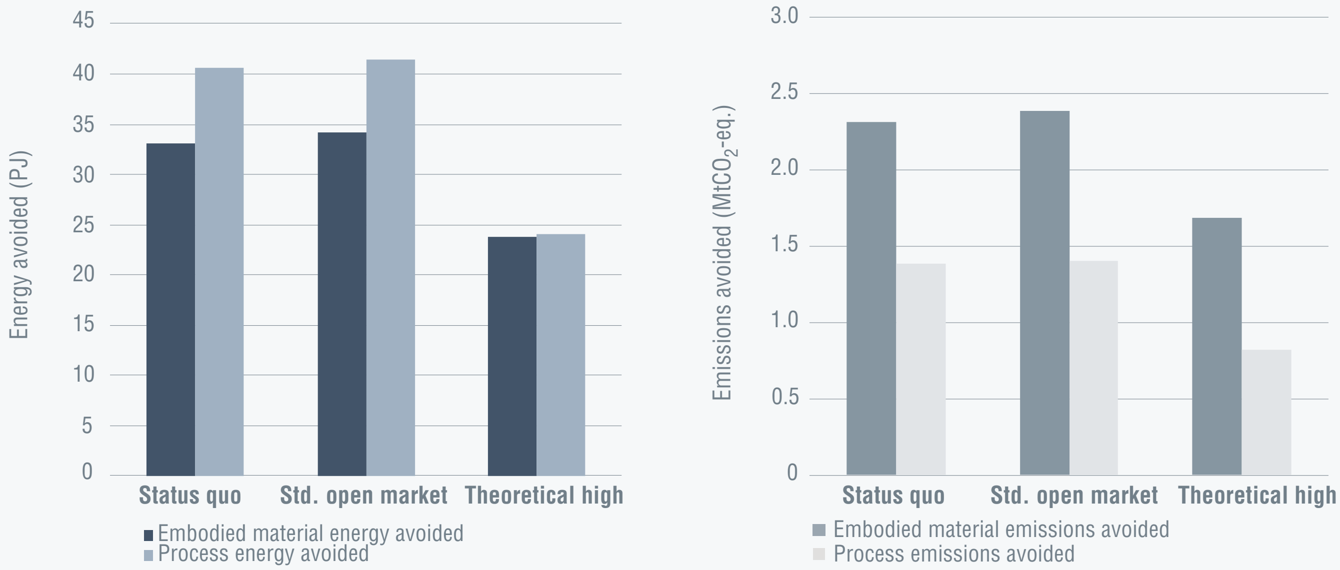


Figure 62: Estimated aggregate 7-year impacts avoided via Brazil vehicle parts production with value-retention processes

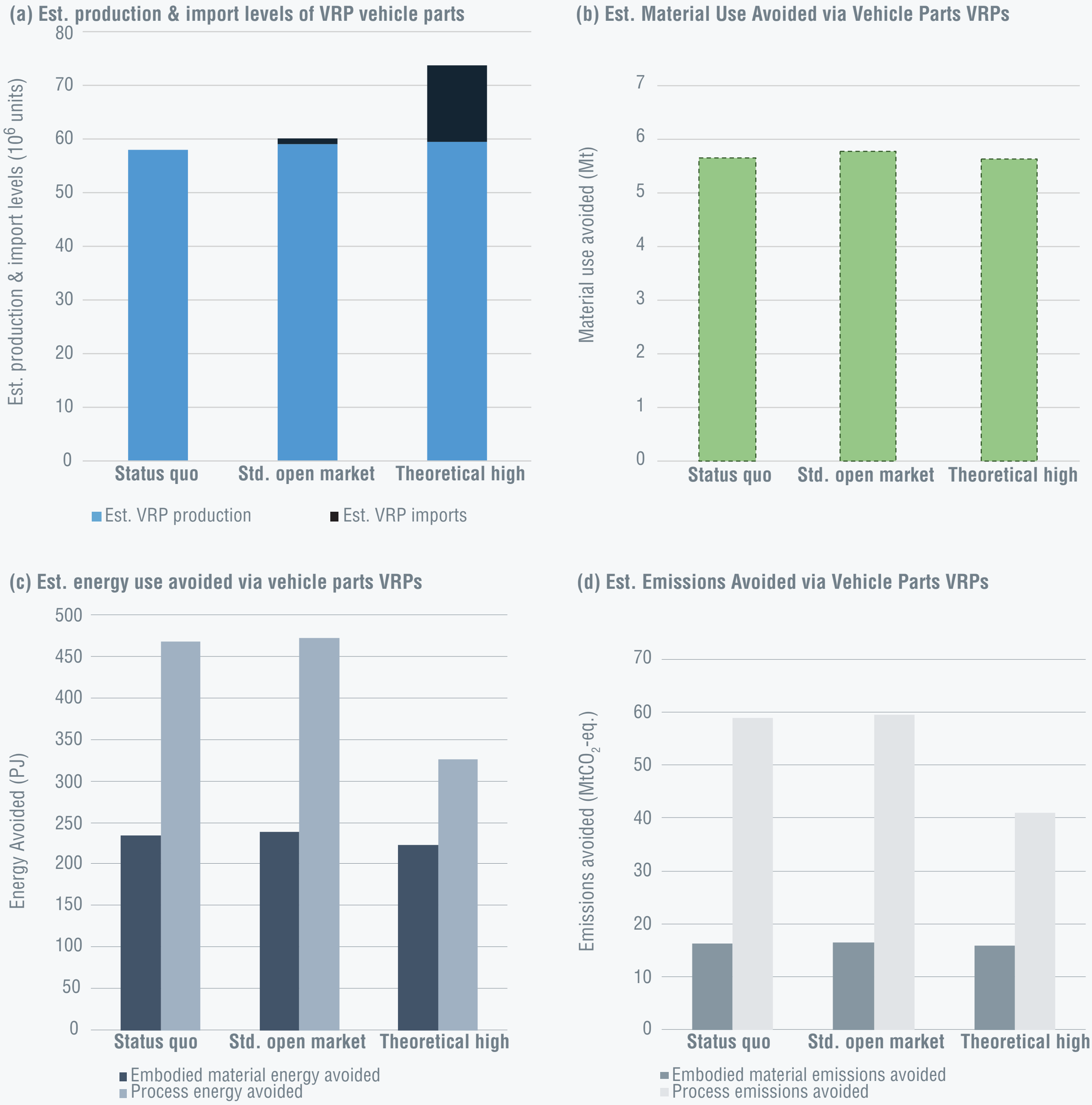


Figure 63: Estimated aggregate 7-year impacts avoided via China vehicle parts production with value-retention processes

To this end, the complexity of VRPs within a market requires careful consideration of not only the policy objectives (e.g. impact reduction), but also the implications of social norms and practices. In addition, while these results directly measure impact avoidance in absolute terms, it must be remembered that the value and utility created via a full new product life through remanufacturing is significantly greater than the value and utility created via arranging direct reuse and repair.

In the case of vehicle parts, VRPs generally require less per-unit process energy, and therefore relatively less associated process emissions. As such, there are net-positive avoided impacts across all measured impact categories in every economy.

7.6 Analysis of HDOR equipment parts sector

The heavy-duty and off-road sector consists of companies that produce equipment and systems used in the commercial trucking, construction, mining, agriculture, and bulk transportation industries. This sector is primarily focused on mobile equipment that is highly durable and of high value. These products often experience high use over an extended period, and their service life cycles are often many years' longer than general consumer products. Many of the components in the HDOR equipment parts sector, for which VRPs are employed, are similar in function and design to vehicle part equivalents; however, given workload expectations, rigorous product use, and significant wear-and-tear, they are much larger is size, and are designed for greater durability and even scheduled overhaul refurbishment and preventative maintenance activities.

The nature and value of HDOR equipment parts are substantially different than the other case study sectors presented in this study: the customer market for HDOR equipment parts is typically highly-specialized and educated about VRP options; in addition, many of the major producers of OEM New HDOR equipment parts are also actively engaged in some degree of VRP production, and as a result there are large and relatively efficient reverse-logistics systems in place to enable refurbishment and remanufacturing. Often, these processes may be offered as part of a customer service model in which refurbishment activities are planned for and scheduled. The rigorous oversight of HDOR equipment in the market, as well as the systems supporting active collection and reuse through VRPs, ensures a unique perspective on VRPs for the HDOR equipment parts sector.

7.6.1 HDOR equipment parts production levels

The estimated production levels of HDOR equipment parts, by OEM New and VRP production types, and by economy, are presented in Figure 64 through Figure 67. Also shown are estimated total domestic market demand levels for each economy, which are indicative of the relative levels of imported products to supply domestic demand and/or exported products.

Recent HDOR equipment industry performance has shown market contraction, particularly in developed/industrialized economies such as the US (Figure 64); in contrast, developing/newly industrialized economies like Brazil and China that offer favorable production incentives as well as growing demand from construction and mining industries, are poised for significant market growth (Figure 66 and Figure 67). Despite the relatively low production share in the US, there is great opportunity for material efficiency and impact reduction through VRPs. As with the vehicle parts sector, the scale-up of VRPs in the HDOR equipment parts production mix demonstrates net-positive impact avoidance, to varying degrees, across each studied economy.

Please note that, since the Standard Open Market scenario is reflective of some of the US conditions, there is no change to US production levels and associated production impacts between the Status Quo and Standard Open Market scenarios.In the cases of Germany and Brazil (refer to Standard Open Market scenario in Figure 65 and Figure 66), overall production level decreases because of an increase in the import-ratio, imposed as a condition of the scenario.

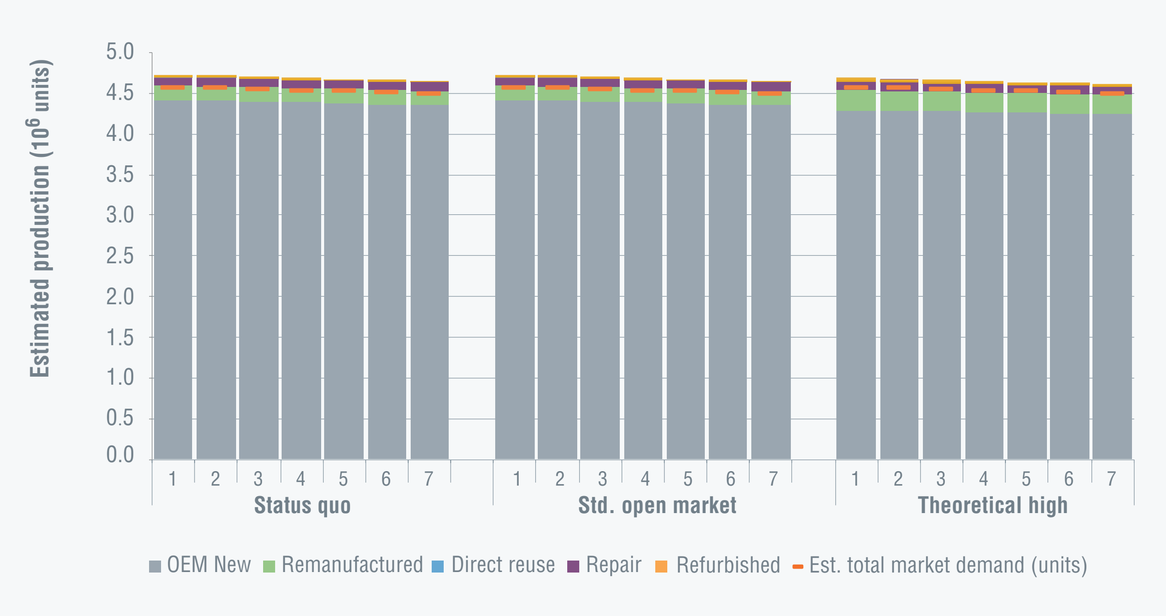


Figure 64: Estimated US production of HDOR equipment parts relative to estimated demand in US, simulated over 7 year scenarios

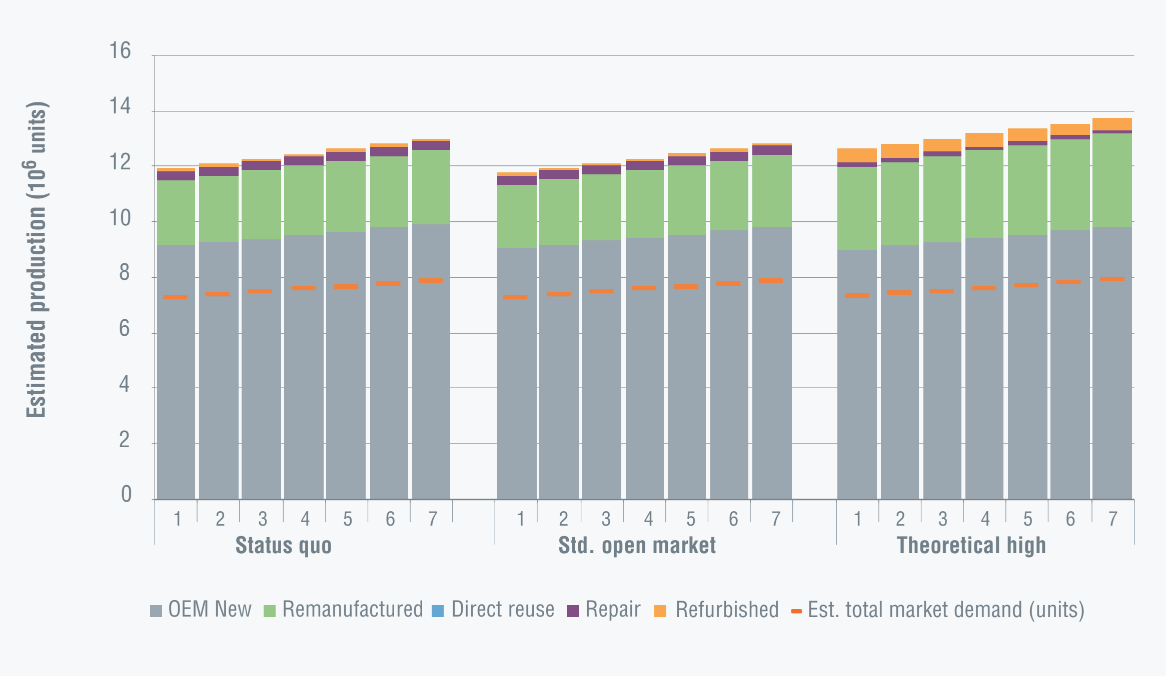


Figure 65: Estimated Germany production of HDOR equipment parts relative to estimated demand in Germany, simulated over 7 year scenarios

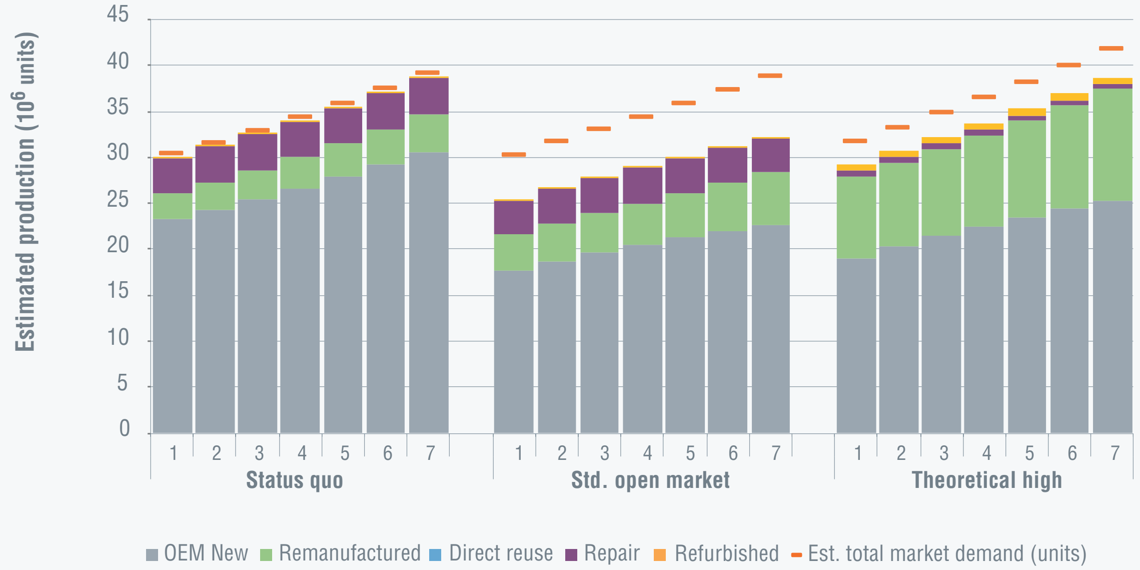


Figure 66: Estimated Brazil production of HDOR equipment parts relative to estimated demand in Brazil, simulated over 7 year scenarios

It is important to note the reduced domestic production levels resulting from the imposed scenario conditions. In addition, the displacement of lower-impact partial service life VRPs with higher-impact full service life VRPs in the Theoretical High scenarios for Brazil (Figure 66) and China (Figure 67) reflects an unrealistic transition away from more common repair and direct reuse activities. The decrease in potentially avoided impacts that result from such a transition are demonstrated in Figure 75 and Figure 76, and discussed in greater detail in Section 7.6.4.

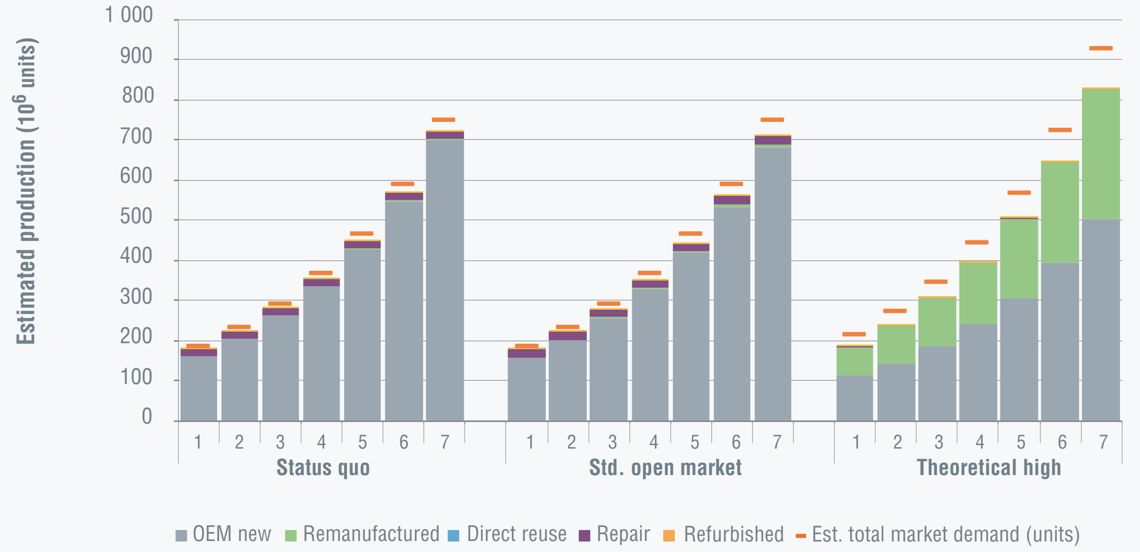


Figure 67: Estimated China production of HDOR equipment parts relative to estimated demand in China, simulated over 7 year scenarios

7.6.2 Analysis of material-level impacts from hdor equipment parts production

The production level and growth rates of production in each economy and scenario both inform and affect the associated impacts that are of interest to this study. The impacts of production are presented in Figure 68 through Figure 71, however a demonstrative example of the aggregation approach is provided first in this section, and in Section 7.6.3.

As with the previous case study sectors, aggregated production is simulated over a seven-year period, and the associated impacts are calculated accordingly. Figure 68 depicts the new materials both used and avoided through the incorporation of HDOR equipment parts remanufacturing for each of the seven-years, across all three scenarios, while Figure 69 highlights just the quantity of new materials avoided over the same period and scenarios.

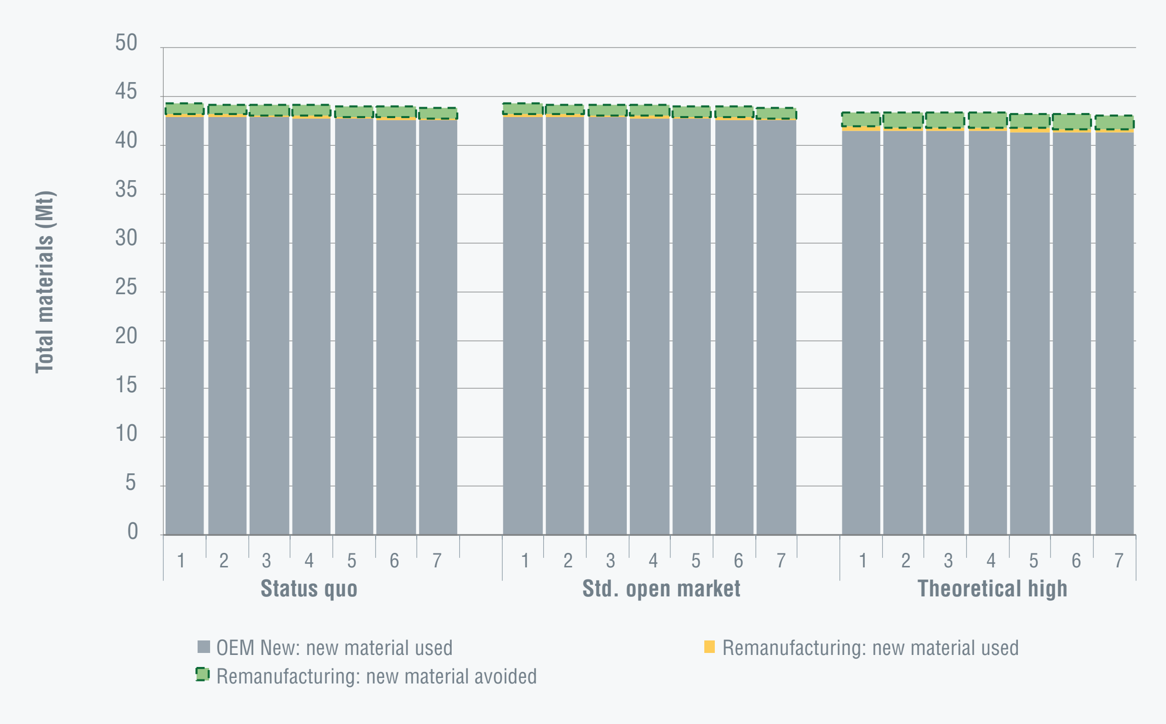


Figure 68: Estimated aggregated new material used and avoided via US remanufacturing of HDOR equipment parts, simulated over 7 year scenarios

Even in the Theoretical High scenario, the lower share of VRPs in the US production mix (relative to OEM New production) constrains the potential for avoided negative environmental impacts, as shown in Figure 68 and Figure 69.

Figure 69: Estimated aggregate new material avoided via US remanufacturing of HDOR equipment parts, simulated over 7 year scenarios

7.6.3 Aggregation of impacts from HDOR equipment parts production

From the absolute material, energy and emissions data generated over the seven-year simulation, an aggregate value for the entire period is calculated. Figure 70 describes, as an example, the cumulative new material that is both used and avoided, when comparing US HDOR equipment parts production via OEM New versus remanufacturing processes.

The implications of the relatively smaller production share of VRPs in the HDOR equipment parts sector is clearly observable in Figure 70, with a significantly lesser quantity of new material offset. As emphasized before, however, it is important to note that despite the apparently ‘smaller’ magnitude of material avoided, there is still a significant benefit created in terms of absolute quantity of new material that is offset through the application of VRP production.

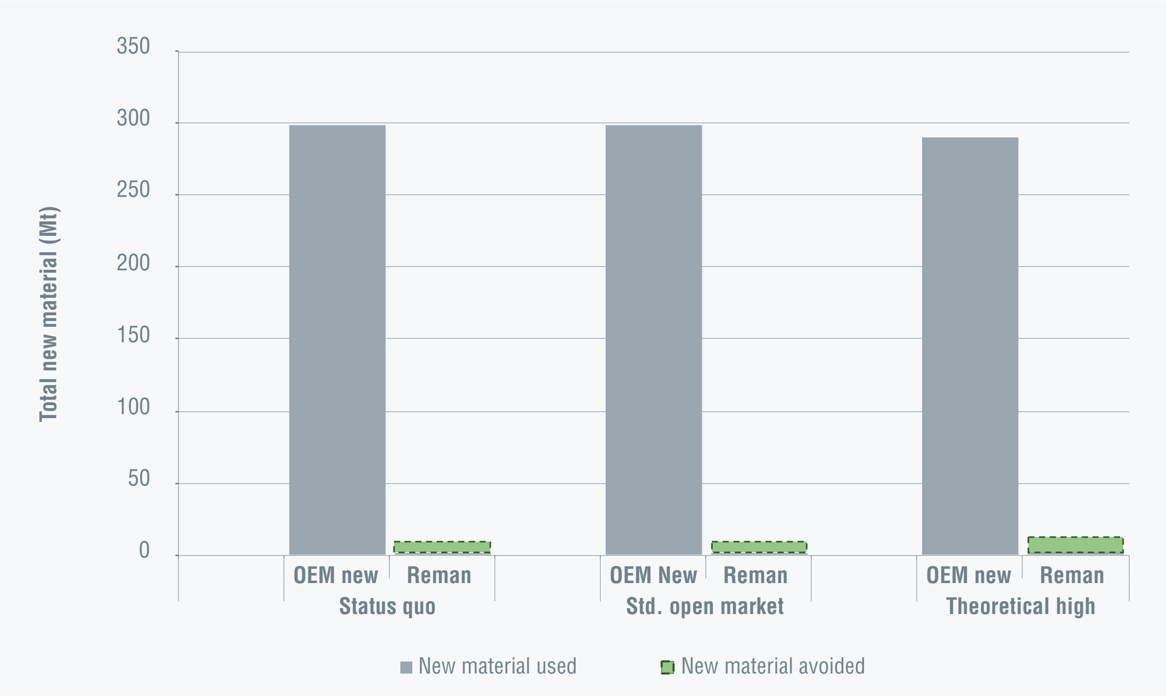


Figure 70: **Comparison of aggregate 7-year new material used and avoided via US remanufacturing of HDOR equipment parts**

The substantial size and designed durability of HDOR equipment parts requires a significant volume of material input at the per-unit level; in addition, the production process is quite energy intensive. As such, there are opportunities for reduction in material requirement, embodied energy and emissions, and process energy and emissions in the US market through the increased adoption of VRPs in the production mix (Figure 71 and Figure 72). These opportunities increase exponentially for developing/newly industrialized markets in which HDOR equipment parts production is substantially higher and/or is expected to grow significantly. Please refer to Brazil (Figure 75) and China (Figure 76).

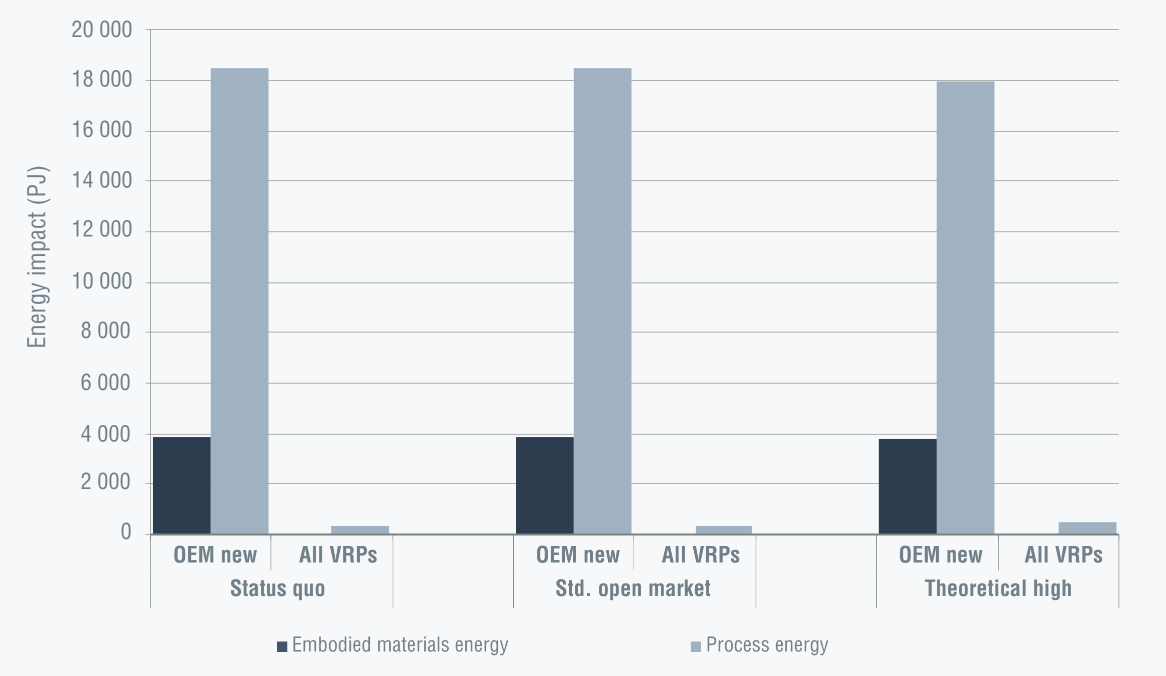


Figure 71: **Estimated aggregate 7-year embodied and process-based energy for US production of HDOR equipment parts**

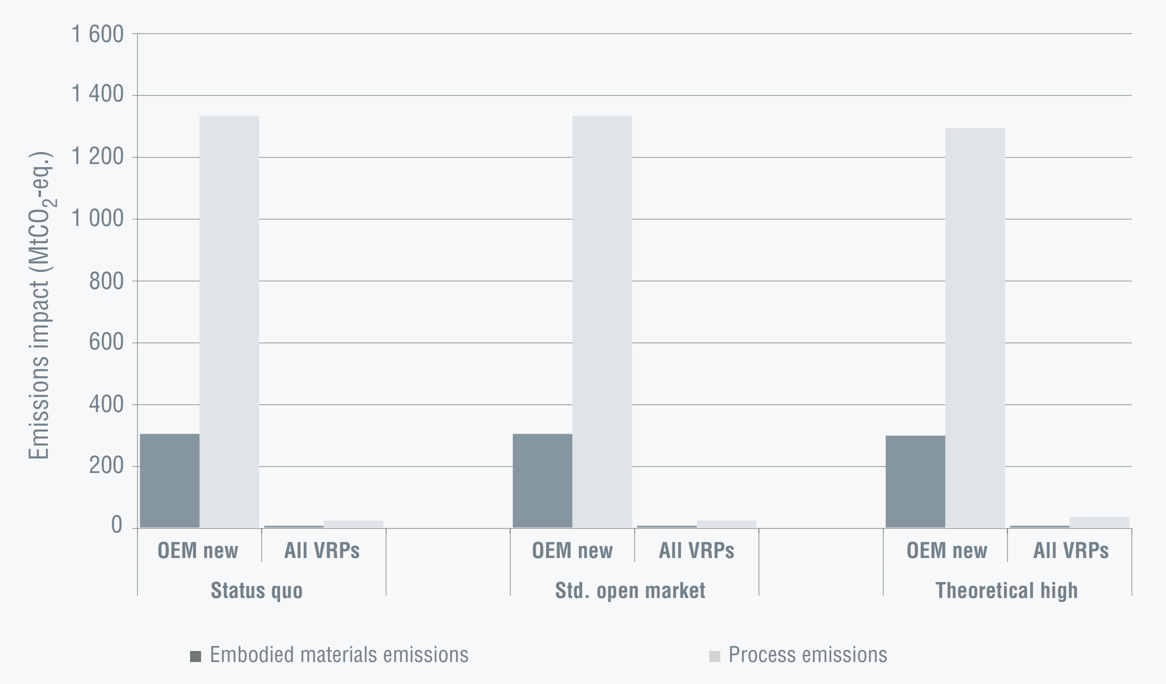


Figure 72: **Estimated aggregate 7-year embodied and process-based energy for US production of HDOR equipment parts**

7.6.4 HDOR equipment parts sector: impacts avoided through value-retention processes

Using the approach described in Sections 7.6.2 and 7.6.3, the aggregated impacts that are avoided in each economy as a result of VRP HDOR equipment parts produced domestically and imported are estimated and presented in Figure 73 (US), Figure 74 (Germany), Figure 75 (Brazil), and Figure 76 (China). For each of these figures, estimated production and import levels of VRP HDOR equipment parts are depicted in panel (a); estimated material use avoided as a result of VRP production are depicted in panel (b); estimated embodied and process energy use avoided as a result of VRP production are depicted in panel (c); and estimated embodied and process emissions avoided as a result of VRP production are depicted in panel (d).

In review of these results, it is important to note the differing scales: not only do production levels vary significantly across these economies, but the factors influencing the associated impacts of production also vary significantly.

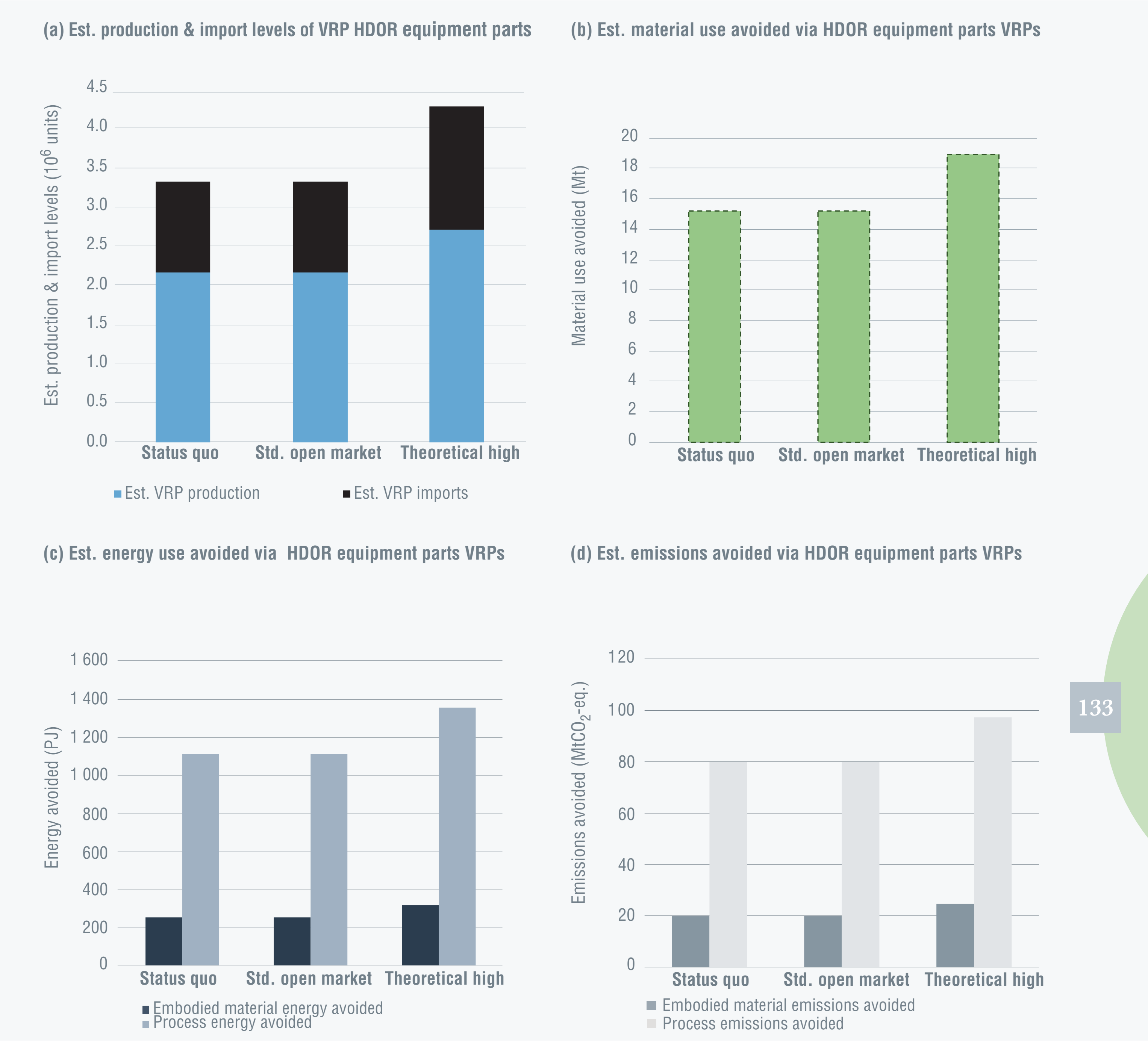
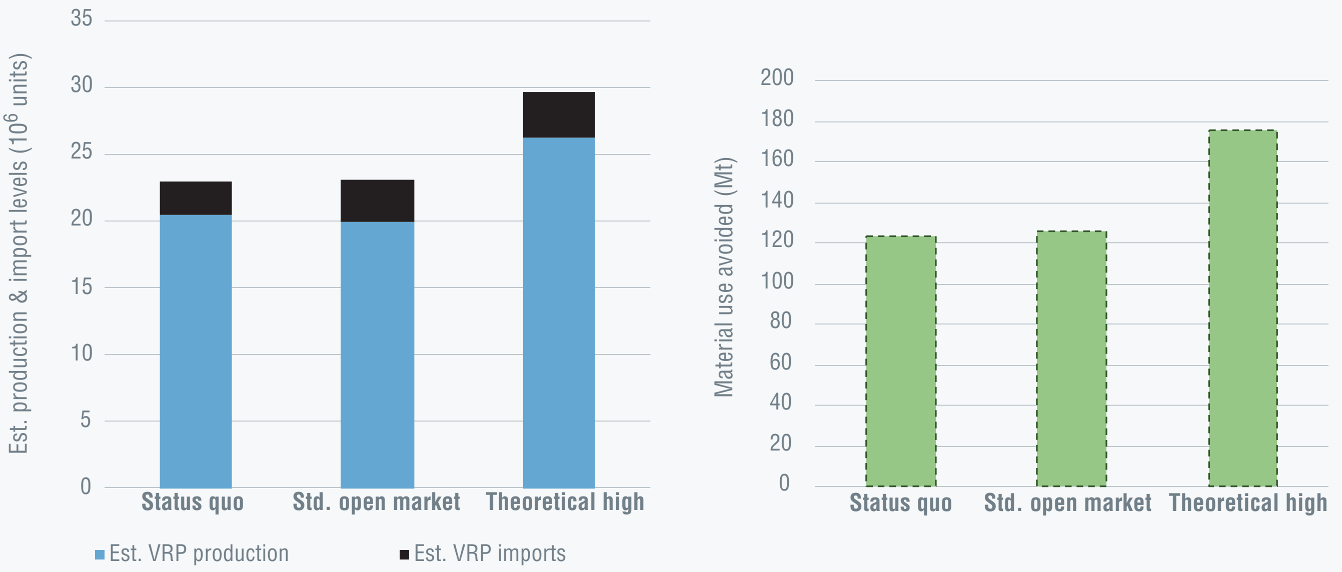
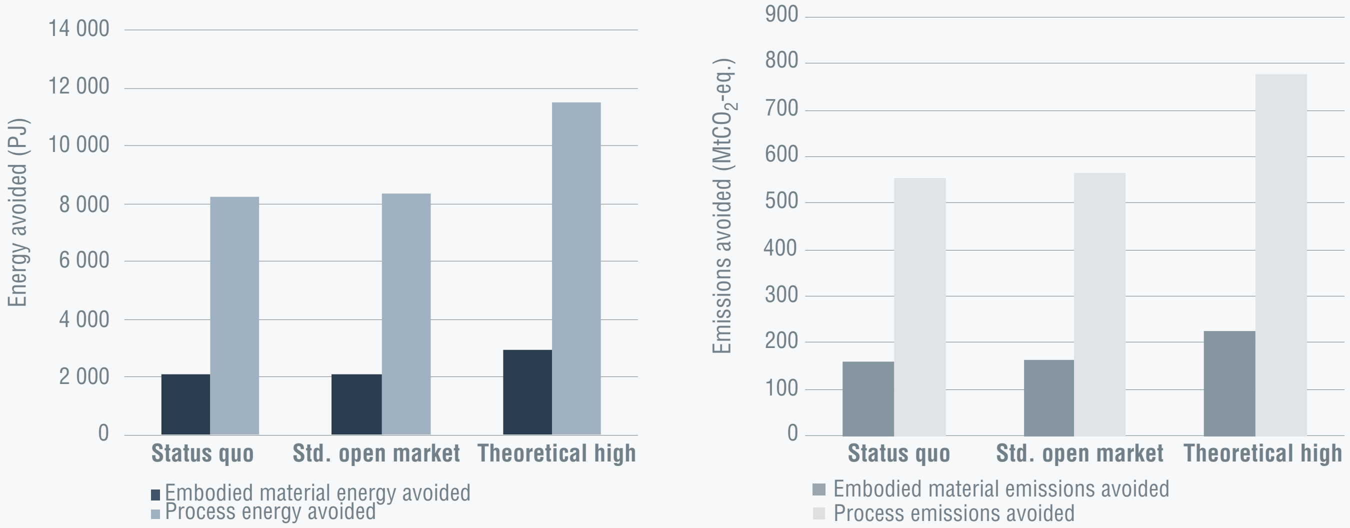


Figure 73: Estimated aggregate 7-year impacts avoided via US HDOR equipment parts production with value-retention processes

In each sample economy the increase in VRP production and imports across the three scenarios is correlated to an increase in avoided negative environmental impacts, to varying degrees. In China, where adoption of VRPs under the Theoretical High scenario is most significant (Figure 67), the correlated increase in estimated avoided impacts is highlighted (Figure 76).


(a) Est. production & import levels of VRP HDOR equipment parts

(b) Est. material use avoided via HDOR equipment parts VRPs


(c) Est. energy use avoided via HDOR equipment

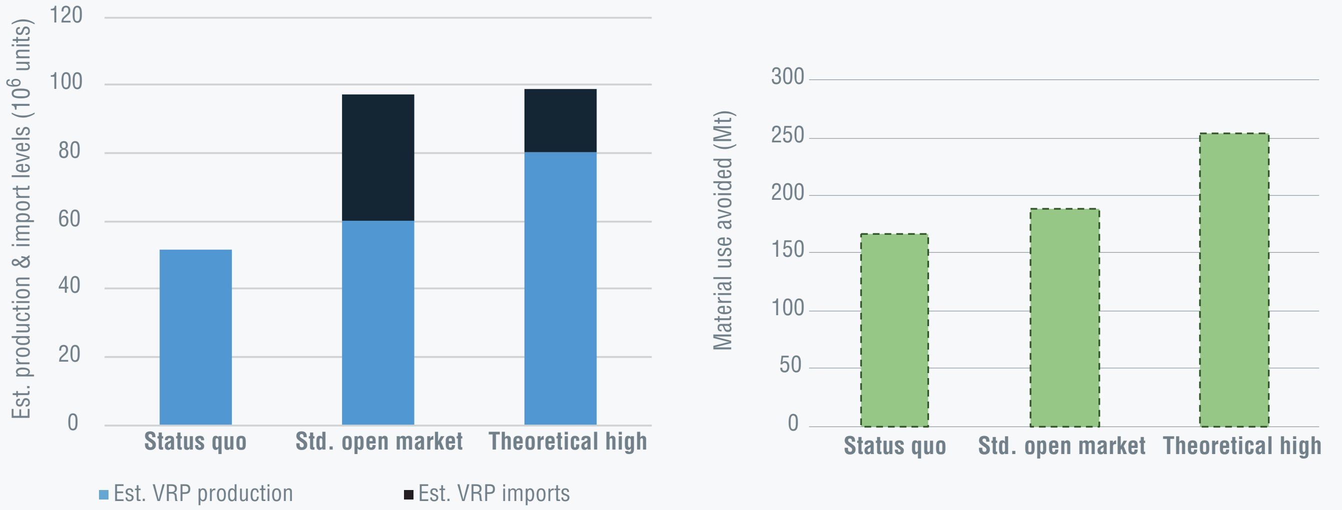
(d) Est. emissions avoided via HDOR equipment parts VRPs

Figure 74: Estimated aggregate 7-year impacts avoided via Germany HDOR equipment parts production with value-retention processes

To this end, the complexity of VRPs within a market requires careful consideration of not only the policy objectives (e.g. impact reduction), but also the implications of trade ratios and balances, as well as social norms and practices. Overall, there are net-positive avoided impacts across all measured impact categories in every economy.

(a) Est. production & import levels of VRP HDOR equipment parts

(b) Est. material use avoided via HDOR equipment parts VRPs



(c) Est. energy use avoided via HDOR equipment

(d) Est. emissions avoided via HDOR equipment parts VRPs

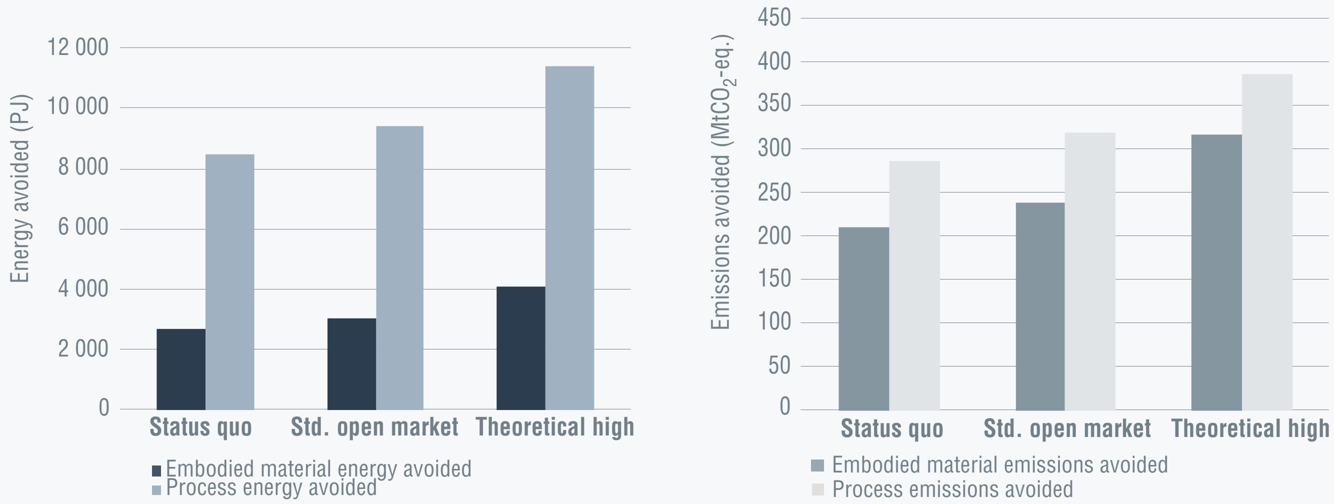
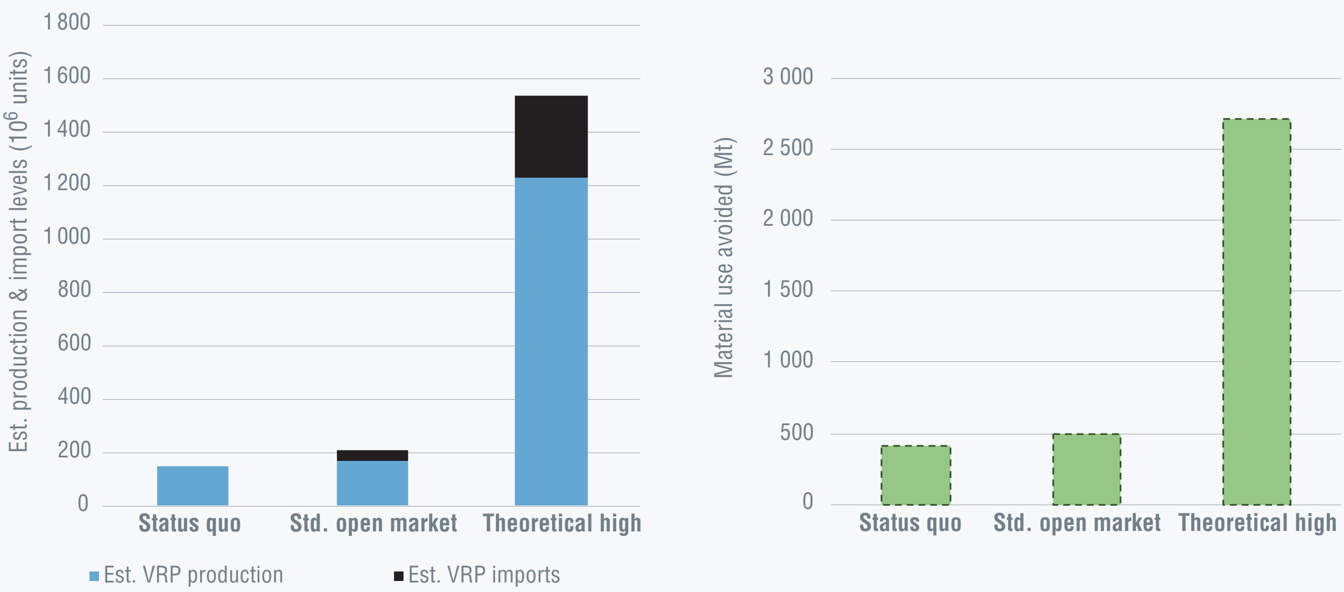


Figure 75: Estimated aggregate 7-year impacts avoided via Brazil HDOR equipment parts production with value-retention processes

(a) Est. production & import levels of VRP HDOR equipment parts **(b) Est. material use avoided via HDOR equipment parts VRPs**



(c) Est. energy use avoided via HDOR equipment **(d) Est. emissions avoided via HDOR equipment parts VRPs**

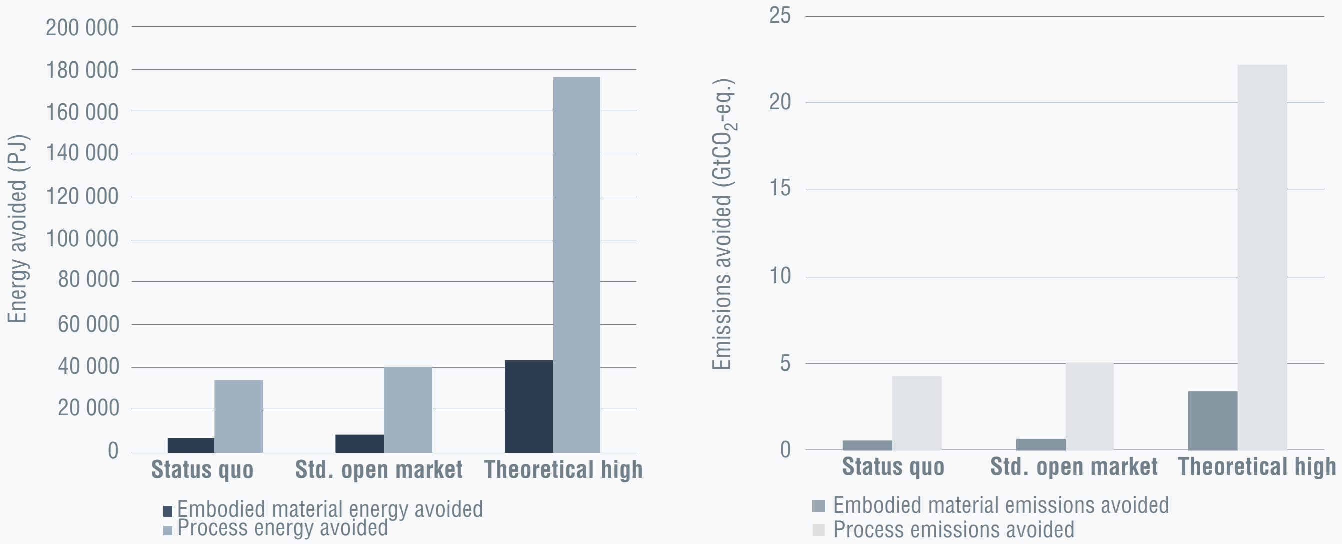


Figure 76: Estimated aggregate 7-year impacts avoided via China HDOR equipment parts production with value-retention processes

8

Discussion of key insights

As indicated, a primary objective of this assessment is to evaluate whether innovation within the production process can enable reduced negative environmental impacts of production without compromising economic opportunity and the satisfaction of consumer needs. The following sections describe the implications of product- and economy-level environmental and economic impacts associated with VRPs.

The pursuit of a circular economy is focused on improving the retention of value within the system as a strategy for reducing the pressures and demands on our natural resources. From this assessment, the inclusion of VRPs as part of a product design and business model plan, and as an increasing share of an economy's production mix, presents a viable and essential strategy for circular economy and the inherent benefits thereof. It must be noted that the outcomes of these case study products and sample economies do not provide universal conclusions and insights about the potential for VRPs and/or circular economy to reduce environmental damage and increase economic opportunity. As highlighted previously, the unique nature of the product (refer to Section 5) and complex system conditions (refer to Section 6) can significantly impact whether, and to what extent, environmental and economic objectives can be achieved.

The following sections organize the major findings and insights of this assessment into four main strategic categories:

1) the net-positive outcomes that are enabled when VRPs are incorporated into the product-system and as an increasing part of an economy's production mix;

2) the value and necessity of expanding the boundaries of product-related decisions to consider the product within the broader system that it will exist within for its life-cycle (product-system);

3) the importance of identifying and understanding the systemic barriers that constrain the scale-up of VRPs, with the objective of strategically alleviating these to help meet national economic and environmental objectives; and

4) the reality of current system mechanics and dynamics, including the risk of rebound effects, that affect the integration of VRPs within a circular economy.

8.1 Value-retention processes create net-positive outcomes for circular economy

Across each of the impact metrics analyzed within this study, a clear and apparent net-positive outcome was observed in almost all cases. While the environmental impacts of the use-phase of case study products is beyond the scope of this assessment, there are environmental impact reduction opportunities that can be realized in the pre-and post-consumer stages of a product's lifecycle (c.f. Cooper et al. 2017)

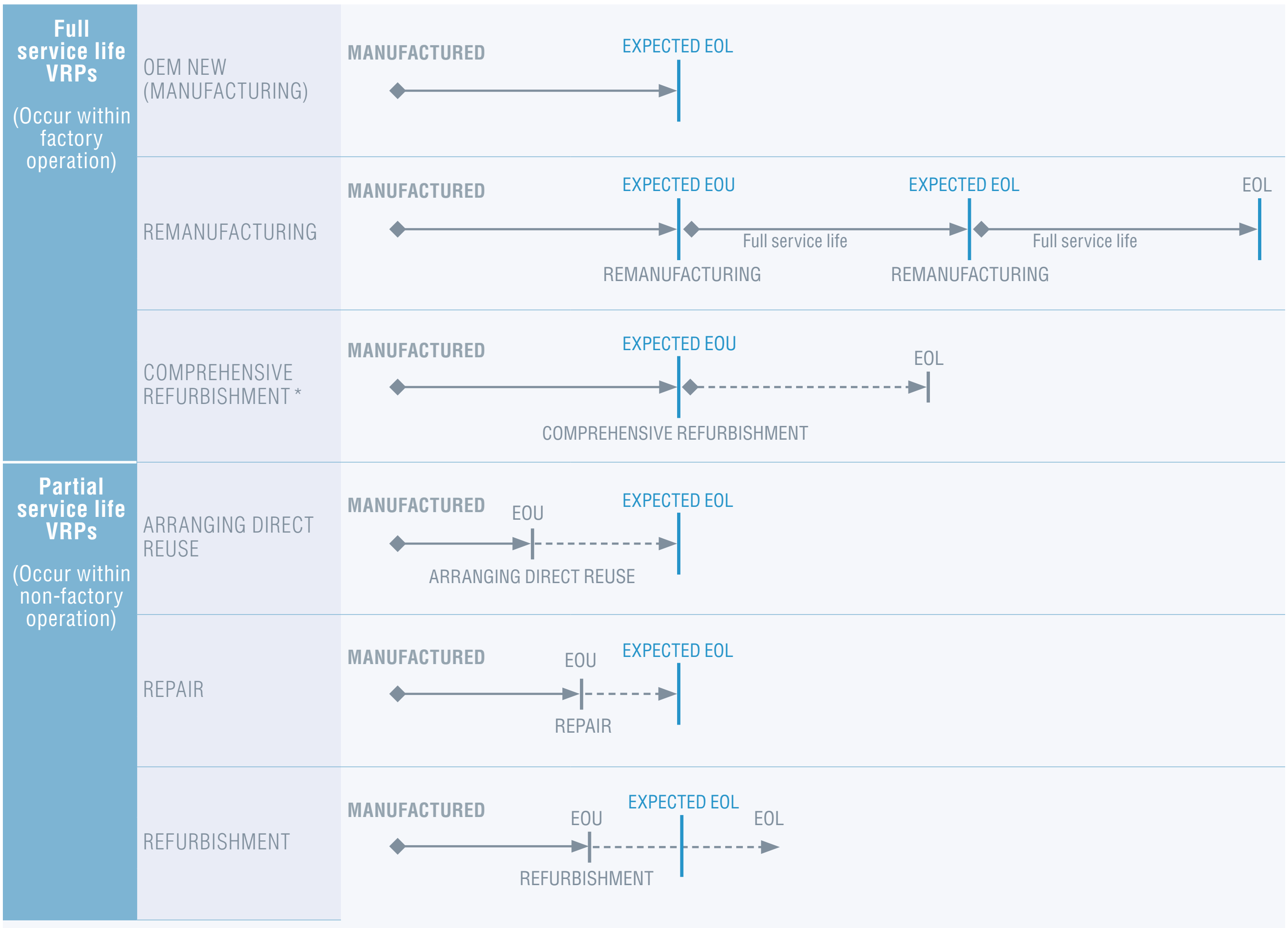
8.1.1 Value-retention processes are not created equal

Studies on the broad-scale potential of circular economy are starting to appear (Cooper et al. 2017, Ellen MacArthur Foundation 2013a, 2016, World

Economic Forum and Ellen MacArthur Foundation 2014). Cooper et al. (2017) assessed global implications of circular economy for industrial energy use, using an input-output based model focused on full supply chain embodied energy at the materials level. Although a different methodology focused on primary energy extraction and energy dissipation, Cooper et al. (2017) utilized many common assumptions necessary for higher-level modeling of circular economy: acknowledging flows of materials between national economies, and therefore shared effects of circular economy for both producing and consuming societies. Although aggregated via a different method and perspective, these findings demonstrated the potential for circular economy to contribute to a reduction of supply chain embodied energy of 6 per cent - 11 per cent at the global level (Cooper et al. 2017).

As revealed in the review and case studies of this report, the magnitude of environmental impact avoided, economic opportunity created, and ultimately the value retained within the system, depends upon the specific VRP that is employed. As highlighted in Section 3, and in the summary presented in Figure 77, VRPs can be divided into two groups or categories: (1) Equivalent full service life processes, which enable a full, or almost full new service life of the product; and (2) Partial service life processes, which enable a partial extension of the service life of the product. Associated with the service life and the specific VRP, differing degrees of value creation, value-retention, and therefore utility for the customer, can be achieved.

When considered in the context of the process definitions (refer to Section 2), and the subsequent quality and performance of the VRP product, it becomes clear that different VRPs are appropriate for different objectives. Remanufacturing and comprehensive refurbishment (equivalent full service life processes) both add and retain relatively greater value in the system in terms of both materials and functional form than partial service life processes;



* This only exists for certain sectors and products.

Figure 77: Summary of value-retention process differentiation within the context of EOU and EOL

however, for some products and economies these relatively more intensive industrial processes may increase the relative process energy requirement and associated process emissions as well. This was observed in case studies of industrial digital printers. At the same time, the rigorous industrial process can lead to greater economic opportunities in the form of increased labor requirement, decreased waste management costs, and greater utility, via relative price and quality, for the customer.

As a reminder, the length of the lines in Figure 77 are only intended to reflect relative service life duration enabled by different VRPs, and do not suggest quantified actual service life duration. The dotted lines reflect *potential* service life extension enabled by each VRP, as compared to the service life *guarantees* indicated by the solid lines.

In contrast, arranging direct reuse, repair, and refurbishment (partial service life processes) can be undertaken at a relatively lower cost than full service life processes, enabling customers with budget constraints to continue participating in the market; and they can be completed with lesser material requirement, energy requirement and associated emissions and waste. However, partial service life processes offer relatively limited value and utility to the customer and retain less value in the system over time.

The case studies of this assessment show more significant value-retention opportunities stem from remanufacturing and comprehensive refurbishment rather than from direct reuse and repair activities at the product-level.

The specific impact avoidance and economic opportunity potential created by each different VRP for each of the case study products are further clarified in Sections 8.1.2 and 8.1.4, respectively.

8.1.2 Product-level efficiency gains lead to economy-level efficiency gains

At the product-level, offset (reduced) embodied energy and emissions create immediate and obvious ranges of potential impact reduction and value-retention associated with the adoption of VRPs, as presented in Section 7.3, and highlighted in Table 16 through Table 20. The magnitude and nature of these impact reduction and impact avoidance ranges can be attributed to two key factors: 1) the product type; and 2) the nature of the VRP being employed (See Section 8.1.3). As the numbers of VRP products as part of an economy's production mix increases, the impact reduction potential becomes significant, as highlighted in Sections 7.4.4, 7.5.5, and 7.6.4, respectively.

The comparative differences between the environmental impacts, enabled by the presence of VRPs within an economy's production mix, are demonstrated in Figure 78 through Figure 83, where example products from each sector are shown under US conditions. It is important to consider that although the full service life VRPs (e.g. remanufacturing and comprehensive refurbishment) show relatively greater negative impacts than partial service life VRPs, they also retain greater value within the product, and enable greater utility for the customer over time

The values presented in the tables below reflect US-based empirical product-level case study results per unit. In the case of materials input and energy consumption for remanufacturing of vehicle parts, these results are aligned with the literature from studies in other jurisdictions, including China (Smith and Keoleian 2004, Liu et al. 2014, Liu et al. 2018). It must be noted, as discussed in greater detail in Section 8.2.4, that VRPs may not be appropriate for all products: The ranges presented in the tables below reflect the relative potential product-level environmental benefits (impact avoidance) that were observed for the case study products, and may be possible for other products and sectors under the necessary conditions.

Table 16: Summary ranges of relative potential product-level material value retention via VRPs

	Case study industrial digital printers		Case study vehicle parts		Case study HDOR equipment parts	
	Material value-retention range (kg/unit vs. OEM new)		Material value-retention range (kg/unit vs. OEM new)		Material value-retention range (kg/unit vs. OEM new)	
	Low	High	Low	High	Low	High
Remanufacturing	91%	98%	80%	95%	81%	91%
Comprehensive refurbishment	95%	99%	–	–	82%	82%
Repair	99%	99%	96%	99%	94%	99%
Arranging direct reuse	100%	100%	100%	100%	–	–

Table 17: Summary ranges of relative potential product-level embodied material energy avoidance via VRPs

	Case study industrial digital printers		Case study vehicle parts		Case study HDOR equipment parts	
	Embodied energy avoided range (MJ/unit vs. OEM new)		Embodied energy avoided range (MJ/unit vs. OEM new)		Embodied energy avoided range (MJ/unit vs. OEM new)	
	Low	High	Low	High	Low	High
Remanufacturing	87%	99%	80%	96%	79%	90%
Comprehensive refurbishment	92%	99%	–	–	80%	80%
Repair	99%	99%	97%	99%	93%	99%
Arranging direct reuse	100%	100%	100%	100%	–	–

Table 18: Summary ranges of relative potential product-level embodied material emissions avoidance via VRPs

	Case study industrial digital printers		Case study vehicle parts		Case study HDOR equipment parts	
	Embodied emissions avoided range ($kgCO_2$-eq./unit vs. OEM new)		Embodied emissions avoided range ($kgCO_2$-eq./unit vs. OEM new)		Embodied emissions avoided range ($kgCO_2$-eq./unit vs. OEM new)	
	Low	High	Low	High	Low	High
Remanufacturing	86%	99%	80%	96%	79%	90%
Comprehensive refurbishment	92%	99%	–	–	80%	80%
Repair	99%	99%	97%	99%	93%	99%
Arranging direct reuse	100%	100%	100%	100%	–	–

The potential reduction in embodied materials energy enabled by VRPs (refer to Table 17) supports the similarly scoped study and findings of Cooper et al. (2017), who determined a potential reduction of 6 per cent – 11 per cent of global industrial energy use related to economic activity. It must be noted that VRPs represent only some of the circular economy approaches incorporated into the study by Cooper et al. (2017).

Table 19: **Summary ranges of relative potential product-level process energy avoidance via VRPs**

	Case study industrial digital printers		Case study vehicle parts		Case study HDOR equipment parts	
	Process energy avoided range (MJ/unit vs. OEM new)		Process energy avoided range (MJ/unit vs. OEM new)		Process energy avoided range (MJ/unit vs. OEM new)	
	Low	High	Low	High	Low	High
Remanufacturing	57%	64%	65%	87%	65%	87%
Comprehensive refurbishment	69%	85%	–	–	74%	74%
Repair	100%	100%	100%	100%	100%	100%
Arranging direct reuse	100%	100%	100%	100%	–	–

The magnitude and nature of these impact reduction and impact avoidance ranges can be attributed to two key factors: (1) the product type; and (2) the nature of the VRP being employed (refer to Section 8.1.3). As the numbers of VRP products as part of an economy's production mix increases, the impact reduction potential becomes significant, as highlighted in Sections 7.4.4, 7.5.5, and 7.6.4, respectively.

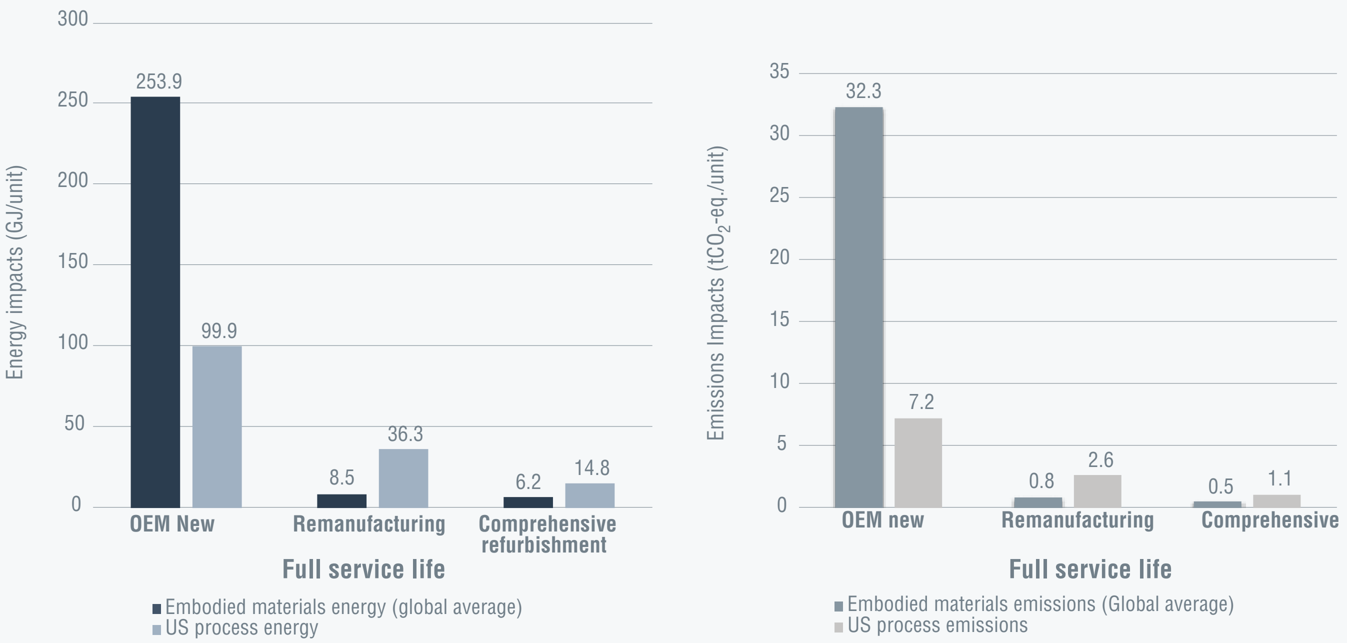
The comparative differences between the environmental impacts, enabled by the presence of VRPs within an economy's production mix, are demonstrated in Figure 78 through Figure 83, where example products from each sector are shown under US conditions. It is important to consider that although the full service life VRPs (e.g. remanufacturing and comprehensive refurbishment) show relatively greater negative impacts than partial service life VRPs, they also retain greater value within the product, and enable greater utility for the customer over time.

Table 20: **Summary ranges of relative potential product-level process emissions avoidance via VRPs**

	Case study industrial digital printers		Case study vehicle Parts		Case study HDOR equipment parts	
	Process emissions avoided range (kgCO_2-eq./unit vs. OEM new)		Process emissions avoided range (kgCO_2-eq./unit vs. OEM new)		Process emissions avoided range (kgCO_2-eq./unit vs. OEM new)	
	Low	High	Low	High	Low	High
Remanufacturing	57%	64%	65%	87%	65%	87%
Comprehensive refurbishment	69%	85%	–	–	74%	74%
Repair	100%	100%	100%	100%	100%	100%
Arranging direct reuse	100%	100%	100%	100%	–	–

(a) Comparative energy impacts of full service life vrps

(b) Comparative emissions impacts of full service life VRPs



(c) Comparative energy impacts of partial service life VRPs

(d) Comparative emissions impacts of partial service life VRPs

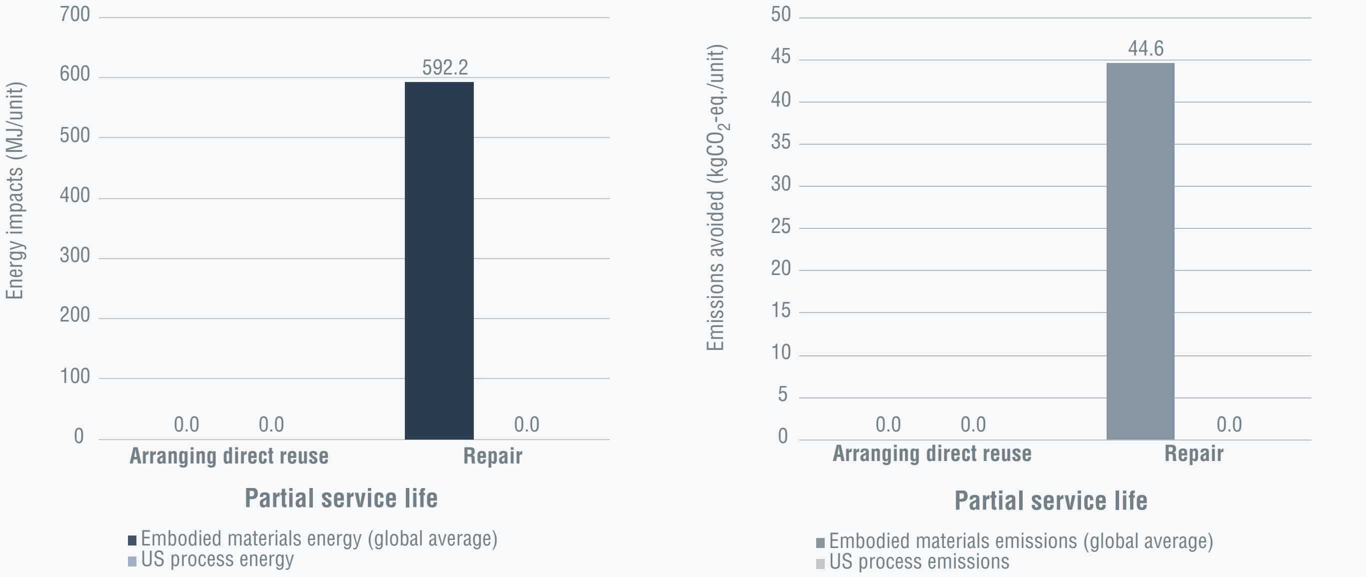
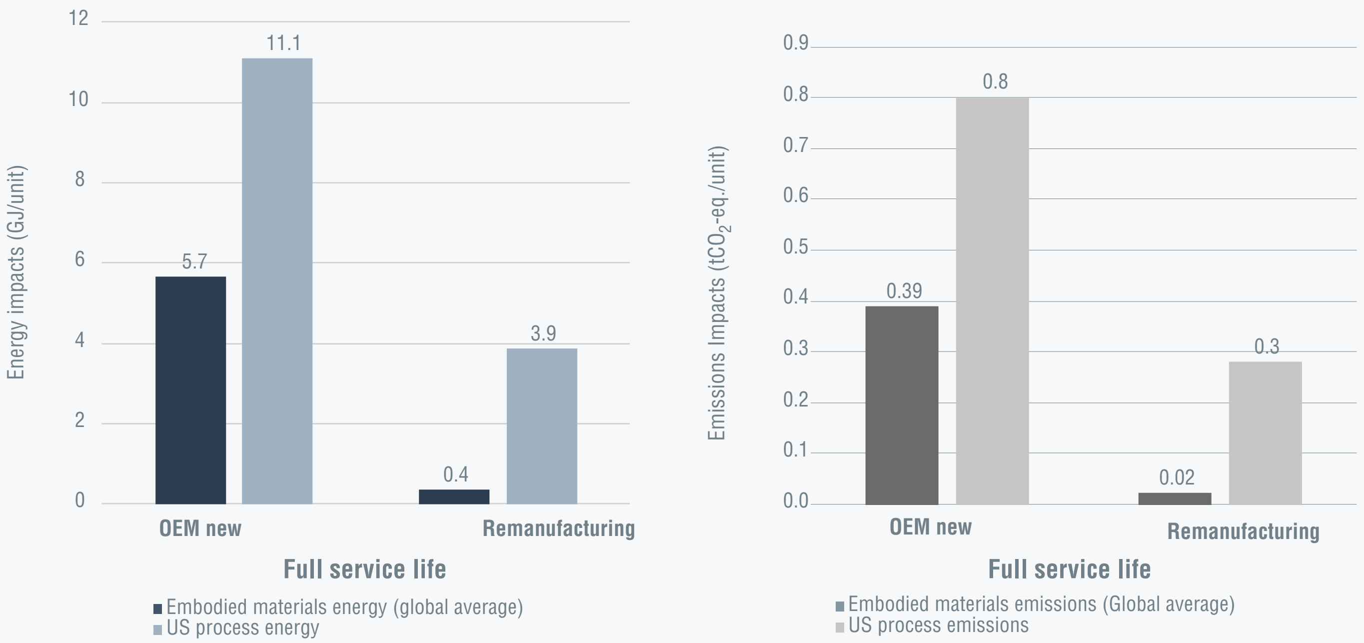


Figure 78: Comparative environmental impacts of VRPs for US industrial digital printing press

(a) Comparative energy impacts of full service life VRPs

(b) Comparative emissions impacts of full service life VRPs



(c) Comparative energy impacts of partial service life VRPs

(d) Comparative emissions impacts of partial service life VRPs

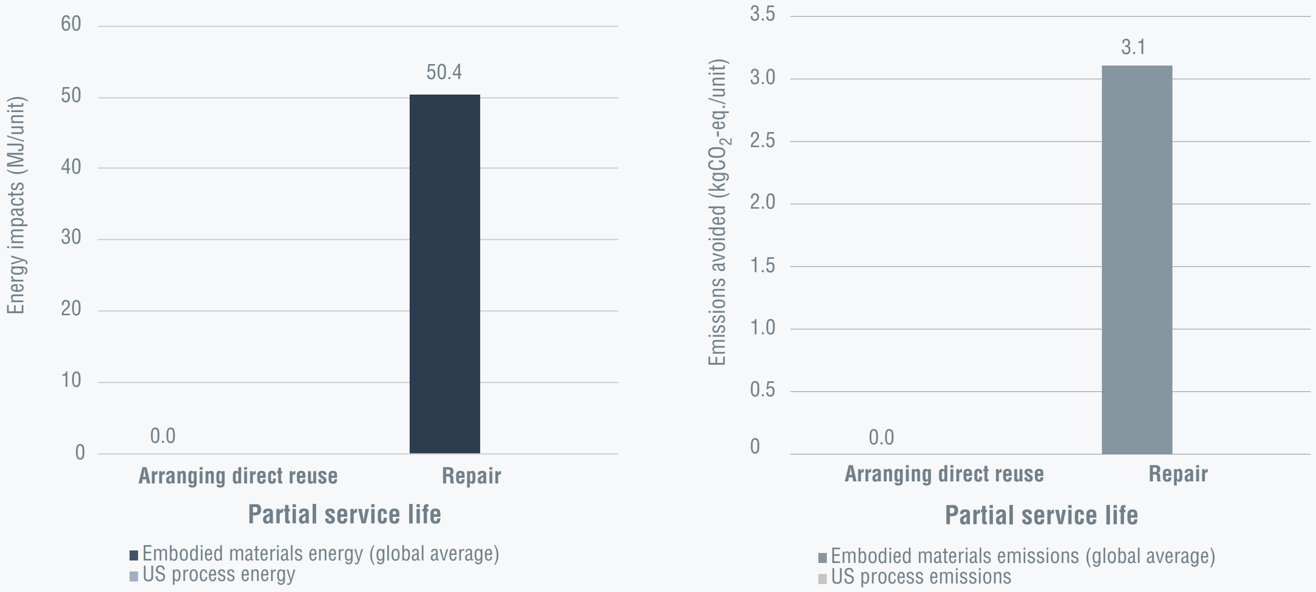
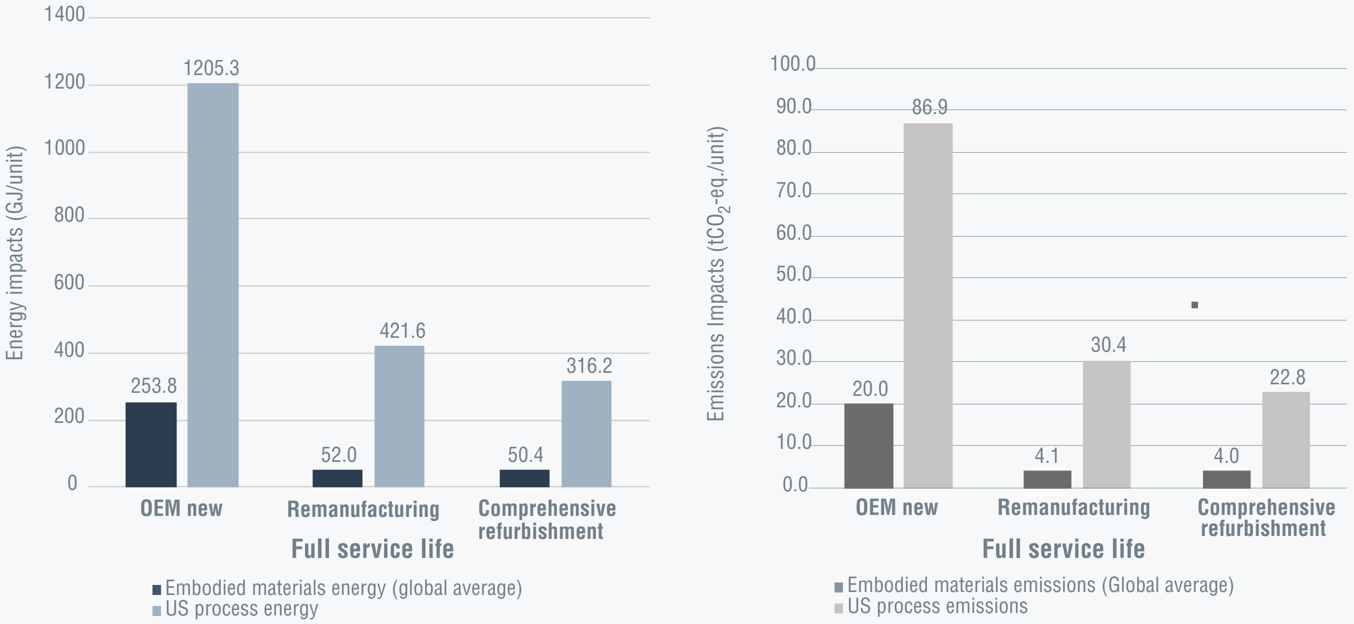
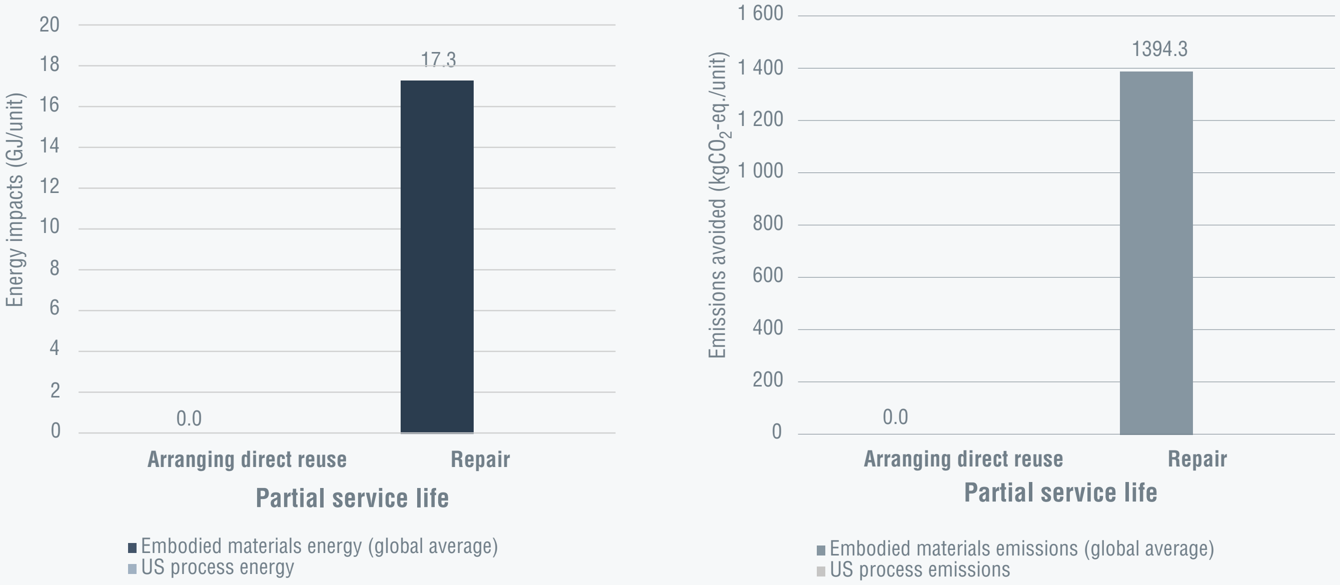


Figure 79: Comparative environmental impacts of VRPs for US traditional vehicle engine

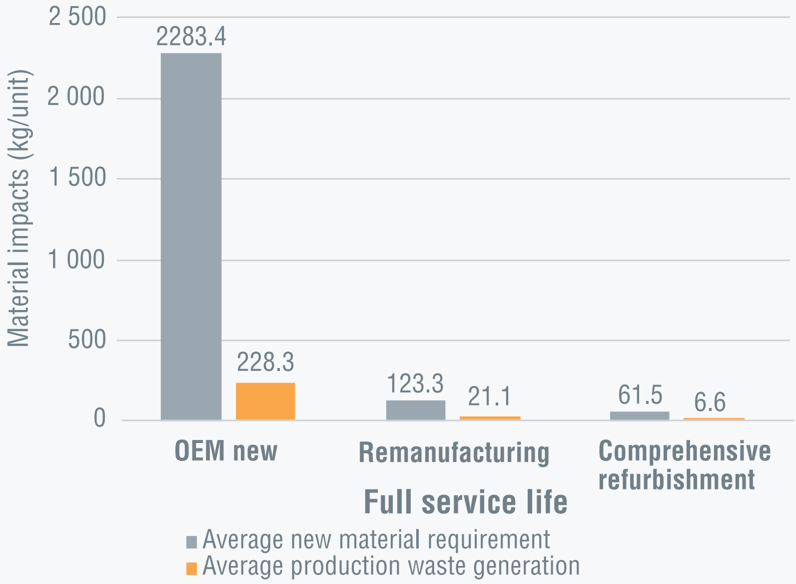

(a) Comparative energy impacts of full service VRPs

(b) Comparative emissions impacts of full service VRPs

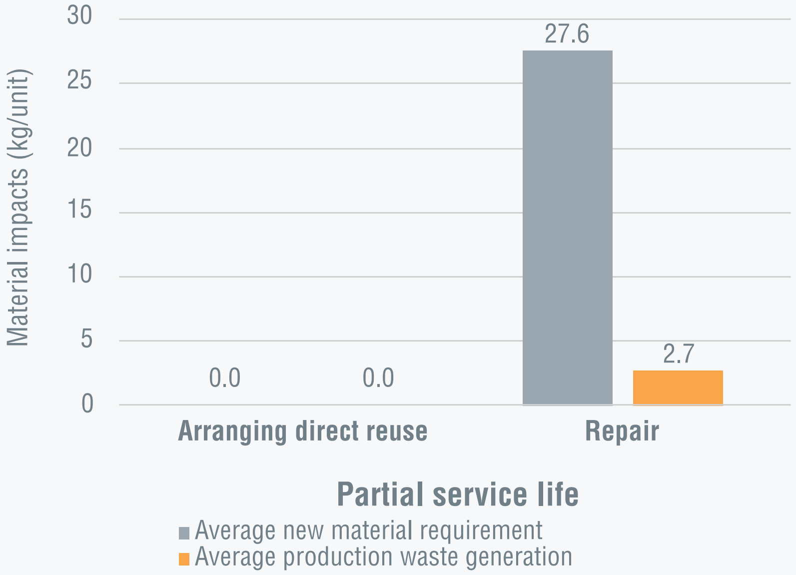

(c) Comparative energy impacts of partial service VRPs

(d) Comparative emissions impacts of partial service VRPs

Figure 80: Comparative environmental impacts of VRPs for US HDOR engine



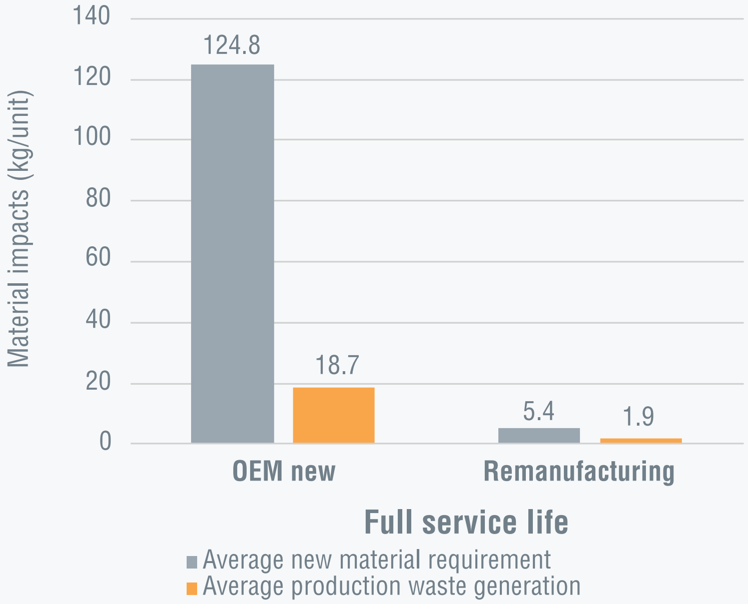
(a) Comparative material impacts of full service life VRPs



(b) Comparative material impacts of partial service life VRPs

Figure 81: Comparative material impacts of VRPs for US industrial digital printing press

(a) Comparative material impacts of full service life VRPs



(b) Comparative material impacts of partial service life VRPs

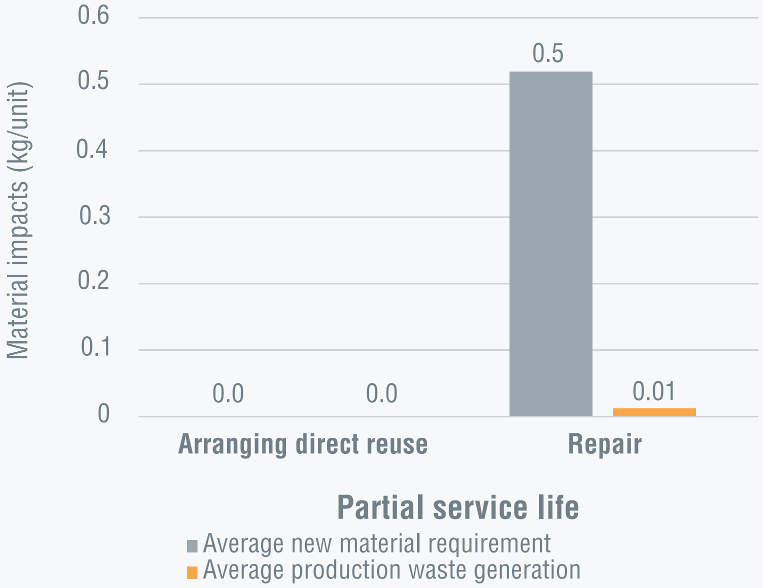


Figure 82: Comparative material impacts of VRPs for US traditional vehicle engine

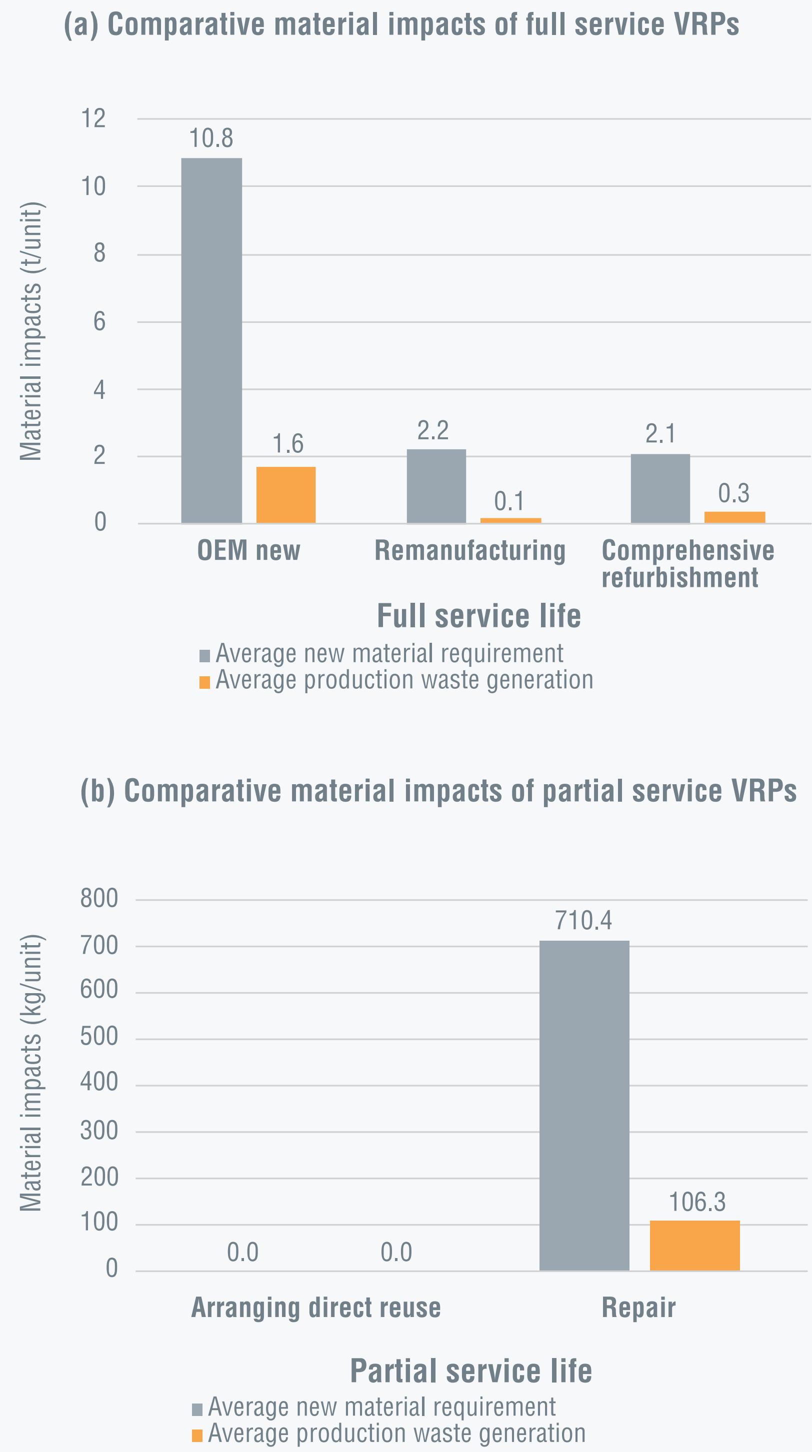


Figure 83: Comparative material impacts of VRPs for US HDOR engine

There is often a perception that the pursuit of sustainability must come at an economic cost. While this perception may be warranted in a short-term context, this assessment has revealed that, through the adoption of VRPs, significant impact reduction can be achieved at the same time that economic opportunity, including reduced production costs and potential new customer and consumer segments, is created, albeit at different levels for each different VRP (Figure 81, Figure 82 and Figure 83).

As demonstrated in Section 5.3 and the comparative impacts highlighted in Figure 81, Figure 82, and Figure 83, the reduction in new material input requirement, and the embodied value inherent in the already-functional form, ensure that VRPs can offset a significant share of costs that would otherwise be required for OEM New production. This cost advantage to the producer, typically in the range of a 30 per cent – 80 per cent reduction versus the OEM New product, generates additional economic opportunities in several ways: first, with lower operating costs there are fewer cost barriers to entry into the marketplace for potential VRP producers, and this can support and enable faster scale-up within domestic industry; and second, lower operating costs enable VRP producers to pass the cost advantage along to their customers. Lower-priced VRP product options in the market can enable new segments of customers to participate where budget constraints may previously have prevented such engagement (Atasu, Sarvary, and Van Wassenhove 2008, Debo, Toktay, and Wassenhove 2006, Debo, Toktay, and Van Wassenhove 2005, Hamzaoui-Essoussi and Linton 2014, Hazen et al. 2012). This is particularly true in markets where access to VRP products has been historically constrained, as observed in the Standard Open Market and Theoretical High scenarios for Brazil and China. Being able to position VRP products at a lower price-point, even in unconstrained markets like the US, can enable VRP producers to compete more effectively against lower-priced options, once again creating the potential for faster adoption and scale-up in the domestic economy.

When aggregated to the level of a complex economy with a mixture of different OEM New and VRP production activities, net-positive outcomes continue to be observed for the case study products in the sample economies. While the magnitude of impacts-avoided is directly related to the size of the case study sectors in each studied economy, the relative positive outcome of avoided impacts can be observed across each sector and economy. These observations highlight the importance of utilizing a systems-view when assessing the potential for VRPs within the circular economy:

1. Any increase in VRP production reduces average new material demand, and in other words, creates an opportunity to avoid requirement for new materials. Under the Standard Open Market and Theoretical High scenarios, the increase in VRP production within each sample economy showcases the potential for significant reductions in aggregate new material requirements. This is particularly significant for products that require large quantities of energy-intensive materials, such as industrial digital printers.
2. The avoidance of new material inputs creates significant benefits in the avoided embodied materials energy and embodied material emissions impacts that would otherwise be incurred through the extraction and primary processing of those new input materials. Regardless of which VRP is adopted, a net-positive reduction in embodied energy and embodied emissions is consistently observed across every sector and economy.
3. Inversely correlated to the increase in VRP production is the relative decrease in production waste. In the case of vehicle parts and HDOR equipment parts, a significant amount of production waste is generated through the transformation of new material inputs into an OEM New product. The significant retention of the functional form and material value of component parts enabled via VRPs thus also offsets the production waste associated with original production.

8.1.3 Product type affects possible gains from value-retention processes

An important insight from this assessment is that product type and design have important roles to play in determining the magnitude of value retention and impact avoidance potential. More specifically, the potential benefits from VRPs are tied to the nature of the product and product architecture (refer to Section 8.2.4 for more detailed discussion), and relates to whether the VRP is applied to the 'whole' product, or to product 'components', as exemplified by industrial digital printers, and vehicle parts, comparatively. As such, the interconnectivity and consideration of appropriateness between the product and the VRP must be considered as a design priority. This highlights further the necessity for adopting a product-system approach, which is discussed in greater detail in Section 8.5.

The nature of products like industrial digital printers is that, despite other design considerations, they are designed to be a single product within a single product-system. In other words, when an industrial digital printer fails in a way that cannot be repaired, it is typical for the customer to require a new industrial digital printer. This allows the OEM to have greater control over the entire system and makes it much easier to design the product and system for VRPs. This enhanced level of control, resulting from the product being a 'whole' product, means that for industrial digital printers there can be an entire infrastructure in place to ensure that value retention can be maximized in the system through VRPs. In more general terms, when the product is, in and of itself a 'whole system' (versus parts or spares), it has been designed to work as a complete unit (e.g. product information stays relatively more intact), and the opportunity and ability to retain value in the system and foster greater material efficiency is much higher. For these reasons, the OEM of these types of 'whole' products have an advantageous position in being able to construct and control the product-system approaches. As indicated, higher EOU collection and VRP reuse rates were observed for these case study products when the OEM was engaged in reverse-logistics and VRPs. As such, engagement of OEMs is a central and essential strategy for enhancing the efficiency of the systems supporting 'whole' product VRPs globally.

In contrast, products like vehicle parts represent only a small part of the entire vehicle (which is itself a 'whole system') and are often produced across a much broader and more complex supply chain system. In other words, when a vehicle part fails in a way that cannot be repaired, it is typical for the customer to replace the vehicle part, not the entire vehicle. While compatibility with OEM vehicle design is essential, there is also significant space in this market for parts suppliers to engage in the production of replacement parts and spares, separate from the OEM. In this more decentralized product system, there is implicitly greater complexity and less control. In addition to a larger number of supply chain players, there are significantly more customers; as only small components of a whole vehicle, the reverse-logistics associated with collection vehicle parts for VRPs can be more intricate and costly. In the case of vehicle parts, it is also very easy for customers to secure lower-cost replacement parts without having to deal with the OEM. In more general terms, when the product can only be utilized as a component part of another product, the opportunity and ability to retain value in the system and foster greater material efficiency is more challenging, and greater collaboration between OEMs, VRP producers, and third-party reverse-logistics entities may be required.

As expanded on in Section 8.2.4, the complex nature of VRP products, processes and business models means that the costs of pursuing VRPs, and the potential environmental and economic benefits, can vary significantly for different firms. The decision to pursue VRPs must be a carefully considered and strategic choice by industry decision-makers.

8.1.4 Impact avoidance potential through barrier alleviation

In addition to the economy-, process-, and product sector-specific insights outlined in the previous sections, there are some overarching insights that can be observed from the Theoretical High scenario, in which barriers are alleviated in an exaggerated simulation.

Assuming current design and technological conditions, the US and German economies that do not face significant technological or regulatory barriers do not see significant market demand growth beyond the expected compound annual growth rates (CAGR) estimates specific to each case study product and sector. However, as the share of VRPs in the production mix increases under the different scenario conditions, net-positive avoided impacts of embodied material energy requirement, embodied material emissions generation, and material consumption are observed (refer to Figures in Sections 7.4.1, 7.5.1, and 7.6.1).

In contrast, the economies of Brazil and China, assuming current-state regulatory, technological, market, and infrastructure conditions, do show market demand growth opportunity beyond the expected case study product and sector CAGR, in both the Standard Open Market and Theoretical High for VRP Products scenarios. This additional growth is attributed to increased access by way of barriers alleviation to VRP products, previously unavailable under Status Quo conditions, as new producers and consumers engage in the VRPs and VRP products. Customers previously unable to participate in the market due to budget constraints, can access lower-cost refurbished and remanufactured options under simulated barrier-alleviation scenarios. In some economies (e.g. China), this may offset on the prevalence of arranging direct reuse and repair activities to some degree, as other affordable VRP options become available. It must also be noted that in economies that previously restricted access to VRP products, the alleviation of barriers may increase the share of imports that help to supply domestic demand, and this can have downward pressure on domestic production levels. This is specifically observable in the results from the Standard Open Market for VRP Products scenario for HDOR equipment parts in Brazil and China (Figure 66 and Figure 67).

It is also apparent that the pre-existing conditions of each economy have a significant influence on the adoption of circular production processes, relatively. Although *aggregate* impacts of domestic production show correlated increase, the *average* per-unit impacts of domestic production decrease as the share of VRP production scales-up within an economy.

Of significance are the starting levels of VRP products in the market and production mix, as well as customer attitudes and perceptions of VRPs products, and the presence of competing alternatives (e.g. repair, and/or lower-priced OEM New versions of the product) (Rogers 2003, 1976). These factors were observed to affect the rate at which different VRP products were demanded by a scenario market over the simulated period, as well as the rate at which producers adopted and engaged in VRPs. This is particularly apparent in the case of China's Standard Open Market for VRP Products scenarios, where even though significant relative VRP production growth potential may exist, when applied to the almost non-existent starting production share for VRPs (effectively zero), market transformation is still slow (Figure 38, Figure 51, and Figure 67). From a strategic perspective, in economies that have low starting VRP market share and low levels of market awareness, it will take longer to reach meaningful thresholds for uptake of VRP options.

The extent to which an economy relies upon imported products to meet domestic demand influences the extent of benefit that can be achieved by increasing domestic demand for VRP products. This can be seen in the case study examples for Germany, Brazil and China in the Standard Open Market scenario for all case study sectors: the imposition of a higher import share than normally exists in those economies (based on US import ratios for each specific sector), leads to a minor reduction in domestic production levels in the short-term. While environmental impacts of that offset domestic production have been reallocated elsewhere, in these cases the domestic economy misses out on the economic opportunities that would otherwise be associated with increased demand for VRP products. If increased VRP imports come from economies with less efficient and/or more harmful production conditions, the impact reduction opportunity may have been negated, or even worsened; in contrast, if increased VRP imports come from economies with more efficient and/or less harmful production conditions, the impact reduction opportunity may be improved. This leads to the important insight that the alleviation of trade barriers can create additional issues and complexity in the short term, and therefore must be considered carefully in the context of the entire production-consumption system. These concerns are tied to one of the systemic rebound effects identified by this assessment and are further discussed in Section 8.3.2.

As observed in this analysis, regardless of how quickly, or to what extent VRPs increase within the production mix and/or market demand, the potential to offset new material requirement, and retain value within the system is automatically increased with the alleviation of barriers to VRPs through the Standard Open Market for VRP Products and Theoretical High for VRP Products scenarios.

While the absolute magnitudes of new material offset, energy requirement, and emissions generation are dependent upon the product type, and the magnitude of the domestic industry and production level, the opening of markets and alleviation of barriers can lead to net positive impact avoidance, and automatic improvements in material efficiency. This was observed consistently across each case study sector.

The inclusion of VRPs into domestic production activities has demonstrated efficiency opportunity across each studied scenario economy: through enhanced technology and processes in economies that currently have *low or no* VRPs, VRP innovation

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enables new efficiency and opportunities to pursue circular economy with positive impacts that can ripple across the entire economy. Through improved design, distribution, and market transformation in economies that currently have *well-established* VRP activities, higher efficiency and impact reduction gains are possible. However, as observed under this assessment, the most meaningful impact reduction potential will only be possible through bold and assertive initiatives that enable the extreme, but essential vision of the Theoretical High scenarios.

8.2 Implications for industrial design strategy and practice

The design community has identified that there are key differences between design for sustainability (eco-design), and design for circular economy: most fundamentally, design for sustainability principles are typically based within the traditional waste hierarchy, and founded in the assumption that a product will inevitably become waste; this contrasts with the ideal circular economy vision that waste does not exist (den Hollander, Bakker, and Hultink 2017). Critiques of the waste hierarchy emphasis that has traditionally guided eco-design suggest that the inclusion of disposal within the waste hierarchy framework is problematic because it legitimizes the option (Van Ewijk and Stegemann 2016). In addition, from a product design perspective, the dismantling and destruction of a product's integrity required by recycling makes this the least preferable process in the context of a circular economy (den Hollander, Bakker, and Hultink 2017).

As discussed, more circular systems can be created in several ways: by directly reusing products that still have useful life; repairing and servicing products to restore quality to diminished life; refurbishing products to extend life beyond the traditional end; or remanufacturing products to create an entirely new service life. In other words, utilizing product and product-systems design to minimize the need for recycling and disposal within the product's life cycle.

Ensuring that these approaches can be successful and effective, however, requires both business models and product characteristics that make such strategies economically viable (den Hollander, Bakker, and Hultink 2017). Working back from the end-of-life, the greatest influence on a product's viability for VRPs comes invariably from its design, where decisions made early in the design process can dramatically impact both the economic viability and sustainability of a product. Huthwaite (1988), for example, found that while product design processes are responsible for only 5 per cent of a product's cost, the design itself determines 75 per cent or more of manufacturing costs. Similarly, Nasr et al. (2002) suggest that design decisions also influence more than 80 per cent of a product's environmental and social impacts. It is thus clear that without early design intervention, the value recovered through and benefits created by these VRPs cannot otherwise reach a point of economic viability.

Guided by the Inertia Principle, Stahel's guidelines for circular design (2010, 195) highlight meaningful logic for a circular design hierarchy : "Do not repair what is not broken, do not remanufacture something that can be repaired, do not recycle a product that can be remanufactured. Replace or treat only the smallest possible part in order to maintain the existing economic value of the technical system." While this approach does not embrace the potential for value creation through upgrades and/or exceedance of the functional specifications of the original product, it provides a product-centered focus on design principles that can help to guide the design decision process (den Hollander, Bakker, and Hultink 2017).

It is important to note that product design goals are often dictated by the underlying objectives and constraints of the producer, and the conceptual production approach. When the producer framework relies on a basis of widely accessible, inexpensive materials and a business model that champions sale volume, product design objectives become focused on balancing cost, quality, functionality, and delivery. In this context, durability and longevity are often sacrificed willingly, as eventual obsolescence and replacement become drivers of continued sales. As such, the pursuit of circular economy depends largely on business strategies recognizing the need to decouple economic growth from volume-based prosperity, and decision-maker understanding of where to start.

8.2.1 Integrating design and circular economy business model innovation

When considering the integration of circular economy business models and product design, Bocken et al. (2016) identifies two primary objectives: the objective of slowing flows of materials and resources; and the objective of closing loops within the system.

The closing of material loops is heavily focused on the material level (not the VRP product level), and requires radical firm and system changes, and collaboration with other system actors to identify industrial symbiosis opportunities, and to extend resource value by exploiting the residual value of materials (Bocken et al. 2016). To close product-loops, design principles targeting the dis- and reassembly of products can contribute to the efficiency, effectiveness, and cost-management of VRP systems (Bocken et al. 2016).

The slowing of material and resource flows within circular systems requires different product- and business-design considerations. An overarching sufficiency approach incorporates the objective of reduced consumption into product design via durability, upgradability, reparability, the provision of service warranties, and a non-consumeristic approach to the market (Bocken et al. 2016). At the product-level, this may involve design for long-life (e.g. durability, repair), and design for product-life extension (e.g. design for remanufacturing), all oriented at keeping the product in the system for longer, thus slowing the flows of materials and resources into and out of the system. For the firm, this may involve a business model focused on providing access and performance (rather than ownership), and systems to enable product value extension (e.g. via VRPs) and long-life (e.g. service warranties) (Bocken et al. 2016).

To design for product integrity (den Hollander, Bakker, and Hultink 2017) a systems-perspective must encompass the expanded life cycle view of the product and product-system, as well as consider the various stakeholders that need to be involved in the process. As highlighted by Bocken et al. (2016) circular economy business models looks to generate value and profit from the flow of materials and products over time. Innovative service-oriented product and business models show promise in minimizing disposal of potentially valuable resources by enabling producers to retain ownership of the product; with retained ownership comes the additional opportunities (and challenges) to improve and optimize product design and delivery, service contracts, and systems to facilitate VRPs at product EOU and/or EOL.

Product-Service Systems (PPS) are one type of approach that, through different mechanisms, provides access and performance (delivery of service) alongside, or instead of providing just a physical product (ownership) (Bocken et al. 2016). Where ownership by the firm is maintained under some PPS-approaches (refer to Box 3), firms are incentivized to design their products for efficiency, durability, serviceability, value-retention, and multiple service life potential (Tukker 2015b). There are different types of PSSs, as outlined in Box 3.

Box 3: Product Service Systems in a Circular Economy

According to Boehm and Thomas (2013) "… a Product-Service System (PSS) is an integrated bundle of products and services which aims at creating consumer utility and generating value." There are three main categories of PSS: (1) Product-oriented PSS, which are mainly focused on sales, with some added services; (2) Use-oriented PSS, in which the product stays owned by the producer, is made available to the user in a different form, and may be shared by multiple users (e.g. leasing, renting/sharing, pooling); and (3) Results-oriented PSS, in which the client and the provider agree on a valued result, not necessarily on a product (e.g. activity management, pay-per-service unit; pay-per-fractional result) (Tukker 2004, 2015b).

There is increasing academic interest in PSS, with research and investigation approaching the potential opportunity from engineering, business, and environmental perspectives (Tukker 2015b). The design perspective requires that PSS integrate additional considerations and steps, including demand identification, feasibility analysis, concept development, service model development, realization planning, and service testing (Tukker 2015b). Design for modularity, requirement engineering, and economic optimization techniques are particularly important design principles within the context of PSS approach (Tukker 2015b).

Shared-ownership models, involving collaborative agreements between users is often a proposed model for reduced total consumption and value creation (Bocken et al. 2016). The communal sharing of services (e.g. cleaning, maintenance) and access (e.g. to a product) creates value for stakeholders by helping to reduce costs across the network (Bocken et al. 2016). Additional approaches including the exchange of by-products enables participating parties to capture value by avoiding costs and engaging the creation of new business opportunities generated from former waste materials (Bocken et al. 2016). Lifset (2000) notes that sharing models may create the risk of moral hazard: without appropriate protections and contracts that require the individual user to ensure maintenance of the shared good, there is the potential risk that use-phase environmental burdens may be increased, and/or product lifespan may be reduced.

Although much of the current research on PSS demonstrates the opportunity for improved resource efficiency (Stahel 1982, Schmidt-Bleek 1993), not all approaches to PSS are equally effective. Per Tukker (2015b), the design focus from product- and use-oriented PSS approaches lack clear sustainability outcomes and may have unintended consequences: product-oriented PSS is still highly motivated to sell more products; careless and/or more intensive use under use-oriented PSS can affect service life and potential for VRPs (Tukker 2015b); whereas results-oriented PSS have demonstrated some success at achieving resource efficiency – not because of the sustainability motivation, but rather as a result of the built-in business incentive for keeping costs low, thereby decreasing associated material use and impacts (Tukker 2015a).

Not all offerings may be appropriate for a PSS approach, and firms must consider the costs and opportunities of PSS versus product for their particular offering (Tukker 2004). Specific considerations must include the market value – including tangible and intangible value to consumers/users,-- the production cost of operating the PSS, the inherent capital and investment needs for PSS production, and whether a PSS approach will enable a firm to capture value in the current and future value-chain (Tukker 2004). PSS have been found to work best for products that are expensive, technically-advanced, require maintenance and repair within their service life, are easy to transport, are used infrequently by the customer, and are not heavily influenced by fashion or branding (Tukker 2015b) (please refer to Section 8.2.4 for further discussion on appropriate use of VRPs).

In a B2C context, the intangible value created by accessibility and convenience is important but often overlooked factor that can affect the success of a PSS initiative. In addition, PSS do not deliver the ownership 'extras' of status and esteem that may motivate consumers (Tukker and Tischner 2006). In contrast, important considerations for B2B relationships included a well-regarded brand reputation, relevant service competencies, and strong buyer-seller relationships indicative of the firm's ability to provide value beyond the product (Brown, Sichtmann, and Musante 2011, Tukker 2015b).

One PPS approach that falls into the results-oriented category of PPS offers a pay-per-use or pay-per-unit-service approach that shifts the firms profit center away from the provision of the product to the provision of a result that is valued by the customer. For example, an industrial printer provides the service of printed materials, degrading over time with use. Under a pay-per-unit approach, users pay for every printed sheet: this approach, by design, helps the user to associate the product degradation from use with a real unit-cost, ultimately encouraging the minimization of total costs of ownership and the maximization of product life times (Baker 2006, Lifset 2000). Alongside some critiques of shifted ownership models, Lifset (2000) notes that the emphasis on possession and results (instead of the product) does not necessarily change the design or impacts of a product and product-system. Implicit for mutual circular economy and sustainability objectives to be achieved is the need to integrate these innovate business models with circular economy design principles.

Successful approaches to alternative business models for circular economy involve an appreciation for both the functional and non-functional characteristics of a product (Lifset 2000). Understanding the potentially multiple aspects of a product or service that generate value for the user/customer can help firms to envision new ways of approaching the marketplace: for example, Interface Inc. may manufacture modular and recyclable commercial floor tiles, but what they provide to their customers is a flexible, reliable, aesthetically-pleasing, and maintainable floor-covering service that includes environmentally-sound management at EOU (Johansen 1998, Ceschin 2013). Firms that identify and properly integrate these customer value perspectives into their business models, alongside other principles outlined in Box 3 can potentially achieve greater savings, consume fewer resources, and reduce their net impact on their environment.

A business case and business model focused on maximizing the useful life and utilization rates of a product significantly reframes the design objectives and parameters. Accompanying this type of model is an incentive to build and enhance effective and efficient product collection systems and networks throughout all markets in which the company operates. Some of the successes observed in the industrial digital printer and HDOR equipment parts sectors, as analyzed within this study, relate to the willingness of producers in those sectors to develop and invest in more innovative business models that not only help to accomplish the actual needs of the customer, but which also contribute significantly to circular economy through the adoption of VRPs.

8.2.2 Integrating product circularity into product development

Looking specifically at VRPs, *design for product integrity* as proposed by den Hollander, Bakker, and Hultink (2017) aims to prevent product obsolescence and recover resources at the highest level of integrity. Several design for product integrity strategies are proposed targeting long use (design for physical durability, design for emotional durability), extended use (design for maintenance, design for upgrading), and recovery (design for recontextualizing, design for repair, design for refurbishment, and design for remanufacture) (2017, 521). They also call for an acknowledgement that product design for circular economy must take place with a systems perspective that considers the business model needed to enable the retention of production integrity and economic value over multiple service life cycles (den Hollander, Bakker, and Hultink 2017).

While the importance of educating designers and engineers about VRPs and equipping them with the proper tools cannot be understated, even the best-educated design team could not create a product within the context of circularity if not explicitly called for in the product specifications and requirements. This is because designers are not the primary decision-makers regarding what a product does or how it does it; rather, they focus on using creativity to *meet* such product requirements—specifications that are defined much earlier in the product development process.

Many industry leaders use a structured product development process to identify critical action and decision points between the emergence of an idea and the commercialization of a product. Although the actual implementation of each process can vary significantly by company, product, and context, there are six key phases— (1) planning, (2) business case, (3) define, (4) concept, (5) design, and (6) launch—that are common across nearly all industries. After each phase, a final decision of whether to continue product development is made based on the degree to which development up to that point has fulfilled the preceding phases’ criteria for success.

Figure 84 illustrates this process framework and the critical decision points within each phase, including conceptual examples of where VRP considerations (red text) might be integrated to create systemic viability.

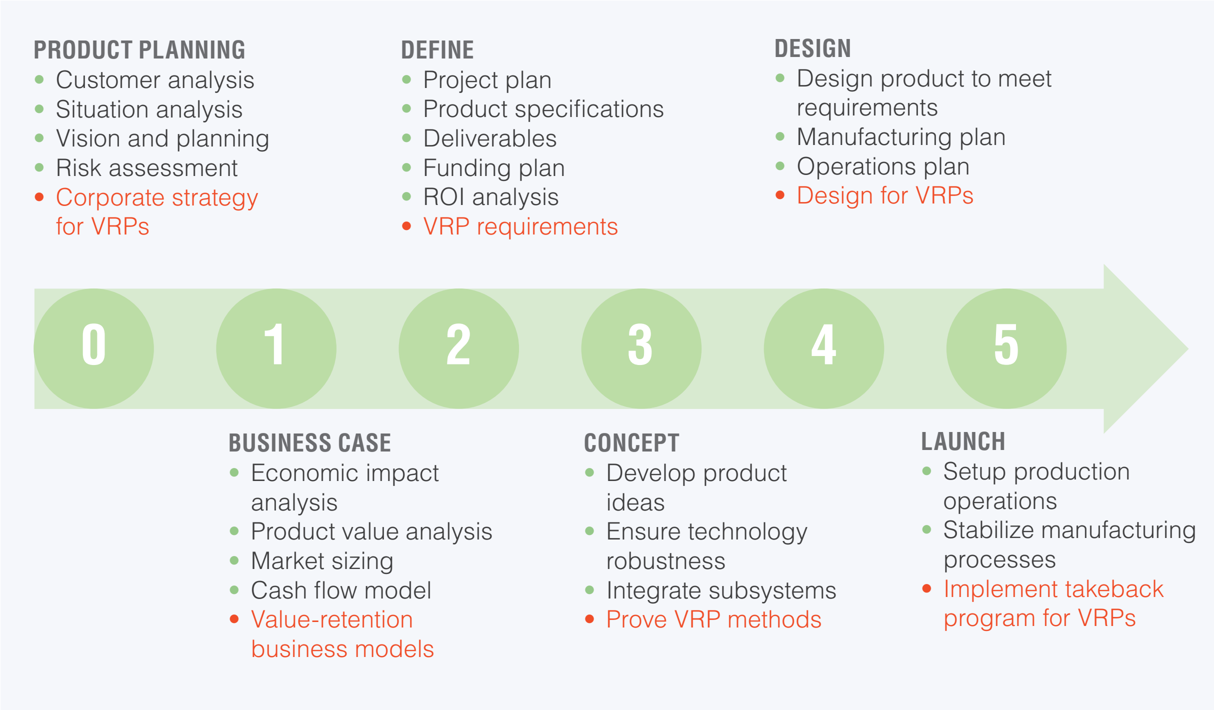

Figure 84: Product development processes with integrated value-retention processes

The conceptual framework that defines what a product must do—what needs it will meet, and how it will meet them—is created early in the product development cycle, long before the design team begins. Before designing, a company must first decide whether VRPs fit within its corporate strategy and business models; whether it has the knowledge and the infrastructure to support these VRPs; and whether it can overcome regulatory and market barriers on the path to economic viability (refer to Section 8.2.4). These decisions ultimately inform the degree to which VRP considerations may feasibly become specified product requirements.

Thus, the design phase is too late in the development process to *begin* addressing the opportunity for VRPs, and while strengthening the design team’s tools and education is important, it is also insufficient as an isolated strategy in pursuit of circular economy. Instead, requirements for VRPs must be made a central component of the product specifications before designers are asked to approach them; this will better enable designers to leverage the appropriate knowledge and tools to fulfil these requirements. Of relevance to this assessment are the planning, business case, and design phases of this process.

8.2.2.1 Product planning

The planning phase of a product development program is used to define the fundamental market and business needs in each product space. From there, a company outlines a set of high-level requirements to describe what a product should do to meet these needs. In these investigations, a company explores the overall market opportunity, identifies market risks, defines the customer requirements, surveys existing products and their features, develop the financial goals and priorities for manufacturing, and indicate key priorities for further development. It is in this phase that governmental regulations, customer expectations and demands, and the awareness created externally may most influence the trajectory of product development and, ultimately, its final characteristics. These factors create the context in which any new product will exist, and thus by extension influence the constraints and characteristic expectations to which it must adhere. Understanding the systems-implications of customer preferences, regulations, or purchasing influences favoring VRP products and systems—or highlighting the potential costs of neglecting these factors—can help to guide companies in the integration of VRP potential into the fundamental product plan.

8.2.2.2 The business case for the product

The business case phase is a critical data collection phase in which the product is defined, justified, and a project plan developed. It is in this phase where the team develops and uses financial models to evaluate the impact on the business case of using VRPs. Under traditional business models based in the assumption of 'ownership', corporate responsibility for the product is typically considered up to the point at which it leaves the production facility; after which, all things related to the product are left to the new owner: the customer. The value that is accounted for is reflected in terms of profit margin.

However, there are innovative business models already in the market place which are much more supportive and enabling of circular economy (refer to Section 8.2.1). Use-oriented PSSs offer a new approach to more sustainable business models, offering opportunities to enhance the competitiveness of the business while achieving additional sustainability objectives at the same time (Tukker 2004, 2015a, Beuren, Ferreira, and Miguel 2013). For example, the producer may retain the ownership of the product, and the business case value would then instead be based on regular fee-based revenue that the customer pays for the service provided, such as pages printed, or miles driven (e.g. leasing, renting, and pooling models) (Tukker 2004). Inherent in this approach is a different perspective of the product in question: rather than a business case focused on short term cost minimization, profit maximization, and the accomplishment of sales objectives and targets, the business case may instead be informed by an incentive to consider the full life-cycle of the product, rather than just cradle-to-gate; it may also be informed by an incentive to retain asset value, design the product for longevity, and potentially to design the product for additional usage cycles through VRPs.

8.2.2.3 Product design

In this phase, product concepts are developed from proof-of-concept technologies into product designs, manufacturing approaches, and systems-level prototypes that are fully functional and may lead to full commercialization. Design strategies must, of course, leverage knowledge and tools that support the creation and integration of circularity-enabling product features and technology systems. As the penultimate phase in the product development process, however, the design stage is certainly too late a point at which to *begin* considering product circularity. In this sense, product design processes absolutely depend upon thorough upstream integration of and investment in circular considerations in order to create products and systems that may actually achieve the desired circularity and value-retention.

Ultimately, designs must be translated into prototype products and systems, which must be fully tested under the actual economic and environmental conditions of the intended deployment context. Comprehensive plans and simulated models for manufacturing, financing, introducing, and distributing the product can then be designed and developed based on these prototypes. In this, design, development, and testing stages serve primarily to validate the entire project—from the product to the manufacturing processes to the economic viability and customer acceptance in competitive markets. A product's circularity, then, is not a *function* of its design, but rather a systemic effect, caused by preceding influences in Phases 0 through 3 and finally only *enabled* by design.

8.2.3 Designing for product circularity

It is thus clear that enabling a more circular industrial economy is a systemic endeavor that begins long before product developers create physical product designs or functional prototypes. Given the potential risk of unintended trade-offs between design principles, a systems-perspective is essential: where a high-level of modularity and integration may help to reduce part count and/or better organize product sub-systems, these design paths may constrain future potential for upgradability within a VRP process, or even constrain recyclability at EOL.

Many of the formative business and market decisions that ultimately drive the adoption of a circular philosophy require supporting decision-makers with the knowledge that circular industrial and economic models are indeed available, accessible, and technically feasible. To this end, it is necessary to discuss the principles by which products and systems may be designed for circularity not just in Phase 4, but throughout the entire product development process across three major principles— (1) creating value, (2) protecting and preserving value, and (3) easily and cost effectively recovering value—under which different approaches to designing products for a circular economy may be explored. These principles along, with corresponding design approaches, are illustrated in Figure 85.

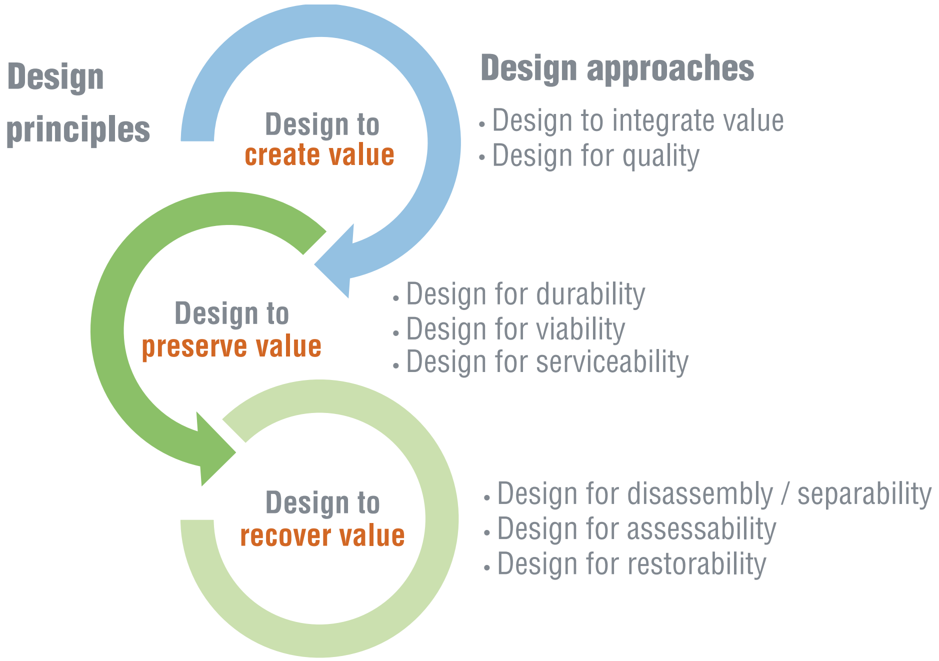

Figure 85: Design principles for VRP products

8.2.3.1 Creating value

Priem (2007) defines value creation as “innovation that establishes or increases the consumer’s valuation of the benefits of consumption. When value is created, the consumer will either (1) be willing to pay for a novel benefit, (2) be willing to pay more for something perceived to be better, or (3) choose to receive a previously available benefit at a lower unit cost, which often results in a greater volume purchased.”

The total value created can be viewed as the sum of all the enhancements and efforts that are embedded in the product through the process of conceiving, making, and providing the product to the customer plus any additional perceived benefits by the customer. It is a sum of all the effort exerted to create the product including the intellectual capital invested in inventing and refining ideas. It is also a measure of the effort required to harvest raw materials from nature in diluted and unorganized forms, such as mineral ores or crude oil, and to convert the raw materials into usable intermediate materials, such and metal sheet or bar stock, or pelletized plastic resins. The value also includes the materials and effort to develop the manufacturing processes that convert the usable intermediate materials into higher form parts and assemblies, and the investment required for part and assembly tooling. Finally, the embedded value includes the cost of business practices, marketing, infrastructure, and logistics used to get the product to the consumer.

VRPs have advantages over recycling because they recover value beyond just the materials. VRPs can recover the entire function of the part or assembly. Inherently, VRPs then retain the unique technological function and the resources used to invent and manufacture the part or assembly. VRPs can also recover the engineered plastics, carbon fiber, laminates, and alloyed metals that are not typically recovered by recycling.

Accordingly, product design must consider product circularity as a specific requirement in order to maximize the ability to recover value. This can be accomplished by integrating product functions, concentrating the value into parts and assemblies that are easy to recover, and assuring that the product meets high quality standards. The collection of high value-added products through VRPs is therefore generally much less costly than fabricating new products from virgin materials.

8.2.3.1.1 Design to integrate value

A similar principle includes that assemblies should be designed to be multifunctional with a high level of integration to minimize part count. This consolidation reduces the overall number of parts, reduces the assembly and disassembly complexity, and enables a modular structure further improving access to systems and components needing further processing (Sa'ed and Kamrani 1999). This approach is also referred to as Design for Modularity (DfM) and is a common design approach in leasing-focused business models for industrial digital printers (Agrawal, Atasu, and Ülkü 2016). However, when applied to consumer electronics, the upgradability of products can result in conflicting outcomes in economic and environmental benefits related to consumer interest, competitiveness, and consequent demand (Agrawal, Atasu, and Ülkü 2016, Ülkü, Dimofte, and Schmidt 2012). In addition, the nature of the product and product architecture can affect whether the modular upgrade results in superior or inferior environmental performance relative to the OEM New versions (Agrawal and Ülkü 2012).

Where modularity is an appropriate design strategy, products should be designed with standardized parts allowing reuse in other models or subsequent models, maximizing the demand and outlets for reused, refurbished, and remanufactured parts. Finally, many manufacturers use VRPs to extend their ability to deliver products for several years after the main assembly line has been decommissioned. Examples include auto parts such as engine control units or alternators in which these products are required to support warrantee claims years after the main production has been shut down.

8.2.3.1.2 Design for quality

Designing a product for VRPs also requires setting high standards for the quality of the original product. The value for which customers pay is ultimately in the function a product performs. As such, developers must design VRP products to retain their value over multiple life cycles, seamlessly fitting back into the production line and meeting the original tolerances despite part-to-part variation.

Designing-in quality beyond what is required to satisfy minimum customer first-use expectations will improve the quality of products recovered at EOU for reuse in VRPs, and, in turn, help to reduce costly rework, sorting, scrap, and requalification costs that might threaten the economic viability of VRPs (Anderson 2004, Shimbun 1989). Maintaining product viability in these markets is both economically and environmentally preferable to simply recycling intermediate materials and can enable more systems-level circularity and profitability than material reclamation alone. Based on the embodiment of high value at product EOL, the initial investment in tight product tolerances, quality tooling, durable materials, and functionally flexible design strategies can pay off with high collection yield.

8.2.3.2 Preserving value

Designing to preserve the product value starts with making the product durable to be able to last multiple lifecycles, surviving the potential for both physical and emotional obsolescence (den Hollander, Bakker, and Hultink 2017). This includes selecting materials appropriate to resist the environmental conditions that cause wear, corrosion, and fatigue. This principle also includes designing the product to be viable for future life cycles, designing around requirements that are likely to change, such as aesthetics, energy efficiency, or functional performance. Preserving value also means enabling appropriate service and maintenance preventing the product from failing prematurely, and to be forward looking and proactive when designing to be compliant with government regulations.

8.2.3.2.1 Design for durability

Products that are targeted for VRPs, need to be durable and built to last the intended life cycle. The product durability needs to match the intended life, and not be overdesigned (Keoleian and Menery 1993). The design for durability approach considers the product's longevity, reparability and maintainability. Many products are exposed to harsh environments and environmental stresses such as: solar radiation, thermal cycling, mechanical bending, mechanical friction, impact, or chemical degradation. Preserving the product's value includes designing-in durability so that the product resists material degradation, corrosion, and wear. This includes selecting the appropriate material and may include material hardening or corrosion resistant coatings to extend component life. It also includes avoiding materials that degrade with age, exposure to environmental conditions, or exposure to chemicals such as the ones used in cleaning processes. Products can also receive damage not only during use, but also during collection and processing (Bras and Hammond 1996). Designing to preserve function may therefore also include shielding and protection against damage during use and collection. If degradation cannot be avoided, then larger components can be designed with replaceable wear surfaces to minimize the size of the components to be remanufactured or replaced. Another design alternative could be to use sacrificial parts as wear surfaces to protect the more valuable components. Many OEM producers of HDOR equipment incorporate this design approach, with scheduled maintenance and refurbishment procedures scheduled at the point-of-sale of the original OEM New product.

8.2.3.2.2 Design for viability

Preserving value also assures that the design is viable at the time of collection. Design viability refers to how long a product is expected to occupy a competitive position in the marketplace. Product designs in stable technological domains can remain viable for long periods of time. For example, basic diesel engine platforms for over the road trucking and rail transportation remain relatively unchanged for many years. However, many products have requirements that are likely to change over their life cycle; such as aesthetics, energy efficiency, technology integration, software, or functional performance. Preserving the product's value for multiple life cycles may therefore require that the product be designed to consider the consumer-product relationship (den Hollander, Bakker, and Hultink 2017), to ensure viability at the time of collection, either through timeless design or through upgradeability.

There are a number of strategies that can be used to increase design viability when rapid technological obsolescence is an issue. Computer servers are an excellent example of a design for upgradeability (DfU) which is a subset of the design for viability approach used to extend the product's useful life. A survey of the IT market by the International Data Corporation (IDC) Research revealed that replacing a server after three years of operation will have a return on investment (ROI) of less than one year as compared to continual operation of current equipment, based on the efficiency, reliability, and performance gains of the new equipment (Scaramella et al. 2014). Additionally, the cost for power and cooling grew eight times as fast as the server purchasing costs, and the costs for maintenance and management grew four times as fast as the server purchasing costs enhancing the effects of the efficiency gains (Scaramella et al. 2014). The increasing difference in cost of operating the existing design over new demonstrates how a product can lose viability over time.

This rapid change in performance is an opportunity for manufacturers to design in features to enable upgrades to extend the life and viability of the product. Server manufacturers have taken this principle to heart and have designed many of the components with the demonstrated history of improving performance to be "refreshed" or upgraded such as: memory, mass storage devices, network connectivity, processors, and power supplies extending the service life of the product and reducing the need for wholesale replacement.

Other products, such as the PuzzlePhone,[25] are designed with various technology subsystems concentrated in modules so that entire subsystems with expiring function can be replaced or upgraded preserving the value of the remaining product. This type of "upward remanufacturing" (Nasr and Thurston 2006) or "adaptability" (Li, Xue, and Gu 2008) enables the remanufactured product to be incorporated into a new or "next generation" system (Bras 2007, 2010).

It is also important to design products in order to meet potential future regulations that may be enforced at the time the product is recovered for reuse in VRPs. This includes avoiding potentially hazardous substances and materials in the product, checking for human health, safety, and environmental product aspects, and selecting lower impact materials. Another way to be forward looking is to evaluate the regulatory trend lines on the metrics of interest. Regulations such as automobile emissions or equipment energy efficiency continue to tighten as the product technology catches up with the current requirements. A forward-looking product designer may try and project where regulations are going and design to meet the future regulation rather than just meeting the regulations currently being enforced.

8.2.3.2.3 Design for serviceability

Predictive processes have been a mainstay of maintenance for decades; the Reliability Centered Maintenance process (RCM), for example, was first published by United Airlines in the late 1970's. RCM introduced the difference between potential failures—identifiable conditions indicating that a complete failure is either about to occur or is in the process of occurring—and functional failures in which the product can no longer perform the required function.

However, the advancement and increasing complexity of industrial technologies compels maintenance systems to extend beyond regular testing and maintenance and enable continuous performance management, component condition monitoring, and prognostic analysis as a means of ongoing equipment support. Developments in these technology areas promise not only to maximize efficiencies and extend product life, but also to minimize downtime and interruptive assessments that can cost valuable time and energy. Collectively, technologies that enable this kind of advanced monitoring are termed Prognostic and Health Management (PHM) systems.

Prediction methodologies in this space are widely underdeveloped, and while the potential benefits of such systems are immense, many industrial users rely on products and equipment that supports only limited performance monitoring and prognostic systems. In this respect, circular system across multiple industry sectors stand to benefit enormously from the development of technologies and methodologies that allow circular systems to be integrated with advanced PHM capabilities. Resultant benefits in product life extension passed on to users will subsequently minimize recurring capital costs of maintaining, repairing, and replacing equipment, and will also allow for improvements in energy efficiency, as well as reductions in downtime and production interruptions.

8.2.3.3 Recovering value

Designing to economically recover the product value starts with being able to accurately assess the value of the product when it is returned so that decisions can be quickly made on the next steps required in the process. This may include designing in visual indicators to help improve the speed and accuracy of visual inspection, or it may include more sophisticated sensor data. This principle also includes designing the product so that it can easily be disassembled and separated, both to access and remove valuable components, and to enable further processing. This principle includes designing appropriate fastening and joining methods, access, and ease of handling. Finally, the design should enable any required processing to bring the product back to the required standards. In many instances, this includes cleaning, material restoration, functional restoration, and re-assembly.

8.2.3.3.1 Design for assessability

Fast and accurate assessment of the products functional state and level of degradation at the time of recovery is essential for enabling efficient and appropriate decisions about the effort necessary

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[25] (http://www.puzzlephone.com)

to restore additional life and value. In most cases at the EOU some level of functional degradation or failure has occurred. The design for assessability approach is to enable the functional degradation to be more easily detected. This includes designing the product such that the components can be inspected in the least number of disassembly steps as possible.

As such, the design team should determine if the functional failures can be detected at the system level or if some level of disassembly is required. For example, there may be some system level precursors to failure which may be used to determine the level of remaining function. Precursors are measurable metrics that will change as the part or assembly ages (vibration, heat, color, wear length, resistance, etc.). Additionally, the failure mode may have a wear out pattern. The product may therefore be designed with a wear surface that changes color to indicate the depth of wear to improve the speed and accuracy of visual inspection. The highest form of assessment is to design a "smart part" with sophisticated sensors that are capable of tracking and recording the product usage (e.g. operating hours, environmental conditions) and can relay this information during recovery enabling a quick assessment of remaining life (Bras 2007, Charter and Gray 2008).

Additionally, it is necessary to understand if the product has already been through a VRP (reused, refurbished, or remanufactured). All parts and modules should therefore be designed to be marked or tracked so that the number of cycles can be identified. This documentation and tracking mechanism should be available from cradle to grave and could include product documentation, markings or labels, bar code identification, or radio-frequency identification (RFID) technology.

8.2.3.3.2 Design for disassembly / separability

Design for disassembly (DfD) is a design approach that considers the future need to disassemble and separate a product for VRPs. This design approach starts with structuring the product to make the most important components accessible and not buried within the assembly. In the context of VRPs, components are "important" if they require processing, such as cleaning, upgrading, material restoration, functional restoration, collection, or replacement, and need to be removed from the product. This approach also looks to create a modular structure, or co-locate or group similar materials, parts that wear out, or parts with the same technology in close proximity so that they can be simultaneously and easily separated, replaced, and recycled. Also, the approach looks to design components to be multifunctional to reduce the overall number of components since fewer components make disassembly easier and faster.

Design for disassembly includes designing appropriate fastening and joining methods, access, and ease of handling (Boothroyd and Alting 1992, Bogue 2007, Bras 2007). Common practice include avoiding permanent fastening techniques such as welds, adhesives, heat staking, crimping, or rivets between modules or components that will be replaced, remanufactured, or recycled. These permanent fastening techniques increases the disassembly time and cost. In addition, joint designs should consider all VRP characteristics such as load conditions, assembly and disassembly efficiency, operating environment, cleaning, and overhaul and maintenance.

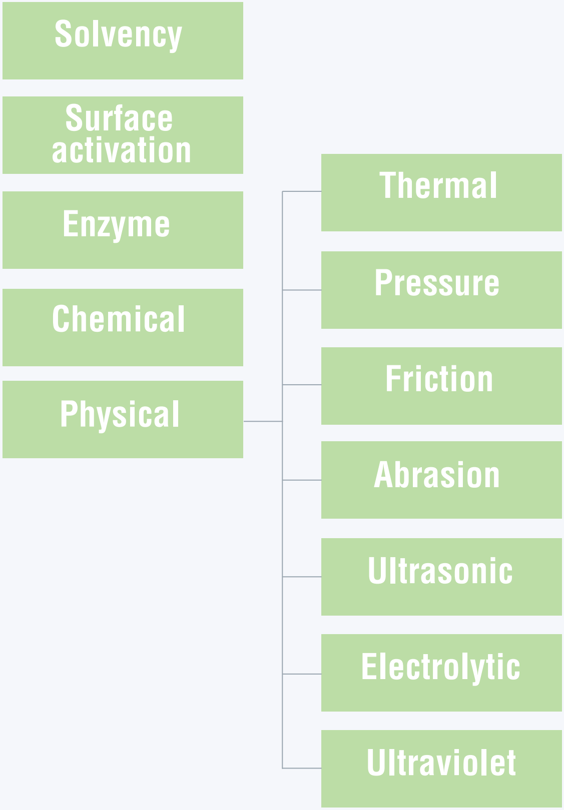
8.2.3.3.3 Design for restorability and cleaning

After the product is assessed and separated, the design should enable restorative processing to bring the product back to its original standards of condition and performance. In the case of remanufacturing-focused design literature this is sometimes referred to as 'remanufacturability', or design for remanufacture (den Hollander, Bakker, and Hultink 2017). In so doing, a new, valuable lifecycle may be created from the product without the loss of the value embodied in the processes that built it or the materials from which it was constructed. The ability to recover value implicitly depends on how well the elements that constitute that value—the parts and materials that perform the product's function—were preserved, how easily they can be accessed, how quickly they can be evaluated, how simply they may be processed, and how well they can compete with contemporary products once restored (den Hollander, Bakker, and Hultink 2017). And in this sense, a product's restorability is not so much an independent characteristic as a natural function of all the design factors that precede.

In many cases, however, products may be designed with all the preceding characteristics – from quality and reliability to regulatory compliance – without ever being explicitly designed for circularity. What separates a durable design from one that is truly circular, is the ability to endure restorative processes that products designed for a conventional linear system often neglect to consider might ever be applied. Beyond functional restoration and reassembly, such processes primarily include unique cleaning methodologies and material restoration techniques that can, in some cases, even enable products to perform better than their contemporary virgin counterparts (Ijomah 2009, Bras 2007).

Cleaning—a generic term used for the removal of a contamination or pollution from a component or assembly—occurs throughout refurbishment and remanufacturing processes and is sometimes repeated in several stages. Cleaning may be a part of incoming inspection, enabling assemblies to be assessed and inspected, or may be done after disassembly to enable individual components to be inspected and sorted. Cleaning may also be done prior to reconditioning to prepare surfaces for restoration, or simply after reassembly to prepare the entire product for paint and packaging.

The technical challenge is that the type of contamination (e.g. grease, biologic, dust, rust, paint), the types of surfaces (e.g. rough, smooth, blind corners), the sensitivity of the surface to cleaning processes (e.g. water resistant, solvent resistant), and the required level of cleanliness (e.g. paintable, particulate free, non-volatile residue, hygienic) can vary with industry and level of use. The fundamental concept of cleaning can be broken down into the basic forces used to remove contamination. These categories of cleaning forces are described in Figure 86 (Liu et al. 2013).



Modified from (Liu et *al.* 2013)

Figure 86: Categories of cleaning force

Not only is the diversity of contamination an issue, industry is also challenged with the environmental responsibility of cleaning products and systems. All cleaning processes must effectively bring the recovered product to a useable or new-equivalent state. In effort to maximize the environmental benefits of VRPs, "Green Cleaning" processes must meet required cleaning function cost effectively, as well as perform the cleaning process in an environmentally preferable manner.

Given that cleaning is generally required, products should be designed to withstand the cleaning processes that will be specifically used to recover the value. This is done through an understanding of the aggressiveness of the cleaning process (time, temperature, chemistry, agitation) and selecting product materials that will be stable, will not react, and will resist damage during the cleaning operation. Products should also be designed with an understanding of the contamination particle to part surface attraction forces and then designed with the best materials or surface treatments to minimize these forces. Product geometric features such as corners, ribs, holes, and cavities should be designed to minimize contamination accumulation or enhance the cleaning operation. The product design may include features such as drainage holes, or removable traps to maximize the cleaning effectiveness. Finally, the product should be designed to shield or protect high value modules or components from environmental contamination to minimize cleaning requirements.

Like cleaning, material restoration is a process that is unique to the circular model. A product's ability to adapt to different technologies in this space is therefore an imperative design consideration even in the earliest stages. Material restoration through advanced additive manufacturing technologies is becoming a particularly important consideration. Over the last decade, the industry has seen significant advances in additive manufacturing technologies which have led to promising new circular applications such as material surface restoration and recoating, improved surface properties for wear resistance, increased corrosion resistance, part repair, improved mechanical properties, and complete new or replacement cost-effective on-demand part production. It is also likely that this technology will be transformative in the service and maintenance sectors, where on-demand part production will eliminate the need for production overrun and warranty support inventories.

Additive manufacturing creates or modifies parts by adding materials in layers with each layer consisting of a thin cross-section of material. Various additive manufacturing technologies differ by the materials that can be used, how the material layers are created, and how each layer is bonded together. These technology differences impact both the accuracy and material and mechanical properties of parts, as well as machine size, cost, and processing speed.

Additive manufacturing can fundamentally change the way products are recovered by restoring worn components and surfaces back to the specified dimensions. Directed Energy Deposition (DED) technologies such as laser engineered net shaping (LENS), direct metal deposition (DMD), laser consolidation (LC), laser cladding, or plasma transferred wire arc (PTWA), use thermal energy (e.g. laser, electron beam, or plasma arc) to melt and deposit material onto specified surfaces, where the material solidifies. These processes can be used with either powders or wire, with a range of polymers, ceramics, and metals. Other technologies such as kinetic or cold spray ballistically impinge non-molten particulates upon a surface at supersonic velocities to form a coating.

Part of designing for circular processes is to understand which parts and materials are going to degrade, and if these areas cannot be improved with design as discussed in previous sections, then design these parts with the ability to restore the material and surfaces to the desired specifications. Additive manufacturing techniques and machines have limitations on materials, part size, and part orientation, and accuracy. Design needs to consider these limitations and plan for material application and potential secondary operations. Additionally, planning for additive manufacturing techniques can change the way parts are initially designed. For example, PTWA is often used to remanufacture and coat aluminum engine block cylinder bores, eliminating the need to design in heavy cast iron sleeves.

8.2.4 Appropriate use of VRPs

As the more intensive VRP processes, comprehensive refurbishment and remanufacturing may not always be the optimal strategy within a circular economy, and there are extensive findings in the literature affirming that the appropriateness of full service life VRPs, in particular, must be evaluated on a product-by-product basis (Matsumoto, Nakamura, and Takenaka 2010, Schau et al. 2011, Östlin, Sundin, and Björkman 2009, Gutowski et al. 2011).

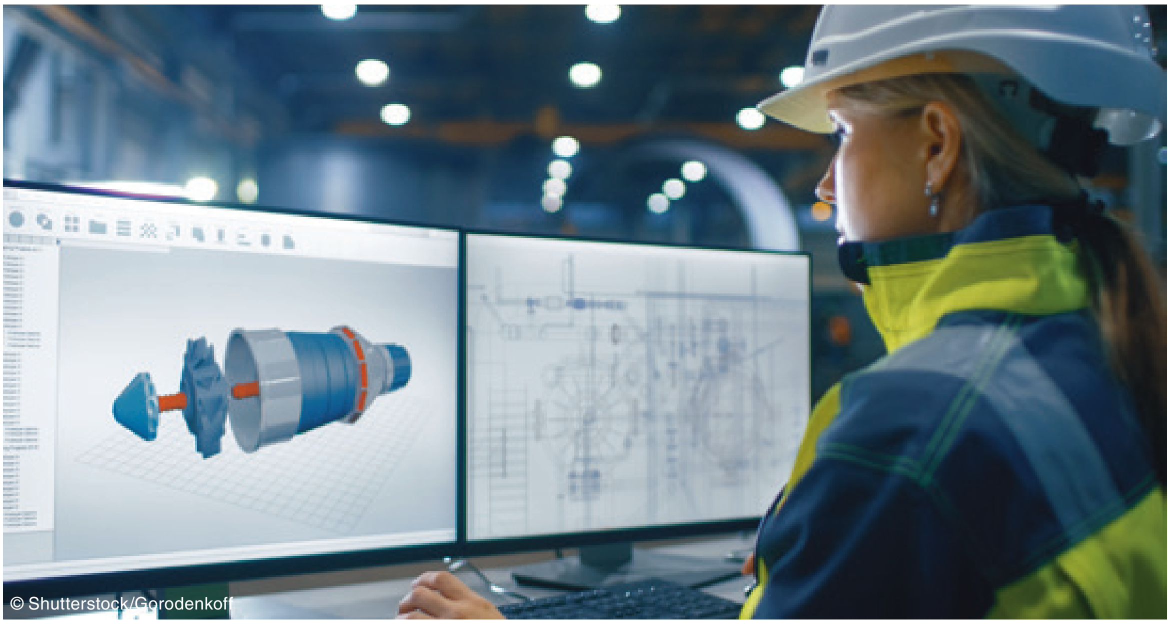
Extending the proposed categorization by Gutowski et al. (2011), product characteristics and conditions that are needed to optimize the decision to engage in VRPs, including remanufacturing, must include: the nature of the product and its sub-system components; its use-phase energy requirement and energy efficiency; the residual value that can be retained in the system by keeping the component parts intact via remanufacturing; and the material composition of the product, which can affect extraction, processing and manufacturing-phase energy requirements when considering multiple product service lives.

The interaction between the product and its sub-systems is an important aspect of this approach. For many products, it is expected that some sub-system components may last for only a single planned service life. In some cases, sub-system components may require replacement during the planned service life due to faster degradation from wear-and-tear, or the technological obsolescence of software. In many of these cases the unaffected chassis and other mechanical components or sub-systems of the product may still offer competitive functionality and have retained significant value.

8.2.4.1 Optimized VRP decision framework categorization

Please note that the following discussion emphasizes remanufacturing within a VRP decision framework, in order to pursue maximized value-retention as the priority of a circular economy. Implicit in this approach is that *where a product/component may not be suitable for remanufacturing, the other VRP options of refurbishment, repair, and arranged direct reuse remain viable value-retention strategies. As remanufacturing sets the highest-level of production requirement of all the VRPs, other VRPs can be considered for appropriateness on an individual basis, relative to this standard.*

This concept is clarified further in Figure 87 which describes four different example products to support the framework categorization. Example products A (e.g. medical imaging equipment), C (e.g. industrial digital printer), and D (e.g. mobile phone) reflect products with more complex sub-systems. Example product B (e.g. office furniture) reflects a product with a relatively simpler sub-system. These examples are provided to highlight the considerations that business decision-makers should assess when evaluating whether to engage in remanufacturing and other VRPs.



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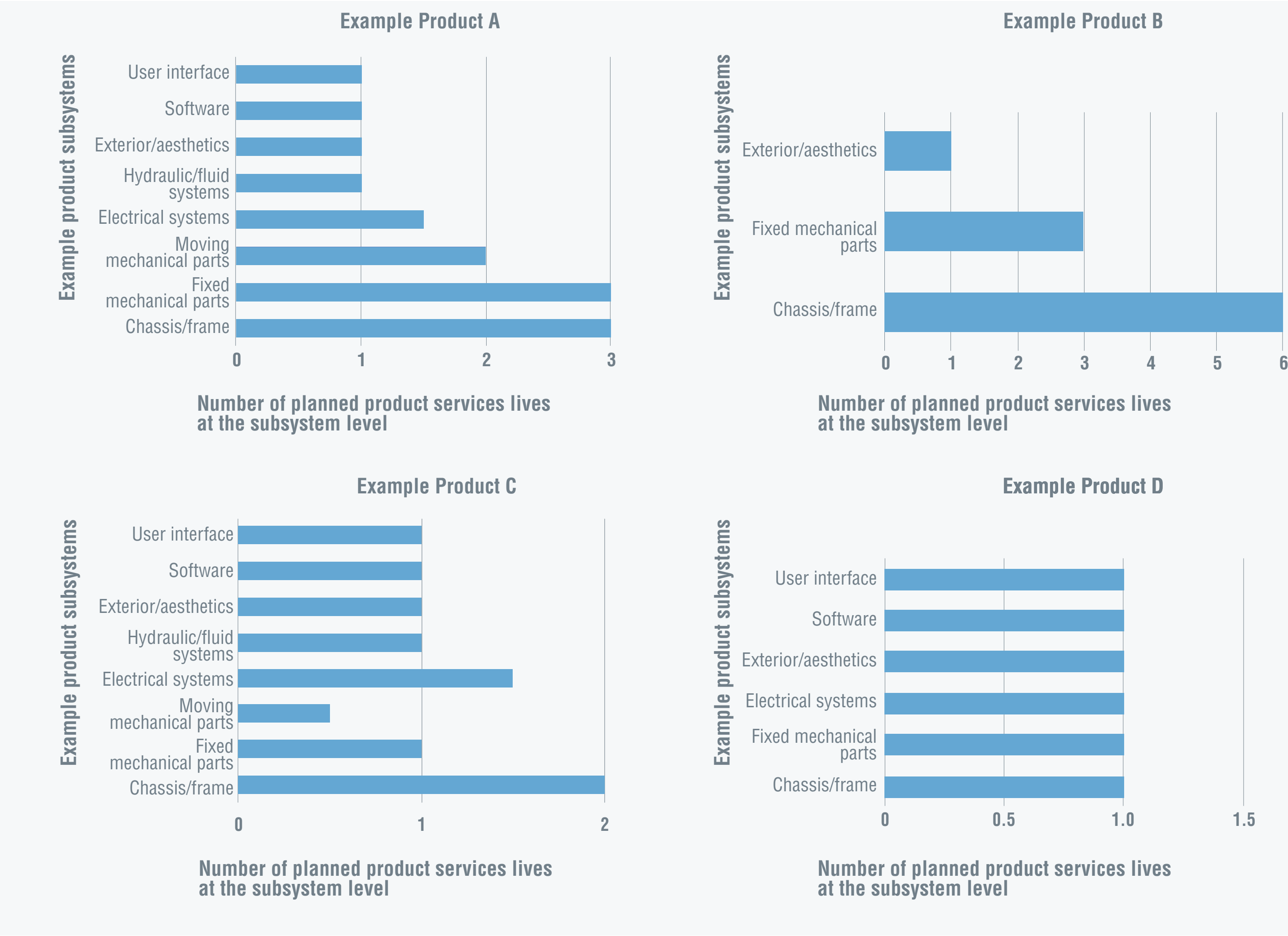

Figure 87: Planned service lives of product sub-systems for example products (A, B, C, and D)

Some complex product sub-systems have the potential for multiple full service lives via VRPs (e.g. moving mechanical parts, fixed mechanical parts, and chassis/frame) (refer to Example Product A in Figure 87). It is important to consider whether these multi-service life sub-systems constitute significant retained value, in the form of avoided new material requirement. Other considerations should include whether the retained value of the remanufactured product exceeds the investment required to remanufacture and return it to as-new condition, assuming repair and/or replacement of single-life sub-systems (e.g. user interface, software, exterior, and fluid systems).

In other cases, the product sub-systems are more simplified, with the majority having the potential for multiple full service lives (refer to Example Product B in Figure 87). Given that the required investment appears to be largely aesthetic in nature, provided that the investment required to bring the product back to as-new condition does not exceed its retained value, remanufacturing appears to be a viable option.

Some products present very complex considerations for remanufacturing decisions, as a result of the number of parts, and/or the number of linkages required for the circular system to function effectively (refer to Example Product C in Figure 87, and refer to Section 8.5 for additional discussion). As the majority of product sub-systems last only for the first service life, and some may require a degree mid-life repair/maintenance, remanufacturing may not seem like an ideal investment. However, the chassis/frame can still be recovered and incorporated into a remanufacturing process, provided that the current versions of the product still use the same design. For product lines that offer upgraded features and enhancements with every new version, remanufacturing using the original chassis can reduce the environmental and economic impacts of the product, while also enabling upgraded performance potential through replaced user interface, software or electrical systems.

Finally, some products and sub-systems are designed to only last for a single planned service life (refer to Example Product D in Figure 87). In this case, none of the products sub-systems retain value after the completion of the first planned service life; the short life of the chassis/frame also negates much of the potential for upgrading software and user interface technology through remanufacturing. Refurbishment to enable short-term extension of product functionality (only) may be possible.

Based on these conditions and considerations, the following groups are proposed and applied for the purposes of this study. These are summarized further in Table 21.

- **Group 1 – Remanufacturing-appropriate (example products A and B):** Refers to products which, for the relevant time-period being considered, have not generally undergone design modifications that significantly affect the product's use-phase energy requirement, or that significantly affect the material composition of the product. Design changes have not resulted in improved use-phase energy efficiency, and/or have resulted in the replacement of lower energy-intensive material/components with higher energy-intensive materials/components. In addition, the use-phase of the product has not overly degraded or diminished the functionality of its primary components. There must be sufficient value retained within the functional form of the product that additional investment into remanufacturing does not negate the potential for profit.

- **Group 2 – Not remanufacturing-appropriate (example product D):** Refers to products which, for the relevant time-period being considered, have generally undergone design modifications that significantly affect the product's use-phase energy requirement, or that significantly affect the material composition of the product. Where design changes have resulted in improved use-phase energy efficiency or have resulted in the replacement of lower energy-intensive material/components with higher energy-intensive materials/components, these products are not generally appropriate for remanufacturing. Alternately, the use-phase of the product has overly degraded and diminished the functionality of primary components, requiring extensive investment to return them to as-new condition. In this case, the investment required exceeds the value of the product both in the sense of the retained value of the functional form, as well as the profit-potential of the product in the market.

- **Group 3 – Complex, potentially remanufacturable (example product C):** In many cases, modifications to design may result in a complex outcome of associated life-cycle energy requirements. For example, a design enhancement that increases the share of higher energy-intensive materials/components may also be accompanied by a use-phase energy efficiency improvement. In these cases, a more comprehensive assessment of the retained value of the product, as well as the costs and benefits of engaging in remanufacturing are needed before an informed business decision can be made.

For the purposes of this study, all product examples selected for the case study are considered to belong to Group 1 or Group 3, as remanufacturable products. This approach was used to enable comparison across the range of VRPs, to demonstrate the product-level opportunities, as well as aggregate economy-level insights about VRPs within the context of circular economy.

Table 21: Summary of remanufacturing-appropriate product categories

Consideration	Group 1: (1) Reman-Appropriate	Group 2: (2) Not Reman-Appropriate	Group 3: (3) Complex, Potentially Remanufacturable
Example product	**A and B**	**D**	**C**
Product design modifications (over the time-period being considered)			
Significantly improve use-phase energy-efficiency[26]	No	Yes	Potentially
Significantly increase share of high-energy materials composition	No	Yes	Potentially
Change the chassis/frame	No	Yes	Potentially
Product and sub-systems			
Chassis/frame has more than one service life	Yes	No	Potentially
Retained value exceeds investment to bring to as-new condition	Yes	No	Potentially
Use-phase has not overly-degraded functionality of primary components	Yes	No	Potentially

As demonstrated, remanufacturing is clearly not appropriate for all products; the decision to engage in remanufacturing and/or other VRPs must remain with decision-makers and strategists, with consideration of the costs and requirements unique to their product-system. From this perspective, design priorities to facilitate the effective employment of different VRPs can be pursued: for example, for products that are expected to become obsolete due to functional, psychological, compliance, or economic factors in a short time-frame should not be designed for remanufacturing. Instead other design priorities including serviceability, modularity, and upgradability should be emphasized to facilitate other VRPs including repair and refurbishment.

8.2.5 Design strategy conclusions

Products *can* be designed for circularity, but such designs can only be effective if product developers identify circularity as central to the broader business and market objectives underlying the purpose for product development.

The entire system of product development must be designed to consider circularity, resource efficiency, and regenerative value. To accomplish this, product developers must incorporate three essential concepts into product and system design: the need to create value, protect value, and recover value, all in cost effective ways. In this context, product quality, durability, reliability, separability, assessability, and restorability can replace inexpensive materials, low-cost labor, and high-volume sales as the indicators of value. Metrics for resource efficiency, product utility, and environmental impact must supplement discussions on the cost of quality and return on investment.

Optimizing design for circular economy requires serious consideration of the nature of the product and product-system: not all products are appropriate for full service life VRPs, and in such cases other design principles that facilitate

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[26] Adapted from Gutowski, Sahni, Boustani, and Graves (2011)

service-life completion and extension through partial service life VRPs must be incorporated. This highlights the fact that there are inherent design trade-offs that must be considered in order to avoid unintended consequences of design decisions that can interfere with the value-retention potential of VRPs, and ultimate recyclability of the product at EOL.

Finally, it must also be noted that every product, no matter how well it was designed for VRPs, will eventually cease to meet the required function. The final disposition of all products should consequently be considered during product development and therefore, each part should also be designed to allow for efficient recycling opportunities.

8.3 The mechanics of a system designed for value-retention processes

The reality is that the designers of future VRP systems will not have the luxury of having a 'clean-slate' on which to start. Existing market and social norms must be taken into account, and accommodated in the short-term, and adjusted through strategic interventions over time. In industrialized economies, existing production, logistics and collection infrastructure are well-entrenched, and the business case for overhauling these systems in pursuit of maximum VRP efficiency alone may be difficult, thus requiring an incremental approach. In contrast, many non-industrialized economies face the challenge of strategically building-up production, logistics and collection infrastructure where none currently exist. There is significant pressure on non-industrialized economies to avoid the sustainability-related pitfalls of industrialization by leap-frogging over less efficient production systems and technologies (Cranston and Hammond 2012, Allen and Thomas 2000, UNEP 2011, Hammond 2006).

Taken at the aggregate, these types of undertakings appear daunting and very costly in the short-term. However, true to the value-retention objective of the circular economy, this does not necessarily need to be the case.

There are many existing attributes and aspects of current production systems that can be leveraged in the pursuit of a system designed for optimized VRP production. While every economy faces different challenges and barriers to VRPs, each also has an already established relationship with the key aspects of the VRP system that can inform a policy and implementation strategy. For industrialized and non-industrialized economies that currently engage in diversion and collection to recycling markets, these systems can be adapted, formally or informally, to include diversion to secondary markets for reuse and VRP production, and can include new value-chain members that can help to facilitate efficiency within global flows of EOU products for VRP inputs. For industrialized and non-industrialized economies that do not engage in collection or reverse-logistics, expertise in current forward-logistics systems (e.g. trade, sales, and distribution) can be leveraged to improve overall logistics system utilization and productivity, alongside the application of Best Practices that may have already been established for collection programs in other jurisdictions. For economies with technological barriers affecting producer capacity, the learnings about technology transfer enabled through improved access and trade in other products categories can be employed to the benefit of VRP production. Further, the vast body of knowledge about consumer behavior, innovation diffusion, and effective marketing that have been employed in the past to guide consumers away from less beneficial products (e.g. CFC-containing aerosols) can be utilized.

It is important to note that although non-industrialized economies may face technological and infrastructure barriers that inhibit the scale-up of full service life VRPs in the short-term, the broader system elements described within this assessment can facilitate and enable improved efficiency and opportunity even within partial service life VRPs of repair and direct reuse.

Some additional key insights related to the mechanics of a system designed for VRPs and to enable circular economy are outlined in the following sections.

8.3.1 Value-retention processes are a gateway to recycling

There is a common perspective that VRPs may detract from, or compete against recycling; in fact, all VRPs and recycling are essential within the context of a circular economy. A hierarchical perspective on value-retention is useful: where *VRPs* ensure that both material value *and* functionality are retained within the product, once functionality has degraded it is the *recycling* system that ensures material value is still retained within the broader system.

An example of how VRPs can create a gateway to recycling is in the case study of industrial digital printers, where the nature of VRPs and recycling can be observed. The structural steel form of the industrial digital printer comprises the majority of product weight and does not typically degrade through normal use. These steel components contain recycled content, and are designed to be strong, durable and robust for multiple life cycles through VRPs. First, and by design, the re-circulation of industrial digital printers through VRPs ensures that a significant share of the materials in product (min. 90 per cent by weight) can be retained in the original functional form, over multiple useful lives. This retains the value of the product and component materials over an extended period and creates additional economic value for both producers and customers. Then, once the material value has been degraded sufficiently over time that VRPs are no longer able to create value (e.g. product technology is no longer relevant or valued), the reduced but still substantial value inherent in the structural components of the industrial digital printer can be retained in the system through appropriate recycling activities.

At the same time, because the industrial digital printer has been designed for VRPs and multiple life cycles, there is new opportunity for more sustainable business models (e.g. product-service basis and/or leasing), and for the establishment of efficient product collection infrastructure. Because of this system-wide approach to VRPs and product circularity, for certain producers of industrial digital printers, a very high product collection rate for VRPs is enabled, and in turn, a much more significant diversion-to-recycling rate as well. A high-level example of the potential for refurbishment and remanufacturing to act as a 'gateway' to improved recycling is described in Figure 88.

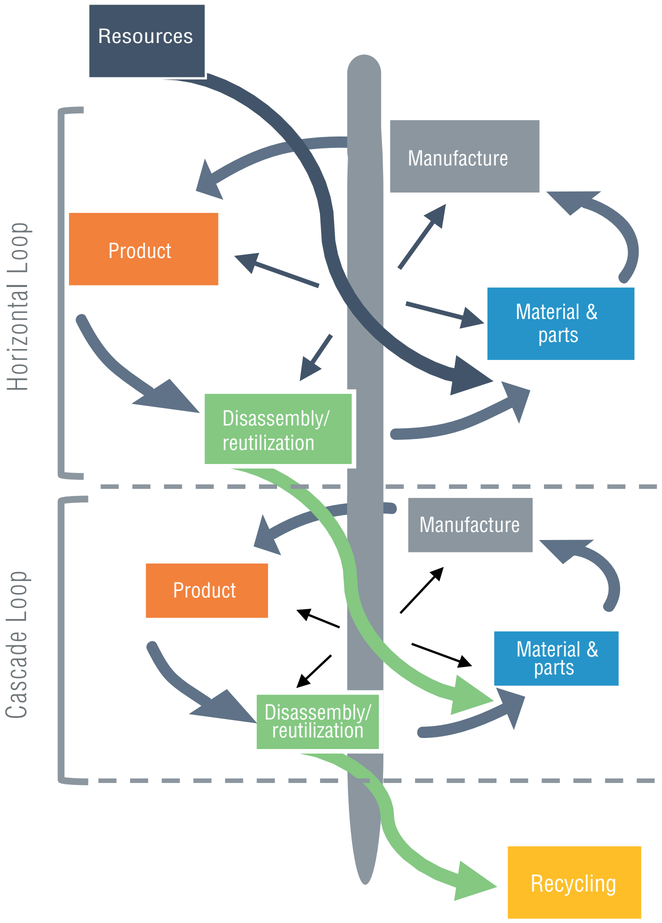

Figure 88: Value-retention process as a gateway to recycling

If the industrial digital printer was recycled immediately at the end of its original life, the material value would still be retained within the system, but the additional benefits of offset process energy requirement, process emissions, and economic value of the product's functional form would be lost. Instead, as part of a set of EOL options, VRPs and recycling can be strategically used to maximize value retention over an extended period and multiple service lives, thus increasing the efficiency with which the circular economy retains value overall.

From a value-retention perspective, reliance on recycling alone ultimately leads to lost value for the system and customer and reduced economic opportunity. In addition, the value-retention potential of any economy is directly tied to the effectiveness and efficiency of reverse-logistics systems: disruption of global and local reverse-logistics, whether diverting to recycling or to VRP production, reduces the value retained by the system, and ultimately degrades the ability of VRP producers to achieve economies of scale, and the ability of the country to pursue a circular economy.

8.3.2 Rebound effect and systemic implications of value-retention processes

The effectiveness and appropriateness of circular economy has been questioned in the literature regarding the extent that actual primary production is reduced or displaced by circular economy reuse activities and VRPs (Allwood 2014, Geyer and Blass 2010, Zink et al. 2014). The actual displacement of primary production activities and reduction in absolute impacts is influenced as much by the individual product and process attributes, as by the market forces acting within the system (McMillan, Skerlos, and Keoleian 2012, Thomas 2003). Zink and Geyer (2017) note that where absolute material and production displacement occurs, it cannot be assumed that it is occurring on a 1:1 basis due to the presence of other influences and forces acting within the system.

As emphasized by the results presented in Sections 5, VRPs at the product-level provide an opportunity to offset or displace new material requirement, and thus the associated embodied material energy and emissions implications. This displacement, even if not 1:1, presents an efficiency gain from VRPs that can manifest as material efficiency, resource efficiency (energy use, emissions), and cost efficiency.

The origins of rebound-effect discussion is based in the economic perspective heavily focused on the direct price effects of increased efficiency: where increased efficiency contributes to decreased cost of doing or receiving, there is the potential that the cost reduction will drive an increase in demand, ultimately increasing the absolute impact (Greening, Greene, and Difiglio 2000).

There have been many calls in the literature to expand on this limited price-effect focused view of rebound, drawing from insights on energy efficiency rebound (Borenstein 2013, Berkhout, Muskens, and Velthuijsen 2000, Sorrell and Dimitropoulos 2008), and unintended positive and negative effects of environmental protection measures (Hertwich 2005). A strict environmental perspective on rebound effects tends to focus on the many valid environmental implications of increased production and consumption; however, the circular economy and broader sustainability perspectives must also acknowledge important market and socioeconomic implications that are an important part of sustainability and circular economy transformation pathways.

Differentiated from energy efficiency rebound, the potential for unintended positive and negative effects of 'circular economy rebound' (Zink and Geyer 2017) extend beyond price-effects and energy efficiency considerations to consider the implications of increased production or consumption efficiency in the context of market influences and user/customer perspectives. Further differentiating VRP-related rebound from 'circular economy rebound' is the assessment of these rebound impacts at the product-level. Thus, although many of the rebound considerations presented by Zink and Geyer (2017) reflect valid material-level recycling rebound concerns, these are beyond the scope of this discussion focused on VRP-related rebound effects.

An extended consideration of VRP-related rebound effects are presented, and in accordance with the insights and structure proposed by Zink and Geyer (2017) these effects are organized to account for:

- price effects tied to VRPs and VRP products;
- substitutability of VRPs and VRP products; and
- other economy-level and transformational effects.

As with all rebound effect, wherever there are efficiency gains resulting from the introduction of new technology, these can be offset by unexpected (or expected) behavioral and system responses. It must be remembered that all VRPs rely upon high-quality, durable original manufactured products: there will always be a need for original manufacturing activity. Thus, engagement in VRPs should not cause an OEM New product to be avoided in every case, and the potential for rebound effects is real and must be acknowledged.

8.3.2.1 Price effects tied to VRPs and VRP products

8.3.2.1.1 Increased demand and product efficiency leads to increased consumption

Increased demand for VRP products can derive from the discounted price point (in all markets), as well as from the alleviation of access barriers (in restricted markets). Price discounts are attractive to customers, particularly where quality and performance are maintained and warrantied (e.g. remanufacturing). Price discount is a primary aspect of demand modeling for VRP products (Atasu, Sarvary, and Van Wassenhove 2008, Agrawal, Atasu, and Van Ittersum 2015, Atasu, Guide Jr, and Van Wassenhove 2010, Debo, Toktay, and Wassenhove 2006), and is in alignment with the literature on direct rebound (Berkhout, Muskens, and Velthuijsen 2000, Greening, Greene, and Difiglio 2000, Borenstein 2013, Sorrell and Dimitropoulos 2008) as well as neo-classical economic theory (Bertrand 1883).

As noted by Zink and Geyer (2017), in consideration of market influences, the complete displacement of an OEM New product, and associated primary production, cannot be assumed. Implicit in this perspective is that when less than 1:1 displacement is occurring, there is also some degree of production growth occurring (Thomas 2003). Scitovksy (1994, 37) found that markets for non-new consumer durables "…stimulate the economy partly by enabling the well-to-do the sooner to replace their worn out or obsolescing durable goods with new ones, and thereby increasing the total demand for them."While this increase in demand for VRP products enables continued economic growth – one important consideration for the circular economy – it also necessitates the continued increase in aggregate consumption of new materials and energy, as well as the generation of waste and emissions.

It also raises concerns about socioeconomic divides that may be highlighted through the growth of VRP and/or non-new product markets. An implication of growing markets for VRP products is that in some cases the reduced price point of the less-efficient technology enables new market demand from those users/customers otherwise unable to participate in the market (Thomas 2003). In many cases, these users/customers are in less wealthy and/or non-industrialized economies, and unregulated or unmonitored transactions can quickly lead to concerns about dumping, particularly in the case of VRP electric and electronic products (Zhang, Schnoor, and Zeng 2012, Sthiannopkao and Wong 2013, Ni and Zeng 2009, Schmidt 2006, UNEP 2005). In cases where VRP product quality cannot be guaranteed there exists a concern, if not a valid tension, between social (e.g. consumer safety) and environmental (e.g. use-phase energy efficiency) interests, and the economic opportunity for otherwise inaccessible lower-priced VRP products. As discussed in Sections 6.1.2 and 7.2.1, many non-industrialized countries have implemented regulatory policies that work to mitigate the potential downside of this tension via import restrictions on VRP inputs and finished products (Thomas 2003).

As with other aspects of circular economy, the broader system must always provide context; for example, the case of remanufactured industrial digital printers (refer to Product C in Figure 87). Given that remanufacturing enables the upgrade and enhancement of the product to as-new or better specification, a remanufactured industrial digital printer can meet current functionality and performance requirements. Particularly in the case of industrial printers, equivalent performance quality and a lower cost may lead to increased printing activity by customers, resulting in higher use-phase impacts of both energy and paper consumption. At the same time, this higher consumption still comes at a lower relative cost: a significant share of product materials, embodied materials energy, and embodied materials emissions are retained within the system, which enables a lower average resource requirement overall.

8.3.2.2 Substitutability of VRPs and VRP products

In many cases, users/customers will not consider the VRP product to be equivalent or substitutable for the OEM New version of the product, often due to perceptions about product quality, and implicitly the risk associated with a non-new product (Mitra and Golder 2006, Debo, Toktay, and Van Wassenhove 2005, Kirmani and Rao 2000, Hazen et al. 2017, Brucks, Zeithaml, and Naylor 2000, Jacoby, Olson, and Haddock 1971, Geistfeld 1982, Lichtenstein and Burton 1989, Ovchinnikov 2011, Hazen et al. 2012). However, prospect theory and other literature on VRPs suggests that potential customers evaluate VRP products based the interaction between perceived risk, perceived benefit (e.g. price reduction), and perceived value (Kahneman and Tversky 1979, Atasu, Sarvary, and Van Wassenhove 2008, Monroe and Chapman 1987).

The issue of whether, and to what extent VRPs are considered substitutable remains an important focus in the literature. Attributes of perceived quality, price and brand, can highly influence customer decision-making; alongside product attributes, social norms and networks will also influence the speed of adoption of VRP products (McCollough 2010, Wang and Hazen 2016, Ülkü, Dimofte, and Schmidt 2012, Jansson, Marell, and Nordlund 2010, Rogers 1976, 2003, Peres, Muller, and Mahajan 2010, Mylan 2015, Kahneman and Tversky 1979).

Adoption of VRP products, as innovative new options in currently restricted markets, are a function of distribution infrastructure, other regulatory conditions, as well as social norms that may predispose customers towards different options (Peres, Muller, and Mahajan 2010, Wang and Hazen 2016, Hofstede 1980)..

The following sections relate to the implications of substituting VRP products for OEM New products, as well as the implications of substituting different (e.g. lower-impact partial service life versus higher-impact full service life) VRPs within the production mix.

8.3.2.2.1 The presence of less efficient technologies in the market

Aligned with environmental perspective on rebound effects is the concern that the reuse of products with high use-phase energy consumption and emissions generation may encourage the retention of less-efficient product models in the marketplace (Berkhout, Muskens, and Velthuijsen 2000, Greening, Greene, and Difiglio 2000, Borenstein 2013). Rather than displacing older, less efficient and higher-polluting product models with more efficient, cleaner designs, VRPs may serve to keep older models in the market, potentially preventing the uptake of more efficient designs, and thus increasing the net impact of these products in the use-phase (Gutowski et al. 2011, Cooper and Gutowski 2017).

While in many cases, the comparative evaluations of life-cycle impacts are based upon the VRP for a significantly older product model and a newly upgraded, efficient model, as highlighted in Section 8.2.4 VRPs are not always appropriate and the decision to engage in VRPs must carefully consider the nature of the product and the product-system. According to interviews with industry experts, formal VRPs (especially full service life VRPs) for significantly older models and/or less-efficient versions of a product are typically not pursued, as it is often more difficult to develop market demand for VRP versions of these products, and therefore are often not deemed to be worth the investment by the VRP producer.

It must also be noted that, despite use-phase impact reductions enabled by newer and more efficient product models, the economic reality of many users/customers must be considered. In accordance with market influence observations of McMillan, Skerlos, and Keoleian (2012) and Zink and Geyer (2017), the latest, most efficient product models are often far more expensive than the VRP option. This suggests the opportunity for future research into reasonable substitution behaviors, and the life cycle impacts between VRPs versus OEM New products that are actually likely to be considered substitutes in the mind of the customer.

The potential for less-efficient product models to be retained in the marketplace is real; however through the education and engagement of industry members regarding the appropriate applications of

VRPs, some of this risk may be mitigated (refer to Section 8.2.4).

A realistic middle-ground must be acknowledged in the short-term that, while potentially imperfect compared to the ideal state in which only the most efficient products are used, VRP products present a viable alternative to a comparably efficient OEM New product model, and a meaningful alternative to the user who would otherwise be unable to participate in the market at all.

8.3.2.2.2 Displacement of lower-impact partial service life VRPs may increase total impacts

As observed from the Theoretical High scenario for vehicle parts in China (Figure 63), there is a potential rebound effect for economies with currently high shares of partial service life VRPs (e.g. repair and arranging direct reuse) and low shares of full service life VRPs (e.g. remanufacturing and comprehensive refurbishment). In these cases, the lower value, lower impact VRPs may be displaced by VRPs with relative higher value, but also relatively more negative impacts. With access to full service life VRPs, customers may choose these options over arranging direct reuse or repair. The displacement of low-impact repaired vehicle parts by higher-impact remanufactured or refurbished vehicle parts could potentially result in an increase to process energy and process emissions associated with that sector, as observed in the case of China (refer to Figure 63). While this rebound effect may only occur in the short-term, it is a reminder that *all* VRPs play an essential and important role in a circular economy, and that the complexity of the broader VRP system must be considered in the development of programming, and prior to significant policy interventions. In non-industrialized economies the prevalence of lower-impact partial service life VRPs (namely repair) reflects what is currently possible and appropriate given the economic, infrastructure, and technological conditions of those economies (Weeks 1975, Bell and Albu 1999). Displacing high levels of repair in non-industrialized economies without sufficient advance in the other essential system aspects including technological capacity and economic viability for consumers is unrealistic. In addition, the displacement of lower-impact partial service life VRPs with higher-impact full service life VRPs will lead to absolute increases in material and resource consumption and other environmental impacts within these types of economies.

8.3.2.3 Economy-level and transformational effects of VRPs and VRP products

8.3.2.3.1 The earlier opportunity for technology upgrade interventions

A contrasting perspective on this issue is that the presence of effective VRP options in a market may enable an intervention opportunity that creates positive rebound effect. For many product sectors that deal with electronic components, when the product is returned into the VRP system before its expected life is complete, full service life VRPs (comprehensive refurbishment and remanufacturing) can allow for the upgrade of the products to enhance and improve performance efficiency, and potentially other use-phase environmental impacts.

As described in Section 8.2.4.1 Optimized VRP Decision Framework Categorization, depending on the specific product and process, full service life VRPs can reutilize product components that have no use-phase impacts (e.g. the chassis, frame, exterior) (Figure 87) and undertake the upgrade of software and/or electronic systems. This is common practice in the comprehensive refurbishment and remanufacturing of industrial digital printers (refer to Product C in Figure 87).

When used appropriately, full service life VRPs may offer intervention opportunities that enable reduced life-cycle impacts of the product, relative to its original specification. In highly efficient and organized VRP systems, value can be retained within the system longer (e.g. materials), without compromising on technological efficiency advancements, such as emissions reductions during use-phase. Although not part of this study, technology and performance upgrades through VRPs are quite common for the electrical components and systems in the automotive, marine, locomotive, heavy-duty, and aerospace sectors.

As expanded on in Section 8.2.3, upgradability is just one design strategy that can enable the creation and retention of value within the industrial economic system (Section 8.2.3.2.2). The economic opportunity created via the cost efficiencies of VRPs may serve to motivate more organized and standardized design approaches, including design for modularity (Section 8.2.3.1.1) and design for disassembly (Section 8.2.3.3.2). These design approaches must necessarily exist within a broader system designed for VRPs, and implicit in these approaches is more transformational change in attitudes and systems.

8.4 Overcoming barriers to value-retention processes

All economies have the potential to optimize the role of VRPs within their circular economy strategy. From this assessment, there is no evidence that the ‘developing/newly industrialized’ status of an economy affects the ability to fully engage in VRPs, and there is confirmation that this is not an issue of ‘developed/industrialized versus developing/newly industrialized’ economic standing. Mexico, considered to be an advanced developing economy, has demonstrated capability and high-performance in remanufacturing, largely enabled through trade and investment collaboration with entities from the US and Canada (U.S. International Trade Commission 2012). The introduction of remanufacturing as part of the production mix can help to enhance technological capacity, know-how, skilled labor opportunities, and increased awareness of domestic customers; these economic benefits are in addition to the reductions in net material requirement, process energy and process emissions that are achieved by Mexican remanufacturers (Lund and Hauser 2010, Brent and Steinhilper 2004).

What becomes clear from the case study results, and observation of other non-case study sectors, is that it is the presence and nature of the barriers to VRPs within the economic and production systems that determine the magnitude of, and speed at which the benefits of both full and partial service life VRPs can be realized.

A simplified overlay of how these barriers affect different aspects of the VRP system is presented in Figure 89.

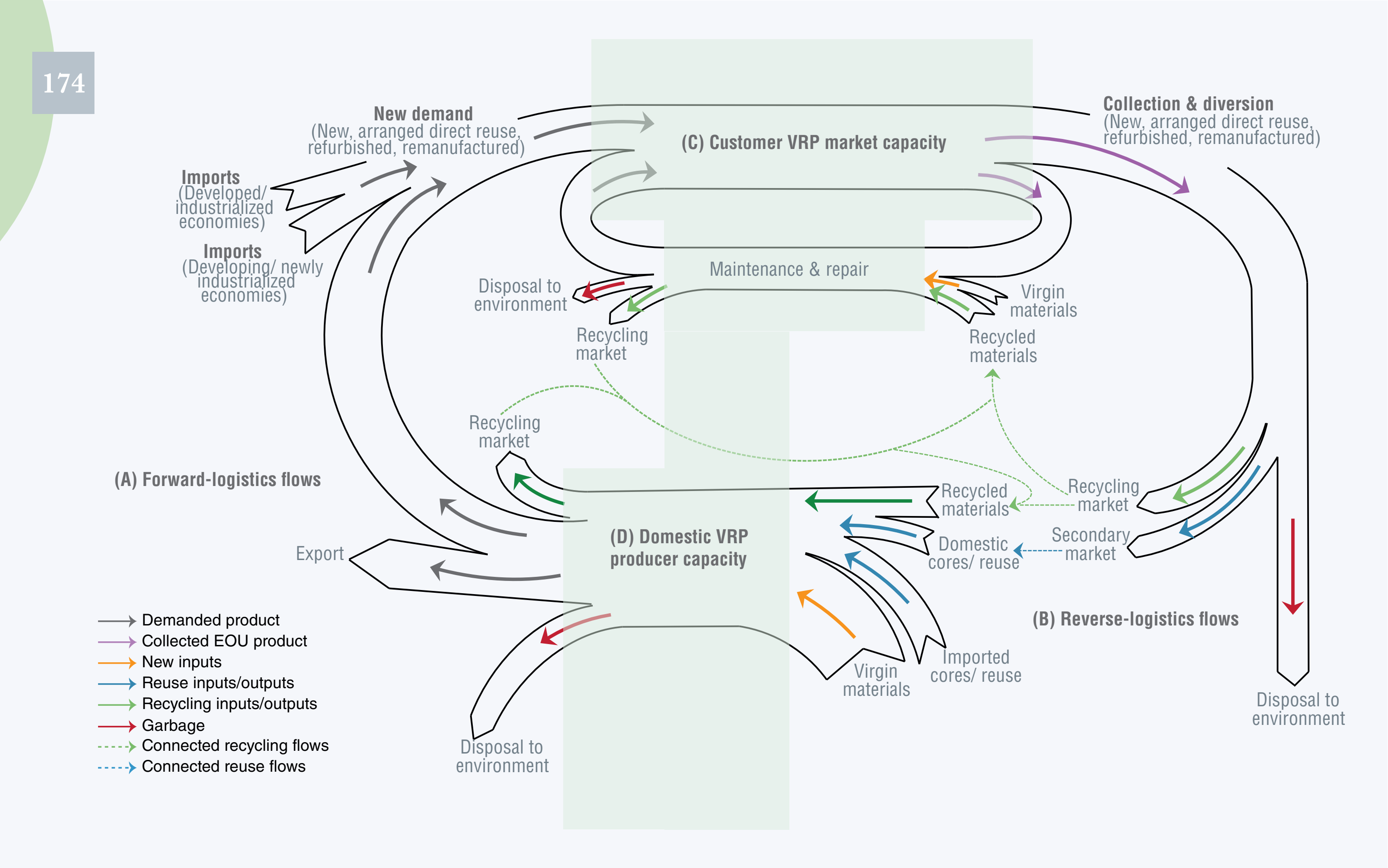

Figure 89: Description of the economic system required to support value-retention process

Barriers that affect forward and reverse flows: Point (**A**) highlights the areas of the system where regulatory and access barriers can affect flows of finished VRP products from producers to customers in domestic and/or international markets. Point (**B**) highlights the areas of the system where collection infrastructure barriers can affect flows of EOU products and components from the customer/user back into the secondary markets and/or to the OEM to be used as inputs to VRPs.

Barriers that affect capacity: Point (**C**) highlights where market barriers may create capacity constraints for the domestic VRP customer market. Point (**D**) highlights where technological barriers, may create engagement and capacity constraints for domestic VRP producers.

The presence of barriers in the system not only constrain and limit the potential of VRP production: they are also interconnected. As such, further reinforcing the necessity of a systems-perspective, the alleviation of these barriers must be considered in the context of the entire system and all interplaying conditions. These observations are clarified further in Section 6.1.

8.4.1 Economic conditions and access to VRP products

Fundamental variables affect the speed of innovation diffusion and adoption, including the perceived attributes of the innovation, the communication channels through which information is disseminated, and the norms of the social community (Rogers, 2003).

In practice, the pattern of the adoption of an innovation depends on the interaction of different factors that can be grouped as follows: supply-side factors (availability of information, relative advantage of the innovation, barriers to adoption and feedback between suppliers and consumers); demand-side factors (adopters with different perceptions, imitation of early adopters); and cross-country factors (culture, religion, opinion leaders). The choice between the different models of diffusion of an innovation and the factors which will most influence its adoption will depend on the characteristics of the innovation and the nature of potential adopters.

As discussed by Karakaya, Hidalgo, and Nuur (2014), the adoption of new innovations depends on the interaction of a variety of factors that can differ across and even within economies, including: (1) supply-side factors that include the availability of information, the perceived relative advantage of the innovation, and information asymmetry between the buyer and seller; (2) demand-side factors that include customer/user perceptions, and incentives for adoption; and (3) economy-wide factors that include social norms, culture, religion, and politics (McPherson, Smith-Lovin, and Cook 2001, Kimura and Hayakawa 2008). However, Karakaya, Hidalgo, and Nuur (2014) also point out that the nature of the innovation itself is also an important factor, and in the case of eco-innovations there is limited evidence that adoption can be predicted according to traditional innovation diffusion models (c.f. Rogers 2003). There is significant need for future research to assess and better understand the unique factors and influences that facilitate the adoption of eco-innovations, including VRPs, in order to support the faster transition to circular economy.

Precluding diffusion and adoption, however, is the need for customers and producers in a market to have access to the innovation in the first place – literally (e.g. ability to access VRP products and/or technologies), and figuratively (e.g. exposure to and education about VRPs and VRP products).

In this assessment, the presence of access barriers dominates the ability of an economy to realize the benefits from VRPs through uptake and diffusion: where customer access barriers were present in the scenario, the number of VRP products in the customer market remained very low. The lack of understanding of value and opportunity, and the diluted network effect ensured the slow uptake of VRP products, as well as a delay in customer market awareness of benefits. In the absence of clear domestic market demand and access to VRP technologies, potential VRP producers are unable to support the business-case for VRPs, despite the known environmental and economic benefits.

The delays related to access barriers can be observed in the case studies of Brazil (refer to some examples: Figure 50 and Figure 66) and China (refer to some examples: Figure 51 and Figure 67), where under the more realistic Standard Open Market for VRP Products scenario, the uptake and adoption of

VRPs in both production and demand mix remains minimal relative to the other prevalent practices of OEM New, repair and arranging direct reuse.

Access barriers slow the growth of VRP production within the domestic economy, as well as the speed of VRP capacity scale-up, and the related growth in domestic demand for VRP products. Technology and knowledge transfer that is essential for enhancing the learning curve of domestic producers is inhibited, ultimately preventing opportunities for improved production and operational efficiency. As a result, customer market awareness of VRP options and benefits are preempted, and the ultimate development and maturation of VRPs within an economy is stunted. From a strategic perspective, these delays interfere with domestic producer readiness and capacity to engage in VRPs quickly, ultimately affecting competitiveness within the global economy, and reducing the ability of the economy to pursue circular economy and impact reduction through VRPs (Bell and Albu 1999, Del Río, Carrillo-Hermosilla, and Könnölä 2010).

8.4.2 Environmental and technology policy opportunities

Although the modeling approach in the case studies of this report do not reflect a transformative approach, economic innovation is an important perspective for circular economy and VRPs. Evolutionary economics considers how technologies, technological competition, and socio-technical systems can affect the trajectories of innovation and how potential barriers to innovation can be mitigated via strategic policy, demonstrating a systems-perspective that is common to circular economy thinking and research (Del Río, Carrillo-Hermosilla, and Könnölä 2010, Green and Randles 2006). In the context of innovation, VRPs represent incremental eco-innovation at the process-level, in which traditional approaches to production and product-responsibility are adjusted to reduce negative environmental impacts and enhance the value-retention potential of the system. In contrast, circular economy requires more substantive and radical innovation concerned with creating new and efficient linkages between diverse and numerous stakeholders in the production-system.

From a barriers-perspective, the barriers to circular economy are systemic, affecting multiple stakeholders, and requiring facilitation and mitigation only possible via policy; in contrast the barriers to VRPs are more specific and/or isolated, and hence process-level changes may be targeted by individual firms and industry organizations (Del Río, Carrillo-Hermosilla, and Könnölä 2010). The barriers facing VRPs, and associated circular economy can be organized into three categories originally proposed by Del Rio, Carrillo-Hermosilla, and Könnölä (2010) in the context of eco-innovation: (1) the lack of pressure or push to change from the external environment; (2) the conditions internal to the firm that can inhibit change, including lack of resources, technological capacity and priority; and (3) the techno-economic characteristics of VRPs and design-for-VRPs can be too expensive, and/or incompatible with existing processes and infrastructure.

In addition to these, complicated definitions associated with the trade of VRP products can interfere with the uptake of VRPs, often because of associated complicated compliance and reporting requirements. Remanufacturing needs an accepted international definition that reflects the rigorous industrial process of remanufacturing itself. It is important that the development of these definitions be distinguished from the related, but inherently different, discussion of whether ‘cores’ constitute waste and/or other classifications. Oversimplified and uninformed definitions of remanufacturing create unnecessary regulatory barriers for legitimate VRP product offerings; alternate methods to control the quality and nature of VRP products entering an economy through trade, outside of waste-related compliance systems, should be considered. It is also important for those involved in the process of definition creation to enable optimized integration and alignment of definitions across economies: whether this occurs through the enhancement of relevant existing international agreements (e.g. recent clarifying explanatory notes for the term “wastes” in the Glossary of Terms in Document UNEP/CHW.13/4/Add.2), or through specific and appropriate inclusion in developing and future bi-lateral and other trade agreements. Given the demonstrated economic and environment benefits, improved recognition and inclusion of appropriate types of VRP products in trade discussions may enable significant opportunity for economic growth and impact reduction, as well as faster scale-up through technology and knowledge transfer opportunities.

In response to these barriers and challenges, there is a push to distinguish between product innovation (e.g. design) and process innovation (e.g. remanufacturing), as there are different opportunities to influence and affect each (Del Río, Carrillo-Hermosilla, and Könnölä 2010). Where product-level innovation tends to be driven more by customer and cost pressures, environmental legislation, and compliance with internal firm policy (Triebwester and Wackerbauer 2004), process-level innovation tends to be more affected by customer pressure (versus environmental legislation) (Triebwester and Wackerbauer 2004), and the need to comply with existing regulation (del Río González 2005).

Both technology policy and environmental policy offer complementary opportunities to encourage environmentally-preferable technology and systems (del Río González 2009, Del Rio Gonzalez 2004). Del Rio, Carrillo-Hermosilla, and Könnölä (2010) present an excellent compilation of framework conditions for policy that involves a combination of approaches to balance and accommodate the diverse conditions, characteristics, and stakeholders within circular economy and VRP innovations. There is a clear need to balance short-term environmental interests alongside the need for more radical systemic change to mitigate suboptimal technological lock-in (Kemp 2000, Del Rio Gonzalez 2004); in addition it is essential that the limits of policy, such as the potential to create powerful interest groups that can perpetuate technological lock-in, be acknowledged (Del Río, Carrillo-Hermosilla, and Könnölä 2010). Policy measures that are known to support and facilitate the supply-push of eco-innovation via technology development, include research and development subsidies; in contrast, policy measures that enable demand-pull via new market creation include public procurement.

The advancement and enhancement of Science, Technology and Innovation (STI) systems is of paramount importance on most national agendas as a key requirement to facilitate meaningful economic growth.

Strategies and investments for the STI systems of both developed/industrialized and developing/newly industrialized economies need to be expanded to consider the additional and unique requirements of VRP production systems; alongside traditional STI system enhancements, development of technology, investment, industry-institute collaboration, labor force skills, and R&D that support VRP production processes are essential strategies for pursuing the potential benefits of an optimized Theoretical High scenario for each diverse economy. Government regulations can act as a positive influence in guiding product development decisions toward circular considerations. A Directive of the European Union (2000/53/EC), for example, lays out explicit guidelines stipulating that automotive manufacturers must account for ease of disassembly, reuse, collection, and recycling of components at the end-of-life during their initial design processes, as well as work with material manufacturers to increase the quantity of recycled materials used in new vehicles (European Commission 2000). This directive also outlines the intermediate processes that must occur between the end of a vehicle's useful life and the recovery of its embodied value. In this example, governmental regulation does not solely incentivize by creating risk of non-compliance, it also influences by providing base-level guidelines that assist affected industry players in determining how best to meet such regulations.

In addition to specific government regulations, global organizations are developing metrics and indicators (e.g. input-output ratios, utility values, and recycling efficiency) to create new values that will work in conjunction with legislation and policy to influence companies toward engaging with VRP products and systems (refer to Section 8.4.3). Globally, there are also significant efforts to identify and define circular economy indicators that can be used to track progress in the transition away from linear industrial models, including the recently-adopted Circular Economy Monitoring Framework for the EU (European Academies Science Advisory Council 2016, Bourguignon 2016, European Commission 2018). Hundreds of indicators are being studied: from material flows, energy balance, and resource efficiency, to waste treatment and management. While such metric-based programs remain voluntary, producers—and, importantly, investors—are acknowledging the benefits of environmentally-considerate performance considering evolving consumer demands that favor conservation-minded, low-impact products. In addition, these metrics and the associated emergence of green product labeling methodologies are increasingly being integrated into information that can be accessed by customers and consumers, with the potential to influence their purchasing decisions. In these ways, outside parties can significantly influence the integration of VRP products into the industrial economy by reshaping the customer expectations and market opportunities upon which product developers seek to capitalize and around which their products are designed.

In looking specifically towards policy interventions to facilitate VRPs within a circular economy, the targeting of radical systemic change must be a priority for policy-makers, but this must be combined with the facilitation of incremental (process-level) innovations. Applying the call by Norberg-Bohm (2000), a combination of technology and environmental sector and system policy approaches is essential for targeting system barriers to circular economy, and the more isolated barriers to VRPs. In addition, policies need to combine sector-specific insights with cross-sectoral perspectives: many circular economy and VRP opportunities tend to be more aligned with and unique to product-type, but changes to the larger circular economy system can provide efficiency opportunities across sectors (e.g. shared reverse-logistics and/or collection system infrastructure) (Heaton and Banks 1997). The style of regulation also needs to be innovation-friendly in order to appropriately engage stakeholders in dialogue and consensus via open, flexible, and reflective multi-stakeholder collaborations. (Jänicke et al. 2000) Information asymmetry can create significant challenges for collaborative approaches on product- and process-level innovations, and efforts to ensure transparency and optimal levels of information are essential as part of the process between regulators and those being regulated (Jänicke et al. 2000).

A policy priority for the effective transition to circular economy must be to overcome the current passive throw-away culture exhibited by both consumers and producers in economic systems around the world (Ghisellini, Cialani, and Ulgiati 2016). Circular economy approaches largely evolved in the world as a waste management strategy, in response to increasing concerns about waste management issues and impacts (Ghisellini, Cialani, and Ulgiati 2016, Geng, Tsuyoshi, and Chen 2010, Yong 2007). In many economies (typically industrialized), recovery and recycling infrastructure has been in place for more than thirty years (e.g. Germany, Canada), and this has enabled knowledge, competencies, and efficiencies well-suited for transitioning to circular economy (Ghisellini, Cialani, and Ulgiati 2016). In contrast, many economies have not yet begun to adopt or formalize basic waste management policies and infrastructure (Ghisellini, Cialani, and Ulgiati 2016). China's approach to circular economy differs somewhat from the traditional approach: although still very reliant upon landfilling for municipal solid waste, which prevents the meaningful closing of consumer-level material loops under the circular economy perspective, the adoption of new circular economy business models is required by law, alongside the integration of cleaner production practices and the development of eco-industrial parks (Yong 2007, Geng, Tsuyoshi, and Chen 2010, Ghisellini, Cialani, and Ulgiati 2016).

An essential aspect of any policy approach is the integration of the innovation and complexity of both VRP processes and products; incremental innovation (e.g. process) and radical innovation (e.g. system) (Del Río, Carrillo-Hermosilla, and Könnölä 2010, Velte and Steinhilper 2016). Specific approaches have been assessed within the literature, and must guide policy-decisions related to VRPs and circular economy:

- **Command and control**: Although they have demonstrated greater effectiveness at facilitating incremental changes (e.g. within VRP process adoption by firms), command and control approaches may be less effective at radical systemic change (e.g. circular economy) than market-based mechanisms (del Río González 2009, Del Río, Carrillo-Hermosilla, and Könnölä 2010). A particular priority for policy-makers must be the assessment of existing policies and regulations that prevent or inhibit producer engagement with VRPs, and/or consumer adoption of VRPs.
- **Voluntary agreements**: Appealing to individual stakeholders as they allow for longer-term planning and dialogue. However, there are risks that desired impact and outcomes may negated for several reasons: where asymmetrical information exists between participating actors voluntary agreements may be less effective (Del Río, Carrillo-Hermosilla, and Könnölä 2010); in addition, the outcomes of voluntary standards agreements tend to be distributed (refer to Section 8.4.3).

- **Market-based instruments**: Often most effective at enabling a demand-pull effect to facilitate adoption of innovative products in a market, in the case of VRPs these can include information-sharing, eco-labelling, financial incentives, and environmental-awareness raising (Del Río, Carrillo-Hermosilla, and Könnölä 2010).
- **Financial instruments**: Often most effective at facilitating a supply-push effect to facilitate the adoption of innovative processes by producers, in the case of VRPs these can include technology-focused R&D subsidies, low-interest loans, investment subsidies, and the development and exchange of best practices to limit learning curve requirements (Del Río, Carrillo-Hermosilla, and Könnölä 2010). In addition, the adoption of appropriate instruments that reward positive externalities (e.g. pollution reduction) may help firms to overcome the pressure to focus on profits (Ghisellini, Cialani, and Ulgiati 2016).

A major challenge facing the adoption of VRP processes and products is the required integration of producer and consumer perspectives. A combined approach of integrated and complementary technology and environmental policy is required (Del Río, Carrillo-Hermosilla, and Könnölä 2010). Effective policy approaches for VRPs should consider and incorporate the following characteristics:

- **Technology-focus**: To facilitate VRP process adoption, firms must first have confidence that the market will adopt the resulting VRP products before they will invest in transformation of their business model and production processes. Technological assistance and training programs, can help to facilitate interest, comfort, and ability to transition towards circular economy and VRPs, and to mitigate the risk of asymmetrical information across circular economy stakeholders (Del Río, Carrillo-Hermosilla, and Könnölä 2010).
- **Environment-focus**: Given the likelihood of associated economic growth that may accompany VRP adoption, the effectiveness of VRPs and circular economy in achieving cleaner production practices and reduced negative environmental impact is dependent upon the capacity of policy-makers to require producers to continuously-improve their environmental performance, their environmental responsibility, and their engagement of consumers in facilitating reverse-logistics for VRPs (Ghisellini, Cialani, and Ulgiati 2016).
- **Small-medium enterprise (SME)-focus**: SMEs face a concentration of financial and technological barriers to VRP process adoption, but may also provide an essential launch platform for growth of circular economy service providers and value-chain stakeholders (Del Río, Carrillo-Hermosilla, and Könnölä 2010). Additional opportunities for SME value-chain members who facilitate the closing of product-loops within the circular economy (e.g. via outsourced reverse-logistics systems) can also be enabled and supported within technology and environmental policy initiatives.{Ponte, 2014, 'Roundtabling'sustainability: Lessons from the biofuel industry}
- **Strategic niche management**: The protection of niches within VRP system and/or circular economy can enable early growth by facilitating financial flows, stakeholder collaboration, and network development. Technological network development and growth strategies are complementary to environmental policies, and focus on supporting the agents within the VRP system through technology policy, R&D support, and other initiatives specifically focused on a particular niche of the VRP system (e.g. full or partial service life VRPs; forward- vs. reverse-logistics) (Del Río, Carrillo-Hermosilla, and Könnölä 2010).
- **Public procurement**: Helps to establish/create a new market for early stage product innovations and/or low rates of adoption for innovative processes (Del Río, Carrillo-Hermosilla, and Könnölä 2010).

Additional measures may include (1) supporting and/or facilitating the establishment of eco-industrial parks that can facilitate product, material, and knowledge flows amongst strategic segments of within and across-sector stakeholders; (2) the provision of adequate and required infrastructure to facilitate product reverse-logistics, particularly for SME actors within the VRP and circular economy system that do not have the scale or capacity to efficiently engage in reverse-logistics independently; and (3) systems-level promotion and education programs targeting both producers and consumers, helping to alleviate some of the capacity-burden from SME actors (Ghisellini, Cialani, and Ulgiati 2016).

Given that economies face distinct combinations of VRP barriers and may have unique objectives for VRPs as part of an economic or environmental agenda a range of potential strategic interventions are available to policy- and decision-makers. As shown in Figure 90, different policy priorities can lead to increasing flows of VRP products within an economy (horizontal plane), and/or to increasing capacity for VRP processes and products within an economy (vertical plane). For example, enhancing EOU product collection infrastructure, programs, and systems will facilitate increased flows of essential VRP process core inputs to VRP producers, but will do little to increase the capacity of producers, alone; in contrast, supporting education and training for improved skilled VRP labor pools will contribute to capacity growth for VRP producers, but will do little to increase the flows of core inputs.

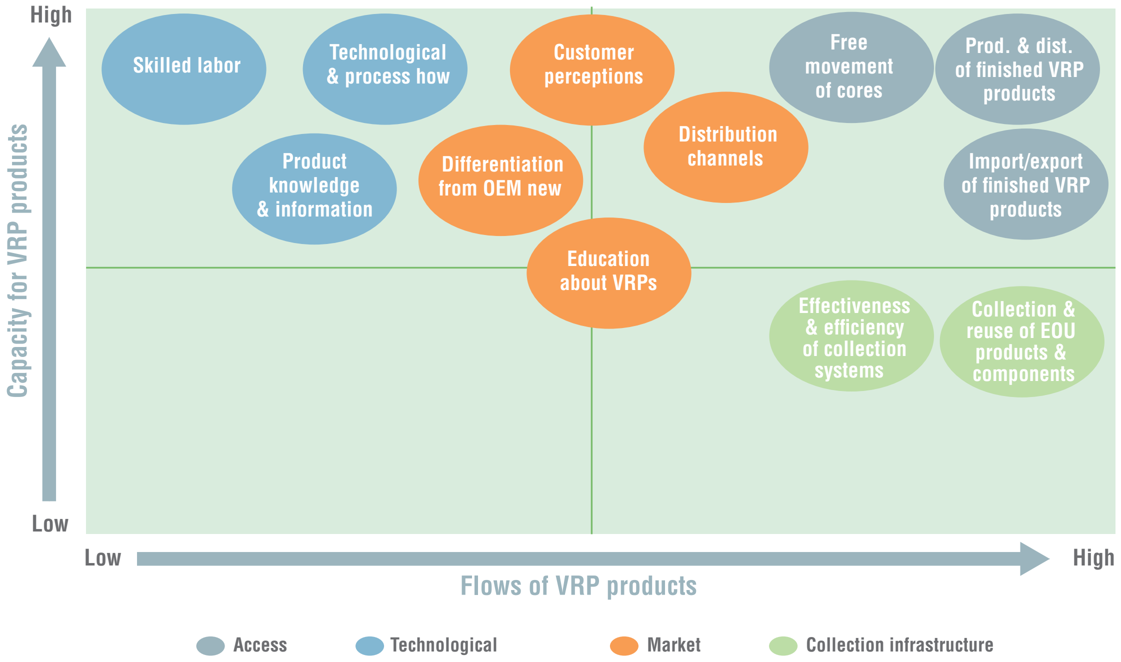

Figure 90: Differentiated barrier alleviation strategies for different economic objectives

Depending on the specific conditions and priorities of an economy, different policy priorities and instruments can be used, in combined environmental-technology approaches as previously discussed. Encouraging and enabling stakeholder awareness of the need for circular economy practices, and the development of systems and infrastructure to enable basic material and product diversion is a logical starting point for any circular economy strategy.

In non-industrialized economies rates of formal and informal direct reuse and repair tend to be high, as a form of knowledge accumulation, and suggesting that there is consumer-level awareness of the retained value of products, and the opportunity for product-life extension (Weeks 1975, Bell and Albu 1999). In the longer-term evolution towards more complex and sophisticated reverse-logistics systems and production technology, an emphasis on partial service life VRPs enables a short-term and transitional opportunity to acquire knowledge and advance technological systems necessary for circular economy (Bell and Albu 1999).

8.4.3 Integrated global responses to barrier alleviation

Economic growth within the context of circular economy may be an option if integrated and coordinated action by both global North and global South is possible: where economies in the global North can focus on decoupling production impacts from economic growth, and potentially even de-growth strategies, economies in the global South may initiate growth pathways that are informed and guided by planetary constraints and carrying capacity limits (Ghisellini, Cialani, and Ulgiati 2016).

Industries that are experienced in VRPs have begun discussions on the development of voluntary standards as a means of addressing competition, trade, and information asymmetry issues affecting growth, performance, and opportunity (Motor & Equipment Remanufacturing Association 2016). In many cases, this interest is motivated by fair competition: in the absence of market awareness, information, and standardization, firms practicing high VRP standards are unable to compete against those meeting lower standards (Ponte 2014). Standards development is often viewed as a form of voluntary regulation that is increasingly being used by governments to delegate responsibility for dealing with and addressing environmental and social issues to industry (Ponte 2014). Once established, these standards effectively become de facto mandatory, and the process for developing standards is often explicitly specified to include multi-stakeholder perspectives and steps (Ponte 2014). Given the systems-perspective of circular economy, voluntary standards for VRPs require a multi-stakeholder 'collective' approach, with required institutional features and procedures to help establish legitimacy of the effort (Ponte 2014).

Despite positive intentions, the outcomes of industry-roundtable standards development tend to be distributed. The experiences of the Forestry Stewardship Council (FSC) and Marine Stewardship Council (MSC) demonstrate that a common emphasis on the 'global North' often results in limited involvement of, and therefore adoption by, stakeholders in the 'global South' (Ponte 2014, Marx and Cuypers 2010). In addition, the failure to engage and successfully certify compliance of stakeholders in the global South limits the potential for desired outcomes (Ponte 2014). In the case of Responsible Sustainable Palm Oil (RSPO), the lack of awareness, interest, and conflicting trade priorities led to low certification of high-consuming economies (India, China, and Pakistan); effectively, as a voluntary initiative 'opting-out' remains a viable decision, albeit one that threatens the legitimacy and success of the overall global sustainability initiative (Ponte 2014, Cheyns 2011, Djama, Fouilleux, and Vagneron 2011, Schouten and Glasbergen 2011).

To be meaningful, voluntary agreements focused on the development of, and compliance with high standards for circular economy and sustainability must overcome two key barriers: (1) small certification markets that limit scale, impact, and value-chain adoption; and (2) competing standards initiatives that can dilute the message, scale, and effectiveness of the standards (Ponte 2014). VRP producers must be particularly careful in any initiative towards voluntary standards to include smaller actors and engage value-chain members in the global South. Government guidance can facilitate an effective and legitimate standards-development process; however additional normative pressures from NGOs and social movements can help to ensure optimally inclusive and representative interests at the table (Ponte 2014).

8.4.4 Diversion and collection infrastructure

An essential part of increasing customer openness to and acceptance of VRP products is first engaging them in end-of-life diversion programs and educating them on the importance of retaining value within the economic system.

VRPs are reliant on the diversion and collection of EOU products for use as inputs to the process; while individual companies may have established their own networks and collection infrastructure to ensure sufficient supply of reuse inputs, this creates a significant and inefficient cost-burden on the individual organization. Other examples of shared collection infrastructure, such as e-waste diversion and packaging extended producer responsibility (EPR) programs have demonstrated the ability to both increase collection rates and distribute the costs of operating the system. The requirement that these systems be funded by industry can provide an incentive to pursue greater cost-efficiency and performance over time. While not advocating for EPR, these systems have demonstrated that *creative and shared approaches* to collection infrastructure may have some merit in cases where the objective is to increase collection and retention of value within a system.

Where existing collection and/or recycling systems are in-place, they can be assessed for characteristics that would also contribute to and support collection systems for VRPs. For example, the inclusion of specific products under framework diversion legislation can ensure their status as a 'regulated' item, and this can facilitate the prevention of these products being directed to landfill. Where recycling systems are already required for specific products (e.g. Ontario's Waste Electrical and Electronic Equipment (WEEE), and Germany's End of Life Vehicle Ordinance), it may be possible to utilize and share overlapping system requirements, such as distributed collection networks (Ontario Electronic Stewardship 2009, Martens 1998).

In addition to government-initiated diversion and collection systems, opportunities for new members of the value-chain are arising from the transition to circular economy. Businesses interested in pursuing full service life VRPs face significant cost barriers related to the reverse-logistics required for refurbishment and remanufacturing activities, especially when their products are sold globally. However, new businesses focused on the provision of reverse-logistics and quality-control services specifically in the context of circular economy and VRPs are demonstrating additional economic potential of the circular economy.[27]

8.5 The necessity of a product-systems approach

System complexity, and the management of that complexity, is a very real concern for both industry decision-makers and policy-makers in the context of circular economy. The complexity of a single production operation often feels significant to those who try to influence and/or enhance it. This is much more so in the case of an interconnected, interdependent, dynamic, and evolving economic system of independent producers, third-party value chain parties, consumers, regulators, economics, and socio-technical factors implicit in a circular economy. In modeling and assessing the circular economy system, this is ever apparent. However, the circular economy system need not be any more complex that other systems that have been considered, adopted, and mastered, including human health and global trade. Rather than permit complexity to overwhelm and stunt the transition to circular economy, the perspective of Senge (1997) supports a strategic approach to assessing and understanding the complexity of circular economy that policy-makers and firms must face: detail complexity, which originates in the number of details that must be considered and incorporated; and dynamic complexity, which originates in the fact that interventions in the system may not produce expected or obvious effects, and these effects may also differ between the local versus global, and the short- versus long-term experience. Applying complexity perspectives to the circular economy, Velte and Steinhilper (2016) note that particularly for firms, the circular economy can be both too big and too diverse for any single firm to meaningfully connect all the elements (details and linkages) that should ideally be considered. In addition, the dynamic changes within the fast-evolving circular economy system can neither be predicted nor controlled by the firm, leading to increased sense of risk and potential exposure associated with the pursuit of firm-level circular economy.

To design both system and product for circular economy effectively, Velte and Steinhilper (2016) recommend a complexity-prevention approach: preventing the challenge before it can, or needs to be reduced. However, without careful consideration and applied systems-perspective, the traditional approach to circular design may actually increase complexity: for example, design for reparability/remanufacturing/modularity/serviceability/etc. can actually increase the number of elements and connections required at both product- and system-levels. Similarly, the closing of material and/or product loops requires an increase in the number of links between stakeholders and system agents, but these links can be diverse, crossing a range of differently motivated/oriented stakeholders. As such, the performance management of both

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[27] Some business models support the transition of individual businesses towards more circular practices by facilitating the collection of their used products/parts around the world and returning them to a defined destination for refurbishment and remanufacturing (https://www.c-eco.com/).

individual actors and system performance can require significant resources and time, beyond the capacity and/or capability of a single firm (Velte and Steinhilper 2016). Finally, the interdependencies of the system can affect efficiency and effectiveness of any single actor or initiative within the circular economy: the responsibility to manage and optimize all non-linear and unpredictable conditions of such a system is an unrealistic burden to assign to any single firm or actor (Velte and Steinhilper 2016).

Therefore, while the complexity of the circular economy may be manageable, the need to engage and initiate collaboration across a range of stakeholders and decision-makers is obvious: where firms must be responsible for addressing product-level complexity within a particular product design and business model, this must integrate with broader systems-level initiates to simplify and optimize linkages and performance management – responsibilities better managed by industry collaboratives, the rise of new service providers within the value-chain, and governments.

It is increasingly clear that the complexity of more circular product and economic systems requires a more comprehensive, non-linear approach if they are to be optimized in pursuit of environmental and economic benefit. From the product perspective, there is need to expand the boundaries beyond what the firm has direct control over, and beyond what is traditionally considered as part of the design process. As highlighted in Section 8.2, product development responsibility must extend beyond the point of product sale and must include important design considerations to accommodate and optimize multiple service lives, forward- and reverse- logistics, as well as the social and economic systems that the product will exist within. From the economy's perspective, the benefit-potential enabled via VRPs cannot be realized without optimizing the broader system that VRP products exist within. Aspects of the economic system that cannot be controlled or influenced by the firm, or which require a more centralized and standardized approach to ensure optimized flows and capacity for VRPs within the domestic economy, must become part of the policy-makers priority under a circular economy initiative. In other words, to realize the potential of VRPs as part of a circular economy strategy, policy-makers must focus on streamlining and maximizing the efficiency of the broader system, to enable and incentivize industry to innovate and thrive through VRPs. The following sections highlight the key insights of the "product" approach, the "systems" approach, and the necessary integration of both into a comprehensive and robust "product-systems" approach.

8.5.1 Product design systems require expanded boundaries

Product design is important, but not the only determinant of circular economy potential. Product design goals are themselves dictated by the underlying objectives and constraints of the producer, as well as the conceptual approach they take to production. Implementing system circularity into the business model, and ultimately into the product development process, therefore requires a comprehensive approach.

Currently most VRPs are undertaken as an 'art' not as a 'science': they are often customized for a specific product or component, within a limited

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supply chain scope. Customized VRP approaches enable high levels of effectiveness and efficiency in the context of that single product or component, but ultimately inhibit the scale-up of those VRP practices to more expanded applications, and the limit the standardization of those practices outside of the organization from which they originated. Under this 'artful' approach to VRPs, the intensity of VRPs even in well-established markets remains low, and the realization of efficiency potential is limited. While the pursuit of more 'scientific', standardized approach requires a comprehensive product-systems approach, the path towards a product-systems perspective requires investment.

As discussed in detail in Section 8.2, the nature of VRPs creates an implicit requirement to consider the entire life-cycle of the product beyond the warranty. However, responsibility for designing circularity into products and systems cannot be left to designers alone: a comprehensive consideration for, and objective of, incorporating VRPs must occur very early in the product development process, prior to conceptualization and design. The decision to develop VRP products must be undertaken as a strategic business decision and must be incorporated into every aspect of the business, including product design. A well-designed VRP product must go hand-in-hand with an effective and efficient business model for maximizing value-retention of the product (e.g. reducing degradation during use-phase), and the reverse-logistics system for EOU products (e.g. maximizing collection rate and collection quality). The product development process must incorporate design principles of value creation, value preservation, and value collection, alongside strategic design approaches that ensure consideration of the entire product-system.

The pursuit of this new approach requires an overhaul of both technical and social systems that are predominant in organizations worldwide. From a social perspective, changing product development procedures requires significant communication and buy-in creation across potentially enormous organizational networks and teams: these cannot happen overnight, and require significant leadership and capital investment to accomplish. From a technical perspective, product design is currently constrained by existing technology and technological processes, and by the data and information that the product development team has access to. Adopting an expanded view of product-system boundaries will be, alone, ineffective: an expanded systems-view requires significant quantities of new information and data to support development teams and design engineers in their pursuit. In addition, significant investment in advanced technology will be needed to facilitate higher value-retention and faster adoption of VRP production approaches.

8.5.2 All economies require a systems-perspective for circular economy

While the circular economy suggests a simplified vision, it entails complexity and interconnectedness at both macro- and micro- scales that must be appreciated and understood by system stakeholders. As suggested throughout this report, the mechanisms by which an industrialized economy pursues circular economy and VRPs, may necessary differ from those appropriate for a non-industrialized economy, largely because of varied technological, infrastructure, market, and regulatory conditions that can increase the cost and effort required to achieve the desired transformation.

Given the systems-perspective advocated for circular economy approaches, in the case of non-industrialized economies there are some key system conditions that can affect an economies ability and interest in pursuing adoption of VRPs and other circular economy practices that industrialized economies may take for granted, including: the existence of waste diversion and recycling regulations; the presence of public and/or private infrastructure to facilitate diversion and recycling; the extent of domestic production and technological capacity; the ability to influence nature of imported products via trade relationships; and the ability to engage and educate customers/users in the market. While these types of systemic challenges face both industrialized and non-industrialized economies alike, the optimal strategies employed to overcome them likely differ.

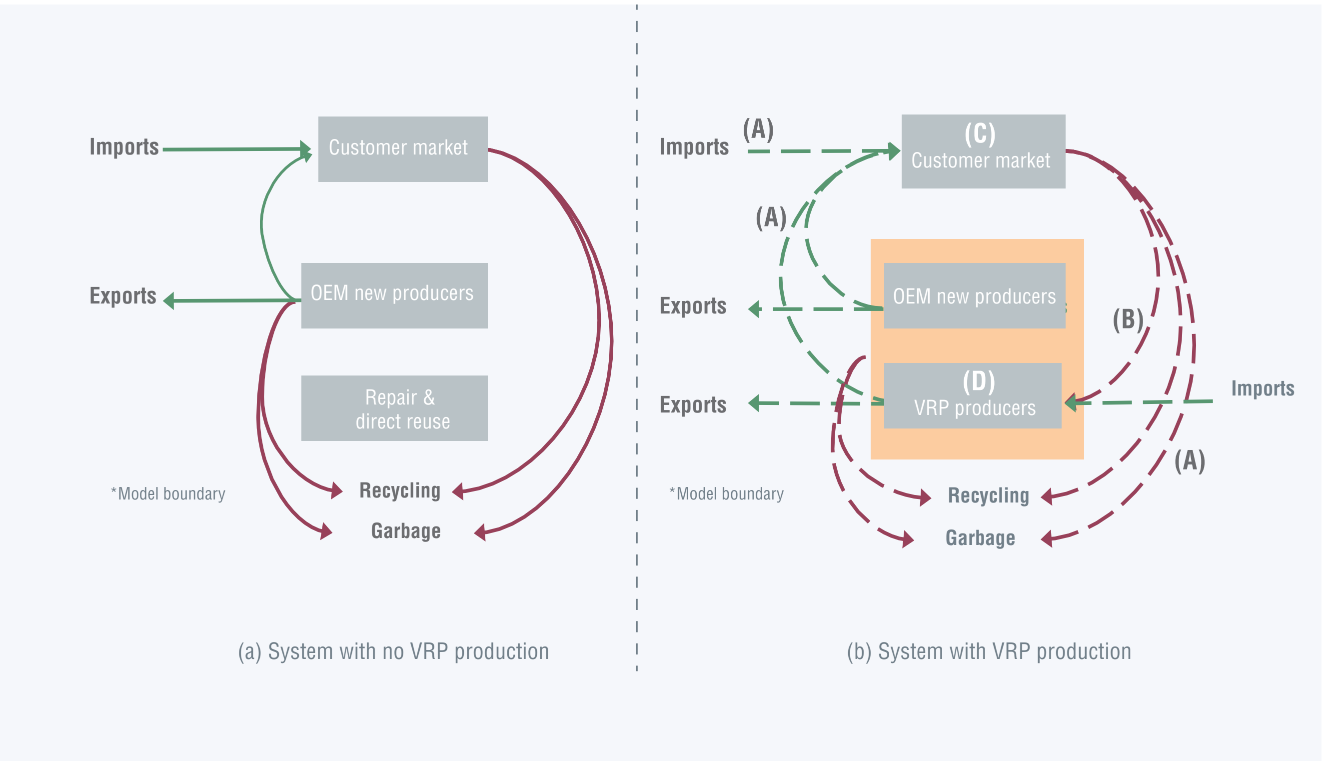
For example, as mentioned, where a non-industrialized economy has a strong reliance on informal repair activities and a low level of formal industrial capacity (Weeks 1975, Bell and Albu 1999), the optimized circular economy strategy will not seek to displace repair with higher-impact VRPs in the short-term; instead it will focus on improving and enhancing the efficiency and value-retention ability within the existing repair system, and potentially expanding that system to achieve better outcomes for independent repair entities and customers alike. This approach is consistent with the overarching strategic approach outlined in Section 1.2.1 (Ellen MacArthur Foundation 2013a):

1. maximizing collection and capture of materials at the 'gaps' between lifecycle stages at which loss could occur;
2. retaining the highest possible value of materials, once recovered; and
3. remodeling the linear system through infrastructure development, process innovation, and product innovation to increase the use of high-value recovered materials as inputs into the production system, in place of raw inputs.

As suggested throughout this report, not all VRPs are appropriate for all products or all economies: collaborative initiatives between domestic industry decision-makers and policy-makers to share information and to identify opportunities for improving circularity is needed: via closing loops and mitigating system losses; and via implementing the adoption of VRPs and VRP products in a manner that works within the existing production and collection infrastructure.

The reliance of VRPs upon the presence and efficiency of collection infrastructure, as just one example, highlights this fact. To appropriately plan, organize and implement for circular economy, a systems-perspective is essential. In the context of this study, Figure 91 simplifies the system to (a) known primary product flows, and (b) four overarching system factors to highlight how the current system may need to be adjusted:

- (A) Regulatory and access barriers;
- (B) Collection infrastructure barriers;
- (C) Customer market barriers; and
- (D) Technological barriers.



(a) System with no VRP production

(b) System with VRP production

Figure 91: Overview of comparative system complexity

From this perspective five important implications become clear:

1. **There is an essential requirement for continued OEM New production**, without which VRPs would not be possible. If differentiated and positioned appropriately, VRPs may serve to enable growth opportunities for the entire product segment by targeting and engaging new, previously untapped, market segments that are underserved by OEM New products. For non-industrialized economies that do not have production capacity for OEM New products, identifying other opportunities to access EOU products to facilitate value-retention and product-life extension in the context of a global circular economy.

2. **The inclusion of VRPs in the system increases complexity significantly**: OEM New versus VRP production processes and requirements are differentiated, and require differentiated technology, knowledge, and labor skill requirements. Due to regulatory and/or market conditions, VRP products are differentiated from OEM products in terms of how they can flow from producer to customer; and there is an essential reliance upon collection of EOU products and components through secondary markets in order to enable the production of VRP products. For non-industrialized economies, the expansion of VRP technology, knowledge and labor skills is not predicated on pre-existing domestic industrial infrastructure. Where domestic R&D funding may not be available, partnerships with globally-operating OEM producers can help to facilitate the transfer of technology and the opportunity to engage in new value-chain roles as part of a global circular economy VRP network (Weeks 1975, Bell and Albu 1999). Integrated and coordinated action by value-chain members and stakeholders in both global North and global South is needed to enable a movement towards decoupling production impacts from economic growth in economies in the global North, alongside sustainability-guided growth pathways for economies in the global South (Ghisellini, Cialani, and Ulgiati 2016).

3. **There is a distinct difference in how the identified system conditions (barriers) affect and influence the system when VRP production is present**. The objective of increasing the scale and prevalence of VRPs and VRP products within an economy requires a holistic approach that considers the magnitude and cause of barriers throughout the entire system, as well as how those barriers may interact to compound or negate one another. In economies that currently lack sufficient environmental regulation and programming to require and facilitate waste diversion and recycling, technology-focused policy initiatives that ignore the reverse-logistics supply-chain requirements of VRPs will be less effective because essential flows within the VRP system are still constrained. Similarly, in economies with comprehensive reverse-logistics systems, but insufficient customer/user interest and awareness, supply-stimulating initiatives will be less effective because they do not address the lack of market demand for VRP products. This complexity, as highlighted by Velte and Steinhilper (2016) may be approached meaningfully via combined environmental and technology policy initiatives (Del Río, Carrillo-Hermosilla, and Könnölä 2010).

4. **There are multiple, diverse, and interconnected stakeholders, each with a potential role to play in the transition to circular economy and the uptake of VRP production.** It is essential to consider the intersection and interplay of barriers and stakeholders within the system, and doing so in the context of this study enables additional observations about potential system interventions, opportunities and responses:

- government policy-makers have a central and pivotal role related to the presence and alleviation of regulatory, access and collection infrastructure ‘flow’ barriers, (A) and (B) respectively. This holds true for both industrialized and non-industrialized economies;
- other stakeholders, including industry, may have an important role to play in the alleviation of barriers related to the customer market and technological capacity, (C) and (D) respectively. This also holds true for both industrialized and non-industrialized economies.

5. **There is an underlying order essential for the circular system that must be acknowledged** to optimize strategic policy responses:

- Demand originates in the market with the customer;
    - In response to that demand and the inherent economic opportunity, demand will be met with supply from domestic production and/or imports; and
    - Once the product reaches an EOU stage, it will be directed into a secondary system that will dictate the magnitude of value and utility retention of the system.

An appreciation of this hierarchy is critical for the success of VRPs within any system, as it leads to the necessary conclusion that strategic interventions must be made within the context of the interconnected system:

- Since demand originates in the market with the customer, barriers that inhibit the generation of awareness and of demand for VRPs, such as access restrictions that prohibit VRP products to enter the customer market, are particularly problematic for creating the business case for domestic producers to engage in VRPs and/or to increase VRP production capacity. Engaging in value-retention can include all or just a single VRP process as part of a circular economy initiative, as may be most appropriate in the short-term for non-industrialized economies.

- Therefore, barriers that restrict the VRP producers' access to technological capacity, skilled labor, process know-how, and/or essential inputs to VRP production, ultimately restrict production capacity even in markets where demand may be prevalent; and

- Finally, where demand and access exist, there is an opportunity for OEMs and third-party entities to initiate strategic responses that make sense for their organization, and which create opportunities within the value-chain for new members and circular economy services. Although some OEMs may be concerned about the potential for cannibalization of their OEM New product offerings, it must be acknowledged that the failure to offer VRP products is ultimately a missed economic opportunity. In addition, the decision to pursue these opportunities need not necessarily be in the form of extensive capital investment into a new VRP production division: alternate business models, including but not limited to partnerships with 'OEM-certified' third-party VRP entities, have already been successfully employed in many sectors and economies to help meet demand for VRP options, while maintaining brand integrity and quality perceptions. As observed, current approaches to circular economy have largely evolved from waste management (environmental), or from eco-innovation (economic and technological) policy strategy (Ghisellini, Cialani, and Ulgiati 2016, Geng, Tsuyoshi, and Chen 2010, Yong 2007). Both foster an appreciation for the cyclical nature and potential of value-retention within circular economy, and when combined, may foster a faster scale-up of VRP adoption and transition to circular economy.

For economies wishing to pursue circular economy and VRPs as a key aspect of an effective system, acknowledgement of the underlying order within the system can help to guide strategic policy opportunities, as simplified in Figure 92.

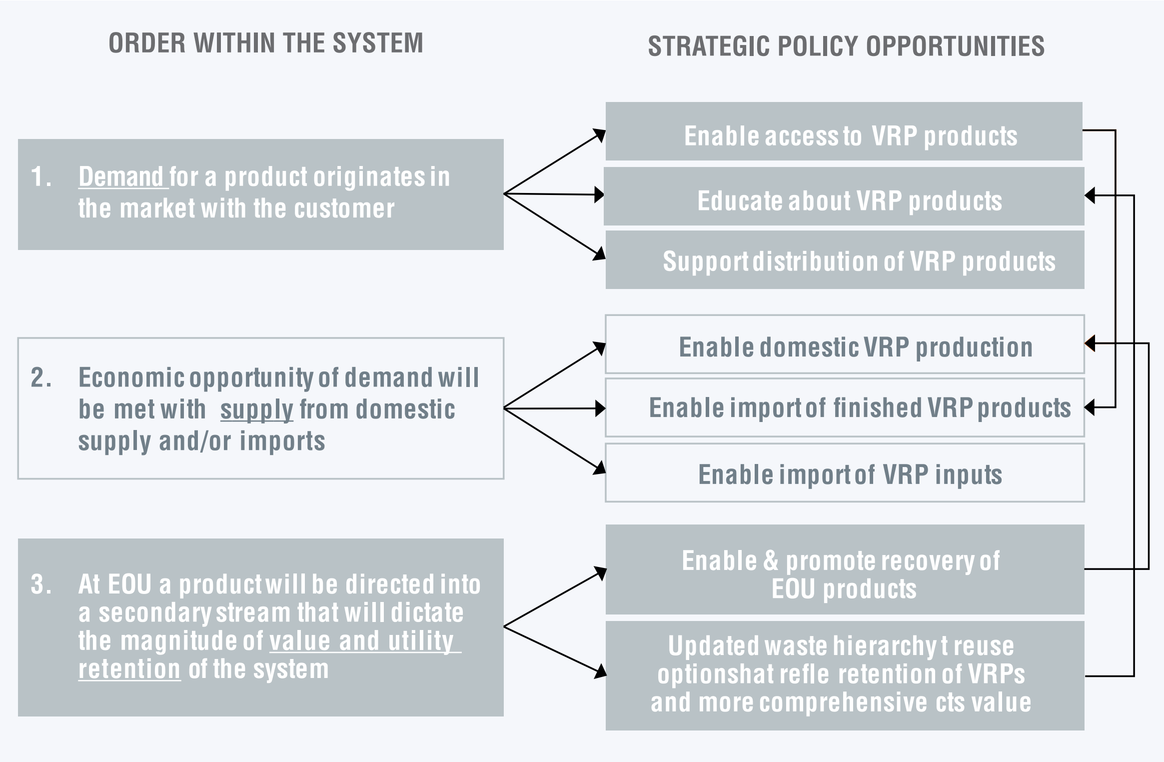


Figure 92: Inherent system order enables priorities for alleviation of VRP barriers

A simplified approach to barriers assessment and the role of government and industry members in developing strategic responses to barrier alleviation is outlined in Figure 93.

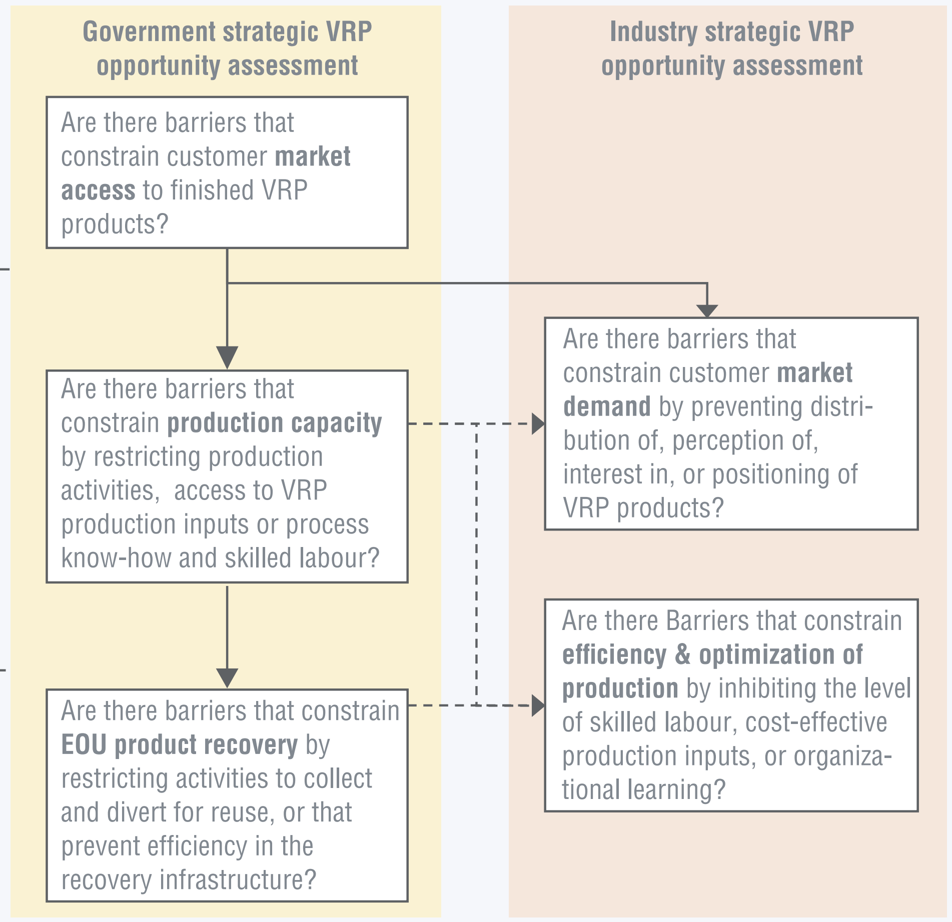
Establishing strategic priorities:

Where market access barriers:
- constrains both capacity & flow;
- affects production & customer market;
- slows uptake, and knowledge & technology transfer.

Where production constraints:
- limits domestic VRP capacity;
- inhibits competitiveness of domestic VRP producers;
- may necessitate imports;
- may necessitate reliance on OEM New.

Where market barriers:
- may constrain domestic demand;
- constrains the business case for domestic VRP producers;
- VRP products.

Where efficiency constraints:
- may restrict all system aspects: access, production, and market demand;
- limits the speed and magnitude of VRP uptake and adoption;
- limits the achievement of VRP benefits.



Government strategic VRP opportunity assessment

Are there barriers that constrain customer **market access** to finished VRP products?

Are there barriers that constrain **production capacity** by restricting production activities, access to VRP production inputs or process know-how and skilled labour?

Are there barriers that constrain **EOU product recovery** by restricting activities to collect and divert for reuse, or that prevent efficiency in the recovery infrastructure?

Industry strategic VRP opportunity assessment

Are there barriers that constrain customer **market demand** by preventing distribution of, perception of, interest in, or positioning of VRP products?

Are there Barriers that constrain **efficiency & optimization of production** by inhibiting the level of skilled labour, cost-effective production inputs, or organizational learning?

Figure 93: Role of government and industry decision-makers in assessment of VRP barriers and strategic priorities

As suggested throughout this report, there is a need to balance the tension between short-term economic priorities of growth and human well-being, and longer-term objectives of a cohesive socioeconomic relationship with the environment via sustainability. The marginal reduction in the environmental impacts of production that are enabled via VRPs and circular economy provide an opportunity to bridge both short- and long-term, economic- and environmental, objectives via material efficiency and productivity (UNEP 2016b).

Accepting the tension between these short-term and longer-term objectives, short-term efforts must seek out opportunities for increased material efficiency, resource efficiency and productivity, including marginal reduction in the environmental impacts of production (UNEP 2016b). This must occur in parallel with efforts focused on longer-term social and system transformation in pursuit of sustainable economic systems, including the ultimate decoupling of production from negative environmental impacts.

9

Conclusions

Motivated by an increasing awareness of the need to decouple escalating resource use and environmental degradation from economic growth, this assessment has investigated the current state, potential contribution, and barriers to more broad-scale incorporation of VRPs within industrial economic systems. This comprehensive assessment has revealed important insights that will inform the strategies and decisions of governments and industries around the world. The product-level analysis of five production processes (OEM new, arranging direct reuse, repair, refurbishment or comprehensive refurbishment, and remanufacturing) for nine products, revealed the varying degrees and types of benefits that VRPs can offer to three major industry sectors of the global economy. Four key global economies of US, Germany, Brazil, and China, revealed how current-state conditions, as well as the presence and nature of systemic barriers to VRPs, will affect the transition to circular economy, and the realization of economic opportunity and environmental benefits enabled through VRPs.

The need to transition towards greater resource efficiency is clear (UNEP 2017, 2014, 2016a, b). While it does not provide a universal solution to all sustainability challenges, the circular economy offers an opportunity to mitigate some of the tensions between economic, environmental, and social priorities set out by the United Nations' Sustainable Development Goals (United Nations 2017) by pursuing a modified and more efficient economic system that retains value and eliminates the inefficiency of waste (Geissdoerfer et al. 2017, Ghisellini, Cialani, and Ulgiati 2016, Cooper et al. 2017, Ellen MacArthur Foundation 2013b, World Economic Forum and Ellen MacArthur Foundation 2014). As demonstrated throughout this report, where employed appropriately VRPs, as a subset of tools for the circular economy, can provide an opportunity to reduce the marginal impacts of production while still enabling the achievement of economic and environmental enhancement (refer to Section 5). As such, where employed appropriately, the adoption of VRPs worldwide can support the objectives of increased system circularity in both industrial and non-industrial economies, the decoupling of economic growth from environmental degradation, and the pursuit of improved resource efficiency (refer to Section 7).

While some decoupling technologies and techniques are already commercially available and/or used in non-industrialized, developing/newly industrialized and developed/industrialized economies, increasing the dissemination, adoption, and economic viability of these approaches remains a challenge (UNEP 2014, 2011). The following four sections highlight the most significant conclusions resulting from this assessment.

9.1 Value-retention processes create efficiency opportunity at the product-level

The inclusion of VRPs within the domestic production mix of studied sample economies has been shown to create net-positive product-level reduction in new material requirement, embodied material energy, embodied material emissions, and in many cases, process energy and emissions as well. At the product-level, VRPs offset environmental impacts and allow for cost reduction; in the case of full service life VRPs (e.g. remanufacturing and comprehensive refurbishment), new skilled employment opportunities and customer utility are also created. VRPs do not offer equal benefits for circular economy, but, alongside recycling, are essential aspects of a circular economy strategy. Based on the case studies in this study, the most significant value-retention comes from full service life VRPs of remanufacturing and comprehensive refurbishment, despite their current low prevalence in the most well-established economies. Arranging direct reuse and repair activities (partial service life VRPs) offer an important function of extending product utility at a relatively minimal impact. These insights hold consistent when considered for additional non-case study products (printer cartridges, office furniture, and mobile phones) as well (refer to Section 5.4). It is important to note that VRPs are not necessarily appropriate for all products, and it is important for firms to carefully consider the circular economy business model and VRP adoption strategy that is optimal given their operating environment. Further discussion of the required product and system characteristics and conditions for VRPs is provided in Section 8.2.4. In the case of the industrialized sample economies studied in this assessment, when aggregated up to the scale of an economy, the increased presence of VRPs leads to an increase in avoided production impacts in every case. Although an extreme example, the Theoretical High scenarios applied to each product sector for the US, Germany, Brazil and China highlight the potential benefit that can be achieved from an increase in VRPs as part of the economy's production mix. In economies where VRPs are already well-established and accepted, market barrier alleviation that focuses on increased VRP consumption, enhanced product-system design and improved distribution channels enables new efficiency and opportunity for impact reduction. In economies where VRPs are currently low or non-existent, the alleviation of access, regulatory and collection infrastructure barriers lead to better technology, processes, and knowledge for domestic VRP producers, thus establishing a sustainable industrial foundation that can support the pursuit of circular economy.

As discussed throughout this report, the pursuit of circular economy and VRPs can be substantially affected by a range of system factors and conditions, including production and market capacity, forward- and reverse-logistics infrastructure, regulatory conditions, and social norms and cultural attitudes of an economy (refer to Section 6). While every economy must necessarily differentiate its approach, the distinction between appropriate strategies for industrialized and non-industrialized economies is worth noting, and the need to integrate perspectives and needs of the global North and global South must be emphasized (Hammond 2006, Cranston and Hammond 2012). The industrial emphasis of circular economy does not preclude the engagement of non-industrialized economies in value-retention initiatives, and the absence of industrial manufacturing systems does not imply the absence of economic systems; instead, distributed and informal approach to value-retention, including informal repair and reuse VRPs, are common (Weeks 1975, Bell and Albu 1999). Sustainability literature often emphasizes the need for economic development, including support and technology transfer from richer, industrialized economies of the global North (Hammond 2006, Cranston and Hammond 2012). Where pursued as a combined initiative of environmental and technology policy to support eco-innovation (refer to Section 8.4.2), and where global industry value-chain members from both global North and global South are engaged in voluntary pursuit of improved standards and performance (refer to Section 8.4.3), there is significant opportunity to non-industrialized economies to further engage in both domestic and global circular economy opportunities.

There is no evidence that economic status determines a country's ability to successfully engage in VRPs as a strategy for more sustainable production; rather, it is the presence and nature of systemic barriers to VRPs that affect the speed at which VRPs can be integrated and adopted, and the resulting economic and environmental benefits realized. Naturally every economy will face different barriers, and therefore it is important that the efficiency opportunity of VRPs be assessed with consideration for the unique conditions specific to each economy. While the potential for efficiency is real, the magnitude of benefits and realistic pathway to achievement of greater VRP adoption will vary, and these considerations must be incorporated into strategic policy and decision-making (refer to Sections 8.4 and 8.5).

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9.2 Adoption of product-system design approaches is critical

The cause of low prevalence of VRPs in relatively ‘open’ industrial economies is largely attributed to the fact that most VRPs are currently undertaken as an ‘art’ not as a ‘science’. A scientific approach to VRPs requires a product-systems view, in which products are developed with VRPs in mind. This inherently requires an expansion of the product’s ‘system boundaries’, to consider design requirements that maximize value-retention, enable multiple service life-cycles, and ensure efficiency within all forward- and reverse-logistics systems and subsequent VRPs (refer to Section 8.2).

Products must be designed in the context of a new set of objectives that include value-creation, value-preservation, and value-recovery; and these objectives must be established early in the product development process, long before product design engineers undertake conceptualization and design activities. The product-system design approach requires engagement and buy-in at all levels of decision-making within an organization and must be adopted very early in the product development process as a key requirement and objective of the development process. Product-Service Systems (PSSs) have provided an innovative business model foundation for further research and exploration and have demonstrated the potential for viable circular economy business models that create value for both producers and customers/users (refer to Section 8.2.1).

A scientific product-system approach also suggests an enhanced degree of standardization of the qualities and outcomes of VRPs – for example, standardization of what qualifies as a remanufactured versus a refurbished product. The diverse nature of the products that VRPs are being designed for requires significantly different steps, phases and processes to be undertaken. However, the objective outcome should be consistent, per the example set through the agreement of global vehicle parts remanufacturers (Motor & Equipment Remanufacturing Association, 2016) which establishes standard aspects of remanufacturing:

- a standardized, fully documented industrial process;
- yields same-as-new, or better, condition and performance of the remanufactured product;

- aligns with relevant technical specifications, including engineering, quality and testing standards; and
- yields a fully-warranted product.

It is essential to acknowledge that the product-system approach cannot be started fresh from a blank-slate: there are complex and comprehensive organizational and economic system conditions that must be adapted and incorporated into the new approach. Despite best intentions, education of product designers alone is insufficient: design is currently constrained by the information and data that a company has access to, and the incumbent production technology. To best support an expanded product-system approach, system information and data related to distribution, markets, forward- and reverse-logistics, and VRPs must be provided to product development and design engineers. In addition, significant investment to enhance system efficiency and adopt advanced technology, including additive manufacturing, is required. Ultimately, a high degree of data, understanding, and comfort with the additional requirements inherent to a product-systems approach is essential for engaging industry and supporting the scale-up of VRPs within an economy.

9.3 Existing reverse-logistics must be enhanced

VRPs and recycling are essential aspects of a circular economy that, in combination, optimize the retention of value within the economic system. Where VRPs retain the material value and functionality of the product, recycling retains material value in the system once product functionality has degraded. Given the value-retention objective of circular economy, VRPs must be employed alongside recycling as part of a comprehensive approach to material efficiency. In addition, the systems that govern the flows, or reverse-logistics, of EOU products from the customer market back into the system, must be optimized and enhanced. Developed and industrialized economies have invested in the achievement of highly efficient and optimized forward-logistics that have facilitated significant economic growth under the traditional linear model; enhancing the design, infrastructure, investment, and extended value-chain membership to achieve similar levels of efficiency and optimization in reverse-logistics must become a new priority as a strategy for economic and environmental improvements (refer to Sections 8.4.4 and 8.5).

Many economies have embraced recycling as an important infrastructure system, and many have set aggressive recycling system performance targets. From this perspective, and like the accepted waste hierarchy, where VRPs ensure that material value and functionality are retained within the product, once functionality has degraded it is the recycling system that ensures that material value is retained within the broader system (refer to Section 1.3.1).

Implicit in this is the fact that reliance on recycling alone can lead to lost value within the system and lost economic opportunity. The inclusion of VRPs as a requirement of a circular economy strategy, can lead to increased economic capacity and opportunity at reduced impact, simply deferring the arrival of material in the recycling system until after the functional value of a product has been used-up through extended or multiple service lives.

The effectiveness of VRPs and recycling are both determined by the effectiveness of reverse-logistics systems that capture and direct EOU products and components back into the appropriate reuse or recycling market. In effect, without the optimized flow of EOU products and components back into a value-retention process through reverse-logistics, any strategy to pursue circular economy will be ineffective. As discussed, the origin of many circular economy initiatives around the world is in the pursuit of a solution to a waste management challenge (Ghisellini, Cialani, and Ulgiati 2016, Geng, Tsuyoshi, and Chen 2010, Yong 2007) (refer to Section 8.4.2). As such, the establishment of appropriate policy and infrastructure to facilitate waste diversion, collection for recycling, and reverse-logistics for VRPs must be a top priority for any economy in which these systems do not currently exist.

As highlighted in Section 8.4.4, the success of VRPs and recycling is reliant on the effective and efficient diversion and collection of EOU products for use as inputs to the process. Collection infrastructure cannot be left to industry alone: the significant and inefficient cost-burden is prohibitive for individual organizations. Creative approaches to creating opportunities for improved efficiency performance of collection infrastructure, which may be shared by multiple organizations and/or industry, has been demonstrated by existing e-waste and packaging diversion programs worldwide, and may exist within, or separate from EPR legislation as appropriate.

In many cases, shared collection infrastructure can be initiated with the support of national funding for both education and system design. Secondary markets exist in all economies but are not always as efficient or productive as they could be. A policy-focus on the implementation of, and efficient performance of value retention and EOU collection systems is an important starting point.

In addition, new businesses opportunities within the value-chain that are focused on the provision of reverse-logistics and quality-control services have already begun to demonstrate the economic potential of business models for the circular economy.[28] It is important that policy initiatives that facilitate, encourage, and support such reverse-logistics initiatives be developed in parallel to these industry-led initiatives.

9.4 Market transformation for value-retention processes relies on government and industry

The circular economy sets out a framework in which VRPs work alongside other essential economic and behavioral strategies to reduce the environmental burden of the global economy. However, this is a grand vision, and significant market transformation is required to achieve the potential economic and environmental benefits promised by circular economy.

In the case of VRPs, ultimately, responsibility for scale-up and adoption rests with every decision-maker on the planet: from the individual consumer making an everyday purchase decision, the business leader evaluating how to improve the climate footprint of the company, the project manager establishing design requirements for a new product, through to the policy-maker considering how to plan for economic growth in the context of international GHG emissions reduction commitments. The next market transformation must ensure a shift in understanding, awareness, access and adoption of VRPs for each one of these decision-makers.

There are a range of opportunities to help kick-start this much-needed market transformation, and both governments and industry have an important role to play in helping to increase the adoption of VRPs.

As covered extensively in Section 8.5, and highlighted in Section 9.2, industry has an essential role to play in initiating and scaling-up the adoption of VRPs. In addition to adopting a product-systems approach to development, new innovations in business and ownership models can have a significant impact in the necessary market transformation (refer to Section 8.28.2.2.2). For example, there are increasing examples of business models that are focused on the service provided by a product, rather than on the ownership of the product. Under a service model, ownership and responsibility for value-retention remain with the producer, increasing the likelihood of EOU collection and repurposing into a VRPs, while still providing value and utility to the customer. Inherent in this approach is a shift away from the traditional business case focus on cost minimization, profit maximization and accomplishment of sales targets, towards a business case that emphasizes the service fee, prolonged customer relationship, and the duration of service provision – all strongly tied to high performance, value-retention, and utilization of the service-providing product.

In economies where access and regulatory barriers to VRPs exist, alleviation of these barriers must be the top priority of a government's strategic plan to pursue circular economy. However, as mentioned, the presence of these types of barriers often originated out of interest to protect human health and the environment, and these interests must continue to be protected in any barrier alleviation strategy.

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[28] Some business models support the transition of individual businesses towards more circular practices by facilitating the collection of their used products/parts around the world and returning them to a defined destination for refurbishment and remanufacturing (https://www.c-eco.com/).

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The circular economy encompasses significant complexity in both the details and systems that must be considered and managed by stakeholders, and that must be integrated with the continued traditional consumption motives of quality and performance expectations (refer to Section 8.5). As emphasized in the call for an expanded systems-view (refer to Section 8.5), policy-makers must carefully employ and balance seemingly disparate approaches and perspectives: integrated environmental policy and technology policy to facilitate and enable eco-innovation for circular economy and VRPs; the use of compliance-based (command-and-control) and market-based policy instruments to address the alleviation of barriers and the promotion of VRP adoption; and acknowledging the differing priorities and needs of economies in the global South alongside the priorities and needs of economies in the global North.

The presence of access and regulatory barriers to VRPs dominates an economy's ability to adopt VRPs and to realize the benefits of value retention within a circular economy. The presence of access barriers slows the growth of VRPs production activities, and subsequently the speed of production capacity scale-up and the related growth in customer demand for products from VRPs. Where producers are unable to access and engage in VRPs, technology and knowledge transfer are inhibited, and the business case for VRPs is quickly undermined. As previously described, barriers that inhibit market awareness and demand for VRPs should be considered a priority. In the absence of access to VRPs product options, customer market awareness is preempted, and the development and maturation of VRPs within an economy become incapacitated. The urgent implication of this scenario is that there is little ability to reduce the negative environmental impacts associated with the growth of traditional production activities. In effect, without producer and customer market access to VRPs, any tangible domestic strategy for circular economy will be in vain.

Governments, as major consumers, have an important role to play in increasing domestic adoption levels of VRPs (refer to Section 8.4.2):

1. **Enabling equal treatment of products of VRPs:** the modification of government procurement policies that may currently distinguish and/or discriminate against VRPs, in order to enable equal treatment and consideration of the products of VRPs, is an essential first step. For example, particularly in the case of remanufactured products that meet or exceed the performance requirements of an OEM New product, this equal treatment would enable procurement professionals to consider remanufactured products alongside OEM New product options[29]. Given the unit-level impact reduction enabled by remanufacturing, where appropriate, the procurement decision in favor of the remanufactured option would enable reduced environmental impact, improved economic opportunity, and cost reduction, without compromising on product quality and performance.

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[29] An example of procurement policies that are supportive of equal treatment of VRP products is the EC's Green Public Procurement (GPP) Criteria for Furniture, which specifies criteria for furniture refurbishment services and furniture end-of-life services, alongside criteria for new furniture. Refer to http://ec.europa.eu/environment/gpp/pdf/toolkit/furniture_gpp.pdf

2. **Providing incentives associated with VRPs:** For many companies, the overhaul of existing procedures in pursuit of product-system design perspectives may incite a fear of the potential for substantial short-term cost and resource burdens. The provision of incentives to motivate, reward and promote new industry practices is an essential first step to guiding a transformation of the product development process. As domestic value-retention process production activities accrue environmental impact benefits to the domestic economy, it may be in the interest of governments to support and provide incentives for producers that engage in value-retention process activities. This can help to improve economic system stability in the short-term, allowing for value-retention process production capacity and expertise to grow. Finally, similar to other incentive programs designed to promote more environmental product choices in the customer market (e.g. energy efficient light bulbs), governments may wish to promote and encourage the customer market to consider products of VRPs alongside OEM New through rebate programs or other initiatives. The validation of unfamiliar technologies by government programs may help to alleviate some of the concerns that are traditionally associated with remanufacturing and refurbishment by consumers.

Coordination between policy-makers and industry is essential: the most efficient systems will still be ineffective if products are not designed with VRPs in mind; value retention of the most material-efficient products will still be minimal without effective mechanisms for bringing them into the market and recovering them at EOU.

To help guide the evolution of both market attitudes and government policy that is appropriately supportive of VRPs, industry must take leadership in the development of industry standards and certifications that can help to overcome existing bias in the market (refer to Section 8.4.3). Clarification and standardization of the practices, processes and qualification that entail different VRPs, can help to support more appropriate international definitions.

There is much need for strong government leadership in overcoming the inconsistent and confusing terminology and definitions for VRPs, which remains one of the most significant issues and challenges to increased scale and uptake of VRPs in economies around the world. These policy-related barriers often either directly or indirectly create disadvantage, for a variety of reasons that range from consumer protection interests (e.g. import restrictions) to environmental protection interests (e.g. product recycling targets). Policy language that better reflects the potential embodied value of a core, and/or allows cores to be treated as non-waste materials, can help to better support the impact reduction potential and economic opportunity created through VRPs – including reverse-logistics, value-retention, economies of scale for VRPs, and a compelling business case for VRPs. Going forward, policy definitions of VRPs must evolve to align with, reflect, and acknowledge what is practiced within industry, and the value that these VRPs create for society and the environment alike.

9.5 Final words

The current prevalence of VRP products around the world is low, but through the adoption of VRPs it has been shown that economic opportunity (e.g. via cost reduction and employment opportunity) and the reduction of important negative environmental impacts are possible. VRPs provide the most viable and proven approach to enabling industrial circular economies: it is essential that they form the foundation of circular economy strategies of companies, industries, and economies around the world. Despite very real implementation challenges that vary across each global economy, a bold and brave change is needed if the value of VRPs is to be realized, and the pursuit of circular economies mobilized. This change must entail and embrace product development that is for the entire product-system; flows of global forward-and reverse-logistics systems must be connected, and the efficiency of these systems maximized. To help spur new levels of interest and adoption, producers and customers alike must be able to have access to a greater range of value-retention process technology and products; and new and innovative business models must be developed, tested and deployed to support meaningful market transformation. The pursuit of circular economy is a vital and tangible strategy for overcoming the significant environmental and economic challenges that we are facing. It is time for all decision makers to engage in, and take conscious action that will enable, support and lead to the large-scale adoption of VRPs worldwide.

Appendix A

Overview of case study products and sectors

This report utilizes results of detailed analysis on the selected three product sectors, and three products for each sector, for new production as well as four Value-Retention Processes (VRPs): arranging direct reuse, repair, refurbishment, and remanufacturing. The analysis covers product-level detailed data collection and analysis, as well as modeling to reflect aggregated market-level implications for each product and sector, across the four sample economies (US = A; Germany = B; Brazil = C; and China = D). The data required to complete this analysis necessarily includes:

- Volume of sales and trade; and
- Economic and environmental impacts of each product and process, excluding the use-phase, over:
  - usage Cycle, which includes the original manufacturing cycle and subsequent value-retention processes; and
  - process Cycle, which reflects only the value-retention processes.

Economic and environmental impacts were collected and/or calculated, by product and process, for key metrics:

- new material requirement (kg/unit);
- solid waste generation (kg/unit);
- process energy requirement (MJ/unit);
- process emissions generation ($kgCO_2$-eq./unit);
- relative cost-advantage (% $ USD/unit); and
- labor requirement (Full-time worker/unit).

Industrial digital printers sector

There are three products selected for case studies, representing the Industrial Digital Printers sector: a magnetic ink character recognition (MICR) production printing and finishing Production Printer (144 images/minute), a 4-color electrophotography Printing Press (84 pages/minute), and a 4-color digital color press xerography Printing Press (120-150 pages/minute). Specifically, case studies investigate these products in the category of digital industrial printers.

The industrial printing sector is comprised of both traditional (off-set) and digital print equipment. Offset printers rely on a largely mechanical process that utilizes etched metal plates to apply ink onto a sheet of paper; this traditional form of printing is typically more time consuming and expensive, often only economical when production reaches batch sizes of 2,000+ identical copies.[30,31] In contrast, digital printers use electrostatic charge in the application and fusing of toner onto a sheet of paper. Digital printing is more economical and faster than offset printing and can easily accommodate print batches as small as a single page.[30, 31]

While the market for digital printers is smaller than for traditional offset printers, this share continues to grow slowly: the nature of the market is such that both offset and digital printers are needed for different functions.[31] Where value-retention processes for digital industrial printers take place,

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[30] MGX Copy. 2014. "What's the difference between offset printing versus digital printing". MGX Copy Blog. https://www.mgxcopy.com/blog/san-diego-printing/2014/05/27/whats-difference-offset-printing-versus-digital-printing/. Accessed 24 March 2017.

[31] Chapman, A. 2009. "Product Group Report: Printing Presses: A study of the remanufacturing of offset & digital printing equipment in the U.K. Center for Remanufacturing and Reuse. www.remanufacturing.org.uk/pdf/story/1p300.pdf.

the specialized nature of the products and the specific electronic parts ensure that it is largely the OEM that is conducting the remanufacture, refurbishment or reuse of the device. The lease agreements and part exchange programs run by the OEMs largely influence the reuse of industrial digital printers.[31]

National economic reporting on industrial printers often combines offset and digital technology; while offset industrial printing presses were the dominant technology in the past, the short-run flexibility and economics of digital printers in recent years has indicated technology switching by many firms.[32]

Table A-1: Estimated 2013 market size for industrial digital printers

	Economy A (US)	Economy B (Germany)	Economy C (Brazil)	Economy D (China)
Est. 2013 Total Market Size of Industrial Printing Equipment (B$ USD)	3.78[33]	5.38[34]	0.43[35]	2.3[36]

Vehicle parts sector

There are three products selected for case studies, representing the automotive vehicle parts sector: vehicle engines, vehicle alternators, and vehicle starters.

The vehicle engine represented for the case study is a spark-ignition, internal combustion gasoline or diesel vehicle engines, which are an essential part of the fuel conversion system of non-electric passenger vehicles. A large majority of the vehicles used in United States utilize spark-ignition engines fueled with gasoline.[37] There are many different types and designs of spark-ignition engines, and the typical application is as a new or replacement component in a passenger vehicle. Spark-ignition combustion engines come in 2 and 4-stroke categories, can have multiple cylinders, and are commonly referred to as 'gasoline engines' in North America, and 'petrol engines' in the UK.[38]

Vehicle alternators are used in modern vehicles to power the electrical system and charge the battery while the engine is running. Vehicle alternators are an essential part of the vehicles electrical system, enabling the conversion and storage of kinetic energy created by the engine. Vehicle alternators are relatively 'standard' in design and are among the most commonly remanufactured vehicle components.[39]

The electric starter motor is an essential sub-component of the vehicle engine that provides the initial charge to engage and ignite the vehicle

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[32] Stewart, A. 2016. "The Offset-Printing Department: Alive & Well or in the ICU?" QP Consulting. http://quickconsultant.com/offset-alive-well-or-in-the-icu/#more-925. Accessed 24 March 2017.

[33] Per U.S. 2013 Census, NAICS (333244, 333316), reflecting value of printing machinery and equipment manufacturing (333244) and photographic and photocopy equipment manufacturing (333316).

[34] Est. based on an estimate of share of Global Market, which is $21.5B USD, per Adams, H. and S. Hill "Fundamental Change in Printing Equipment Leads to Growth", 2013. http://www.smitherspira.com/news/2013/may/change-in-printing-equipment-leads-to-growth. Accessed 25 January 2017; and estimated of Europe share (45 per cent), reduced to 25 per cent for Germany, per Production Printer Market by Type. 2016. http://www.marketsandmarkets.com/Market-Reports/production-printer-market-29764400.html. Accessed 25 January 2017.

[35] Est. based on an estimate of share of Global Market, which is $21.5B USD, per Adams, H. and S. Hill "Fundamental Change in Printing Equipment Leads to Growth", 2013. http://www.smitherspira.com/news/2013/may/change-in-printing-equipment-leads-to-growth. Accessed 25January 2017; and estimated of rest-of-world share (5 per cent), reduced to 2 per cent for Brazil, per Production Printer Market by Type. 2016. http://www.marketsandmarkets.com/Market-Reports/production-printer-market-29764400.html. Accessed 25 January 2017.

[36] Estimated per China - Global Print Power Leader. 2014. http://www.npes.org/newevents/newsroom/content.aspx?topic=China_Global_Print_Power. Accessed 25 January 2017.

[37] "4 Spark-Ignition Gasoline Engines." National Research Council. 2011. Assessment of Fuel Economy Technologies for Light-Duty Vehicles. Washington, DC: The National Academies Press. doi: 10.17226/12924.

[38] Najjar, Yousef SH. "Alternative fuels for spark ignition engines." Open Fuels & Energy Science Journal 2 (2009): 1-9.

engine, initiated with the ignition key when the vehicle is 'turned-on'. Vehicle starters, also called vehicle crankshafts, are an essential part of the vehicle's electrical system, responsible for ignition of the spark-ignition internal combustion engine. Alongside vehicle alternators, starters accounted for 92 per cent of revenues in the North American alternators and starters aftermarket in 2005; while this share declined over subsequent years, the remanufacturing of these parts is a dominant process in this industry.[39]

Table A-2: **Estimated 2013 market size for vehicle parts**

	Economy A (US)	Economy B (Germany)	Economy C (Brazil)	Economy D (China)
Est. 2013 Total Market Size of Relevant Vehicle Parts (B$ USD)	48.4[40]	91.4[41]	51.6[42]	344.6[43]

Spark-ignition internal combustion gasoline and diesel vehicle engines represent the vast majority of available vehicle technology options in scenarios markets, as described in Table A-2, with the remainder of the market consisting of electric, hybrid-electric and plug-in hybrid vehicle technologies. As the vehicle alternator and starter are sub-components of the spark-ignition internal combustion vehicle engine, these market shares are assumed for each automotive vehicle part product case study.

Table A-3: **Estimated 2013 market share of internal combusions vehicle engines**

	Economy A (US)	Economy B (Germany)	Economy C (Brazil)	Economy D (China)
Est. 2013 Market Share of Vehicles Using Spark-Ignition Internal Combustion Engines	99.4%[44]	98.5%[45]	99.8%[46]	99.9%[47]

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[39] The Automotive Parts Remanufacturers Association. 2008. http://www.apra.org/.

[40] Est. based on 2013 US Census data (NAICS 336310,336320), for motor vehicle gasoline engine and engine parts manufacturing and motor vehicle electrical and electronic equipment manufacturing. US Census: http://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=ASM_2013_31VS101&prodType=table) Accessed 12 July 2016.

[41] Estimated Germany Production (Total): $91.38B USD (2014). http://www.statista.com/forecasts/391951/germany-vehicle-part-accessory-manufacture---other-revenue-forecast-nace-c2932. Accessed 12 July 2016.

[42] Estimated total Brazil production: 51.6B USD, Per: http://www.statista.com/statistics/295184/revenue-of-the-auto-parts-industry-brazil/. Accessed 12 July 2016.

[43] Estimated China production per Joseph Chow, Chairman APRA Asia-Pacific, in personal email communication 08 February 2017.

[44] International Economic Development Council, 2013 "Creating the clean energy economy: Analysis of the electric vehicle industry". http://www.iedconline.org/clientuploads/Downloads/edrp/IEDC_Electric_Vehicle_Industry.pdf. Accessed 09 February 2017.

[45] JATO Dynamics Ltd. 2016. "Focus on Germany: Electric, Hybrid, and Plug-In Hybrid Vehicles FY2015 Market Overview". http://www.jato.com/wp-content/uploads/2016/03/JATO-Market-Focus-Germany-Electric-Hybrid-Plugin-Hybrid-Vehicles-2015.pdf. Accessed 09 February 2017.

[46] International Council on Clean Transportation, 2015. "Brazil Passenger Vehicle Market Statistics: International Comparative Assessment of Technology Adoption and Energy Consumption". http://www.theicct.org/sites/default/files/publications/Brazil%20PV%20Market%20Statistics%20Report.pdf. Accessed 09 February 2017.

[47] International Council on Clean Transportation, 2015. "Brazil Passenger Vehicle Market Statistics: International Comparative Assessment of Technology Adoption and Energy Consumption". http://www.theicct.org/sites/default/files/publications/Brazil%20PV%20Market%20Statistics%20Report.pdf. Accessed 09 February 2017.

Heavy-duty and off-road (HDOR) equipment parts sector

There are three products selected for case studies, representing the HDOR equipment parts sector: HDOR engines, HDOR alternators, and HDOR turbochargers. Specifically, case studies investigate these products in the category of construction and earth-moving equipment (excludes agricultural applications).

According to the US International Trade Commission (USITC)[48] and European Remanufacturing Network (ERN),[49] the HDOR segment is typically divided into several industries that include construction equipment (back-hoes, excavators), mining equipment (rock-trucks), and agricultural equipment (combines, tractors). The HDOR engine represented for the case study is 3,400 horsepower, electronic unit injection, turbocharged four-stroke diesel engine, with a tandem unit consisting of two 12-cylinder engine blocks.[50]

HDOR alternators are used to power the electrical system and charge the battery while the engine is running. Alternators are an essential part of the electrical system, enabling the conversion and storage of kinetic energy created by the engine. Alternators are relatively 'standard' in design and are among the most commonly remanufactured vehicle components.[51]

The turbocharger is a forced-induction device that compresses air and oxygen for delivery into the combustion chamber of the engine. Turbochargers are credited with increasing the volumetric efficiency of the engine, enabling greater power and fuel efficiency, and hence they are both ideal for the extreme conditions inside HDOR diesel-combustion engines.[52]

HDOR diesel combustion engines represent the vast majority of available HDOR technology options in scenarios markets, as described in Table A-3. As the alternator and turbocharger are sub-components of the spark-ignition internal combustion vehicle engine, these market shares are assumed for each HDOR part product case study.

Table A-4: Estimated 2013 market size for HDOR equipment parts

	Economy A (US)	Economy B (Germany)	Economy C (Brazil)	Economy D (China)
Est. 2013 Market Size of HDOR Construction and Mining Equipment ($B USD)	36.7B[53]	12.3B[54]	48.0B[55]	59.6B[56]

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[48] U.S. International Trade Commission. 2012. Remanufactured Goods: An Overview of the U.S. and Global Industries, Markets and Trade. Washington, D.C.: U.S.: U.S. International Trade Commission.

[49] European Remanufacturing Network. 2015. Remanufacturing Market Study. European Commission.

[50] "Products " Machines " Off-Highway Trucks " Mining Trucks " 797B Benefits & Features Powertrain - Engine". Caterpillar Website. Caterpillar Inc. Archived from the original on 2009-12-10.

[51] The Automotive Parts Remanufacturers Association. 2008. http://www.apra.org/.

[52] Caterpillar. 2015. Turbochargers. https://parts.cat.com/en/catcorp/turbochargers#facet:&productBeginIndex:0&orderBy:&pageView:grid&minPrice:&maxPrice:&pageSize:&. Accessed 20 March 2017.

[53] Per U.S. 2013 Census, NAICS (333120, 333131), reflecting value of construction machinery and equipment manufacturing, and mining machinery and equipment manufacturing.

[54] Germany Trade & Invest. 2016. Industry Overview: The Machinery & Equipment Industry in Germany. https://www.gtai.de/GTAI/Content/EN/Invest/_SharedDocs/Downloads/GTAI/Industry-overviews/industry-overview-machinery-equipment-en.pdf?v=11 Accessed 20 March 2017.

[55] EMIS. Machinery & Equipment Sector Brazil. 2014. https://www.emis.com/sites/default/files/EMIS%20Insight%20-%20Brazil%20Machinery%20and%20Equipment%20Sector.pdf. Accessed 20 March 2017.

[56] Freedonia Group, 2015. "Construction Machinery in China to 2016 - Demand and Sales Forecasts, Market Share, Market Size, Market Leaders". http://www.freedoniagroup.com/Construction-Machinery-In-China.htm. Accessed 12 July 2016

Appendix B

Assessment methodology

Conceptual framework

To help facilitate and support more circular economies, it is important to understand the impacts that different types of innovation can have upon products, businesses, sectors, and economic systems. Given the broad range of innovations that can influence, and are essential to circular economies, a hybrid approach utilizing bottom-up (product and process-level) and top-down (economy-level) perspectives enables appropriate reflection of different VRP impacts across product systems.

The analysis presented in this report utilizes a hybrid of bottom-up and top-down evaluations to capture some of the more significant economic and environmental impacts of both innovation, and barriers to broad applications in the circular economy. This approach does not undertake a life-cycle analysis (LCA) method, however it does incorporate an attributional approach that identifies and accounts for specific states and impacts of the relevant processes at the product-level and at the aggregated economy-level (refer to the following sections). Per Figure B-1, an overview of these approaches is provided below, and expanded on in more detail in subsequent sections.

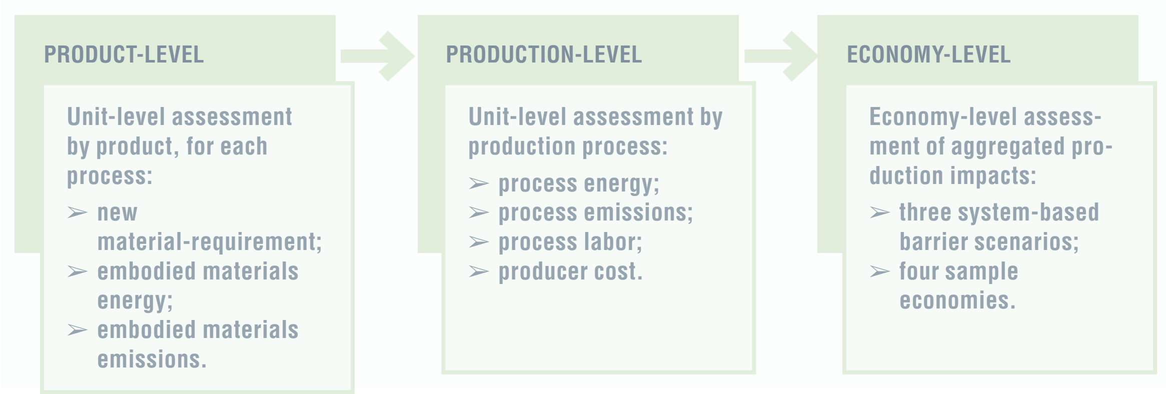


Figure B-1: Overview of conceptual assessment framework

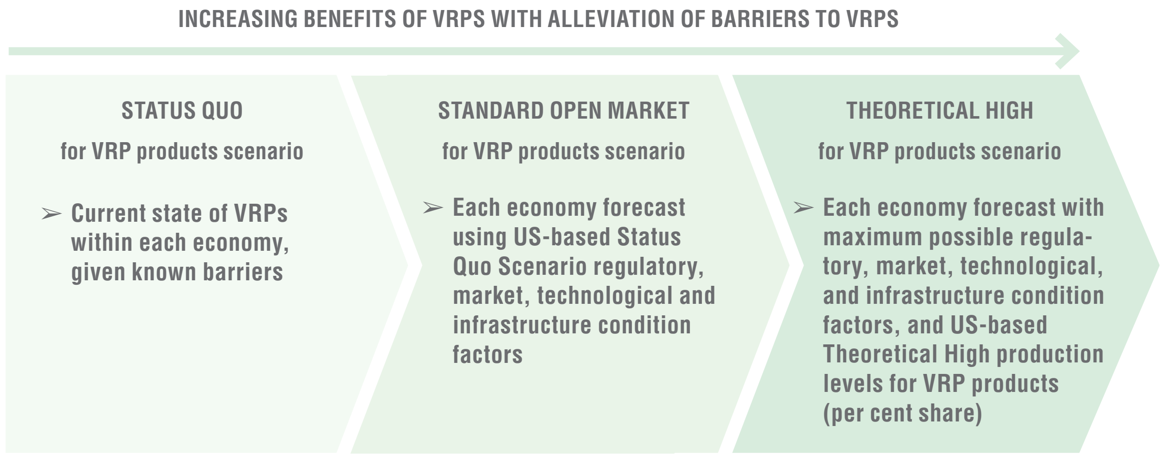
- **Product:** At the product-level, a bottom-up approach is used to assess production requirements and life cycle implications for a single individual product, across each VRP. For example, this includes new material requirement (kg/unit), embodied materials energy requirement (MJ/unit), and embodied materials emissions impact ($kgCO_2$-eq./unit) for every unit produced. Comprehensive empirical data collection for a sample of ten products, representing three different sectors is used to highlight the product-level economic and environmental impacts of VRPs within the circular economy (refer to

Table 1). Appendix A describes these case study products and sectors in greater detail.

- **Production:** Production-level impacts (or factors) layer on the process-specific impacts of production for OEM New and each VRP on a per-unit basis. These impacts include process energy requirement (MJ/unit), associated process emissions (kgCO_2-eq./unit), the labor requirement (full-time worker/unit), and the cost advantage (% $ USD/unit). Production impacts are reflected in a per-unit basis to support and enable subsequent aggregation at the macro-sector and economy scales. Given the differing nature of production across global economies, production impacts are reflected in economy-specific impact factors for each of the example production regions: Brazil, China, Germany, and the United States of America (US).
- **Economy:** Product- and production-level impacts per unit are aggregated to the macro-sector and economy scales differently, depending on production mix, production facility performance, as well as the country of origin. Product-level impact data are incorporated into a top-down aggregation approach, based on estimated production volumes for each case-study product and sector in an economy.

To assess the magnitude of impact that current common barriers to VRPs may have upon economic and environmental impact measurements, the top-down approach normalizes production levels across four sample economies (US, Germany, Brazil and China) under a Status Quo (current state) scenario. Barriers to VRPs are well documented; this analysis extends, through sensitivity analysis, understanding of which barriers to VRPs most significantly constrains the transition to circular economy. Where the impacts of barriers cause inefficiency and/or negative impacts for different stakeholders and/or to the environment, policy approaches may then be used to appropriately and effectively target specific barriers for alleviation/mediation of both the barrier, and the resulting impact.

Two additional barriers-based scenarios are utilized to examine the impact of different barrier alleviation initiatives upon each of the four sample economies: these include a Standard Open Market for VRP Products scenario, and a Theoretical High for VRP Products scenario. The regarding barrier alleviation scenarios are further described in Figure B-2 and further analyzed in Section 7.



- Current state of VRPs within each economy, given known barriers
- Each economy forecast using US-based Status Quo Scenario regulatory, market, technological and infrastructure condition factors
- Each economy forecast with maximum possible regulatory, market, technological, and infrastructure condition factors, and US-based Theoretical High production levels for VRP products (per cent share)

Figure B-2: Overview of barrier alleviation scenarios

A systems-view of the economy, including production of OEM New and VRP products is essential: Understanding the interconnectedness and complexity of relationships between a range of system variables and conditions (factors) ensures a better appreciation of current-state impacts, and implications of future decision-making and policy direction. At a minimum, this study accounts for some of the primary system factors that must be considered in the context of VRP production, as described in Figure B-3.

STATE OF ECONOMY

- ❑ Growth rate for product market

OPENNESS TO PRODUCTION & TRADE OF VRP PRODUCTS

- ❑ Import & export rates of finished reuse products
- ❑ Import & export of cores
- ❑ Regulatory constraints on production, distribution, and/or sale

MARKET READINESS & MARKET PENETRATION

- ❑ Demand share (of market)
- ❑ Production share (of market)
- ❑ Customer/consumer access

STATE OF DIVERSION CUSTOMER & RECOVERY INFRASTRUCTURE

- ❑ Product expected life & EOU fall-out rate
- ❑ EOU diversion to secondary market rate
- ❑ EOL diversion to recycling rate
- ❑ EOL disposal to environment rate

STATE OF PRODUCTION EXPERTISE & INFRASTRUCTURE

- ❑ Share of new material inputs
- ❑ Share of reuse inputs
- ❑ Production waste diverted to recycling
- ❑ Production waste disposed to environment

Figure B-3: Key factors affecting value-retention processes and production systems

Extensive effort was undertaken to ensure a rigorous empirical approach. The following sections describe the model development and methodology for both the bottom-up (product- and production-level) analysis, and the top-down (aggregated economy) analysis. Included are data collection methods, key product/component characteristics used in the model, assumptions used between the various VRPs included, and description of the modeling program.

The following sections provide additional details regarding, but not limited to: non-proprietary data sources and approach to data collection; modeling assumptions and rationale; and additional methodological insights.

Table B-1: Summary of model notation

Notation		Description
SuB-and superscript notation	t	Number of Economy-Level model simulation period (t=7)
	k	Sample economy, Brazil, China, Germany, and US
	j	Case study product (3 industrial digital printers; 3 vehicle parts; 3 HDOR equipment parts)
	i	Production process: OEM New, arranging direct reuse, repair, refurbishment and remanufacturing
	c	Component of the case study product
	m	Material type
	s	Service life cycle of product (j) via process (i), in a given simulation of the Product-Level model
	h	End-of-Life (EOL) routing option for failed components/materials in Product-Level model
	n	Number of product simulations used for Product-Level model (n=1000)
Exogenous parameters and notation	α	Total weight by material type (m) for component (c) in product (j) in Product-Level model
	Y	Upstream material intensity, or upstream waste generation gross-up multiplier in Product-Level model
	δ	Burden factor for EOL routing option by material (m) for component (c) in Product-Level model
	η	Number of expected service life cycles for component (c) in product (j) in service life cycle (s)
	g	Compound Annual Growth Rate (CAGR) for product (j) in economy (k) in Economy-Level model (%)
	λ	Production mix (or share) for product (j) via process (i) in economy (k) in Economy-Level model (%)
	τ	Embodied energy per unit (product (j) via process (i) in economy (k)), global average in MJ/unit
	ω	Embodied emissions per unit (product (j) via process (i) in economy (k)), global average in kg. CO_2-eq./unit
	φ	Process energy/unit (product (j) via process (i) in economy (k)), in MJ/unit
	$\varphi(\alpha)$	Process energy/unit (product (j) via process (i)) produced in developing/newly industrialized economies, in MJ/unit
	φ(b)	Process energy/unit (product (j) via process (i)) produced in developed/industrialized economies, in MJ/unit
	PEF	Process Energy Factor enabling across-economy assessment (Please refer to Table B-23)
	β	Process emissions/unit (product (j) via process (i) in economy (k)), in kg. CO_2-eq./unit
	$\beta(\alpha)$	Process emissions/unit (product (j) via process (i)) from developing/newly industrialized economies, in kg. CO_2-eq./unit
	β(b)	Process emissions/unit (product (j) via process (i)) from developed/industrialized economies, in kg. CO_2-eq./unit
	PMF	Process Emissions Factor enabling across-economy assessment (Please refer to Table B-24)
	π_N	Non-recyclable Production Waste/unit (product (j) via process (i) in economy (k)), in kg/unit
	π_R	Recyclable Production Waste/unit (product (j) via process (i) in economy (k)), in kg/unit

Notation		Description
Exogenous parameters and notation	$\pi(\alpha)$	Total production waste/unit (product (j) via process (i)) from developing/newly industrialized economies, in kg/unit
	$\pi(b)$	Total production waste/unit (product (j) via process (i)) from developed/ industrialized economies, in kg/unit
	PWF	Production Waste Factor enabling across-economy assessment (Please refer to Table B-25)
	v	Process labor req./unit (product (j) via process (i) in economy (k)), in full-time laborer/unit
	$v(\alpha)$	Process labor req./unit (product (j) via process (i)) from developing/newly industrialized economies, in full-time laborer/unit
	$v(b)$	Process labor req./unit (product (j) via process (i)) from developed/ industrialized economies, in full-time laborer/unit
	PLF	Process Labor Factor enabling across-economy assessment (Please refer to Table B-26)
	ψ	Cost advantage (product (j) via process (i), in % $USD relative to OEM New
	RF	Regulatory and access Factor for product (j) via process (i) in economy (k) used in VRP Barrier Scenarios in Economy-Level model
	TF	Technological Factor for process (i) in economy (k) used in VRP Barrier Scenarios in Economy-Level model
	MF	Market Factor for product (j) via process (i) in economy (k) used in VRP Barrier Scenarios in Economy-Level model
	IP	Import share of demand for product (j) via process (i) in economy (k) in Economy-Level model
	IP(α)	Import share of demand from developing/newly industrialized economies for product (j) via process (i) in economy (k) in Economy-Level model (%)
	IP(b)	Import share of demand from developed/ industrialized economies for product (j) via process (i) in economy (k) in Economy-Level model (%)
Endogenous Variables Determined within the Models	M	New material requirement, by material type (m) for product (j) via process (i), in Product-Level model (kg/unit)
	Γ	Embodied energy requirement for product (j) via process (i), in Product-Level model (MJ/unit)
	ρ	Embodied emissions for product (j) via process (i), in Product-Level model (kgCO$_2$-eq./unit)
	D	Estimated demand for product (j) via process (i) in economy (k), in Economy-Level model (# of units)
	F	Fall-out rate of product (j) via process (i), based on expected service life, in Economy-Level model (%)
	C	Estimated units available for collection at end of service life/failure each period (t) in Economy-Level model (# units)
	IB	Estimated total installed base of product (j) via process (i) in economy (k) in period (t) in Economy-Level model (# units)
	X	Domestic production quantity of product (j) via process (i) in economy (k)
	I	Import quantity of product (j) via process (i) by economy (k)
	I(α)	Import quantity from developing/newly industrialized origins of product (j) via process (i) by economy (k)
	I(b)	Import quantity from developed/ industrialized origins of product (j) via process (i) by economy (k)

Bottom-up modeling: empirical data collection and product-level analysis

The empirical model that forms the basis for the product-level analysis, as well as a significant share of the empirical data collected for case study products. The analyses presented in Section 5.1, and the product-level results presented in Sections 5.2 and 5.3 would not have been possible without this foundational contribution.

To ensure that the results obtained from this analysis could be properly applied to industry-wide conclusions, preliminary product selection considerations were discussed thoroughly with industry experts, reviewed in literature, and considered in the context of current market conditions. The resulting case study sector and products were selected largely because these sectors are known to engage in VRPs, interested collaborating industry members were willing to provide access for on-site data collection and interviews, and these products represented sufficient scale within potential sample economies to enable meaningful modeling approaches.

Collection of data on case study products and processes

Where much of the current literature on circular economy and material efficiency relies on assumptions and secondary data, of primary interest to this assessment was the collection of first-hand data about case study products and production processes. Researchers were engaged in the complete disassembly and classification of constituent components and materials, as well as numerous on-site visits with industry collaborators to conduct careful observation of each production process and common practices for each case study product, wherever possible. Where on-site assessments were not possible due to proprietary concerns, industry collaborators provided detailed Bill of Materials (BOM) data sets for product-level materials analysis, as well as comprehensive utilities reports to support and enable process energy and labor requirements, for OEM New and each VRP production. Each on-site assessment involved multiple visits, and direct interaction with all levels of the organization, from front-line operators, through to business unit managers and vice-presidents; It also involved support from across the organization, including operations teams, finance, and facility management. Given the substantial scope of this assessment, in some cases process-based data could not be collected directly due to the dynamic nature of the process (e.g. repair of traditional vehicle engines). In these cases, secondary data from recent LCA and engineering literature were utilized, and additional validation was provided through review by supporting industry experts.

The data collection methodology first required an assessment of the product and product-platform key characteristics of average length of first service life (e.g. up to EOU), and actual useful life of the product-platform (e.g. up to EOL). In addition, it involved, the collection of primary product and component characteristics (e.g. weight, material types, causes of fall-out/failure), types of VRPs available for that product, production waste generation, and the potential reusability (or salvage rate, e.g. 96 per cent) of each product component, under each different VRP. This also included material requirement gross-up estimates to account for production byproduct waste and recycling, substantiated by data from relevant LCA literature.

Data collection methodology

At the material- and product-level analyses, each product was evaluated separately across the relevant metrics. The data collection methodology required working closely on-site with front-line workers and management team members of industry collaborators to study both manufacturing processes, as well as standard procedures and practices throughout each VRP. Specific product-level data collected included: component-level Bill of Materials (BOM); component-level product overview and product platform assessment; component-level characteristics (e.g. material weight, material type, associated production waste generation). The types of VRPs used for each product; component-level reusability assessment (e.g. per cent of component retained via each VRP); and product-level service life potential (e.g. number of years the product is able to be cycled via different VRPs).

Component characteristics collected

Each product is assessed at the component level, where component characteristics were collected to perform the analysis. Some components can be reused for more service lives than other components, as a result of their design, the materials they are constructed of, and the nature of the VRP utilized. By focusing on a component-level approach, the total material recirculation, on-average, for these components as part of the larger product, could be captured. As a primary objective of this study is to enable detailed comparison of impacts across different VRPs, this approach enabled the necessary comparison at a generalizable, but detailed and meaningful level. For each case study product, data collection originated with the primary components of BOM, and included the minimum following details: component weight, material type, reusability mechanism average number of service lives via each VRP, and maximum number of service lives via each VRP.

Product characteristics collected

While most of the product-level analysis is performed using component-level data, some product data considerations were required to allow for the comparison of each VRP relative to the OEM New version of the product. The two product characteristics collected are the average service life and the estimated platform life of the product. These two factors are used mainly to determine limits of components reusability. Because some VRPs do not extend the product life for an additional complete service life, these characteristics allowed for a more accurate comparison of the results across each respective VRP.

Product-level model development and approach

As described previously, a selection of products from key sectors that already engage in VRPs to some degree were selected for the product-level study. These case study products are described in Table B-2.

Table B-2: Summary of case study products and processes assessed

Sector	Case study products	Standard processes
Industrial digital printers	• Production printer • Printing press (#1) • Printing press (#2)	• All; comprehensive refurbishment • All; comprehensive refurbishment • All; comprehensive refurbishment
Vehicle parts	• Traditional vehicle engine • Lightweight vehicle engine • Alternator • Starter motor	• No significant refurbishment • No significant refurbishment • No significant refurbishment • No significant refurbishment
Heavy-duty and off-road equipment parts (HDOR)	• Engine • Alternator • Turbocharger	• All; comprehensive refurbishment • No significant refurbishment • No significant refurbishment

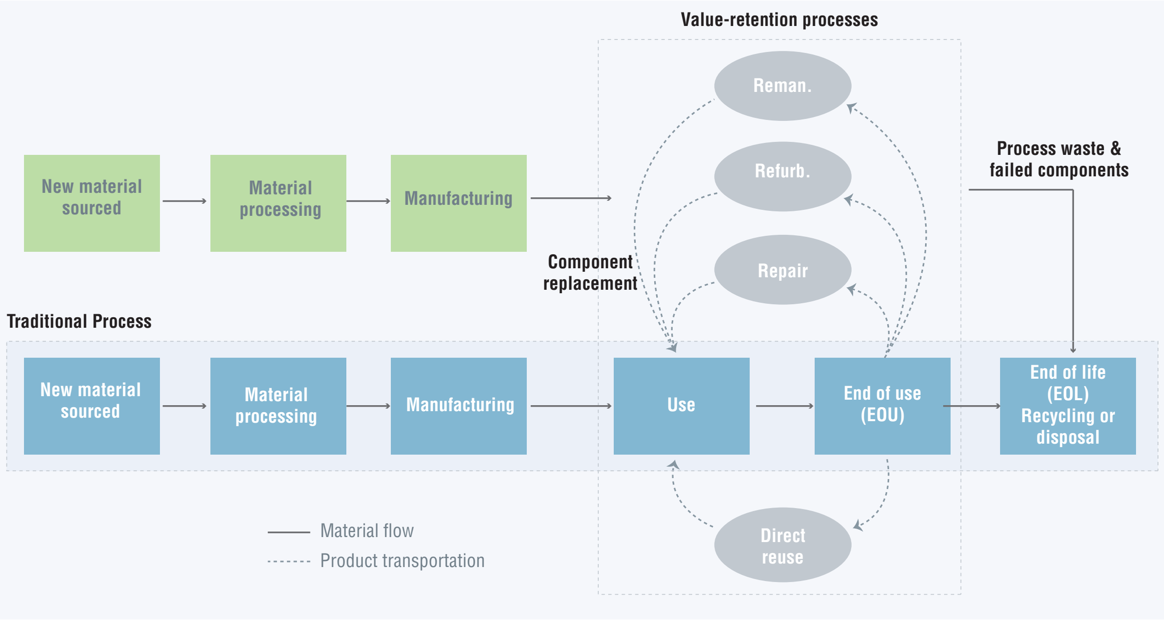


Figure B-4: Product-level system and flows for value-retention processes

The boundaries of the modeled VRPs vs. the traditional linear manufacturing system are illustrated in Table B-4, and comparison is on the basis of a single unit process cycle.

> **It is important to note that** these boundaries do not match with traditional LCA system boundaries: use-phase impacts as well as transportation impacts are specifically excluded from the study, as discussed in greater detail in Section 4.4.

As discussed previously, the way in which a VRP extends the life of the product or components will vary: Where comprehensive refurbishment and remanufacturing can provide a complete new service life to the product (or almost complete new service life, in the case of comprehensive refurbishment), arranging direct reuse, repair and refurbishment are typically used to enable the completion of the original life of the product.

To capture these relative differentiations, Table B-5 illustrates the product life of a population of each of the case study products (assumes normal distribution), in which the products fall-out of the system over the typical life span due to a range of reasons, where VRPs may be introduced, and the resulting product life implications of each VRP. For example, reuse and repair activities enable the EOU product to complete the original expected service life (hence, shorter usage cycle overlapping with the original OEM New product's expected service life curve), In the case of remanufacturing, the EOU product is typically recovered in the later phase of the expected service life (curve) and restored to like-new condition where it will experience, at minimum, an additional fully functional service life.

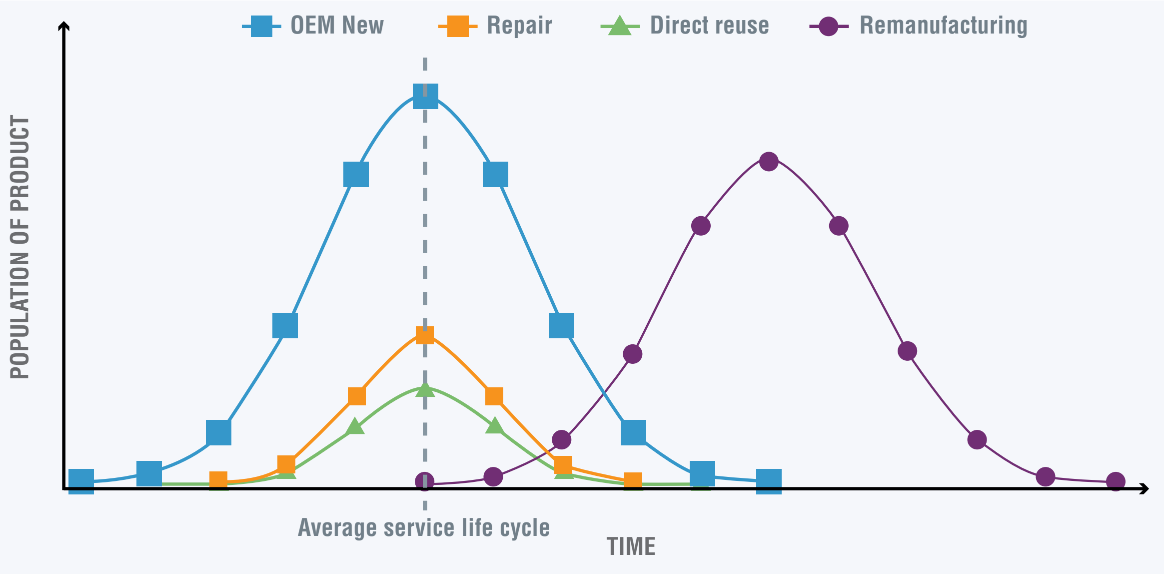


Figure B-5: Example model for reutilization of vehicle parts products at EOU through value-retention processes

The parameters affecting product service life and EOU opportunity for VRPs necessarily varies by product type, country, and market in several ways: the complexity and designed durability of the product or component may affect the length of its technical life and its condition at the typical EOU; depending on the economy, and potentially other consumer preferences and norms in different regions, some products may be kept 'in-use' through repair and reuse activities beyond the original expected life that they were designed for, as a result of income and/or other constraints that affect access to OEM New and other VRP products.

At the material level, a primary advantage of VRPs is the direct related reduction in new material requirement.[57] In other words, rather than meeting one unit of market demand by using 100 per cent new materials (OEM New), that market demand may be met via a VRP product that requires as much as 90 per cent less new material input, without constraining demand. This effectively reflects the 'new material offset' amount that is enabled by material reuse in VRPs; this material reuse results in greater material value-retention and material-use efficiency within the system.

For these case studies, the lifespan characteristics of each component were assessed differently for each VRP. For remanufacturing and refurbishment, industry collaborators participating in the study supported the estimation of the following key data points:

1. Probability of salvage at EOU (salvage rate);
2. Maximum number of times a component could be effectively reused;
3. Additional new material inputs to the process (e.g. replacement);
4. Destination of materials removed during the process (e.g. landfill or recycling);
5. The cause of component EOU, which could consist of:
    - Mechanical fatigue or failure;
    - Hazard losses; or
    - Predetermined failure (intentional replacement); and
6. Maximum potential service life of the product, after which no extension would be possible.

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[57] Please refer to the Glossary of Terms. New material includes a mixture of virgin (primary) and recycled (secondary) content. Given that the vast majority of materials available for purchase in the global economy consists of some mixture of virgin and recycled materials, the assumed ratio of virgin and recycled content used in modeling is based on the global average for each material type, in accordance with the Inventory of Carbon and Emissions (ICE) (Hammond and Jones 2011).

Additional information related to potential process impacts were requested from collaborating companies for each of the relevant products and processes, including: total process energy requirement; labor hours per unit; and average cost advantage created (versus OEM New production) via the VRP. These data points reflect the product-level requirements and impacts of production via linear and VRPs.

Product-level analysis was primarily performed at the component-level for two reasons. First, in the case of remanufacturing and comprehensive refurbishment, different product components can have different reuse-potential. In other words, within the same product, some components can be reused for multiple service lives (e.g. chassis or frame), whereas others may be limited to only a single service life (e.g. software, electronic systems). This differentiation is discussed further in Section 8.2.4. The component-level approach utilized in the product-level model ensured that total material circulation for each component, via the VRP, could be appropriately captured relative to other components and the product-platform overall. In addition, this approach enabled a more detailed assessment of value-retention and reuse-potential across each of the different VRPs. Comparison is assessed on a single unit process basis: One product, unit going through a single cycle of an OEM New or VRP process.

Essential component-level data and information, derived largely from the BOM, included material type, weight (by material), as well as the associated embodied material energy and embodied material emissions of each, using the material-based global averages from the Inventory of Carbon and Energy (Circular Ecology 2017, Hammond and Jones 2011). The presence of recycled-content at the materials-level is accounted for upfront, at the input stage: for example, the embodied materials energy and emissions values are reflective of global average recycled-content for each material, and therefore include the additional energy and emissions associated with that recycled content, on a per-kg basis.

An objective of the product-level assessment was to generalize the impacts of OEM New and VRP production of nine case study products, across facilities and economies. As such, it was not possible to meaningfully assume the origin of each material-input, for each component within each product: Instead, global average values for embodied material energy (MJ/kg) and emissions (kg CO_2-eq./kg) impact data points were used (Circular Ecology 2017, Hammond and Jones 2011). It is important to note, however, that for the process-level analysis, it was crucial to reflect process energy and process emissions, for the economy that production activity was occurring in. Thus, for production activities in each respective case study economy, process-related energy and emissions impacts were based on economy-specific aspects of efficiency (generation, as well as transmission and distribution efficiencies) as well as the implications of electricity grid mixture in terms of Global Warming Potential (GWP, kgCO_2-eq.). Process-related energy and emissions data were taken directly from the Ecoinvent 3.3 database, utilizing the average value for each case study economy.

An important aspect, when considering circular economy and VRPs, is to understand what events or mechanisms may trigger the opportunity to engage in VRPs. There are a range of reasons that a product may reach EOU and fall-out of the market, thus becoming eligible for another service life through VRPs, as discussed in greater detail in Section 3.1. Specific to the case study products assessed in this study, the product-level analysis incorporated three appropriate reusability mechanisms that are discussed in greater detail in Section 4.2.2.

The simulation program uses MATLAB to perform a Monte Carlo simulation on the stochastic model, which enables output results of average new material requirements (inversely, the required component replacement), by material type, for each production process. Due to the analysis being a stochastic model, Monte Carlo is necessary to obtain average results, as well as to address and minimize uncertainty within the model. The program takes the component-level data and simulates multiple service life cycles for the component using randomly-generated probabilities. In other words, this process determines whether the component will be reused in the VRP for an additional service life cycle. The reusability mechanisms are also applied to simulate the probability and implications of that additional VRP service life cycle.

Using the MATLAB program procedure, the product BOM is uploaded into the model, and the number of simulations, n, is defined. This can also be conceptualized as the number of products the model will run. From there, each component, m, is run through multiple service life cycles, i, until it ultimately fails through the assigned reusability mechanism, thus reaching EOL. This procedure is run for every component of the BOM, until all components have been assessed for each OEM New and VRP simulation.

This analysis estimates the average material that reaches EOL through one of the fall-out mechanisms and, inversely, the average new material required to replace that failed component in a VRP, for each consecutive service life cycle. Each product starts out as an OEM New product with original product and material composition necessary to complete a single original service life. After the initial service life, the product then becomes eligible for VRPs; however, it will only undergo a VRP based on what is appropriate for that product and based on the relevant conditions of the sector. For example, in the case of remanufacturing, some components may not be eligible for an additional service life cycle: relative to the whole product, these components may not have retained sufficient overall value to justify remanufacturing them; alternately, there may be an intolerable risk of product failure if certain components were to be reused in the process. This rigorous approach to the product-level analysis enables a more realistic understanding of: (1) the reusability of product components from an original product design standpoint; and (2) the inefficiencies that can exist within VRPs that are related to the design and nature of product components.

Product-level methodology and model

The following sections discuss and describe the modeling, assumptions, methods, and data utilized in the product-level analysis, as presented in the Report. Specifically, the following sections extend Report Section 4.2. (bottom-Up Modeling: Empirical Data Collection and Product-Level Analysis), and Section 5 (product-Level Benefits of VRPs). To ensure that the results obtained from this analysis could be properly applied to offer broader and more generalized insights, potential case study products were discussed thoroughly with industry experts, reviewed in literature, and considered from a market size perspective. To complete the analysis in the respective time, it was determined that three products would be analyzed from each sector, for a total of nine individual product case studies. The products selected are considered representative of industry activities, according to and as suggest by industry collaborators. Key considerations informing the selection of both products and sectors included but were not limited to: the availability of data and willingness of industry collaborators; current and potential technological growth within the industry sectors being studied; the size of product market, which needed to be of meaningful significance within the studied economies; and the presence of VRPs and activities for these products, in each of the studied economies.

Process-specific assumptions

VRPs are complex, and currently differ by individual product design, facility, company, and economy. Although significant efforts have been made to standardize some VRPs, the nature of each individual product requires a tailored approach, even if within a more standardized VRP process. However, for the purposes of this study, generalizations and assumptions were required. While the primary IRP Report contains the definitions and scope of each VRP considered by the study, the following sections provide greater detail regarding the specific VRP assumptions that were incorporated into the product-level model.

Reusability mechanisms

Three reusability mechanisms are included in the product-level analysis. These mechanisms reflected the typical cause of failures at the component-level and enabled the more realistic modeling of the likely reuse/replacement potential of each component, by both weight and material type, and by each VRP. One of the three primary reusability mechanisms outlined below was assigned to each component within the BOM within the product-level model:

- **Fatigue:** Applies to components that typically fail due to wear over time. These components have a durability curve applied to their useful life. Some examples of components likely to fail due to fatigue include shafts, and other mechanical components that experience fatigue. In the product-level model these components are accounted for using Weibull distribution and analysis.
- **Hazard:** Applies to components that typically fail due to misuse by the user or shipping damages (e.g. hazardous fall-out). Examples of this type of component includes structural components such as product housings or frames. In the product-level model these components are represented using a cumulative exponential distribution over multiple service life cycles.

- **Predetermined:** The 'predetermined' mechanism applies to components that are replaced based on a time-schedule or other external indicators determined by the OEM, and not as a result of direct measurement of component performance or failure. These components can include bushings, bearings, and other wear components that will be replaced as predetermined by the manufacturer. This mechanism uses a step-distribution over multiple service life cycles, where the component will be used/reused until it reaches its predetermined end-of-life, after which it is diverted into waste or recycling streams.

OEM new production

New production is used as the base case for the analysis. To compare the relative environmental and economic impacts of VRPs, OEM New products are assumed to have a single service life: the original intended service life. The analysis excludes the use-phase impacts of the case study products, and as such, the impacts of that single new production cycle reflect the environmental and economic impacts of one unit of OEM New production. where no reuse or recycling processes will be used after the typical usage cycle is complete.

Arranging direct reuse

Products that undergo arranging direct reuse are assumed to come to the end of their usefulness to an original user/owner prior to the completion of their original intended service life, and through arranging direct reuse are able to complete that original intended service life, offsetting the requirement for a new replacement unit. It is assumed that arranging direct reuse activities require no additional material or energy inputs, and do not generate waste or emissions within the arranging direct reuse process. Although the industrialized arranging direct reuse process likely creates some waste and resource requirements, these are assumed to be insignificant to the analysis. An example of arranging direct reuse would be a case where the original alternator salvaged from an automobile after an accident might be undamaged and may be directly reused without modification.

Component and material utilization in arranging direct reuse assumes a normal distribution over the typical product service life. Table B-6 shows that very early in the product service life the product will have higher value, and thus is more likely to be directly reused. The further the product service life extends past the peak of the normal distribution, the product is diminishing value and utility, suggesting that there is decreasing value for arranging direct reuse as customers may not want to invest in a product that may fail shortly after purchase.

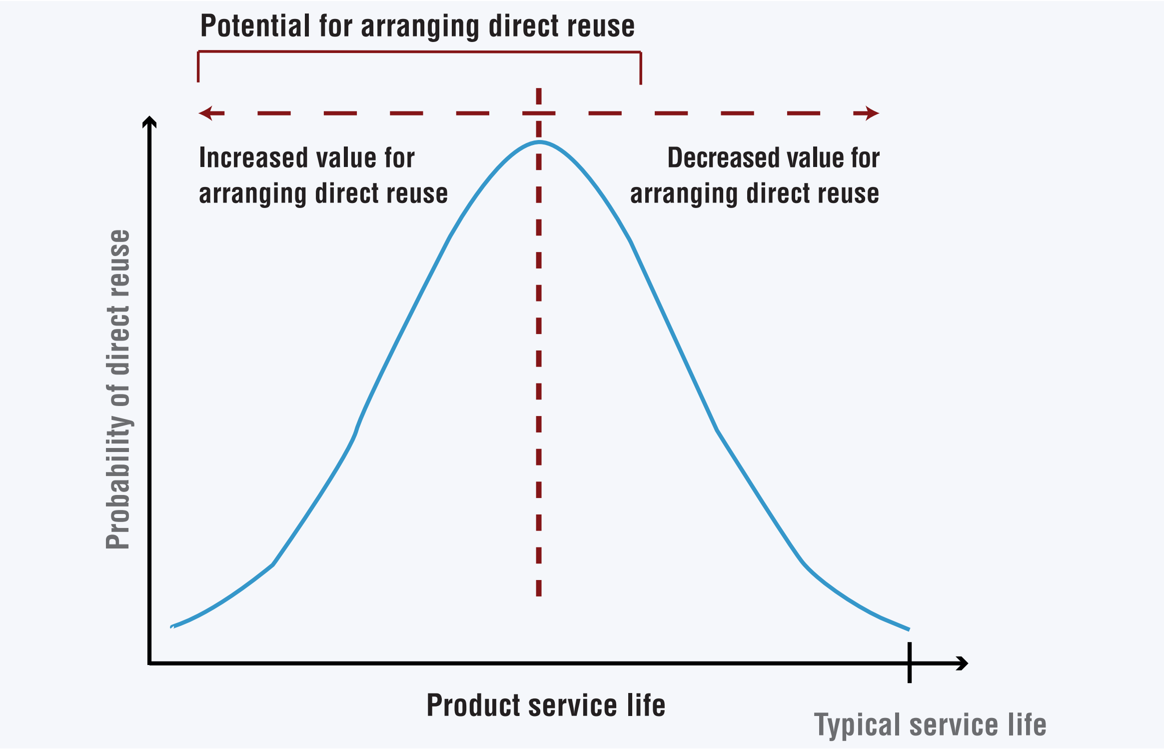

Figure B-6: Probability of arranging direct reuse distribution over typical service life

Repair

Products that undergo repair are assumed to have some component failure prior to the completion of their original intended service life. Through repair, the product can complete the original intended service life, thus offsetting the requirement for a new replacement unit. In many cases, the need for repair is expected by both manufacturer and owner, and so for the purposes of generalization, the model assumes these kinds of failures to be part of the predetermined reusability mechanism. This assumption was confirmed in interviews with relevant industry experts.

The repair process is assumed to only complete the original intended service life, not extend it. Generally, repair will include replacement of a typical failed component with a new one, after which the product is returned to the original owner to complete its service life. Given the new material inputs required by the repair process, the model also assumes the incursion of waste materials, embodied energy, and embodied emissions specific to the new material added. However, while the repair process likely incurs additional process energy and process emissions, in the absence of verifiable data, it was deemed that these process-specific impacts were negligible within the analysis.

Similar to arranging direct reuse, component and material utilization in the repair process is assumed to follow a normal distribution over the typical service life of a product. As depicted in Table B-7, products early in their service life are less likely to fail and need repair operations; in contrast, as the product ages towards the end of its intended service life, value and utility decreases to the point where the costs of repair may not be worth the marginal service life extension they offer.

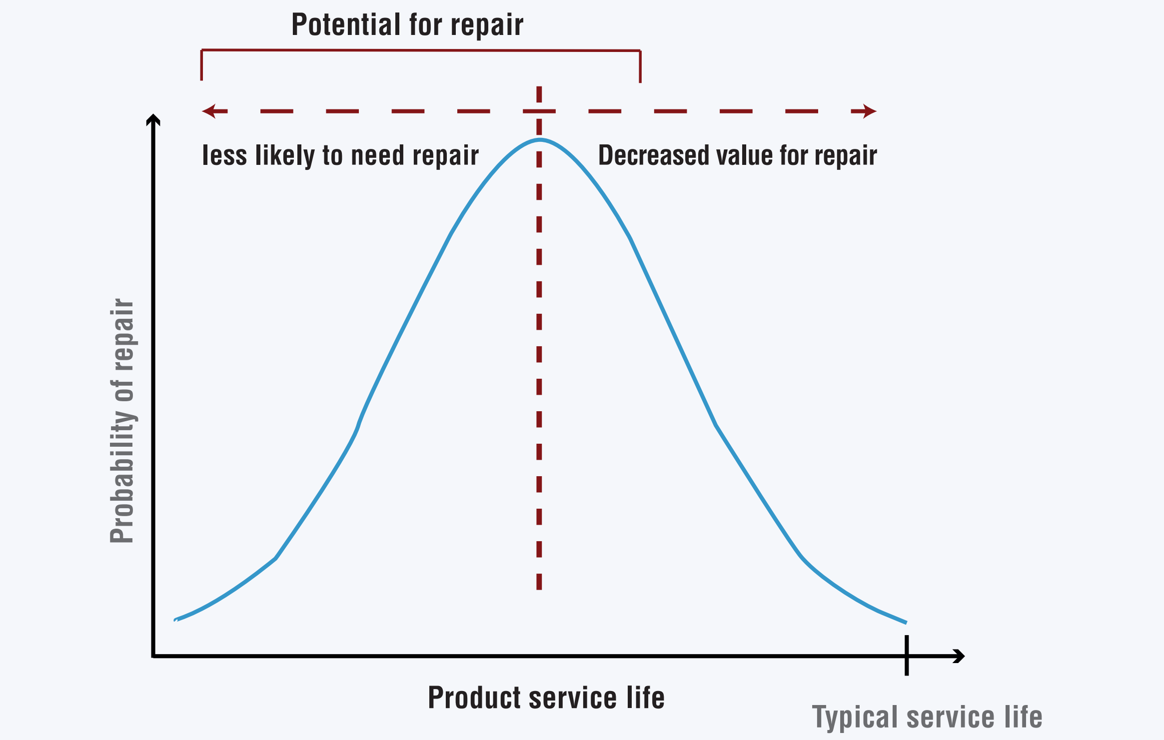

Figure B-7: Probability of repair distribution over typical service life

Refurbishment

The refurbishment process is assumed to start when a product/component reaches end-of-use (EOU) either within or at the end of a particular service life. Refurbishment follows a rigorous process that is like remanufacturing apart from two characteristics, which are assumptions within the model. Given that the product is at least partially disassembled during refurbishment, component-level reusability and impacts are assessed separately and then re-aggregated to reflect the average expected impacts at the product-level. Due to the lower acceptance threshold for refurbishment, modules and components used in refurbishment may not meet "as-new" quality specifications. As such, components that are reused through the refurbishment process are likely to have a higher probability (or rate) of reuse, and a higher probability of being lower quality. In the absence of a higher threshold for quality specifications, the component is assumed to have fewer additional service lives. This assumption is applied only to components that are assigned to the fatigue reusability mechanism.

The new material requirements, associated embodied energy and emissions, process energy and emissions, and related production material waste were all measured for each case study product/component.

Remanufacturing

Due to the robustness of the process and, by definition, the product identity being lost, remanufacturing generates products that are equivalent to the OEM New version in both performance and expectation of a full new service life. Similar to the approach used for refurbishing activities, the model first analyzes each reusability mechanism and impacts at the component level. Component-level impacts are then reaggregated to reflect average expected impacts at the product-level.

The new material requirements, associated embodied energy and emissions, process energy and emissions, and related production material waste were all measured for each case study product/component.

Calculating material requirements for VRPs

A primary advantage of circulating/recirculating products/components is the reduction in required new materials enabled by the VRP. With some inputs sourced through a circular system, the requirement for new material inputs is offset, along with associated waste, energy, and emissions impacts of extraction and processing activities. To best reflect material reuse through VRPs, and to capture the potential multiple service lives enabled via VRPs, a component-level approach is utilized. The following general formula, Equation 1, is utilized:

$$M^{i}_{j.m} = \sum_{s}\sum_{c}\frac{\alpha_{j.m.c}\gamma_{j.m.c.s}\delta_{j.m.c.s.h}}{\eta_{c.s}} \quad \forall\, i, \qquad \text{Eq. 1}$$

Where M is the new material requirement of process i (OEM New, arranging direct reuse, repair, refurbishment, remanufacturing) for each material type, assuming an average mix of primary and secondary material content; α is the material weight, Y is the upstream material intensity (e.g. processing and/or machining scrap) or waste factor, δ is the end-of-life burden multiplier (waste = 100%, 0 < Recycling Efficiency < 100%) and η represents the number of expected service life cycles. Subscripts j, m, c, s, and h represent the product, material type, component, service life cycle, and end-of-life route, respectively.

The new material requirement for each material and each component is calculated, and then aggregated over each consecutive service life. The length and number of component service lives, material reusability, and other assumptions are discussed in greater detail in the following sections.

The extension of material requirements to reflect associated embodied energy per product (ρ) and embodied emissions per product (ρ) is calculated linearly as an extension of Equation 1. With material-based embodied energy requirements reflected via τ (MJ/kg) and associated embodied emissions reflected via ω (kgCO$_2$-eq./kg), the environmental impacts associated with the material requirements of different processes are described in Equations 2 and 3.

$$\Gamma_j^i = \sum_m (M_{j,m}^i \times \tau_m^i)\ \forall\, i,j \tag*{Eq. 2}$$

$$\rho_j^i = \sum_m (M_{j,m}^i \times \omega_m^i)\ \forall\, i,j \tag*{Eq. 3}$$

Values obtained to support the calculation of Equation 2 and Equation 3 are taken from the Inventory of Carbon and Energy (ICE) database, from Circular Ecology (Hammond and Jones 2011).[58] These values and selected supporting assumptions from the ICE database are reflected in Table B-3.

Table B-3: General embodied material energy and emissions values used in product-level model

Material Type	Assumed Recycled Material Content[59] (%)	Embodied Energy (τ) (MJ/kg)	Embodied Emissions (ω) ($kgCO_2$-eq/kg)	% Embodied Energy from Energy Source[57] (%Electricity / %Other)	% Embodied Carbon from Source[57] (%Electricity / %Other)
Steel	59%	20.1	1.5	N/A	N/A
Stainless Steel	N/A	56.1	6.2	N/A	N/A
Cast Iron	0%	25.0	2.0	N/A	N/A
Copper	37%	42.0	2.7	N/A	N/A
Aluminum	33%	155.0	9.2	63.6% / 36.4%	57.2% / 42.8%
Brass	60%	44.0	2.6	87.0% / 13.0%	86.5% / 13.5%
Printed Circuit Board (PCB)[60]	0%	11,880.0	1,723.4	N/A	N/A

Source: Inventory of Carbon and Emissions (ICE), (Hammond and Jones 2011)

Product-level model assumptions

Industrial digital printers

Product-level assumptions used for modeling case study industrial digital printers are presented in Table B-4 through Table B-7. The estimated average service life achieved for each of the VRP processes was determined in interviews with industry experts who were familiar with each model of OEM New industrial digital printer, and the related VRP versions. Given that all VRPs for these case study products, excluding repair, are performed by the OEM, external service life estimates for these products were deemed less relevant and unnecessary for the purposes of this study. For the purposes of clarification, the service life provided by refurbishment of case study industrial digital Printing Press #1 and Printing Press #2 reflects an assumed 90 per cent of the service life for the remanufactured version, as validated by industry experts.

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[58] ICE Database, from the Circular Ecology website: http://www.circularecology.com/ (Hammond and Jones 2011).

[59] Values were based on "Typical", "General", and/or "R.O.W." classification in ICE Database (Hammond and Jones 2011).

[60] Embodied energy and embodied emissions estimates for printed circuit were derived from (Kemna et al. 2005). Embodied energy for copier total PCB estimated to be 3,300 kWh/kg.

Table B-4: Product model parameters and VRP assumptions for Industrial Digital Production Printer

Case Study: Industrial Digital Production Printer

Product Model Value-Retention Process Assumptions

	Estimated Service Life (Years)	Est. # of Service Life Cycles (η)	Avg. Material Reuse Per Component Per VRP Cycle $(1-\Upsilon)$ (by weight)	Avg. Prod. Waste Gross-Up Rate on New Material Inputs (δ, by BOM weight)
OEM New	7.0	1	0.0%	10.0%
Remanufactured	7.0	3	99.2%; 98.5%; 97.7%	
Refurbished	7.0	1	99.3%	
Repair	3.5	1	99.8%	
Arranging direct reuse	3.5	1	100.0%	

Table B-5: Product model parameters and VRP assumptions for Industrial Printing Press #1

Case Study: Industrial Printing Press #1

Product Model Value-Retention Process Assumptions

	Estimated Service Life (Years)	Est. # of Service Life Cycles (η)	Avg. Material Reuse Per Component Per VRP Cycle $(1-\Upsilon)$ (by weight)	Avg. Prod. Waste Gross-Up Rate on New Material Inputs (δ, by BOM weight)
OEM New	9.0	1	0.0%	10.0%
Remanufactured	8.0	4	92.3%; 82.8%; 76.9%; 71.6%	
Refurbished	8.1	1	92.7%	
Repair	4.5	1	98.2%	
Arranging direct reuse	4.5	1	100.0%	

Table B-6: Product model parameters and VRP assumptions for Industrial Printing Press #2

Case Study: Industrial Printing Press #2

Product Model Value-Retention Process Assumptions

	Estimated Service Life (Years)	Est. # of Service Life Cycles (η)	Avg. Material Reuse Per Component Per VRP Cycle (1- Υ) (by weight)	Avg. Prod. Waste Gross-Up Rate on New Material Inputs (δ, by BOM weight)
OEM New	9.0	1	0.0%	10.0%
Remanufactured	8.0	3	85.4%; 83.0; 80.6%	
Refurbished	8.1	1	96.5%	
Repair	4.5	1	98.2%	
Arranging direct reuse	4.5	1	100.0%	

Table B-7: Product model parameters and assumptions for case study Industrial Digital Printers

Case Study: Industrial Digital Printers

Product Model Assumptions

	Avg. Product Weight (kg/ unit)	# of Components per Product[61]	% Components Modeled with Cum. Exp. Distribution (Hazard)	% Components Modeled with Weibull Distribution (Fatigue)	% Components Modeled with Step Distribution (Predetermined)
Production Printer	1 115	100	76.0%	19.0%	5.0%
Printing Press #1	4 634	97	79.4%	7.2%	13.4%
Printing Press #2	2 480	202	74.8%	9.4%	15.8%

Vehicle parts

Product-level assumptions used for modeling case study vehicle parts are presented in Table B-8 through Table B-14. Average expected life of personal vehicles is 150,000 miles/life,[62] and average miles per year driven in personal vehicles is 12, 476 miles/year.[63] As such, 150,000/12, 476 is an estimated average life in years of 12.0 per vehicle. As this assessment is focused on the individual products that are part of the entire vehicle system, the life of the vehicle is used as a proxy for estimating the life of the vehicle parts products used for case study. Given that remanufacturing leads to a full new service life of the product, the remanufactured version and the OEM New version are assumed to offer equal average product service lives of 12.0 years. It is assumed that the arranging direct reuse and/or repair of these products, events which occur prior to completion of the first service life of the product, have service lives equal to 50 per cent of the full service life (partial service life) enabled via OEM New and/or remanufacturing production processes.

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61 Given BOM complexity and industry collaboration constraints, # of components per product are based on actual BOM data, reflect a minimum of 80 per cent by weight of the total product, and account for the major material types used in the production process. This approach allows for the assumption that case study products are representative of similar products for the purposes of assessing material and embodied impacts, as well as processing implications.

62 Per US DOT (U.S. Department of Transportation Federal Highway Administration 2016).

63 Per consumer reports (Bartlett 2009).

Table B-8: Product model parameters and VRP assumptions for Vehicle Engines

Case Study: Vehicle Engine

Product Model Value-Retention Process Assumptions

	Estimated Service Life (Years)	Est. # of Service Life Cycles (η)	Avg. Material Reuse Per Component Per VRP Cycle (1- Υ) (by weight)	Avg. Prod. Waste Gross-Up Rate on New Material Inputs (δ, by BOM weight)
OEM New	12.0	1	0.0%	15.0%
Remanufactured	12.0	5	83.5%; 52.0%; 44.6%; 40.3%; 36.5%	
Refurbished	–	–	–	
Repair	6.0	1	91.3%	
Arranging direct reuse	6.0	1	100.0%	

Table B-9: Product model parameters and VRP assumptions for Vehicle Alternators

Case Study: Vehicle Alternator

Product Model Value-Retention Process Assumptions

	Estimated Service Life (Years)	Est. # of Service Life Cycles (η)	Avg. Material Reuse Per Component Per VRP Cycle (1- Υ) (by weight)	Avg. Prod. Waste Gross-Up Rate on New Material Inputs (δ, by BOM weight)
OEM New	12.0	1	0.0%	10.0%
Remanufactured	12.0	4	76.7%; 43.9%; 27.3%; 16.7%	
Refurbished	–	–	–	
Repair	6.0	1	80.0%	
Arranging direct reuse	6.0	1	100.0%	

Table B-10: Product model parameters and VRP assumptions for Vehicle Starters

Case Study: Vehicle Starter

Product Model Value-Retention Process Assumptions

	Estimated Service Life (Years)	Est. # of Service Life Cycles (η)	Avg. Material Reuse Per Component Per VRP Cycle (1- Υ) (by weight)	Avg. Prod. Waste Gross-Up Rate on New Material Inputs (δ, by BOM weight)
OEM New	12.0	1	0.0%	10.0%
Remanufactured	12.0	4	77.9%; 57.1%; 54.6%; 52.6%	
Refurbished	–	–	–	
Repair	6.0	1	92.7%	
Arranging direct reuse	6.0	1	100.0%	

Table B-11: Product model parameters and VRP assumptions for Vehicle Parts

Case Study: Vehicle Parts

Product Model Assumptions

	Avg. Product Weight (kg/ unit)	# of Components per Product[61]	% Components Modeled with Cum. Exp. Distribution (Hazard)	% Components Modeled with Weibull Distribution (Fatigue)	% Components Modeled with Step Distribution (Predetermined)
Vehicle Engine	136	61	13.1%	41.0%	45.9%
Vehicle Alternator	7	11	27.3%	54.5%	18.2%
Vehicle Starter	4	38	10.5%	57.9%	31.6%

HDOR equipment parts

Product-level assumptions used for modeling case study HDOR equipment parts are presented in Table B-12 through Table B-15. The estimated average service life achieved for each of the VRP processes was determined in interviews with industry experts who were familiar with the OEM New HDOR case study equipment parts, and the related VRP versions. Given that all VRPs for these case study products, excluding repair, are performed by the OEM, external service life estimates for these products were deemed less relevant and unnecessary for the purposes of this study. For the purposes of clarification, the service life provided by refurbishment reflects an assumed 90 per cent of the service life for the remanufactured version, as validated by industry experts.

Table B-12: Product model parameters and VRP assumptions for HDOR Engines

Case Study: HDOR Engine

Product Model Value-Retention Process Assumptions

	Assumed Service Life (Years)	Est. # of Service Life Cycles (η)	Avg. Material Reuse Per Component Per VRP Cycle ($1-\Upsilon$) (by weight)	Avg. Prod. Waste Gross-Up Rate on New Material Inputs (δ, by BOM weight)
OEM New	3.0	1	0.0%	15.0%
Remanufactured	3.0	4	92.8%; 74.4%; 37.7%; 67.6%	
Refurbished	2.7	1	–	
Repair	1.5	1	91.9%	
Arranging direct reuse	–	–	100.0%	

Table B-13: Product model parameters and VRP assumptions for HDOR Alternators

Case Study: HDOR Alternator

Product Model Value-Retention Process Assumptions

	Service Life Per Industry Expert (Years)	Est. # of Service Life Cycles (η)	Avg. Material Reuse Per Component Per VRP Cycle (1- Y) (by weight)	Avg. Prod. Waste Gross-Up Rate on New Material Inputs (δ, by BOM weight)
OEM New	3.0	1	0.0%	10.0%
Remanufactured	3.0	9	71.6%; 52.2%; 37.7%; 27.5%; 19.3%; 12.0%; 6.5%; 3.0%; 1.1%	
Refurbished	–	–	–	
Repair	1.5	1	72.7%	
Arranging direct reuse	–	–	100.0%	

Table B-14: Product model parameters and VRP assumptions for HDOR Starters

Case Study: HDOR Starter

Product Model Value-Retention Process Assumptions

	Assumed Service Life (Years)	Est. # of Service Life Cycles (η)	Avg. Material Reuse Per Component Per VRP Cycle (1- Y) (by weight)	Avg. Prod. Waste Gross-Up Rate on New Material Inputs (δ, by BOM weight)
OEM New	3.0	1	0.0%	10.0%
Remanufactured	3.0	5	91.5%; 68.4%; 49.3%; 40.4%; 37.9%	
Refurbished	–	–	–	
Repair	1.5	1	83.3%	
Arranging direct reuse	–	–	100.0%	

Table B-15: Product model parameters and assumptions for HDOR Equipment Parts

Case Study: HDOR Equipment Parts

Product Model Assumptions

	Avg. Product Weight (kg/ unit)	# of Components per Product[61]	% Components Modeled with Cum. Exp. Distribution (Hazard)	% Components Modeled with Weibull Distribution (Fatigue)	% Components Modeled with Step Distribution (Predetermined)
HDOR Engine	15,323	108	0.0%	100.0%	0.0%
HDOR Alternator	49	12	33.3%	50.0%	16.7%
HDOR Turbocharger	75	6	50.0%	50.0%	0.0%

Simulation product-level program model

As the nature of the model is stochastic, a MATLAB program to perform a Monte Carlo simulation to obtain an estimated new material requirement for the average component, by material type, during a single VRP service life cycle. In order to determine whether the component will be reused for additional service lives, the program imports the component-level reusability and material information to simulate that component over multiple service lives against random generated probabilities. Utilizing the reusability mechanisms, assigned based on the characteristics of each component, the probability of reuse for each additional service life is assessed and compared to the randomly-generated probability to determine whether the component will fail and require replacement. The MATLAB program flow for component analysis is described further in Figure B-8, based on Equation 1.

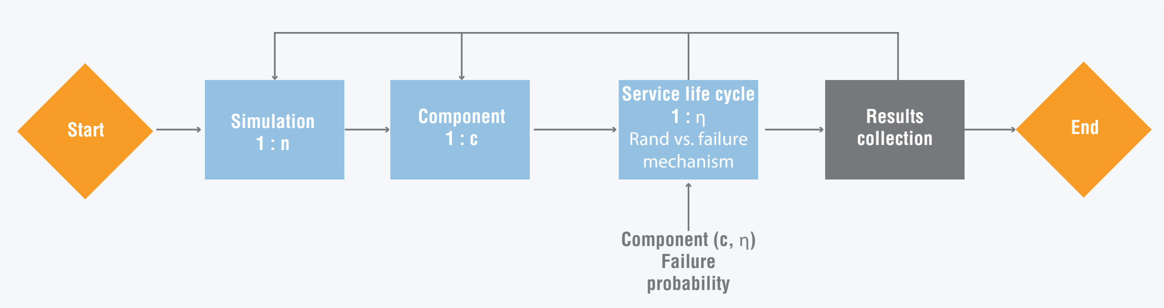

Figure B-8: MATLAB program flow chart

Per Figure B-8, once the product BOM data is imported into the model, the user then defines the number of simulations, or representative *products*, (n = 1000) that the model will run. Each component (*c*) is run through multiple service life cycles (η) until it fails. Component failure is determined for each component within the BOM through the comparison of a random distribution variable to the reusability mechanism distribution for each specific component and service life. The model then returns to the next component and repeats the process. After each of the components have been assessed, the program stores the results for the product, and moves on to the next simulation.

Interpreting outputs of the model

The outputs of the program are reflected as an estimation of material that goes to end-of-life through each consecutive VRP process. The product starts out with the original material composition necessary to complete a single intended service life. After the initial service life, the product can undergo any one of the VRPs. Each VRP has varying levels of failure/reusability within the component analysis. For example, in the case of remanufacturing, some components may not be reused for an additional service life because they do not have enough overall value when compared to the larger product, or, because there may be too much risk of product-level failure if the components are reused. When there is no reuse of the component, it is assumed that the component will go to end-of-life (EOL) for recycling or into the waste stream. This approach to the analysis highlights the reusability of components from an original product design standpoint, and highlights inefficiencies within the different VRPs affecting the reuse of certain components.

The results of product-level modeling, which include average new material requirements for each case study product and process, are included in Section 5.

Methodology for connecting process-level and economy-level models

To standardize the baseline assessment of case study products and production processes, the process-level methodology has production-unit basis. In other words, the process-level requirements and impacts for a single case study product unit, by each production process, were determined. The assessment of process-level unit-production impacts and requirements involved on-site empirical data collection with collaborating industry members. In cases where certain product-level data was not available, the authors referred to relevant LCA literature for additional insight and guidance.

The product-unit basis of process-level impact and requirement measurements ensured that these impacts could be aggregated, based on domestic production and import volumes, to reflect the overarching impacts and requirements of OEM New and VRP production activities for studied products and economies.

The objective of this assessment was not to conduct a comprehensive LCA for each case study product, rather, to provide representative data collection and analysis for studied products and sectors to inform and further the discussion about VRP adoption amongst industry-leaders and policy-makers alike. The following sections provide an overview of detailed data, parameters and assumptions required for the process-level model.

Process-level production impact and requirement factors

For process-related energy requirement and emissions generation, the following information is presented for the US, which was utilized as the base-case comparison for estimation across scenario economies. Impact factors to relate and reflect differing conditions in sample economies are discussed further in Table B-23 through Table B-26.

Process-level environmental impacts

Process energy requirement (MJ/unit) is based upon the at-the-meter (gate-to-gate) production process-cycle energy requirement (MJ/unit), by product, empirically collected for US production activities. Within the mathematical modeling presented in subsequent sections process energy represented as φ. Empirically collected observations and data reflect that the vast majority of energy used in the production processes for case study products is electric in nature. For the purposes of this assessment, process energy is assumed to be in the form of electricity. Thus, at-the-meter process energy values are then multiplied by the electricity infrastructure efficiency factor for each economy to determine an estimated total process energy requirement. This approach also informs the calculation of process-related emissions.

Process emissions impact (kgCO$_2$-eq./unit) were calculated by multiplying process energy requirement (MJ/unit) by the economy-specific GWP 100a factor (kgCO$_2$-eq./ MJ) for medium-voltage market group electricity. Within the mathematical modeling presented in subsequent sections process emissions is represented as β. These data were derived from the Ecoinvent 3.3 database, which utilized the IPCC 2013 methodology. The authors appreciate the implication that emissions impacts are, thus, necessarily conservative estimates. The process-level (gate-to-gate) energy and emission impacts for case study industrial digital printers, vehicle parts, and HDOR equipment parts are reflected in Table B-16, Table B-17, and Table B-18 respectively.

The data shown below reflect assumptions and impacts for the US only. Economy-specific conditions affecting process energy requirement are discussed in the following sections, and the electricity infrastructure efficiency factors for each sample economy are presented in Table B-23. Economy-specific conditions affecting process emissions are discussed in the following sections, and associated emissions factors for sample economies are presented in Table B-24.

Table B-16: Per-unit process energy and emissions assumptions for case study industrial digital printers

		At-the-Meter Process Energy (MJ/Unit)	Electricity Infrastructure Efficiency Factor (US)[64]	Process Energy Requirement (φ) (MJ/Unit)	GWP 100a Emissions Factor (US)[65]	Process Emissions (β) (kgCO$_2$-eq./Unit)
Production Printer	OEM New	3,224.2	2.537	8,179.6	0.183	589.7
	Reman	1,388.1	2.537	3,521.6	0.183	253.9
	Refurb	502.6	2.537	1,275.2	0.183	91.9
	Repair	0.0	2.537	0.0	0.183	0.0
	Arranging DR	0.0	2.537	0.0	0.183	0.0
Printing Press #1	OEM New	95,375.1	2.537	241,464.3	0.183	17,443.0
	Reman	39,622.5	2.537	100,521.4	0.183	7,246.5
	Refurb	29,707.2	2.537	75,366.4	0.183	5,433.1
	Repair	0.0	2.537	0.0	0.183	0.0
	Arranging DR	0.0	2.537	0.0	0.183	0.0
Printing Press #2	OEM New	39,395.8	2.537	99,946.2	0.183	7,205.1
	Reman	14,309.5	2.537	36,302.9	0.183	2,617.1
	Refurb	5,852.7	2.537	14,848.1	0.183	1,070.4
	Repair	0.0	2.537	0.0	0.183	0.0
	Arranging DR	0.0	2.537	0.0	0.183	0.0

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[64] For clarification on electricity infrastructure efficiency factor determination, please refer to Table B-23.

[65] For clarification on GWP 100a emissions factor determination, please refer to Table B-24.

Table B-17: **Per-unit process energy and emissions assumptions for case study vehicle parts**[66]

		At-the-Meter Process Energy (MJ/Unit)	Electricity Infrastructure Efficiency Factor (US)[67]	Process Energy Requirement (φ) (MJ/Unit)	GWP 100a Emissions Factor (US)[68]	Process Emissions (β) (kgCO$_2$-eq./Unit)
Vehicle Engine[69]	OEM New	4 374.0	2.537	11,096.7	0.183	800.0
	Reman	1 530.0	2.537	3,881.6	0.183	279.8
	Refurb	-	2.537	-	-	-
	Repair	0.0	2.537	0.0	0.183	0.0
	Arranging DR	0.0	2.537	0.0	2.370	0.0
Vehicle Alternator[70]	OEM New	261.0	2.537	662.2	0.183	47.7
	Reman	34.9	2.537	88.5	0.183	6.4
	Refurb	–	2.537	-	-	-
	Repair	0.0	2.537	0.0	0.183	0.0
	Arranging DR	0.0	2.537	0.0	0.183	0.0
Vehicle Starter[71]	OEM New	196.1	2.537	497.4	0.183	35.9
	Reman	26.2	2.537	66.5	0.183	4.8
	Refurb	–	2.537	-	-	-
	Repair	0.0	2.537	0.0	0.183	0.0
	Arranging DR	0.0	2.537	0.0	0.183	0.0

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[66] Per Industry Experts, it is assumed that there is no refurbishment performed on case study vehicle parts products.

[67] For clarification on electricity infrastructure efficiency factor determination, please refer to Table B-23.

[68] For clarification on GWP 100a emissions factor determination, please refer to Table B-24.

[69] Case study results for vehicle engines was supported by, and/or informed by max. replacement scenario findings by Smith and Keoleian (2004).

[70] Case study results for vehicle alternators was supported by, and/or informed by findings by Kim, Raichur and Skleros (2008).

[71] Case study results for vehicle starters were informed by findings for the vehicle alternator, by Kim, Raichur and Skleros (2008). These results were evaluated empirically and adjusted if/where necessary to reflect vehicle starter conditions.

Table B-18: Per-unit process energy and emissions assumptions for case study HDOR equipment parts[72]

		At-the-Meter Process Energy (MJ/Unit)	Electricity Infrastructure Efficiency Factor (US)[73]	Process Energy Requirement (φ) (MJ/Unit)	GWP 100a Emissions Factor (US)[74]	Process Emissions (β) (kgCO$_2$-eq./Unit)
HDOR Engine	OEM New	475 077.8	1.472	699 415.3	2.370	1 657 782.0
	Reman	166 179.5	1.472	244 651.4	2.370	579 882.6
	Refurb	124 634.6	1.472	183 488.6	2.370	434 912.0
	Repair	0.0	1.472	0.0	2.370	0.0
	Arranging DR	–	–	–	–	–
HDOR Alternator	OEM New	2 269.6	1.472	3 341.4	2.370	7 919.8
	Reman	303.5	1.472	446.7	2.370	1 058.9
	Refurb	–	–	–	–	–
	Repair	0.0	1.472	0.0	2.370	0.0
	Arranging DR	–	–	–	–	–
HDOR Turbocharger	OEM New	3 460.9	1.472	5 095.1	2.370	12 076.7
	Reman	462.7	1.472	681.2	2.370	1 614.7
	Refurb	–	–	–	–	–
	Repair	0.0	1.472	0.0	2.370	0.0
	Arranging DR	–	–	–	–	–

Process-level select economic impacts

Assessment of select economic impacts of OEM New and VRP production activities were also central to the process-level methodology and assessment. Specifically, the economic impacts of interest included production waste generation (implied cost to facility, and reflection of inefficiency), labor requirement (full-time laborer/ unit), and the average cost, relative to an OEM New version of the product, to the buyer/user of the case study product (per cent $ USD relative to OEM New/unit). The select economic impacts for case study industrial digital printers, vehicle parts, and HDOR equipment parts are presented in Table B-19, Table B-20, and Table B-21, respectively.

Within the mathematical modeling presented in subsequent sections non-recyclable production waste, recyclable production waste, labor requirement, and average cost relative to OEM New are represented by π_N, π_R, v, and ψ respectively. Please note that the data shown below reflects assumptions and impacts for the US only.

Recyclable and non-recyclable production waste factors are derived from estimates by industry experts. Production waste factors for VRP processes reflect only waste generated by the

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[72] Per industry experts, it is assumed that there is no arranging direct reuse for case study HDOR equipment parts products; there is also no refurbishment of HDOR alternators and HDOR turbochargers.

[73] For clarification on electricity infrastructure efficiency factor determination, please refer to Table B-23.

[74] For clarification on GWP 100a emissions factor determination, please refer to Table B-24.

removal of failed components (if applicable), plus the addition of replacement new components/materials which are specific to that product and process. These material-based requirement values are derived from the outputs of the product-level model described previously. These are divided into recyclable and non-recyclable categories, for each material-type, at the component level accorded by case study product BOM data.

Labor requirement estimates are based on actual labor hours required to produce a single unit of each case study product, per interviews with industry collaborators. These values are reflected in terms of full-time equivalency, which assumes 40-hours/week, 50-weeks/year, or the productivity of a single laborer in the production of a single case study product unit.

Table B-19: Select economic assumptions for case study industrial digital printers

		Production Waste (Non-Recyclable) (π_N) (% product weight/Unit)	Production Waste (Recyclable) (π_R) (% product weight/Unit)	Labor Requirement (ν) (Full-Time Laborer/Unit)	Avg. Cost to Buyer/User (ψ) (% \$USD of OEM New/ Unit)
Production Printer	OEM New	3.000%	7.000%	0.0069	100.0%
	Reman	0.027%	0.063%	0.0109	81.6%
	Refurb	0.024%	0.056%	0.0035	34.7%
	Repair	0.003%	0.007%	0.0020	10.0%
	Arranging DR	0.000%	0.000%	0.0000	20.0%
Printing Press #1	OEM New	3.000%	7.000%	0.1220	100.0%
	Reman	0.159%	0.371%	0.1845	81.6%
	Refurb	0.150%	0.350%	0.1350	56.3%
	Repair	0.036%	0.084%	0.0083	5.0%
	Arranging DR	0.000%	0.000%	0.0000	20.0%
Printing Press #2	OEM New	3.000%	7.000%	0.0683	100.0%
	Reman	0.291%	0.679%	0.1033	26.3%
	Refurb	0.087%	0.203%	0.0756	11.6%
	Repair	0.036%	0.084%	0.0047	5.0%
	Arranging DR	0.000%	0.000%	0.0000	20.0%

Table B-20: Select economic assumptions and impacts for case study vehicle parts[66]

		Production Waste (Non-Recyclable) (π_N) (% product weight/Unit)	Production Waste (Recyclable) (π_R) (% product weight/Unit)	Labor Requirement (ν) (Full-Time Laborer/Unit)	Avg. Cost to Buyer/User (ψ) (% $USD of OEM New/ Unit)
Vehicle Engine	OEM New	1.500%	13.500%	0.00002934	100.0%
	Reman	0.150%	1.350%	0.00006425	85.6%
	Refurb	–	–	–	–
	Repair	0.001%	0.009%	0.00000855	20.0%
	Arranging DR	0.000%	0.000%	0.00000000	50.0%
Vehicle Alternator	OEM New	1.000%	9.000%	0.00000118	100.0%
	Reman	0.075%	0.675%	0.00000258	62.8%
	Refurb	–	–	–	–
	Repair	0.022%	0.198%	0.00000034	20.0%
	Arranging DR	0.000%	0.000%	0.00000000	50.0%
Vehicle Starter	OEM New	1.000%	9.000%	0.00000089	100.0%
	Reman	0.058%	0.522%	0.00000194	81.7%
	Refurb	–	–	–	–
	Repair	0.058%	0.522%	0.00000089	20.0%
	Arranging DR	0.000%	0.000%	0.00000000	50.0%

Table B-21: Select economic assumptions and impacts for Case Study HDOR Equipment Parts[72]

		Production Waste (Non-Recyclable) (π_N) (% product weight/Unit)	Production Waste (Recyclable) (π_R) (% product weight/Unit)	Labor Requirement (v) (Full-Time Laborer/Unit)	Avg. Cost to Buyer/User (ψ) (% $USD of OEM New/ Unit)
HDOR Engine	OEM New	1.500%	13.500%	0.07900	100.0%
	Reman	0.096%	0.864%	0.17300	76.9%
	Refurb	0.286%	2.574%	0.02548	54.5%
	Repair	0.098%	0.882%	0.00304	5.0%
	Arranging DR	–	–	–	–
HDOR Alternator	OEM New	1.000%	9.000%	0.00025	100.0%
	Reman	0.040%	0.360%	0.00056	57.6%
	Refurb	–	–	–	–
	Repair	0.030%	0.270%	0.00001	5.0%
	Arranging DR	–	–	–	–
HDOR Turbocharger	OEM New	1.000%	9.000%	0.00039	100.0%
	Reman	0.060%	0.540%	0.00085	33.9%
	Refurb	–	–	–	–
	Repair	0.010%	0.090%	0.00001	5.0%
	Arranging DR	–	–	–	–

Top-down modeling: macro-data and economy-level analysis

The dynamics of a system model that represents an entire economy are complex and have been reasonably simplified to allow for generalization within this model. While the calculation of product-level stocks and flows is largely linear, there are calls in the literature highlighting the importance of accounting for some of the key factors that influence and affect consumer behavior upon the growth and transformation of product markets (Mylan 2015, c.f. Peres, Muller, and Mahajan 2010, Subramanian and Subramanyam 2012, Weitzel, Wendt, and Westarp 2000, York and Paulos 1999).

In this case, all model simulation begins with the product market: The total quantity and representative shares of a product, by each production process type, including OEM New, arranging direct reuse, repair, refurbishment or comprehensive refurbishment, and remanufacturing. Because the objective is to simulate the influence of different conditions (often barriers) upon the various product stocks and flows within a market, all markets are assumed to start with a stock/quantity, or installed base for the specific case study product, that reflects the actual size of the reference economy. The conditions of each economy affect how that installed base is shared by OEMs (New) and VRP producers, as well as how those market shares are expected to evolve over a period of time.

A simplified descriptive representation of the top-down model is presented in Figure B-9, below. To reflect growth, market evolution, and compounding complexity in a realistic and meaningful way, these scenario projections are simulated over a seven-year period. This simulation period does not reflect a suggested or optimal circular economy transformation timeline, as such a comprehensive transformation must be grounded in the actual conditions of each individual economy, and must reflect the priorities of each individual initiative, some of which may require significantly more (less) time to accomplish.

Based on expected demand, OEM New and VRP versions of a product are supplied either by domestic producers, or via imports (top-center and top-left of Figure B-9). Domestic producers rely on a variety of inputs to production, including recycled and virgin materials, as well as domestically- or imported-reuse inputs (cores). In addition to the finished product, other production outputs may include materials directed into a recycling market, or materials that are disposed into the environment (bottom-center and bottom-left of Figure B-9). As described previously, repair activities can take place within the service life of a product and return the product to its original owner. The repair process may require virgin and/or recycled material inputs (via parts replaced), and results in product waste materials that may be directed into recycling markets or disposed into the environment (top-center of Figure B-9). Alternately, EOU/EOL products may fall-out of the in-use product stock (market) becoming available for collection and diversion (top-right of Figure B-9). These products may be diverted into a secondary market for VRPs, into a recycling market, or disposed into the environment (bottom-right of Figure B-9).

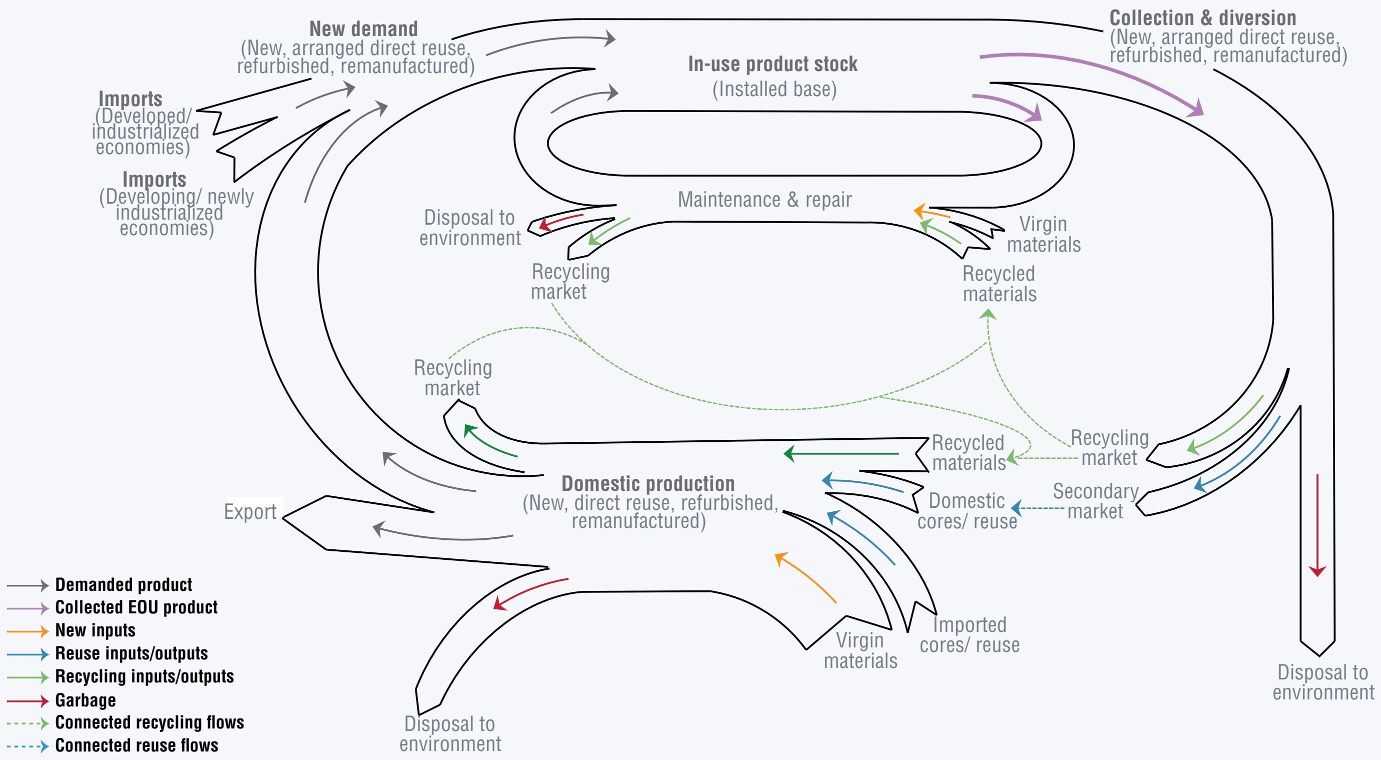

Figure B-9: Descriptive economic system model utilized for top-down analysis

Please note that the arrows within the diagram, reflect presence and directionality of system factors and flows only, and do not suggest the magnitude in any way. For example, materials directed into the recycling market may later be used in production, however these flows are not quantified by the model.

An overview of the comprehensive analytical model that was developed for the economy-level assessment is provided in Figure B-10. As depicted, modeling calculations started with the installed base (stock) of the product in the market (top-left orange box) and the estimated market share of product by OEM New and VRP process (top-center blue box). From these starting points, other values within the model were derived; As impacts of production were assessed on a per-unit basis, the aggregated economy-level results presented in Section 7 are largely based on the Total Finished Domestic Production (center green boxes), Imports from Developed and Developing Economies (center green boxes), and Production Levels of Repair (center-right green boxes).

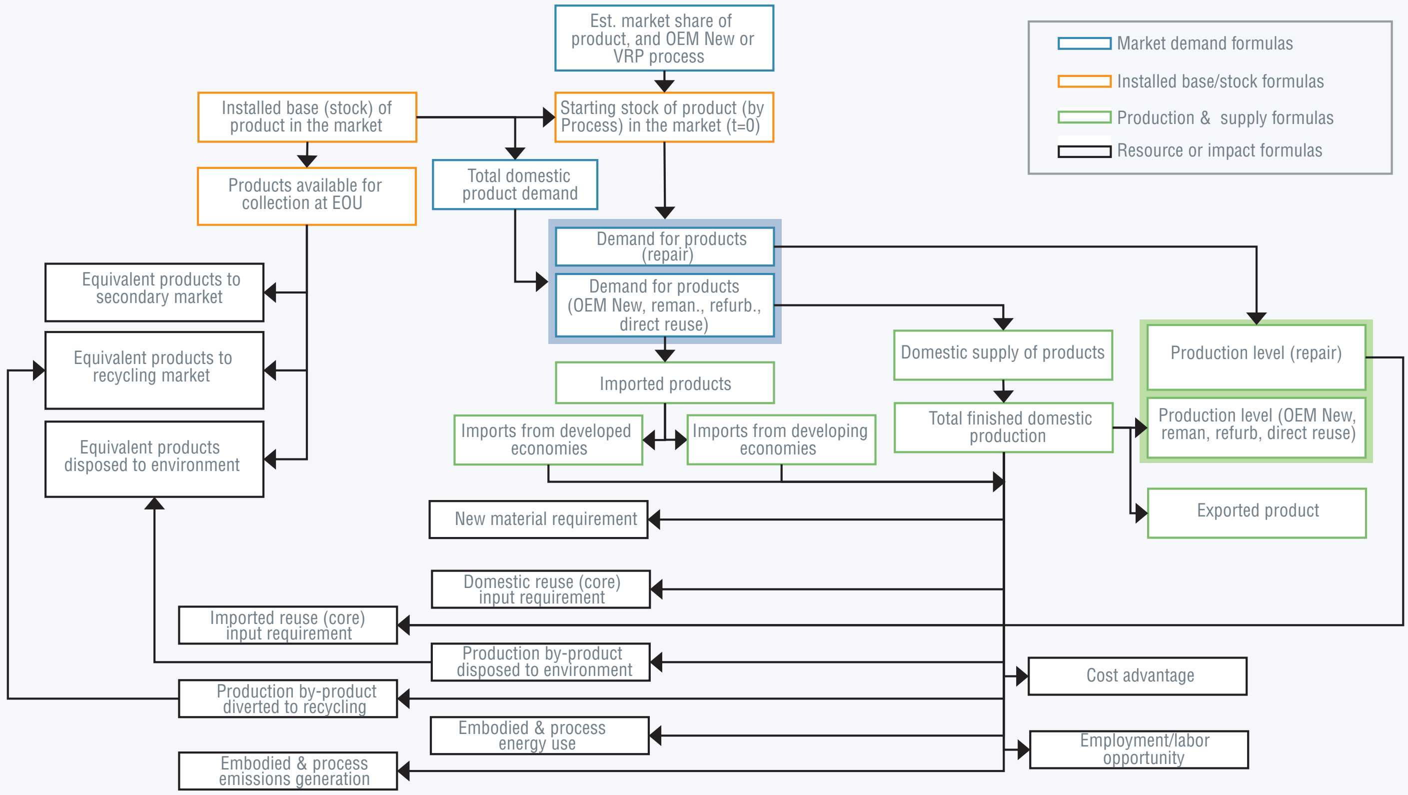

Figure B-10: Overview of comprehenive analytical systems-model mechanics for economy-level assessment

Demand and market share modeling

In the absence of comprehensive micro-data for each economy, a simplified approach was used to model the evolution of market share for each product, by OEM New and VRP production. Projected market demand for each case study product based was on two key parameters. First, demand was partially estimated using the expected implicit growth of the market, based on the historic (2010 – 2015) five-year compound annual growth rate (CAGR) performance of the product category, for each respective economy. Second, the evolving market share of each product, by process type, was an important consideration that enabled the reflection of two different types of demand: new demand, which originates from customers that previously had not participated in the product market; and replacement demand, which originates from the fall-out of an EOU OEM New or VRP product from the market, for which the customer now requires a replacement. This approach enabled the reflection of differentiated value-retention enabled by each VRP.

The model assumes that the total 'installed base' or 'in-stock' market for the case study product can be divided into relevant 'market shares' that reflect each of the available production processes: OEM New, arranging direct reuse, repair, refurbishment or comprehensive refurbishment, and remanufacturing. In most economies, the practices of traditional OEM New production and repair are commonly accepted and understood: as such, it is assumed that the market share percentage for repair is constant. In contrast, the dynamic nature of the model ensures that an increase in demand for VRP products will offset the equivalent demand for OEM New. In other words, and especially in the case of new demand, it is assumed that any new demand not satisfied by a VRP product will instead be satisfied by an OEM New product, and as such the quantity of OEM New product demanded is determined via net-subtraction of VRP demand from total case study product demand.

It is important to note that the model accounts for repair activities differently than other OEM New and VRP activities. OEM New, arranged direct reuse, refurbished and comprehensively-refurbished, and remanufactured products require a complex supply chain with extensive infrastructure and stakeholders; in contrast, repaired products follow a more simplistic flow (Please refer to Figure B-9). It is assumed that the repair process only temporarily removes a product from the economy and that the repaired product is returned to its original owner once the repair process is completed. As such, demand for, and associated requirements of the repair process are modeled separate from demand for the other VRP products that enter the economy via a more complex supply chain. The model assumes that once all repair cycles have been completed, the product will fail and be removed from the in-use product stock, to be replaced in the next cycle.

In this economy-level model, the influence of network effect is reflected in a simplified manner: as the number of VRP products in that market increases, it becomes relatively more significant within the mathematical function, and can demonstrate some degree of 'acceleration'. In other words, the larger the size of the starting market, the larger the relative market share, and the more significant the absolute impact of the growth rate upon actual product volume. While there are many more complex and comprehensive ways to model the diffusion of innovation, this approach enables a generalized, but realistic reflection of market transformation projections.

Within each single-year period of the seven-year simulation, demand is estimated based on real product sector growth projections and market-level conditions. Data from the previous period (year) informs calculations for the next period (e.g. products that reach EOU and fall-out in period 1, are replacement demand in period 2), and the implications of these dynamics are compounded to demonstrate the evolution of each product economy over the total seven-year simulation period.

This form of market share modeling ensures that the sum of all shares does not exceed 100 per cent, and accomplishes the need to balance the impact of increasing (decreasing) demand for OEM New or VRP, as competing production process options become relatively less (more) attractive in the economy. (Sterman 2000) The model assumes constant parameter values over time, with the exception of the size of the installed base, or in-use stock of the product, which is determined endogenously by the model, as a function of the starting in-use product stock in the economy, plus the addition of new product (demand), minus those products that fall-out of the economy due to failure or reaching end-of-use (EOU). Products that fall-out of the in-use product stock of the economy are directed to VRPs (EOU), or to recycling or disposal (EOL).

Modeling the supply chain

All market size and demand estimates within the model reflect conditions of each actual economy, determined through economic reports and market research data sets. In the interests of accounting for consumption behaviors, the model thus also accounts for the extent to which demand is supplied by domestic production, or by imports. A primary implication of imports is that, while they enable the satisfaction of domestic demand, they also result in the allocation of both impacts and benefits (as measured in this assessment) to the producing economy, or economy of origin. In other words, increased uptake of VRP products in an economy only accomplishes domestic impact reduction if at least some of those VRP products are produced domestically. From a global perspective, it is important to note that increased adoption of

VRP products, regardless of origin, can contribute to overall impact reduction, however this may not contribute to the accomplishment of domestic objectives, such as carbon emissions reduction.

Assumptions regarding the split between domestic production and import are determined exogenous to the model, based upon current trade balance conditions for each economy. Import and export rates are held constant over the modeling period and are incorporated to reflect the inherent trade-related policies that would enable or hinder import of cores and finished VRP products to supply domestic demand and enable or hinder export of cores and finished VRP products as a mechanism for increased domestic production capacity. It is assumed that domestic supply accounts for the remaining balance of demand (1 – Import Rate), that there is no stockpiling in the economy, and that there is no trade of arranged direct reuse or repaired products.

Modeling production and production impacts

Through the derivation of total domestic production levels, the model approximates production requirements (inputs), as well as the generation of by-product materials that are either directed into a recycling stream or disposed of into the environment. Although the OEM New and VRP production activities can differ significantly, the model simplifies production inputs into three categories: new material inputs (inclusive of average recycled content), imported core inputs, and domestically-sourced core inputs. The relative shares (per cent of a single unit) of each of these inputs should vary by product and production process, as well as the economy in which the activity is occurring. As one of the primary objectives of this assessment is to quantify the relative impacts of different production processes under different market conditions, this generalization is necessary and sufficient.

To understand the aggregate implications of cumulative economic production, a mass-balance approach is utilized. Given that inputs are presented as shares of the finished product, a constraint within the model requires that the sum of all production input materials (per cent) is equal to 1. All material input share parameters are exogenous to the model and were derived from the component-level and product-level analyses described previously.

Similarly, specific environmental and economic impact metrics are calculated using impact factors that were determined per unit for each different production process. These impact metrics contribute to greater understanding of relative environmental impacts (positive and negative) across OEM New and VRP production activities. As described previously, the impact factors of interest to this study include: new material offset, production waste generation, embodied material energy, embodied material emissions, process energy requirement, process emissions generation, cost advantage, and employment opportunity.

Modeling end-of-use and collection

The premise of circular economy is the cycling of materials (technical and biological) through a system to retain value and mitigate loss. As such, modeling the management of products and materials once they reach the end-of-use (EOU) stage is an essential aspect of a circular system model. In this case, the model once again starts with the actual installed base of the case study product, by process type, and applies a discard or fall-out rate to estimate how many of that particular product (via process type) will reach the EOU stage in that period. The fall-out rate and quantity of product reaching EOU is estimated as a fraction of the installed base, in accordance with the methodology of Elshkaki and Graedel (2013). In this case, the fall-out rate, reflected as 1/L in which L is the expected lifetime of the product, is multiplied by the total size of the installed base of the market for each product and process type.

It is important to note that EOU may refer to a point at which the product can no longer be used due to performance degradation, or that the current owner no longer wishes to retain the product for a variety of reasons.

When the product becomes ‘available for collection’ the model assumes that it leaves the economic market (no EOU product stockpiling[75] or storage) and will enter one of three possible flows: (1) routing to secondary market for reuse via a VRP application;

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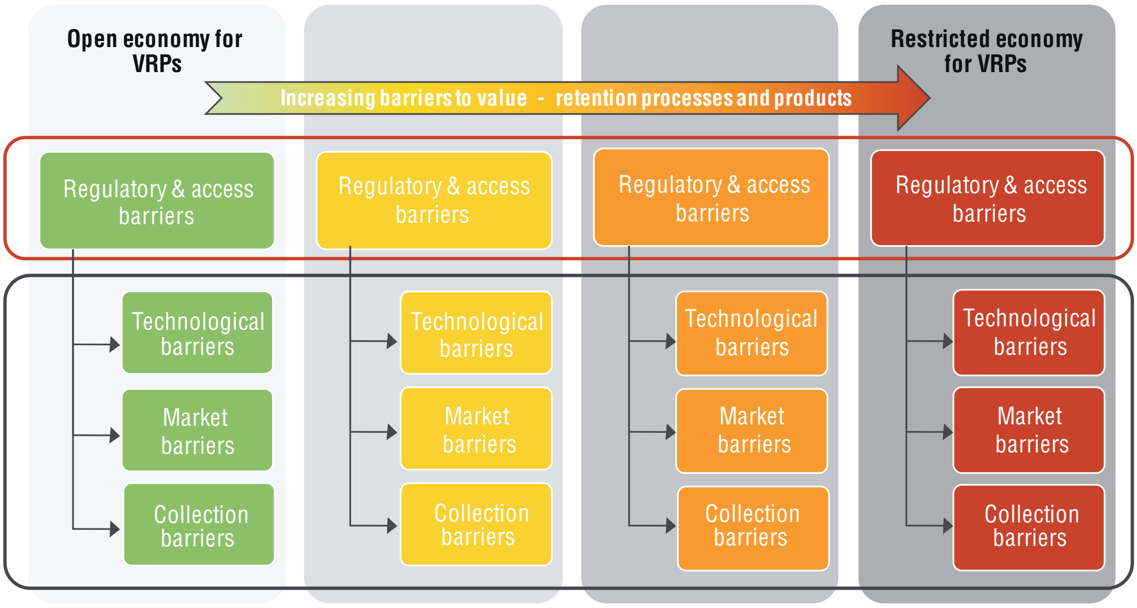
[75] Stockpiling refers to the accumulation of goods or materials, potentially for intended future use. Although stockpiling is a common practice, it was not possible to adequately reflect the diverse range of stockpiling practices and implications within this assessment.

(2) routing to recycling market; or (3) disposal to the environment. The route the product will take is based on collection probabilities which are estimated as a function of product- and economy-level factors that are reflective of, but are not limited to: ease of collection, state of collection and collection infrastructure, cost of collection and diversion in the market, presence of supporting diversion regulations, social norms and attitudes towards diversion, presence of related return incentives (e.g. core deposit), and other barriers to diversion such as the prohibition of reuse. The model utilizes collection probabilities and a mass-balance approach to determine the quantities of EOU products that follow different flows. For simplicity, it is assumed that there is no loss that is not ‘captured’ within the model: the ‘disposal to environment’ flow reflects those products that are deliberately directed into the garbage stream, as well as those that are ‘lost’ to the system because they do not enter either the secondary market or the recycling market. It is also important to note that there is a necessary quality discount that is applied to EOU products directed into the secondary market. This discount reflects the common condition that some recovered products do not meet the necessary quality standards for VRPs, with the low-quality differential being routed into the waste stream instead.

Economy-level methodology

Modeling framework

To reflect the range of conditions that exist in economies around the world, four representative sample economies — Brazil, China, Germany and the US — were identified, each with differing conditions and barriers that affect the adoption and growth of VRPs. Primary barrier categories focus on challenges in regulatory policy, technological capability, market conditions, and collection system (reverse-logistics) infrastructure.



Modified from (UNEP IRP Beijing Workshop and Nasr 2016, UNEP IRP Berlin Workshop and Nasr 2016)

Figure B-11: Spectrum of barrier-conditions and barrier-alleviation scenarios

The overarching approach to modeling and accounting for different systemic barriers to VRPs is described in Figure B-11, which reflects the range from no barriers to VRPs (green), increasingly through to many barriers to VRPs (red). For the purposes of this assessment, each representative economy was then considered in terms of the policy, technological, and economic literature surrounding its industrial systems, and rated on a spectrum of barrier presence and severity. Considered in conjunction with the product-level impacts discussed in Sections 5.2 and 5.3, these baseline economic models provide the socio-economic contexts in which the impacts of barrier alleviation on VRP performance and adoption potential were projected.

The potential for arranging direct reuse, repair, refurbishing and remanufacturing is dependent largely on product type and design, material composition, and the presence of appropriate technical knowledge and infrastructure to support these activities. As such, the potential material efficiency, or 'reusable share' of a single unit of the product is unlikely to change across markets; and as such, these per-unit material efficiency values are held constant across the market economies represented in this report. What may change from one economy to another relates to technical production efficiency: the magnitude of production waste and associated requirement for new material inputs; the labor required to complete the process for a single unit; the associated energy requirement of the production process, reflective of the efficiency of infrastructure in that economy; and the emissions associated with that energy consumption. These factors are presented in greater detail in the following sections.

Barrier alleviation scenarios

As with any form of innovation, a significant determinant of success in VRP adoption is the degree to which the barriers precluding the growth of these process innovations (VRPs) are alleviated. To predict how the circular economy might be enabled, considering the myriad interactions of inhibiting factors, baseline economic models were combined with product-level VRP models to subsequently project the evolution of the industrial economy over a seven-year period under three different scenarios for barrier alleviation (refer to Figure B-12). These scenarios are modeled as follows:

- **Status quo for VRP products:** Industrial economies in all representative markets continue to grow and adopt VRPs at their current rate, with all inhibiting factors held constant, ultimately maintaining current rate of economic and environmental performance.
- **Standard open market for VRP products:** Each representative economy is forecasted to grow under regulatory, trade, economic, and technological conditions that are equivalent to those of the Status Quo United States assessment.[76] Moderate existing barrier intensity is met with similarly moderate interventions toward alleviation.
- **Theoretical high for VRP products:** Barrier alleviation is projected as a priority in all representative markets, reflecting widespread acceptance of and investment in a transition to the circular economy. Research and development of technologies, business models, and policy initiatives to support VRPs proceed at an increased rate and intensity relative to the contemporary US baseline case, and the share of production activity across each VRP is set to reflect the Theoretical High US production share. This scenario is deliberately set to establish an extreme, positive, scenario for VRPs.

It is important to note that the use of a seven-year simulation period does not suggest that this is a sufficient or optimate transformation period for industrialized or non-industrialized economies. The transformation to circular economy is complex and requires comprehensive and integrated engagement of government, industry, and value-chain stakeholders, and as such expectations of the transformation timeline must be firmly grounded in the individual conditions and priorities of every respective economy.

These scenarios reflect the range of market evolution possibilities that may result from different levels of conceptual acceptance of and investment in the circular economy concept, as both the industry and the demands upon it continue to grow. The results of these projections are thus intended to provide insights into how to address barrier factor interactions in pursuit of greater VRP adoption. As previously mentioned, to reflect growth, market evolution, and compounding complexity in a

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[76] The use of the US example as Standard Open Market is not a reflection on the reputation and performance of other progressive countries, but rather a necessary condition for the some of the required modeling. This decision was due to the Industrial Digital Production Printer case study sector, which is affected by Basel Convention rules that constrain (if not volume, then the ease of) the exchange of these units for use in VRPs at the international level. While not a commentary on the value of the Basel Convention, the absence of similar constraints made the US the least-constrained sample economy within the study.

realistic and meaningful way, these scenario projections are simulated over a seven-year period. This duration period was selected because it ensured that systemic changes could be observed over time, without an unrealistic assumption that there would be no other significant endogenous changes in an economy.

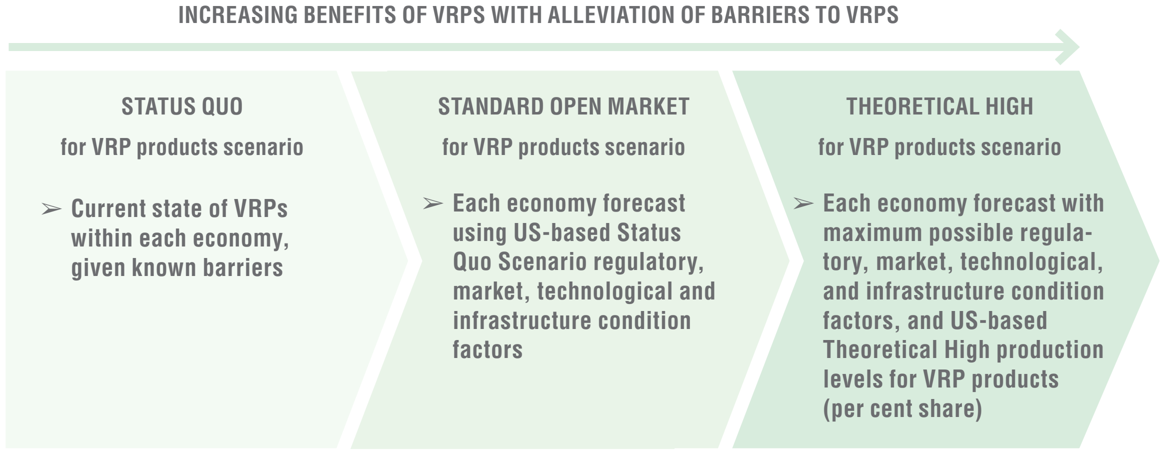

Figure B-12: Overview of barrier alleviation scenarios

As with any strategic initiative, there are three critical stages: First, establish a baseline to understand the reality of the 'current state'; Second, clearly define the objective or target, so that the vision can be articulated; and finally, establish an implementation plan with clearly defined steps and milestones that enable progress from the current state toward the desired future.

In the case of VRPs, the Status Quo and Theoretical High scenarios reflect the first and second stages, respectively. The Standard Open Market for VRP products scenario offers some insight into potential implementation plans – via policy decisions and system interventions – that may guide policy makers and industry decision makers in the development of appropriate strategies for their country's specific conditions and needs.

Within each of these barrier alleviation scenarios several system-based factors were determined and applied: Regulatory Factors, which reflect the presence and relative extent of regulatory-based differentiation and/or discrimination against case study products produced via VRPs, which also differ across case study sectors within each of the represented economies; Market Factors, which reflect relative customer-based differentiation and/or discrimination against refurbished and remanufactured products across represented economies; and Technological Factors, which reflect the relative degree of systemic technological barriers across each of the represented economies. Collection Infrastructure Factors were held constant in each economy, across each scenario.

Regulatory and access factors

Regulatory and access factors are differentiated by case study sector, as a range of regulatory barriers exist specific to different sectors, product types and/or materials. For example, the Basel Convention applies to case study industrial digital printers, thus potentially requiring additional procedural requirements for the movement of affected repaired, refurbished, and remanufactured industrial digital printers between Signatory countries (e.g. US) and countries that are both Signatory and Party (e.g. Germany)[77]. Regulatory Factors are determined quantitatively based on a combination of the OECD's Trade Facilitation Indicators[78] for

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[77] A multilateral agreement under Art. 11 of the Basel Convention (OECD Decision C(2001)107/Final) allows for such movements; however, certain procedural requirements, such as a PIC procedure, apply.

[78] OECD. 2015 Trade Facilitation Indicators. http://www.oecd.org/trade/facilitation/indicators.htm

each represented economy, and the World Bank's 2015 Ease of Doing Business Index[79]. The OECD Trade Facilitation Indicators were developed to help countries alleviate problematic border procedures and reduce trade costs and reflect relative ease of trade across OECD countries across a range of trade factors. The World Bank Ease of Doing Business Index ranks economies, relative to each other, on the basis and presence of business-friendly regulations: countries are ranked out of a possible 190, with a score of '1' reflecting the most business-friendly conditions. These metrics were normalized and multiplied to determine appropriate Regulatory and access factors for each represented country, by appropriate case study sectors (refer to Table B-31).

Market factors

Market factors within the economy-level model reflect a qualitative average 'discount' that might be applied by customers and businesses to refurbished and remanufactured goods within an economy, and which therefore constrains demand for these VRP options. This discount references expectations and perceptions about product quality (e.g. products via VRPs as having lesser quality than that of an OEM New option), as well as market-based preferences for 'new' products as status symbols and indicators of affluence or prestige. Economies that have had greater exposure to VRPs and options are assumed to 'discount' refurbished and remanufactured products to a relative lesser degree than would be in economies with little to no exposure to VRPs. In other words, Market factors are greater for those economies that currently face the greatest market constraints.

Technological factors

Technological factors reflect the relative benchmarking scores from the OECD's Science, Technology and Innovation Outlook 2016 report, which reflects the degree to which national-level science, technology and innovation (STI) policies, instruments, and systems are contributing to growth[80]. For the represented economies, relative scores from the STI Outlook 2016 report are aggregated into five categories describing the current status of the relative STI system (refer to Table B-30).

Import share

Finally, trade conditions, specifically import ratio assumptions were required to simulate Standard Open Market and Theoretical High scenarios, particularly for economies that currently enforce some degree of import restrictions against VRPs. For these scenarios the import share for OEM New products for each economy was held constant; in the Standard Open Market for VRP products scenario, import ratios for VRPs were set equal to that of the equivalent product for the US; in the Theoretical High scenario, import shares were either maintained (Developed/industrialized economies), or set to an assumed 20 per cent share (Developing/newly industrialized economies) (refer to Table B-32 and Table B-33).

Economy-level model

All model simulation begins with the product market: The total quantity and representative shares of a case study product, by each production process type, including OEM New, arranging direct reuse, repair, refurbishment or comprehensive refurbishment, and remanufacturing.

An overview of the comprehensive analytical model that was developed for the economy-level assessment is provided in Figure B-13.

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[79] World Bank. 2015 Ease of Doing Business Index. http://data.worldbank.org/indicator/IC.BUS.EASE.XQ.

[80] OECD. Science, Technology and Innovation Outlook 2016. http://www.oecd.org/sti/oecd-science-technology-and-innovation-outlook-25186167.htm

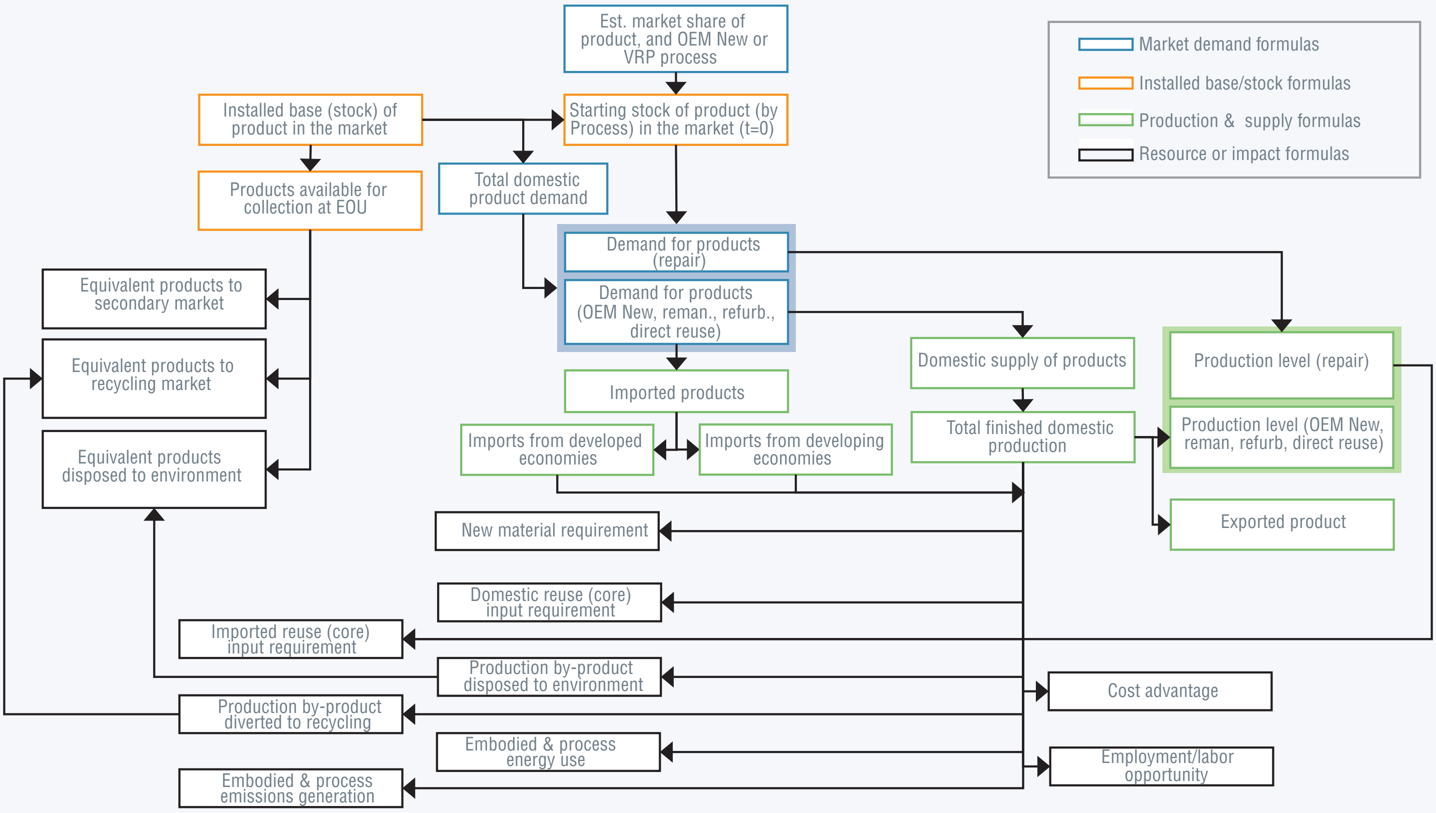

Figure B-13: Overview of comprehenive analytical systems-model mechanics for economy-level assessment

Installed base, demand, and available for collection

In the absence of comprehensive micro-data for each economy, a simplified approach was used to model the evolution of market share for each product, by OEM New and VRP production. Initial market share, or production mix percentage (%), was estimated for each product by production process (OEM New and VRP) based on available data from each sample economy. Using estimated total size of the initial installed based ($IB_{t=0}^{j,k}$), a starting volume for each product (j) by production process (i) was determined for each sample economy (k). In each of the simulation periods (t =7), installed base was adjusted dynamically to account for products reaching the end of service life and becoming available for collection, and the products entering the economy as a result of new demand. The following equations provide a high-level description of the modeling approach reflecting product flow into and out of each sample economy.

Projected market demand for each case study product based was on two key parameters. First, demand was partially estimated using the expected implicit growth of the market, based on the historic (2010–2015) five-year compound annual growth rate (CAGR) performance of the product category, for each respective economy (refer to Equation 4a) As depicted, expected demand ($D_t^{j,k}$) is a function of demand quantity in the previous period and the expected product segment growth rate (g), which is held constant throughout the simulation. As described by Equation 4b, after period t=1, the calculation of demand also includes the replacement quantity for units that have fallen out of the market in each previous period (refer to Equation 6), based on the assumption that the owner/user has a need that must be fulfilled by OEM New or VRP product option that is separate from the projected sector growth rate. SuB-and superscript notations i, j, k, and t represent production process, product, economy, and simulation period, respectively. Expected demand is further disaggregated by production process (i), using a constant parameter for estimated production/demand mix for OEM New and each VRP ($\lambda^{i,j,k}$), per Equation 5.

$$D_{t=0,1}^{j,k} = D_{t-1}^{j,k} * (1 + g^{j,k}) \, \forall \, j,k \qquad \text{Eq. 4a}$$

$$D_{t}^{i,j,k} = (D_{t}^{j,k} * \lambda^{i,j,k}) \, \forall \, i,j,k \qquad \text{Eq. 4b}$$

$$D_{t}^{i,j,k} = (D_{t}^{j,k} * \lambda^{i,j,k}) \, \forall \, i,j,k \qquad \text{Eq. 5}$$

The products that become available for collection each period ($C_t^{j,k}$), as a result of reaching expected end of service life or experiencing failure, are estimated using Equation 6. The fall-out rate ($F^{i,j}$) and quantity of products becoming available for collection each period is estimated as a fraction of the installed base ($IB_t^{i,j,k}$) during the previous period, in accordance with the methodology of Graedel and Elshaki (2013). In this case, the fall-out rate, reflected as $1/\eta$ in which η is the expected service life of the product given its production process (OEM New versus VRP), is multiplied by the total size of the installed base of the market for each product and process type. It is important to note that EOU may refer to a point at which the product can no longer be used due to performance degradation, or that the current owner no longer wishes to retain the product for a variety of reasons.

$$C_{t}^{i,j,k} = (IB_{t-1}^{i,j,k} * F^{i,j}) \, \forall \, i,j,k \qquad \text{Eq. 6}$$

As introduced briefly, the installed base quantity of each product (j), by each production process (i), in the sample economy (k), reflects a simple function of the flows into and out of the economy: the installed base quantity from the previous period, plus new product introduced through demand, less products that fall-out of the market and become available for collection at the end of their service life (refer to Equation 7).

$$IB_{t}^{i,j,k} = \left(IB_{t-1}^{i,j,k} + D_{t-1}^{i,j,k} - C_{t-1}^{i,j,k}\right) \forall \, i,j,k \qquad \text{Eq. 7}$$

To accommodate the simulation of different VRP barrier conditions within the model via VRP barrier scenarios, the calculation of estimated installed base (per Equation 7) was further enhanced to incorporate the effect of economy-level regulatory and access factors ($RF^{j,k}$), technological factors (TF^{k}), and market factors ($MF^{i,k}$), as shown in Equation 8. Please note that Equation 8 is only used in the first simulation period (t=1) to establish the demand conditions that are then incorporated into subsequent simulations (T = 7). It is also important to note that these VRP barrier factors are assumed to only be relevant for VRP processes of refurbishment and remanufacturing. Although this assumption may not reflect absolute conditions across varied economies and social norms, for the purposes of simplification this assumption was necessary and justifiable at the high-level. As repair is a well-established VRP practice across all economies, research and interviews with industry experts suggest that there are few-to-no VRP barriers which, if alleviated, would increase the number of product repairs being demanded in an economy during a given period. Similarly, with arranging direct reuse, per research and industry experts, there are few-to-no VRP barriers which, if alleviated, would increase the number of products demanded for arranged direct reuse in an economy during a given period. A discussion of the VRP barrier factors is included in more detail in Section 1.7.

$$IB_{t}^{i,j,k} = \left(IB_{t-1}^{i,j,k} + (D_{t-1}^{i,j,k} * \left(1 + \left(RF^{j,k} + TF^{k} + MF^{i,k}\right) - 3\right) - C_{t-1}^{i,j,k}\right) \forall \, i,j,k \qquad \text{Eq. 8}$$

As shown in Equation 8, regulatory factors reflect conditions specific to the product (j) and the sample economy (k); technological factors reflect conditions specific to the sample economy (k); and market factors reflect conditions specific to the production process (i = refurbished or remanufactured only) and the sample economy (k). As further described in Table B-28 and Table B-29, these factors are normalized and set to equal 1 ($RF^{j,k} = 1; TF^{k} = 1; MF^{i,k} = 1$) in the Status Quo scenario. For subsequent Standard Open Market, and Theoretical High scenarios, these factors are modified accordingly to reflect the changing scenario conditions (please refer to Table B-29).

The model accounts for the extent to which demand is supplied by domestic production ($X_t^{i,j,k}$), or by imports ($I_t^{i,j,k}$), per Equations 9 and 10, respectively. A primary implication of imports is that, while they enable the satisfaction of domestic demand, they also result in the allocation of both impacts and benefits to the economy of origin. In other words, increased uptake of VRP products in an economy only accomplishes impact reduction and/or economic opportunity if at least some of those VRP products are produced domestically. Assumptions regarding the split between domestic production and import are determined exogenous to the model, based upon current trade balance conditions for each economy[81]. Import and export rates are held constant over the modeling period and are incorporated to reflect the inherent trade-related policies that would enable or hinder import of cores and finished VRP products to supply domestic demand, and that enable or hinder export of cores and finished VRP products as a mechanism for increased domestic production capacity.

The incorporation of import share of demand ($IP^{i,j,k}$) enables the simulation of changing access conditions within sample economies under the Standard Open Market and Theoretical High VRP barrier alleviation scenarios. This is discussed further in the following sections and import share values can be found in Table B-32 and Table B-33. It is assumed that domestic supply accounts for the remaining balance of demand $(1 - IP^{i,j,k})$, that there is no stockpiling in the economy, and that there is no trade of arranging direct reuse or repaired products.

$$X_t^{i,j,k} = D_t^{i,j,k} * \left(1 - IP^{i,j,k}\right) \forall\, i\ ,j, k \qquad \textbf{Eq. 9}$$

$$I_t^{i,j,k} = (D_t^{i,j,k} * IP^{i,j,k}) \,\forall\, i, j, k \qquad \textbf{Eq. 10}$$

Finally, the import share of demand is further split within the model to account for the share (quantity) of imports coming from developing/non-industrialized/newly industrialized economies ($IPa^{i,j,k}$), and the share (quantity) of imports coming from developed/industrialized economies ($IPb^{i,j,k}$). This is accomplished by incorporating estimated import share (%) by origin, per Equations 11 and 12.[81] Import share values can be found in Table B-32 and Table B-33.

$$Ia_t^{i,j,k} = \left(I_t^{i,j,k} * IPa^{i,j,k}\right) \forall\, i, j, k \qquad \textbf{Eq. 11}$$

$$Ib_t^{i,j,k} = (I_t^{i,j,k} * IPb^{i,j,k}) \,\forall\, i, j, k \qquad \textbf{Eq. 12}$$

Aggregating impacts of consumption

The cumulative environmental and economic impacts of consumption reflect the aggregate impact of domestic production and the consumption of imports. As all impact factors were normalized to reflect a per-product basis, the aggregation of impacts is estimated using a linear function based on the total quantity of products. As mentioned previously, environmental and economic impact factors are discussed and described in greater detail in the following sections.

The primary aggregated environmental and economic impacts of consumption, accounting for OEM New and VRP production and consumption mix for each sample economy, are outlined in Equation 13 through Equation 18. A brief summary of nomenclature used in the aggregation of impact formulas is also provided in Table B-22. For simulated aggregation the model assumes seven economy-level model simulation periods ($T = 7$).

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[81] Import and export data was sourced from the Observatory of Economic Complexity for the base year 2015 for Brazil (2015a), China (2015b), Germany (2015c), and the US (2015d).

Table B-22: Summary of nomenclature for aggregated impact formulas

Notation	Description
t	Model simulation period, 1:7 (Set = T)
k	Sample economy, Brazil, China, Germany, and US (Set = K)
j	Case study product (3 industrial digital printers; 3 vehicle parts; 3 HDOR equipment parts)
i	Production process: OEM New, arranging direct reuse, repair, refurbishment and remanufacturing
X	Domestic production quantity of product (j) via process (i) in economy (k)
I	Import quantity of product (j) via process (i) by economy (k)
Ia	Import quantity from developing/newly industrialized origins of product (j) via process (i) by economy (k)
Ib	Import quantity from developed/ industrialized origins of product (j) via process (i) by economy (k)
τ	Embodied energy per unit (product (j) via process (i) in economy (k)), global average in MJ/unit
ω	Embodied emissions per unit (product (j) via process (i) in economy (k)), global average in kg. CO_2-eq./unit
φ	Process energy/unit (product (j) via process (i) in economy (k)), in MJ/unit
φa	Process energy/unit (product (j) via process (i)) produced in developing/newly industrialized economies, in MJ/unit
φb	Process energy/unit (product (j) via process (i)) produced in developed/industrialized economies, in MJ/unit
PEF	Process Energy Factor enabling across-economy assessment (Please refer to Table B-23)
6	Process emissions/unit (product (j) via process (i) in economy (k)), in kg. CO_2-eq./unit
6 a	Process emissions/unit (product (j) via process (i)) from developing/newly industrialized economies, in kg. CO_2-eq./unit
6 b	Process emissions/unit (product (j) via process (i)) from developed/industrialized economies, in kg. CO_2-eq./unit
PMF	Process Emissions Factor enabling across-economy assessment (Please refer to Table B-24)
π_N	Non-recyclable Production Waste/unit (product (j) via process (i) in economy (k)), in kg/unit
π_R	Recyclable Production Waste/unit (product (j) via process (i) in economy (k)), in kg/unit
πa	Total production waste/unit (product (j) via process (i)) from developing/newly industrialized economies, in kg/unit
πb	Total production waste/unit (product (j) via process (i)) from developed/ industrialized economies, in kg/unit
PWF	Production Waste Factor enabling across-economy assessment (Please refer to Table B-25)
v	Process labor req./unit (product (j) via process (i) in economy (k)), in full-time laborer/unit
va	Process labor req./unit (product (j) via process (i)) from developing/newly industrialized economies, in full-time laborer/unit
vb	Process labor req./unit (product (j) via process (i)) from developed/ industrialized economies, in full-time laborer/unit
PLF	Process Labor Factor enabling across-economy assessment (Please refer to Table B-26)

$$Embodied\ Energy^{k}=\sum_{t=1}^{T}\sum_{j}\sum_{i}((X_t^{i,j,k}*\tau^{i,j,k})+(I_t^{i,j,k}*\tau^{i,j,k})\ \forall\ k\ \in\ K \tag*{Eq. 13}$$

$$Embodied\ Emissions^{k}=\textstyle\sum_{t=1}^{T}\sum_{j}\sum_{i}((X_t^{i,j,k}*\omega^{i,j,k})+(I_t^{i,j,k}*\omega^{i,j,k})\ \forall\ k\ \in K \tag*{Eq. 14}$$

$$Process\ Energy^{k}=\sum_{t=1}^{T}\sum_{j}\sum_{i}((X_t^{i,j,k}*\varphi^{i,j,k}*PEF^{k})+(Ia_t^{i,j,k}*\varphi a^{i,j})+(Ib_t^{i,j,k}*\varphi b^{i,j})\ \forall\ k\ \in K \tag*{Eq. 15}$$

$$Process\ Emissions^{k}=\sum_{t=1}^{T}\sum_{j}\sum_{i}((X_t^{i,j,k}*\beta^{i,j,k}*PMF^{k})+(Ia_t^{i,j,k}*\beta a^{i,j})+(Ib_t^{i,j,k}*\beta b^{i,j})\ \forall\ k\ \in K \tag*{Eq. 16}$$

$$\begin{aligned}&Process\ Production\ Waste^{k}\\&\quad=\sum_{t=1}^{T}\sum_{j}\sum_{i}((X_t^{i,j,k}*(\pi_N^{i,j,k}+\pi_R^{i,j,k})*PWF^{k})+(Ia_t^{i,j,k}*\pi a^{i,j})+(Ib_t^{i,j,k}*\pi b^{i,j})\ \forall\ k\ \in K\end{aligned} \tag*{Eq. 17}$$

$$Process\ Labor^{k}=\sum_{t=1}^{T}\sum_{j}\sum_{i}((X_t^{i,j,k}*\nu^{i,j,k}*PLF^{k})+(Ia_t^{i,j,k}*\nu a^{i,j})+(Ib_t^{i,j,k}*\nu b^{i,j})\ \forall\ k\ \in K \tag*{Eq. 18}$$

Factors enabling across-economy and across-scenario assessment

In addressing increasingly interactive global economies, it is often difficult to inform industrial and policy decisions across multiple contexts in a single, uniform manner. Each constituent of the global economy exists within a unique space on a broad spectrum of socioeconomic and industrial development. The technologies available to, processes used in, and management strategies employed by each therefore inherently differ, creating varying degrees of flexibility in and barrier inhibition of the adoption of VRPs. Each constituent thus demonstrates a unique profile of economic and environmental performance that must be considered when exploring the current role and future potential of VRPs. To better understand the implications of these conditions and barriers, four countries representative of different points on this spectrum of development—and for whom sound industrial systems data were available—were selected to serve as the basis of modeling and analysis:

- United States of America (US)
- Germany (DEU)
- Brazil (BRA)
- China (CHN)

There were two different kinds of factors developed to support and enable economy-level modeling that was appropriately reflective of the varied conditions across sample economies, and under each of the barrier alleviation scenarios:

- **Environmental and economic impact factors:** These factors affect across-economy assessment and were applied in each of the VRP barrier alleviation scenarios (see below). These factors were applied as multipliers versus the US base impact data to reflect differing conditions, and therefore environmental and economic impacts, of each economy. These factors include: Process Energy Factor, accounting for electricity infrastructure differences by economy; Process Emissions Factor, accounting for differing electricity generation grid mix in each economy; Production Waste Factor, accounting for differing technical production efficiency conditions and waste diversion infrastructure; and Labor Productivity Factor, accounting for differing labor productivity – and therefore differing labor requirements – within each sample economy.
- **VRP barrier alleviation scenario factors:** These factors affect across-scenario assessment and were applied to each economy to reflect changing VRP barrier conditions. These factors were applied as multipliers to various volume-based parameters within the econo-

my-level model, for each sample economy. VRP barrier alleviation scenario factors include regulatory factors, technological factors, and market factors that capture high-level barrier conditions for each economy, under the Status Quo, Standard Open Market, and Theoretical High barrier alleviation scenarios.

The following sections describe the calculation of these impact and scenario factors, and the way in which they were used within the model.

Environmental and economic impact factors

Process energy factor

This analysis deliberately omits consideration of use-phase energy within each economy, as that requirement would be equal across each; a new automobile engine produced in the United States, for example, would reasonably use the same amount of energy during its use-phase as it would in another economy. Rather, the most significant differences in energy requirements lie in the production process. Thus, by mitigating the requirement for 100 per cent new material inputs and instead leveraging already-existing components or products, VRPs offer reduced per-unit energy requirements in the production phase.

In this respect, the differences of efficiency in the generation, transmission, and distribution of energy used for industrial production can have significant effects on material efficiency—i.e. how much of a product can be made (or re-made) from a given amount of energy input materials—and also on the environmental impacts of consuming that energy.

The interaction between these efficiency measures was examined via the World Energy Council and revealed relative energy efficiency factors for each representative economy. These factors were used to account for the cumulative energy (generation, transmission, and distribution, including losses) required to complete each process within each sample economy. This approach enabled accounting for energy infrastructure efficiency with the process, and so that each representative economy may be assessed relative to each other on a level platform (refer to Table B-23).

Table B-23: Production process energy factor and efficiency comparison across scenario economies

	US	Germany	Brazil	China
Efficiency of Power Generation (%)[82]	42.0%	41.9%	67.9%	41.4%
Efficiency of transmission and distribution (%)[82]	93.9%	96.3%	84.9%	93.8%
Process Energy Factor	**2.5370**	**2.4794**	**1.7347**	**2.5751**

GWP 100a process emissions factor

Energy efficiency factors are inherently related to the greenhouse gas (GHG) emissions for which industrial producers are responsible. For each unit of energy (here measured in megajoules [MJ]) required for manufacturing, a proportional amount of GHG emissions (kilograms [kg] of carbon dioxide-equivalent [CO_2-e] gases) will be created. These emissions—as well as the amount of energy required to complete production processes—are of course related to the particular energy grid and process technology portfolios upon which each representative economy relies. Estimated production process emissions are therefore calculated based country-specific product and process energy requirement and energy infrastructure data from the Ecoinvent 3.3 database,[83] and similarly normalized to a US-based baseline, as shown in Table B-24.

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[82] World Energy Council. https://www.wec-indicators.enerdata.eu. Accessed 15 March 2017 (World Energy Council 2015).

[83] Per Ecoinvent 3.3 dataset documentation, Market group for electricity, medium voltage for period 2015-01-01 to 2016-12-31 using IPCC 2013 method. Accessed 08 May 2017 (Ecoinvent 3.3 2016).

Table B-24: Production process emissions factor and generation comparison across scenario economies

	US	Germany	Brazil	China
GWP 100a (kgCO_2-e/MJ, IPCC 2013)[83]	0.1829	0.1870	0.0589	0.3244
GWP 100a Process Emissions Factor	**1**	**1.02**	**0.32**	**1.77**

Production waste factor

The generation of production waste byproduct is reflected as a measure of production efficiency; the greater the technological development and skill level of a workforce and facility, and the greater the size of the operation, the relatively less production waste is generated per unit. It is necessarily assumed that developed economies exhibit greater production efficiency, and therefore generate less production waste byproduct, than developing economies.

Corresponding to these relationships is another convention of material efficiency in manufacturing: the more waste byproduct created relative to the material embodied in the final product, the greater the new material quantity a process will require to complete that process. In addition, the presence of recycling and/or diversion regulations for industrial facilities represents an opportunity to reduce waste byproduct; inversely, the absence of recycling and/or diversion regulations for industrial facilities represents the potential for higher levels of waste generation.

Given the existence and viability of secondary recycling markets for primary production materials, including steel and aluminum, it is assumed that recyclable production waste factors will be constant and equivalent to US conditions for developed markets (e.g. Germany) (1.0), and increased by 20 per cent for Brazil and China (refer to Table B-25). Each of the representative economies considered here are sufficiently industrialized to have robust (if not formalized) scrap material markets, and as such it is assumed that producers in all economies will be motivated to recycle applicable materials in their production waste stream wherever possible. Variation in waste generation is attributed to the presence (or absence) of industrial recycling regulations, technological efficiency, and the sophistication of waste and recycling infrastructure for industrial production sectors.

Table B-25: Production waste factor comparison across scenario economies

	US	Germany	Brazil	China
Production Waste Factor	1.0	1.0	1.2	1.2

Labor productivity factor

Sufficient access to skilled labor is a well-referenced barrier to cost-effective adoption of circular production processes in both developed and developing markets. To adequately reflect the comparative productivity of different economies, a labor requirement factor was calculated using the GDP value of manufacturing output (in 2014 US Dollars) created per person working in manufacturing. Manufacturing Value / Person Employed is a manufacturing sector productivity measure utilized at the international level, namely by the Organisation for Economic Co-operation and Development (OECD) and the US Bureau of Labor Statistics. This employment productivity factor (refer to Table B-26) represents the relative productivity of full-time equivalent employees across different economies and enables the estimation of employment potential in different markets based upon their current-state labor pool.

Table B-26: Labor Requirement factor comparison across scenario economies

	Economy A (US)[84]	Economy B (Germany)[84]	Economy C (Brazil) [85]	Economy D (China)[86]
Mfg. GDP/ Person Employed in Mfg. (2014) (USD)[87]	$128,560	$100,584	$27,769	$57,833
Labor Productivity Factor	**1**	**0.78**	**0.22**	**0.45**

Together, these factors not only provide a baseline understanding of how each representative economy currently performs, but also reveal areas in which each economy might need to improve in order to support the circular economy and suggest how the adoption of VRPs might unfold, given the particularities of each economic context. Brazil, for example, appears to outperform its counterparts in energy efficiency and emissions production, but is significantly underperforming in human capital and productivity, relatively. In this sense, a focus on VRPs that increase the recoverable value of EOU products through preserving form and function while minimizing the intermediate steps required to extract that value may be of greater benefit than those that preserve value by avoiding process energy requirements.

In any case, the potential to address these differences in economic performance through increased scale of VRPs hinges entirely upon the myriad barriers that presently constrain the industry's transformational willingness and ability. It is these barriers—and, ultimately, the degree to which they can be alleviated through shifts in industrial paradigm and governmental policy—that will either unlock or inhibit the transition to a more circular global economy.

Environmental and economic impacts of imported products

Finally, in assessing the environmental and economic impacts of consumption, the origin of imported products was an important consideration. Using import quantity and import quantity estimates by economy of origin that were based on import share of demand (refer to Equations 11 and 12), the aggregated environmental and economic impacts associated with imported products were determined using average, and representative environmental and economic impacts factors (refer to Table B-27).

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[84] US and Germany manufacturing sector productivity data from US Congressional Research Service, and OECD (Levinson 2013, OECD 2017).

[85] Brazil manufacturing sector productivity data derived from US Congressional Research Service, and CIA World Factbook (CIA 2015, Levinson 2013).

[86] China manufacturing sector productivity data derived from US Congressional Research Service, and Peterson Institute for International Economics (Lardy , Levinson 2013).

[87] GDP from Manufacturing/ Person Employed in Manufacturing is a Manufacturing Sector Productivity measure utilized at the international level, namely by the OECD, and the US Bureau of Labor Statistics (OECD 2017, U.S. Department of Labor 2015).

Table B-27: Process impact factors for imported products

Process Impact Factor	Developing/Newly Industrialized Import Origin Economy Value	Developed/Industrialized Import Origin Economy Value
Process Energy Factor (φ)	Average (Brazil; China)	Average (Germany; US)
GWP 100a Process Emissions Factor (β)	Average (Brazil; China)	Average (Germany; US)
Production Waste Factor (π_N, π_R)	Average (Brazil; China)	Average (Germany; US)
Labor Productivity Factor (ν)	Average (Brazil; China)	Average (Germany; US)

Barrier alleviation scenario factors

The barriers used to reflect current state and alleviation-potential factors are presented in Table B-28 and are described in further detail subsequently. It is important to note that these Factors are only applied in the context of relevant VRPs (e.g. not to OEM New segment): given that repair is a well-established option in every economy, these Factors are not applied to the repair segment; in addition, given that there are little to no interventions that may yield greater demand for arranging direct reuse products in an economy, these Factors are not applied to the arranging direct reuse segment. Please refer to Equation 8 for additional clarification. Further description of the approach and sources that inform the factors presented in Table B-28 and Table B-29 are included in the following sections. The values in Table B-28 inform the simplified representation of current state VRP barriers within sample economies, and colors represent relative barrier factors similar to the model depicted in Figure B-9. The values contained in Table B-28 are further clarified and explained in the following sections.

Table B-28: Overview of relative barrier factors in current state

Barrier Factor	Application	Brazil	China	Germany	US
Regulatory and Access Factors	VRP Vehicle Parts	0.28	0.18	0.86	0.91
	VRP Industrial Digital Printers	0.28	0.18	0.66	0.91
	VRP HDOR Equipment Parts	0.28	0.18	0.86	0.91
Technological Factor	All	0.09	0.11	0.5	0.54
Market Factors	Refurbished Products	0.8	0.5	0.95	0.95
	Remanufactured Products	0.25	0.25	0.75	0.75

In the Standard Open Market and Theoretical High Scenarios, these relative barrier factors are modified to reflect changing VRP barriers in each economy, according to established scenario conditions.

A summary of the VRP barrier factors that are incorporated into the model, via Equation 8, are outlined for each VRP barrier scenario in Table B-29.

Table B-29: Overview of VRP barrier factors for all VRP barrier alleviation scenarios

		Current State	Global Barrier Alleviation Scenarios		
			Status Quo	Standard Open Market	Theoretical High
SCENARIO TARGET	Market Factor (Refurbishing)			0.95	1.00
	Market Factor (Remanufacturing)			0.75	1.00
	Regulatory Factor – VRP Vehicle Parts			0.91	1.00
	Regulatory Factor - VRP Ind. Digital Printers			0.91	1.00
	Regulatory Factor – VRP HDOR Parts			0.91	1.00
	Technological Factor			0.54	1.00
US	Market Factor (Refurbishing)	0.95	1.0	1.00	1.05
	Market Factor (Remanufacturing)	0.75	1.0	1.00	1.33
	Regulatory Factor – VRP Vehicle Parts	0.91	1.0	1.00	1.10
	Regulatory Factor – VRP Ind. Digital Printers	0.91	1.0	1.00	1.10
	Regulatory Factor – VRP HDOR Parts	0.91	1.0	1.00	1.10
	Technological Factor	0.54	1.0	1.00	1.85
Germany	Market Factor (Refurbishing)	0.95	1.0	1.00	1.05
	Market Factor (Remanufacturing)	0.75	1.0	1.00	1.33
	Regulatory Factor – VRP Vehicle Parts	0.86	1.0	1.05	1.16
	Regulatory Factor – VRP Ind. Digital Printers	0.66	1.0	1.37	1.51
	Regulatory Factor – VRP HDOR Parts	0.86	1.0	1.05	1.16
	Technological Factor	0.50	1.0	1.09	2.01
Brazil	Market Factor (Refurbishing)	0.80	1.0	1.19	1.25
	Market Factor (Remanufacturing)	0.25	1.0	3.00	4.00
	Regulatory Factor – VRP Vehicle Parts	0.28	1.0	3.26	3.59
	Regulatory Factor – VRP Ind. Digital Printers	0.28	1.0	3.26	3.59
	Regulatory Factor – VRP HDOR Parts	0.28	1.0	3.26	3.59
	Technological Factor	0.09	1.0	6.16	11.43
China	Market Factor (Refurbishing)	0.50	1.0	1.90	2.00
	Market Factor (Remanufacturing)	0.25	1.0	3.00	4.00
	Regulatory Factor – VRP Vehicle Parts	0.18	1.0	5.10	5.62
	Regulatory Factor – VRP Ind. Digital Printers	0.18	1.0	5.10	5.62
	Regulatory Factor – VRP HDOR Parts	0.18	1.0	5.10	5.62
	Technological Factor	0.11	1.0	4.95	9.18

Technological VRP Barrier Factors

The factors used to reflect current state and potential technological conditions are reflected in Table B-30 and similarly, the factors used to reflect current state and applied import share conditions for scenarios are presented in Table B-32.

Technological Factors were determined as a relative measure of the OECD Science, Technology and Innovation (STI) industry outlook for each economy.[88] The benchmarking undertaken by the OECD incorporates 23 different measures, categorized into the six core areas of competency, per Table B-30 below. The scores included in Table B-30 reflect the normalized index of 2011 performance of each national STI systems relative to the median OECD values, using an index median of 100.

Table B-30: Overivew of technological VRP barrier factors and inputs to calculation[88]

STI Competency Area	US	Germany	Brazil	China
Universities and Public Outreach	83.3	113.3	25.0	31.7
R&D Innovation in Firms	112.5	117.5	13.3	52.5
Innovative Entrepreneurship	145.0	113.3	-10.0	-50.0
ICT and Interact Infrastructure	141.3	87.5	6.7	-8.3
Networks, clusters and Transfers	55.0	112.5	46.7	62.5
Skills for Innovation	125.0	108.0	15.0	60.0
Average (All)	110.3	108.7	16.1	24.7
Average (Available)	107.9	99.3	17.5	21.8
Highest Possible Score	200	200	200	200
Technological Factor	**0.54**	**0.50**	**0.09**	**0.11**

Regulatory and access VRP barrier factors

Regulatory Factors were calculated by combining two different metrics, accounting for specific economy-level conditions of the studied sectors: The OECD Trade Facilitation Performance Indicator, and the World Bank Ease of Doing Business Index. The OECD Trade Facilitation Performance Indicators are a set of 11 different indicators that for the range of border procedures from more than 160 countries of varied income levels, geographical regions and development stages[47]. As shown in Table B-31, the average indicator score for each economy is normalized for use within the calculation of the Regulatory Factor.

Average trade facilitation performance covers scores across a range of relevant areas including, but not limited to: Information availability; involvement of the trade community; advance rulings; appeal procedures; fees and charges; documents; automation; procedures; internal border agency cooperation; external border agency cooperation; and governance and impartiality. In economies where there are VRP-specific conditions that reduce the ease of VRP product trade, a Product/Sector VRP Trade Weighting of < 1.0 is assumed for the Status Quo scenario (refer to Table B-31).

The World Bank Ease of Doing Business Index is a ranking of economies based on their ease of doing business, with a high ease of doing business ranking indicating that the regulatory environment is more conducive to the starting and operating of a local firm (World Bank 2015). The relative Ease of Doing Business is a construct reflecting different

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[88] Per OECD Science, Technology and Innovation Industry Outlook 2015, scores for US, Brazil, China and Germany (OECD 2015a).

operational aspects of business in an economy, including the ease of starting a business, dealing with construction permits, getting electricity, registering property, getting credit, paying taxes, enforcing contracts, trading across borders, and several other factors. For each of these, economies are ranked relative to one another, from 1 – 190 (reflective of 190 economies for which there is sufficient data). In economies where there are VRP-specific conditions inhibiting the engagement of businesses in VRP-related production activities, a Product/Sector VRP Domestic Business Weighting of < 1.0 is assumed for the Status Quo scenario (refer to Table B-31).

Table B-31: Overview of regulatory and access VRP barrier factors and inputs to calculation

	US	Germany	Brazil	China
OECD Trade Facilitation Performance Avg. Score (2015)[89]	1.7	1.6	1.5	1.4
Out of Possible Score	2	2	2	2
Normalized	**0.85**	**0.80**	**0.75**	**0.70**
Product/Sector VRP Trade Weighting				
Vehicle Parts Trade	1	1	0.5	0.5
Industrial Digital Printers Trade[90]	1	0.5	0.5	0.5
HDOR Equipment Parts Trade	1	1	0.5	0.5
World Bank Ease of Doing Business Index (2015)[91]	7	14	121	80
Out of Possible Score	190	190	190	190
Normalized	**0.96**	**0.93**	**0.36**	**0.58**
Product/Sector VRP Domestic Business Weighting				
VRP Vehicle Parts Domestic Business	1	1	0.5	0.01
VRP Industrial Digital Printers Domestic Business	1	1	0.5	0.01
VRP HDOR Equipment Parts Domestic Business	1	1	0.5	0.01
Factor Calculation[92]				
Regulatory Factor - Vehicle Parts	**0.91**	**0.86**	**0.28**	**0.18**
Regulatory Factor - Industrial Digital Printers	**0.91**	**0.66**	**0.28**	**0.18**
Regulatory Factor - HDOR Equipment Parts	**0.91**	**0.86**	**0.28**	**0.18**

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[89] Per OECD Trade Facilitation Indicators, 2015 scores for US, Brazil, China and Germany (OECD 2015b).

[90] Given the impact of Basel Convention definitions upon the movement of case study industrial digital printers by exporters, Parties to the Basel Convention have an additional VRP-related barrier to trade of industrial digital printers, per interviews with industry experts. As such, the Product/Section VRP Trade Factor for Germany, Brazil and China accounts for this additional VRP barrier.

[91] Per The World Bank Doing Business, Economy Rankings for US, Brazil, China and Germany (World Bank 2015).

[92] Each normalized OECD Avg. Trade Facilitation Indicators score and normalized World Bank Ease of Doing Business Index (2015), was multiplied by the Product/Sector VRP Trade and VRP Domestic Business Weightings, respectively, for each case study sector, and then divided by 2 to enable continued normalization.

Import-based VRP barrier factors

To reflect the implications of VRP product imports within sample economies under the different VRP barrier alleviation scenarios, import share of demand ($IP^{i,j,k}$) is incorporated for each scenario as outlined in Table B-32. It is important to note that import share of demand is organized by product sector (Industrial Digital Printers, Vehicle Parts, and HDOR Equipment Parts), as well as by OEM New, refurbished, and remanufactured VRPs, as appropriate in the context of import. Current state, or Status Quo scenario values for import share of demand for OEM New products are based on data for each sample economy from the Observatory of Economic Complexity (2015). Current state, or Status Quo scenario values for import share of refurbished and remanufactured products are derived from the US International Trade Commission (USITC) (2009, 2012), the European Remanufacturing Network (ERN) (2015), and interviews with industry experts.

In the Standard Open Market scenario, import share of demand for Brazil, China and Germany are set to the Status Quo import share of demand of the US, as established by the conditions of this particular scenario. Finally, in the Theoretical High scenario, the import share of demand for Germany is returned to its Status Quo state, however those of Brazil and China are increased to 20 per cent to reflect conditions for which trade of VRP products has reached a greater share of the products reaching the market place.

Table B-32: Summary of import share assumptions across global barrier alleviation scenarios

		Current State	Global Barrier Alleviation Scenarios		
			Status Quo	Standard Open Market	Theoretical High
US	Import Share – Veh. Parts OEM New	21.4%	21.4%	21.4%	21.4%
	Import Share – Veh. Parts Reman	20.8%	20.8%	20.8%	20.8%
	Import Share – Ind. Print OEM New	91.6%	91.6%	91.6%	91.6%
	Import Share - Ind. Print Refurb	21.9%	21.9%	21.9%	21.9%
	Import Share - Ind. Print Reman	21.9%	21.9%	21.9%	21.9%
	Import Share - HDOR Parts OEM New	35.1%	35.1%	35.1%	35.1%
	Import Share - HDOR Parts Refurb	53.0%	53.0%	53.0%	53.0%
	Import Share - HDOR Parts Reman	53.0%	53.0%	53.0%	53.0%
Germany	Import Share – Veh. Parts OEM New	57.5%	57.5%	57.5%	57.5%
	Import Share – Veh. Parts Reman	15.8%	15.8%	20.8%	15.8%
	Import Share – Ind. Print OEM New	61.5%	61.5%	61.5%	61.5%
	Import Share - Ind. Print Refurb	16.9%	16.9%	21.9%	16.9%
	Import Share - Ind. Print Reman	16.9%	16.9%	21.9%	16.9%
	Import Share - HDOR Parts OEM New	82.0%	82.0%	82.0%	82.0%
	Import Share - HDOR Parts Refurb	48.0%	48.0%	53.0%	48.0%
	Import Share - HDOR Parts Reman	48.0%	48.0%	53.0%	48.0%

		Current State	Global Barrier Alleviation Scenarios		
			Status Quo	Standard Open Market	Theoretical High
Brazil	Import Share – Veh. Parts OEM New	12.8%	12.8%	12.8%	12.8%
	Import Share – Veh. Parts Reman	0.0%	0.0%	20.8%	20.0%
	Import Share – Ind. Print OEM New	70.5%	70.5%	70.5%	70.5%
	Import Share - Ind. Print Refurb	0.0%	0.0%	21.9%	20.0%
	Import Share - Ind. Print Reman	0.0%	0.0%	21.9%	20.0%
	Import Share - HDOR Parts OEM New	3.4%	3.4%	3.4%	3.4%
	Import Share - HDOR Parts Refurb	0.0%	0.0%	53.0%	20.0%
	Import Share - HDOR Parts Reman	0.0%	0.0%	53.0%	20.0%
China	Import Share – Veh. Parts OEM New	11.0%	11.0%	11.0%	11.0%
	Import Share – Veh. Parts Reman	0.0%	0.0%	20.8%	20.0%
	Import Share – Ind. Print OEM New	99.6%	99.6%	99.6%	99.6%
	Import Share - Ind. Print Refurb	0.0%	0.0%	21.9%	20.0%
	Import Share - Ind. Print Reman	0.0%	0.0%	21.9%	20.0%
	Import Share - HDOR Parts OEM New	8.1%	8.1%	8.1%	8.1%
	Import Share - HDOR Parts Refurb	0.0%	0.0%	53.0%	20.0%
	Import Share - HDOR Parts Reman	0.0%	0.0%	53.0%	20.0%

Finally, the import and export factors that are held constant within the economy-level model are presented in Table B-33. This offers further clarity with regard to the data and implications of Equations 11 and 12, which account for the quantity and implications of the origin of imported products. In additon, assumptions regarding the destination of domestic production outputs – either into the domestic market, or to export – are also presented Table B-33.

Table B-33: **Import and export factors held constant within model period**

		Constant Import and Export Factors			
		Destination of Domestic Production Outputs		Import Origin	
		Share to Domestic Market (X)	Share to Export (1-X)	Import from Developed Economies ($I(a)$)	Import from Developing Economies ($I(b)$)
US	Vehicle Parts OEM New	83.2%	16.8%	45.0%	55.0%
	Vehicle Parts Reman	90.6%	9.4%	23.8%	76.2%
	Industrial Digital Printers OEM New	51.8%	48.2%	40.0%	60.0%
	Industrial Digital Printers Refurb	96.2%	3.8%	25.0%	75.0%
	Industrial Digital Printers Reman	96.2%	3.8%	25.0%	75.0%
	HDOR Equipment Parts OEM New	51.6%	48.4%	45.7%	54.3%
	HDOR Equipment Parts Refurb	68.4%	31.6%	7.7%	92.3%
	HDOR Equipment Parts Reman	68.4%	31.6%	7.7%	92.3%

		Constant Import and Export Factors			
		Destination of Domestic Production Outputs		Import Origin	
		Share to Domestic Market (X)	Share to Export (1-X)	Import from Developed Economies ($I\ (a)$)	Import from Developing Economies ($I(b)$)
Germany	Vehicle Parts OEM New	89.6%	10.4%	91.2%	8.8%
	Vehicle Parts Reman	89.6%	10.4%	23.8%	76.2%
	Industrial Digital Printers OEM New	44.3%	55.7%	59.9%	40.1%
	Industrial Digital Printers Refurb	96.2%	3.8%	25.0%	75.0%
	Industrial Digital Printers Reman	96.2%	3.8%	25.0%	75.0%
	HDOR Equipment Parts OEM New	15.3%	84.7%	71.5%	28.5%
	HDOR Equipment Parts Refurb	15.3%	84.7%	7.7%	92.3%
	HDOR Equipment Parts Reman	15.3%	84.7%	7.7%	92.3%
Brazil	Vehicle Parts OEM New	98.4%	1.6%	50.7%	49.3%
	Vehicle Parts Reman	98.4%	1.6%	0.0%	0.0%
	Industrial Digital Printers OEM New	88.9%	11.1%	41.9%	58.1%
	Industrial Digital Printers Refurb	98.8%	1.2%	0.0%	0.0%
	Industrial Digital Printers Reman	98.8%	1.2%	0.0%	0.0%
	HDOR Equipment Parts OEM New	97.7%	2.3%	70.1%	29.9%
	HDOR Equipment Parts Refurb	97.5%	2.5%	0.0%	0.0%
	HDOR Equipment Parts Reman	97.5%	2.5%	0.0%	0.0%
China	Vehicle Parts OEM New	99.0%	1.0%	77.6%	22.4%
	Vehicle Parts Reman	100.0%	0.0%	0.0%	0.0%
	Industrial Digital Printers OEM New	8.0%	92.0%	66.5%	33.5%
	Industrial Digital Printers Refurb	100.0%	0.0%	0.0%	0.0%
	Industrial Digital Printers Reman	100.0%	0.0%	0.0%	0.0%
	HDOR Equipment Parts OEM New	96.4%	3.6%	75.9%	24.1%
	HDOR Equipment Parts Refurb	100.0%	0.0%	0.0%	0.0%
	HDOR Equipment Parts Reman	100.0%	0.0%	0.0%	0.0%

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There is growing international interest in the concept of circular economy as a framework for pursuing sustainable economic growth and human prosperity.

A key aspect of circular economy, well-aligned with current objectives of resource efficiency and resource productivity, is the concept of value-retention within economic production-consumption systems. Value-retention processes, such as *remanufacturing, refurbishment, repair and arranging direct reuse,* enable, to varying degrees, the retention of value, and in some cases the creation of new value for both the producer and customer, at a reduced environmental impact.

This report connects the potential for resource efficiency, via circular economy and the processes that retain product value within the systems, with a policy-relevant lens. The report is one of the first reports to quantify the current-state and potential impacts associated with the inclusion of value-retention processes within industrial economic systems. In order to do that the assessment applies the different value-retention processes to a series of products within three industrial sectors and quantifies benefits in relation to the original manufactured product, such as the material requirement, the energy used, the waste as well as the costs and the generation of jobs.

The report also highlights the systemic barriers that may inhibit progressive scale-up including regulatory, market, technology and infrastructure barriers, and how they could be overcome.

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