Influence of high road labor policies and practices on renewable energy costs, decarbonization pathways, and labor outcomes

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Abstract

Achieving an economy-wide net-zero greenhouse gas emissions goal by mid-century in the United States entails transforming the energy workforce. In this study, we focus on the influence of increased labor compensation and domestic manufacturing shares on (1) renewable energy technology costs, (2) the costs of transitioning the U.S. economy to net-zero emissions, and (3) labor outcomes, including total employment and wage benefits, associated with the deployment of utility-scale solar photovoltaics (PV) and land based and offshore wind power. We find that manufacturing and installation labor cost premiums as well as increases in domestic content shares across wind and utility-scale solar photovoltatic supply chains result in relatively modest increases in total capital and operating costs. These small increases in technology costs may be partially or fully offset by increases in labor productivity. We also show that solar and wind technology cost premiums associated with high road labor policies have a minimal effect on the pace and scale of renewable energy deployment and the total cost of transitioning to a net-zero emissions economy. Public policies such as tax credits, workforce development support, and other instruments can redistribute technology cost premiums associated with high road labor policies to support both firms and workers.

Keywords: labor policy, manufacturing, renewable energy, climate change, decarbonization

Introduction

Net emissions of greenhouse gases must approach zero in order to stabilize the global mean temperature [1], [2]. In 2021, the Biden administration issued executive orders committing the U.S. to achieving an economy-wide net-zero emissions target by mid-century [3], [4]. Several states have similarly made net-zero commitments through statute or executive order [5]. Achieving a net-zero emissions goal entails transformational changes in the physical energy system [6], [7], in addition to the energy workforce [8].

Increasingly, policy discourse has focused on embedding social, environmental justice, and equity goals into climate policy [9]–[11], including elements related to the distribution of societal costs, risks, and benefits, such as jobs and air pollution [12]–[14]. With respect to labor equity, taking the *high road* refers to a collection of practices and policies such as local hiring requirements, prevailing wage standards, unionization, gender and racial equity hiring requirements, workforce development and training, and domestic content share requirements [15]. While these practices can increase and concentrate wages and other employment benefits, the policy and political discourse around clean energy often operates under an assumption that there are inherent tradeoffs between addressing climate change or maintaining affordable electricity supplies and supporting jobs.

The aim of this to study is to quantify the relationship between high road labor practices and policies and the cost and pace of clean energy transitions. We focus on the influence of increased labor costs and domestic manufacturing shares on (1) renewable energy technology costs, (2) the costs of transitioning the U.S. economy to net-zero emissions, and (3) labor outcomes, including total employment and wage benefits, associated with the deployment of utility-scale solar photovoltaics (PV) and land-based and offshore wind power.

To evaluate the influence of high road labor policies, we first develop bottom-up capital and operations and maintenance (O&M) cost estimates for 2020, largely based on the National Renewable Energy Laboratory (NREL) benchmarking studies and market reports [16]–[29]. In this bottom-up cost estimation, we confine our scope to focus on domestic manufacturing and direct labor associated with the following segments of the wind and solar supply chains: production of wind blades, towers and nacelles and wind farm installation, and production of polysilicon, wafers, photovoltaic cells, modules and inverters and solar PV system installation. All other raw materials and subcomponent inputs into these specific supply chain steps (i.e. steel or aluminum for wind towers or PV racking, internal power electronics or other components for inverters, etc.) are treated as non-labor cost inputs and we do not estimate domestic content or break out labor costs and compensation associated with these inputs. We modify the 2020 baseline cost estimates to reflect alternative labor cost premiums and increased domestic content share assumptions, and we project costs from 2020 to 2050. We then simulate the effects of high road labor policies and practices on least-cost pathways to achieve net-zero emissions in the U.S. by 2050. We model alternative techno-economic pathways using the modeling approach and specifications developed as part of the *Net-Zero America* (NZA) study [6]. The NZA study implements a macro-energy system modeling framework to select a least-cost techno-economic pathway to achieve net-zero emissions across the U.S. economy by 2050. We use EnergyPATHWAYS, a bottom-up model of future economy-wide electricity and fuel demand, coupled with RIO, a linear programming model that combines capacity expansion with sequential hourly operations over a sampling of representative days to find the least-cost solution for decarbonized energy supply to meet demand over time [7]. Finally, we use the Decarbonization Employment and Energy Systems (DEERS) model to estimate employment and wage outcomes associated with the techno-economic pathways modeled [8].

The following sections outline the findings, and the Supplementary Information (SI) provides technical detail regarding the modeling approach.

Influence of high road labor practices and policies on baseline renewable energy technology costs

We estimate the following 2020 baseline capital cost estimates: \$1.20/W-AC for utility-scale solar (without tariffs), \$1.30/W for land-based wind, \$4.08/W for fixed offshore wind, and \$5.32/W for floating offshore wind.[1] See SI Section 1.1. for derivation of this baseline estimate. We then modify these baseline renewable energy technology costs to evaluate the influence of labor cost premiums and increased domestic content shares, in addition to the potential countervailing effect of productivity gains.

Labor cost premiums associated with manufacturing and installation may arise from prevailing wage standards, unionization, job training programs, and other high road policies and practices. Domestic labor costs represent a small to moderate share of solar and wind installed capital costs (17% for utility-scale solar, 22% for land-based wind, and 10% for offshore wind) and O&M costs (32% for utility-scale solar, 28% for land-based wind, and 16% for offshore wind). As a result, labor cost premiums associated with manufacturing and construction have a relatively small influence on technology costs, as shown in Figures 1 and 2. For example, a 20% increase in domestic labor costs increases installed capital costs for wind and solar power by 2-4% and O&M costs by approximately 3-6% across technologies.

[1] The following baseline technology specifications, consistent with NREL benchmark studies [21], [22] , are assumed: one-axis tracker, 100 MW, Tier 1 mono-crystalline-silicon PV modules; 200 MW land-based wind plant comprised of 2.6 MW land-based wind turbines with a 121 meter (m) rotor diameter & 90 m hub height; 600 MW offshore wind plant comprise of 6.1 MW turbines with fixed or floating bottom, 151 m rotor diameter, and 102 m hub height.

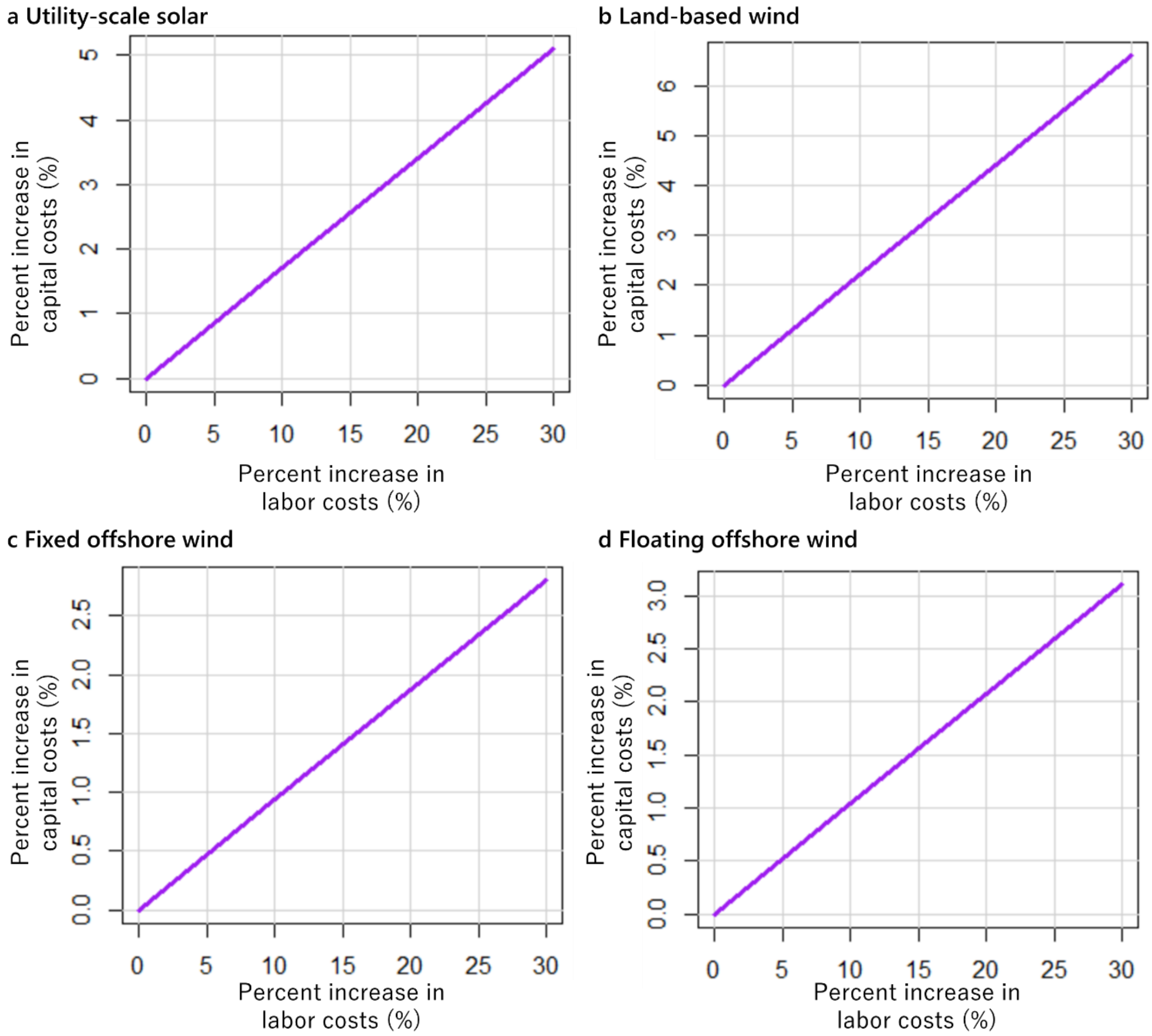

Figure 1. Sensitivity of baseline capital costs to changes in labor costs. Percent increases are relative to baseline assumptions regarding labor costs.

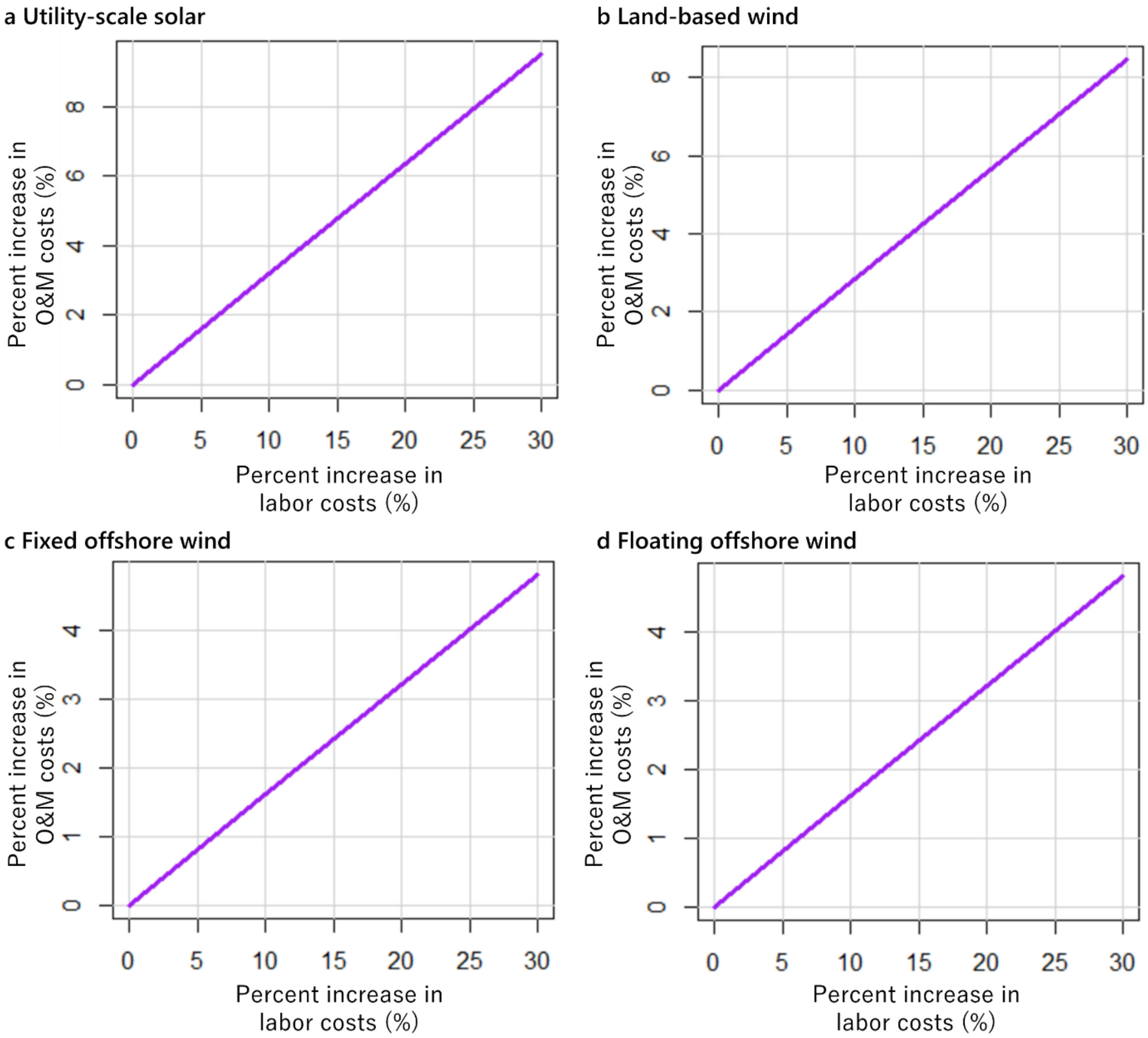

Figure 2. Sensitivity of baseline O&M costs to changes in labor costs. Percent increases are relative to baseline assumptions regarding labor costs.

Figures 3-5 contextualize the sensitivity of capital and O&M costs to the wage distribution across the construction and manufacturing sectors. Wage heterogeneity is associated with, among other factors, occupation, geography, unionization rates, industry differentiation, and firm practices. For example, unionized workers are generally compensated at a higher wage rate than workers not represented by a union, with average wage premiums of 48% and 9% in the construction and manufacturing sectors, respectively; the wage premium associated with unionized workers also varies by occupation and geography [30]. Even large changes in annual wages have a relatively small influence on installed wind and solar project costs. For example, increasing annual wages from the 25th to 75th percentile wage rate for jobs in the construction sector (from $35,870 to $68,690) reported by the U.S. Bureau of Labor Statistics (BLS) increases utility-scale solar installed capital costs by 10%; similarly, increasing wages from the non-union to the union median wage rate ($45,136 to $65,364) increases installed capital costs by 6%.

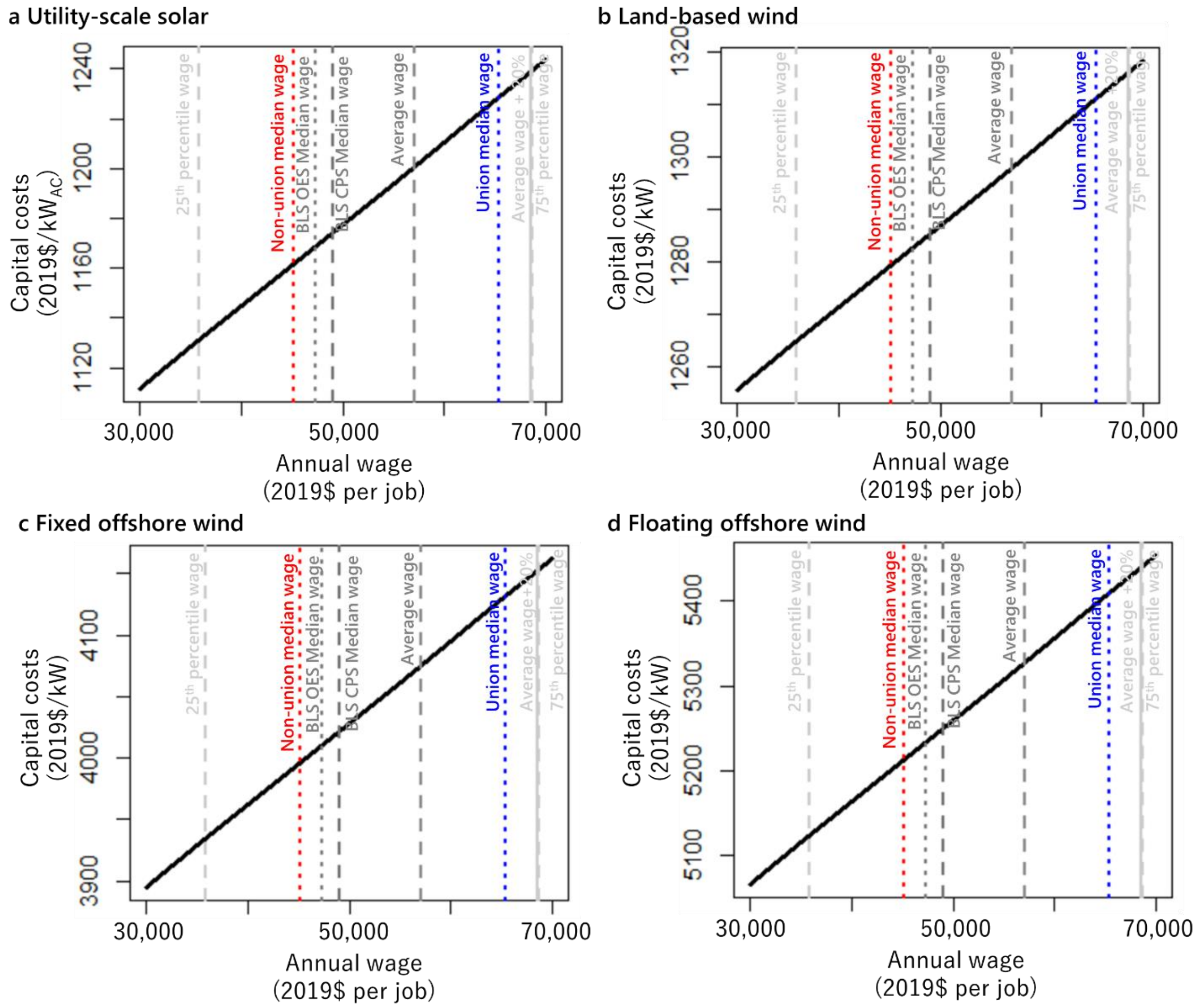

Figure 3. Sensitivity of 2018 capital costs to changes in annual wages for construction sector jobs. For comparison, 2019 annual wage estimates for the manufacturing sector, including 25th percentile, median, average, and 75th percentile wages reported in the U.S. BLS Community Population Survey (CPS) (dotted lines), median, union median, and non-union median wages reported in the U.S. BLS Occupational Employment Statistics (OES) (dashed lines), and U.S. BLS OES average wage plus 20% (solid lines).

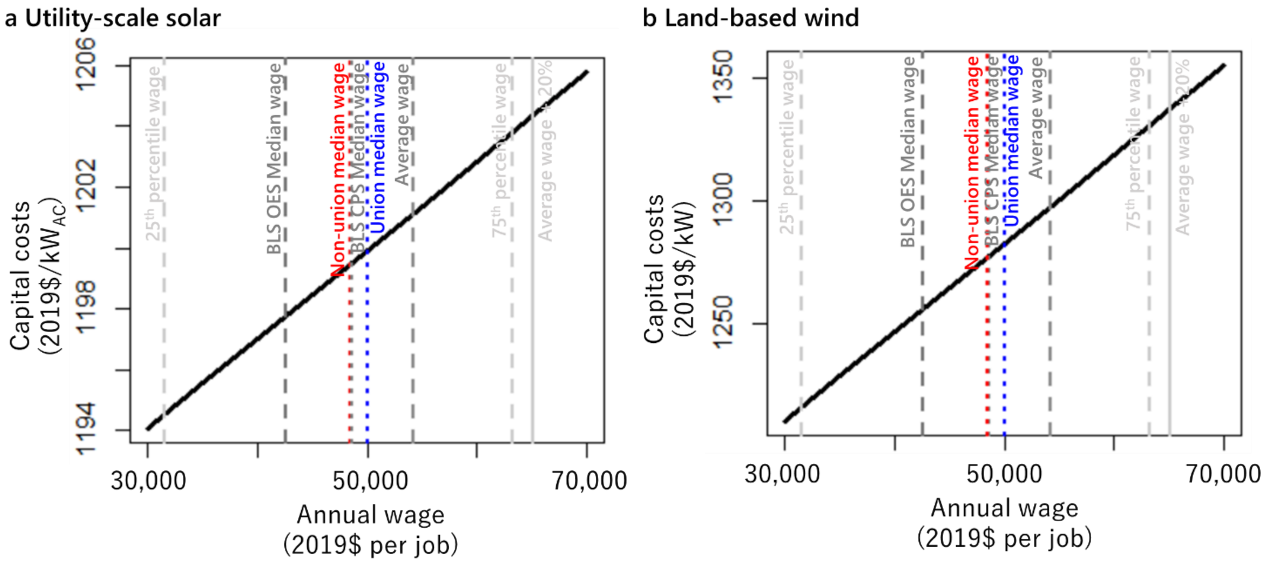

Figure 4. Sensitivity of 2018 capital costs to changes in annual wages for manufacturing sector jobs. For comparison, 2019 annual wage estimates for the manufacturing sector, including 25th percentile, median, average, and 75th percentile wages reported in the U.S. BLS CPS (dotted lines), median, union median, and non-union median wages reported in the U.S. BLS OES (dashed lines), and U.S. BLS OES average wage plus 20% (solid lines).

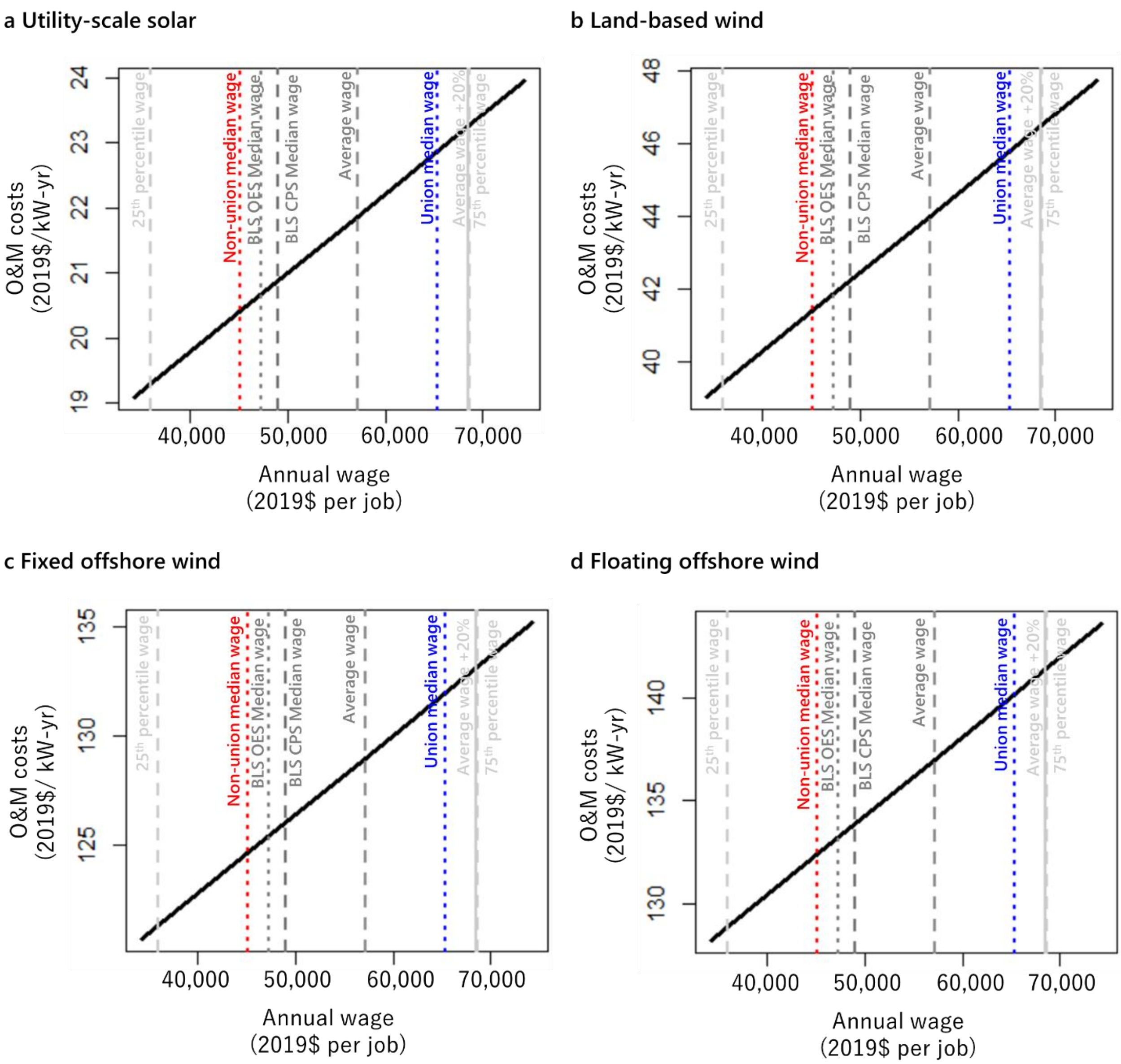

Figure 5. Sensitivity of 2018 O&M costs to changes in annual wages for construction sector jobs. For comparison, 2019 annual wage estimates for the manufacturing sector, including 25th percentile, median, average, and 75th percentile wages reported in the US BLS CPS (dotted lines), median, union median, and non-union median wages reported in the US BLS OES (dashed lines), and US BLS OES average wage plus 20% (solid lines).

Labor policies may also be designed to induce domestic manufacturing along wind and solar PV supply chains. With respect to products along the crystalline silicon photovoltaic supply chain, there is virtually no domestic manufacturing of polysilicon, ingots, and wafers, whereas 15% of cells, 11% of modules, and 37% of inverters are produced domestically [18], [19], [31]. Almost all cell and module imports (as of 2020) are from Asia [20]. Increasing domestic content shares by 10 percentage points (e.g., increasing the domestic content share of cells to 25%) across the PV supply chain (excluding upstream materials and products such as steel and aluminum) results in a 1% increase in average installed solar PV capital costs, as shown in Figure 6. Solar projects sourcing 100% domestic content from across the full polysilicon PV supply chain would have installed costs just 7% higher than current average costs.

The U.S. has substantial domestic manufacturing of many land-based wind products with a domestic manufacturing share of approximately 79% (as of 2019), which is a capital cost-weighted average across the multiple segments of the wind product supply chain including nacelle assembly (90-100%), blades (40-70%), and towers (65-85%) [29], [32]–[34]. There is no current domestic manufacturing for offshore wind products. High domestic content shares partially stem from high international shipping costs for large wind turbine components, making domestic products more competitive. Imports of wind products (as of 2019) come from several different regions, with generating set imports largely from Europe, tower imports largely from Asia, and blades and hubs from North America, South America, Europe, and Asia [34]. We estimate that increasing the domestic manufacturing share does not have a discernible influence on wind power capital costs, which in part is because the price spread between domestically-produced and imported wind products is not well established based on available data.

Increases in both labor costs and domestic manufacturing shares may have a compounding effect, which is most evident in utility-scale solar. However, even in a relatively extreme case in which compensation for all workers is increased 20% and 100% of manufacturing is performed domestically, baseline capital costs increase by no more than 11% for utility-scale solar, 5% for land-based wind, and 4% for offshore wind, as shown in Figure 7 and 8.

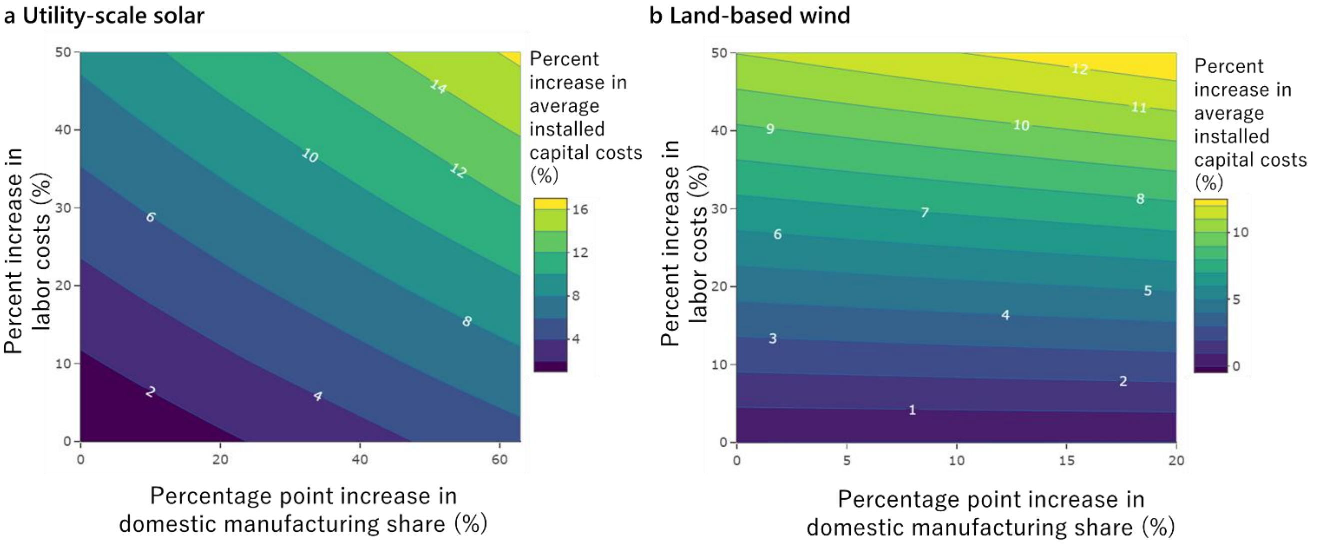

Figure 6. Sensitivity of baseline capital costs to changes in domestic manufacturing shares and labor costs. Percent increases in labor costs and percentage point increases in domestic manufacturing shares are relative to baseline estimates for average labor cost and current domestic content circa 2020.

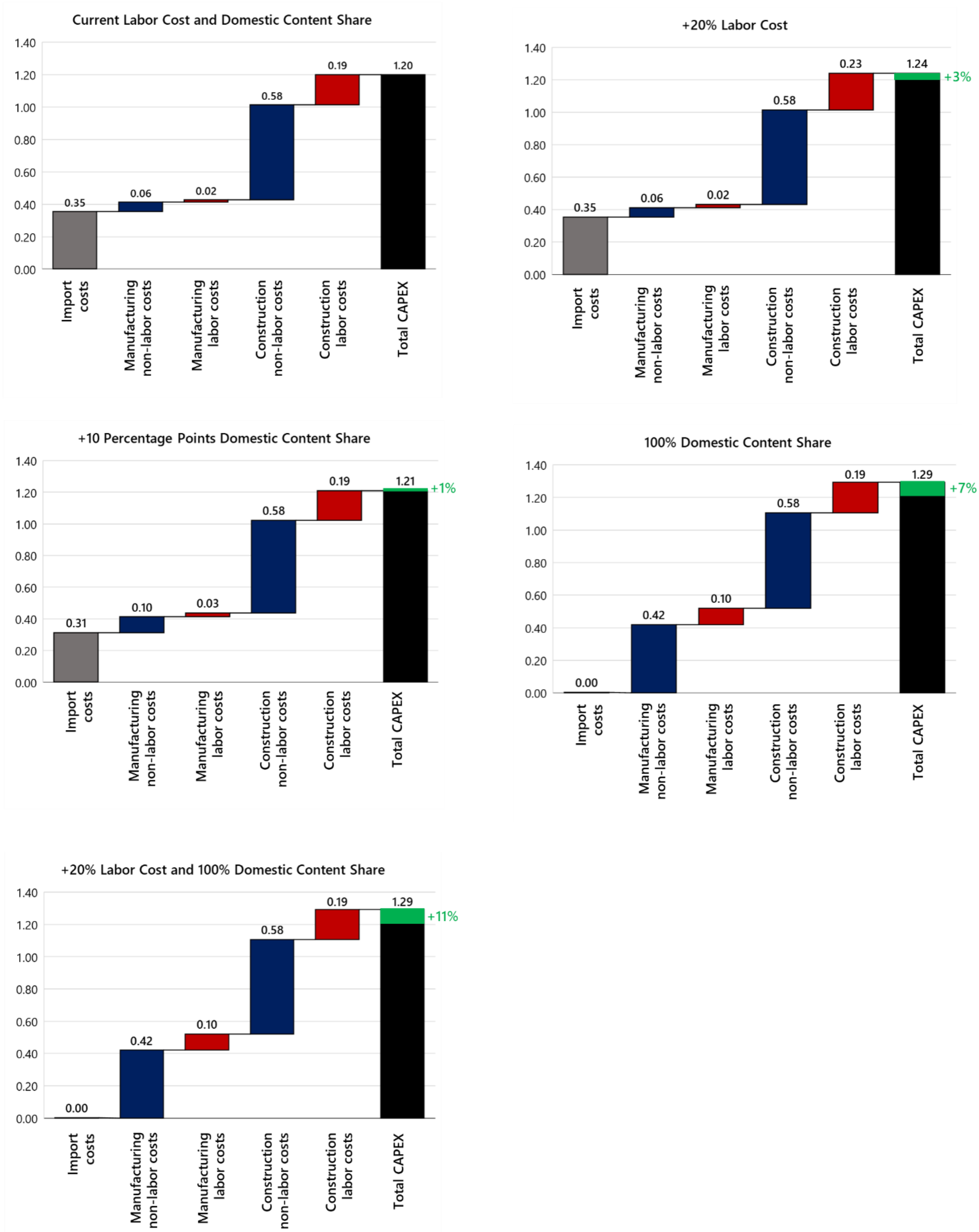

Figure 7. Utility-scale solar capital costs based on alternative labor cost premium and domestic manufacturing share assumptions. Costs are in units of $/W-ac. Green bars indicate the total capital cost premium above the baseline scenario. All estimates are for circa 2020 and exclude tariffs for imported products.

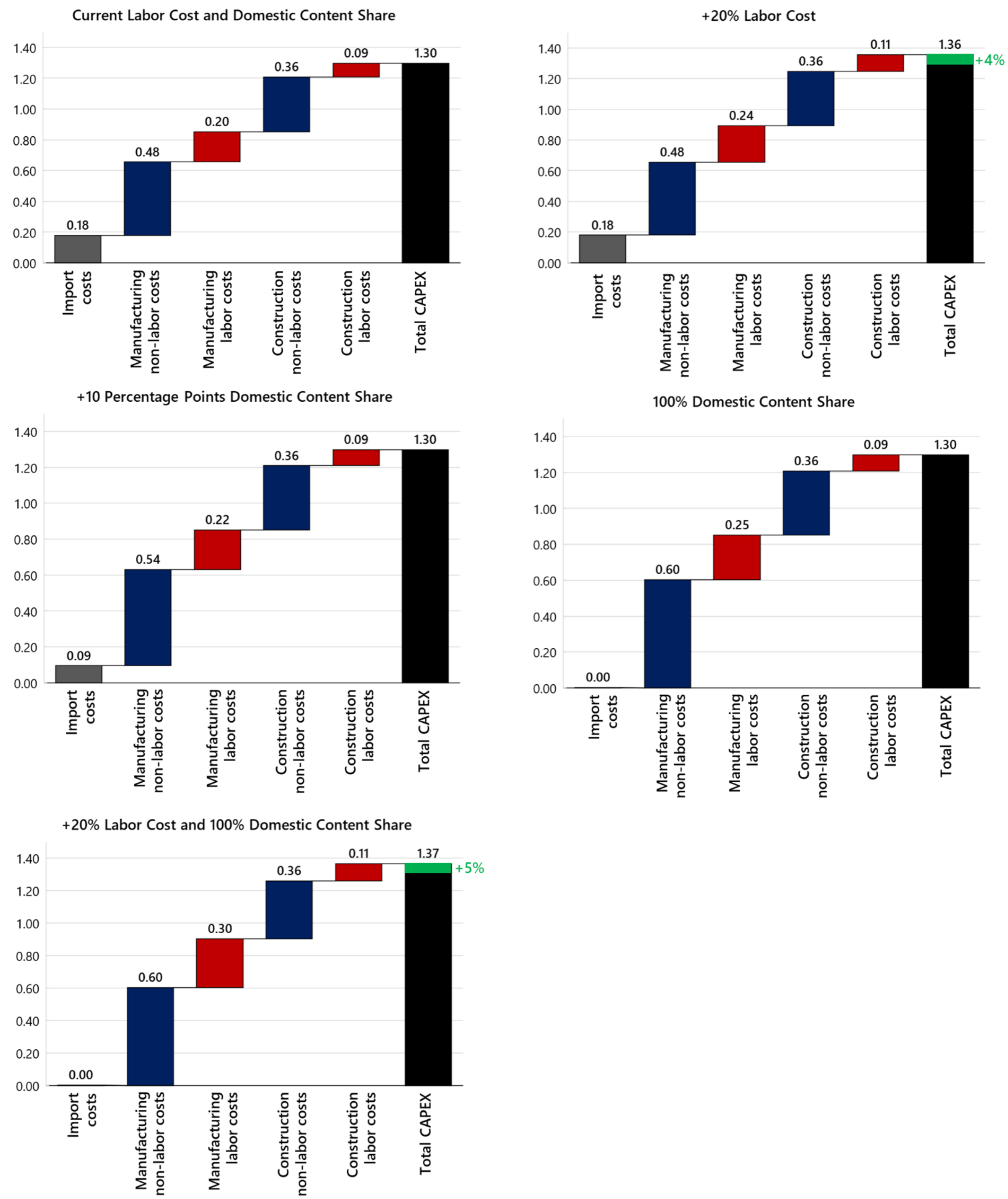

Figure 8. Land-based wind capital costs based on alternative labor cost premium and domestic manufacturing share assumptions. Costs are in units of $/W. Green bars indicate the total capital cost premium above the baseline scenario. All estimates are for circa 2020 and exclude tariffs for imported products.

Increases in labor productivity have the potential to offset the impact of higher labor costs and domestic manufacturing shares. For example, a 20% increase in domestic labor costs can be offset by a countervailing increase in domestic labor productivity by 20%. Labor productivity increases can be induced by a variety of factors. Higher labor compensation may increase worker retention and contribute to associated productivity improvements. There is historical evidence that unionized labor is more productive [35]. Heterogeneity in firm-level productivity is also observed. As such, while prevailing wage requirements may increase wages, total labor costs may not increase; in states with prevailing wage laws, worksite productivity is 14-33% higher [36], [37].

Increasing labor productivity through automation and learning has historically contributed to declining technology costs, making low-carbon technologies significantly more cost competitive over the past decade. There have been historical short- and long-term trends of increasing labor productivity in the manufacturing sector, in addition to rapid increases in productivity in the construction sector associated with solar installation as well as in other historic energy transitions such as the shale gas boom [8], [38].

Future trends of declining renewable technology costs entail, in part, that industries continue to economize on labor; this is an underlying assumption of declining technology cost projections such as the NREL Annual Technology Baseline (ATB) that is commonly used by policy-makers, planners, and analysts to evaluate decarbonization policies and pathways. In addition, solar and wind industries and associated workforces must rapidly expand to meet a net-zero goal by 2050 [6], and given the relatively small size and nascence of the existing solar and wind sectors, it is anticipated that labor productivity will continue to increase, although the extent and pace of productivity changes are uncertain. Technology costs are projected to decrease over time by a much greater magnitude (e.g. 20-37% for utility-scale solar PV, land-based wind 18-25%, and 23-32% offshore wind from 2020 to 2030 [39]) than the potential premium in installed project costs related to adopting high road labor practices.

Influence of high road labor practices and policies on economy-wide net-zero transitions

We examine the influence of high road labor practices and policies on the cost and technology mix associated with techno-economic pathways to achieve net-zero emissions in the U.S. by mid-century. Specifically, we determine how solar and wind technology capital and O&M cost increases associated with labor cost premiums and increased domestic manufacturing shares influence the deployment of renewables and the total investment cost of transitioning the economy.

This work builds from the bottom-up cost break-downs that isolate the role of labor and domestic manufacturing in installed solar and wind project costs outlined in the previous sections as well projections of future cost decreases. We also leverage the techno-economic modeling framework used in the Princeton *Net-Zero America* (NZA) study to determine cost-optimized energy supply pathways [6]. We employ the same suite of modeling assumptions used in the NZA project, with the exception of solar and wind technology capital and O&M cost projections, which are modified to reflect alternative assumptions regarding labor costs and domestic manufacturing shares. Specifically, we model two bounding scenarios that reflect a range of assumptions: 1) labor costs and domestic manufacturing share are consistent with 2019 NREL ATB mid-range cost projections, as a baseline case, and 2) labor costs reflect the 75th percentile of construction and manufacturing sector wages and the domestic manufacturing share of products is 100%. This second scenario reflects a likely upper bound on the impact of high road labor policies.

Through modelling alternative techno-economic pathways, we show that increasing labor costs and/or domestic manufacturing shares has minimal impact on the deployment of solar and wind capacity. As shown in Figure 9, the pace and scale of utility-scale solar, land-based wind, and offshore wind capacity additions are approximately equivalent between the two net-zero transition scenarios, with a 4-fold increase by 2030 and 18-fold increase by 2050 (relative to 2020). As depicted in Figure 10, solar and wind comprise an increasing share of electric power generation over time across both scenarios (12% in 2020, 86% in 2050), while fossil fuels represent a declining share (61% in 2020, <5% in 2050).

Even with higher labor costs, solar and wind technologies remain a pillar of decarbonization and cost competitive relative to other technologies. The modeled changes in labor costs are minimal compared to other production factors contributing to uncertainty and heterogeneity in technology cost projections and total system costs, such as labor productivity trends, improving system controls, and declining material costs.

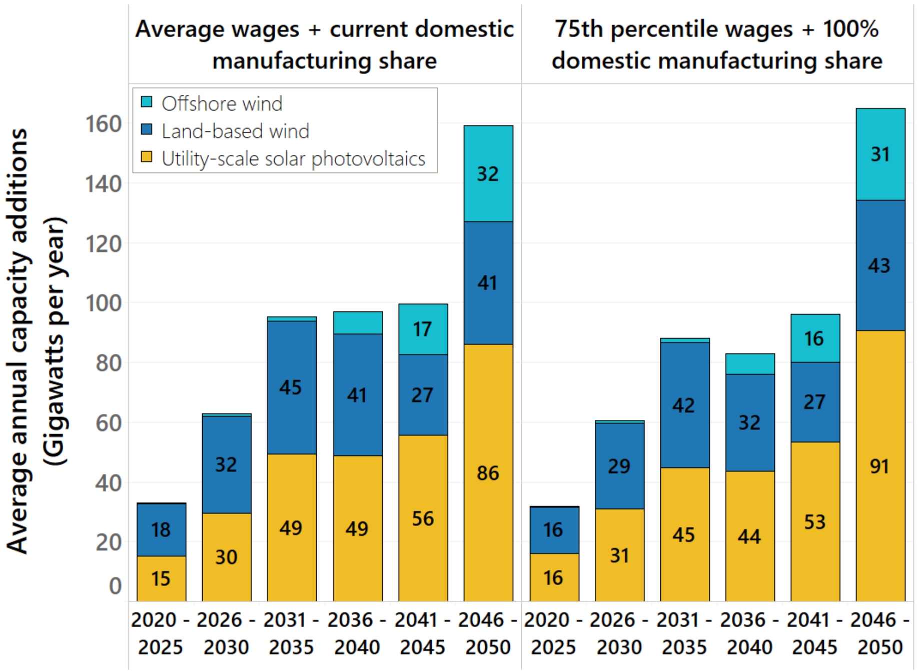

Figure 9. Average annual solar and wind capacity additions associated with alternative U.S. decarbonization pathways to achieve a net-zero emissions goal by mid-century. Baseline decarbonization scenario at left assumes current domestic manufacturing shares of utility-scale solar and wind and average wages across sectors. The alternative high road scenario at right assumes that all workers associated with utility-scale solar and wind manufacturing, installation, and O&M are paid 75th percentile wages for a given economic sector and that 100% of the manufacturing supply chain is domestic.

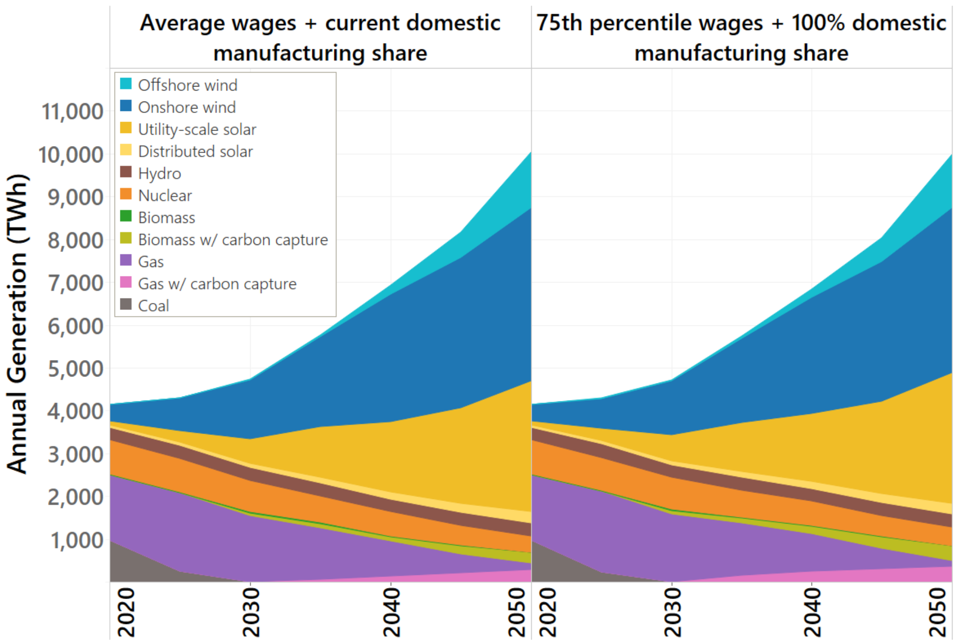

Figure 10. Annual electric power generation by resource as the U.S. energy system decarbonizes to achieve a net-zero emissions goal by mid-century. Baseline decarbonization scenario at left assumes current domestic manufacturing shares of utility-scale solar and wind and average wages across sectors. The alternative high road scenario at right assumes that all workers associated with utility-scale solar and wind manufacturing, installation, and O&M are paid 75th percentile wages for a given economic sector and that 100% of the manufacturing supply chain is domestic.

High road labor practices in the solar and wind sectors have a small impact on the cost of transitioning to a net-zero energy system. Figure 11 shows that there is a small difference in energy supply-related investment costs from adopting high road labor policies and practices in the wind and solar sectors. The total net-present value of supply-side investment cost over the entire transition period from 2020 to 2050 is $3.9T, assuming a 2% social discount rate and average wage rates and the current domestic manufacturing shares. As a bounding scenario, if wages increase to the 75th percentile rate and all solar and wind products are produced domestically, the total supply-side investment costs are $4.0T from 2020 to 2050, an increase of approximately 3%. Cumulative cost increases through 2040 are almost imperceptible, with most of the cost increase accruing in the 2040s (see Figure 11). This scenario represents a relative upper bound on the impact of a high road labor pathway on net-zero energy system transition costs. More moderate increases in domestic content share or lower wage premiums would have correspondingly smaller cost impacts.

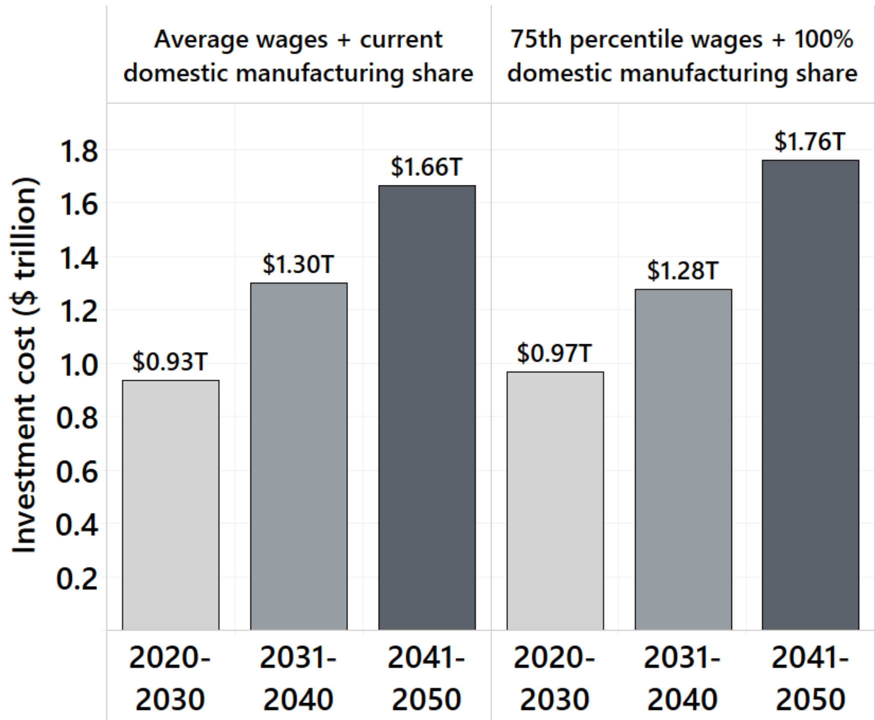

Figure 11. Supply-side investment costs by decade associated with alternative U.S. decarbonization pathways to achieve a net-zero emissions goal by mid-century. Investment costs include all supply-side capital costs across the energy system (including solar and wind capital costs). Baseline decarbonization scenario at left assumes current domestic manufacturing shares of utility-scale solar and wind and average wages across sectors. The alternative high road scenario at right assumes that all workers associated with utility-scale solar and wind manufacturing, installation, and O&M are paid 75th percentile wages for a given economic sector and that 100% of the manufacturing supply chain is domestic.

Influence of high road labor practices and policies on labor outcomes under net-zero transition scenarios

We examine the influence of high road practices and policies on labor outcomes associated with transitioning to a net-zero emissions energy system in the U.S. by mid-century. We use the DEERS model [8], adopting the cost optimal techno-economic pathways described in the previous section as input. We model direct employment and wages associated with solar and wind manufacturing, installation, and O&M under different wage rate and domestic manufacturing share assumptions.[2]

[2] We evaluate the following four scenarios in which we modify occupation-level wages: 1) median wages reported by the U.S. BLS, 2) average wages reported by the U.S. BLS, 3) average wages plus 20%, and 4) 75th percentile wages reported by the U.S. BLS. In addition, we evaluate the following two domestic manufacturing scenarios in which we modify the domestic manufacturing shares of solar and wind products: 1) current domestic manufacturing shares, and 2) 10-percentage point increase in domestic manufacturing share across all segments of the supply chain. We model labor outcomes for the entire U.S. as well as for each state to reflect geographic wage variation.

We show that increasing the domestic manufacturing share of solar and wind products has the potential to substantially increase domestic manufacturing employment as the U.S. transitions to a net-zero energy system. At current domestic manufacturing shares, utility-scale solar and wind sectors support an annual average of approximately 450,000 jobs in the 2020s, as shown in Figure 12. Increasing the domestic manufacturing share of solar and wind products by 10-percentage points across the supply chains has the potential to support an additional 45,000 jobs annually in the 2020s. Over the long-term, as the U.S. energy system continues to decarbonize, an additional 95,000 jobs are supported in the 2040s, an increase of 5% in total wind and utility-scale solar sector employment.

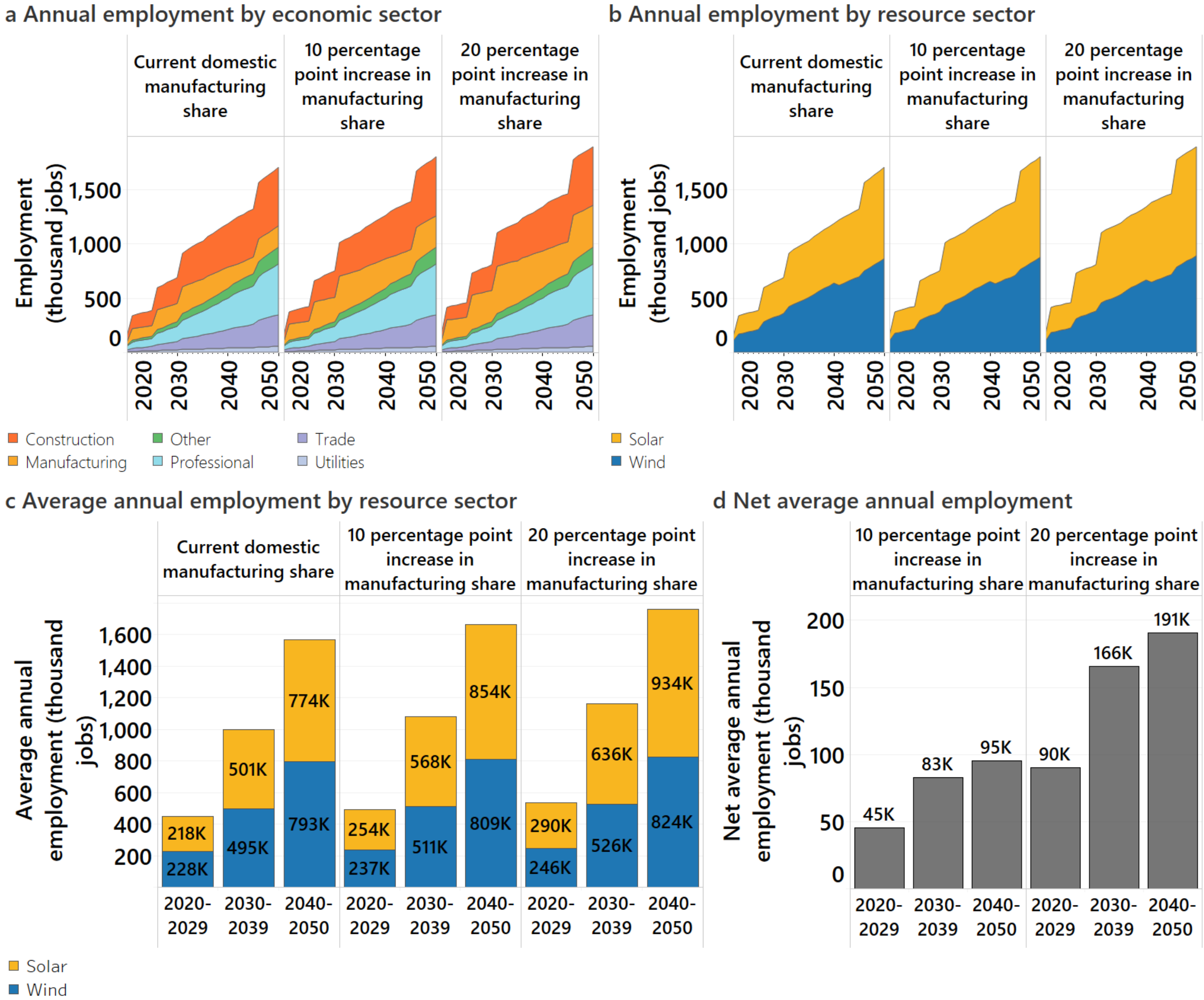

Figure 12. Impact of a 10 or 20 percentage point increase relative to current domestic manufacturing share on utility-scale solar, land-based wind, and offshore wind employment for the U.S. as the energy system decarbonizes to achieve a net-zero emissions goal by mid-century. (a) Annual employment by economic sector, (b) annual employment by resource sector, (c) average annual employment by resource sector and decade, and (d) net increase in average annual employment by decade.

We further evaluate the impact of increasing wage rates. As shown in Figure 13, approximately $25 billion in aggregate annual worker wages are generated in the 2020s from expanding solar and wind manufacturing and electric power capacity, assuming average occupational wage rates. Increasing the occupational wages (or equivalent compensation) for all workers across domestic wind and solar supply chains by 20% has the potential to generate an additional $5 billion in aggregate annual wages in the 2020s. An increase in wages by 20% is equivalent to a $12,000 and $13,000 increase in average annual wages per worker for the solar and wind sectors, respectively, as depicted in Figure 13. Aggregate wages paid to workers in the wind and solar sectors increase over time as capacity expands, and wages are further augmented if a higher share of manufactured products are produced domestically.

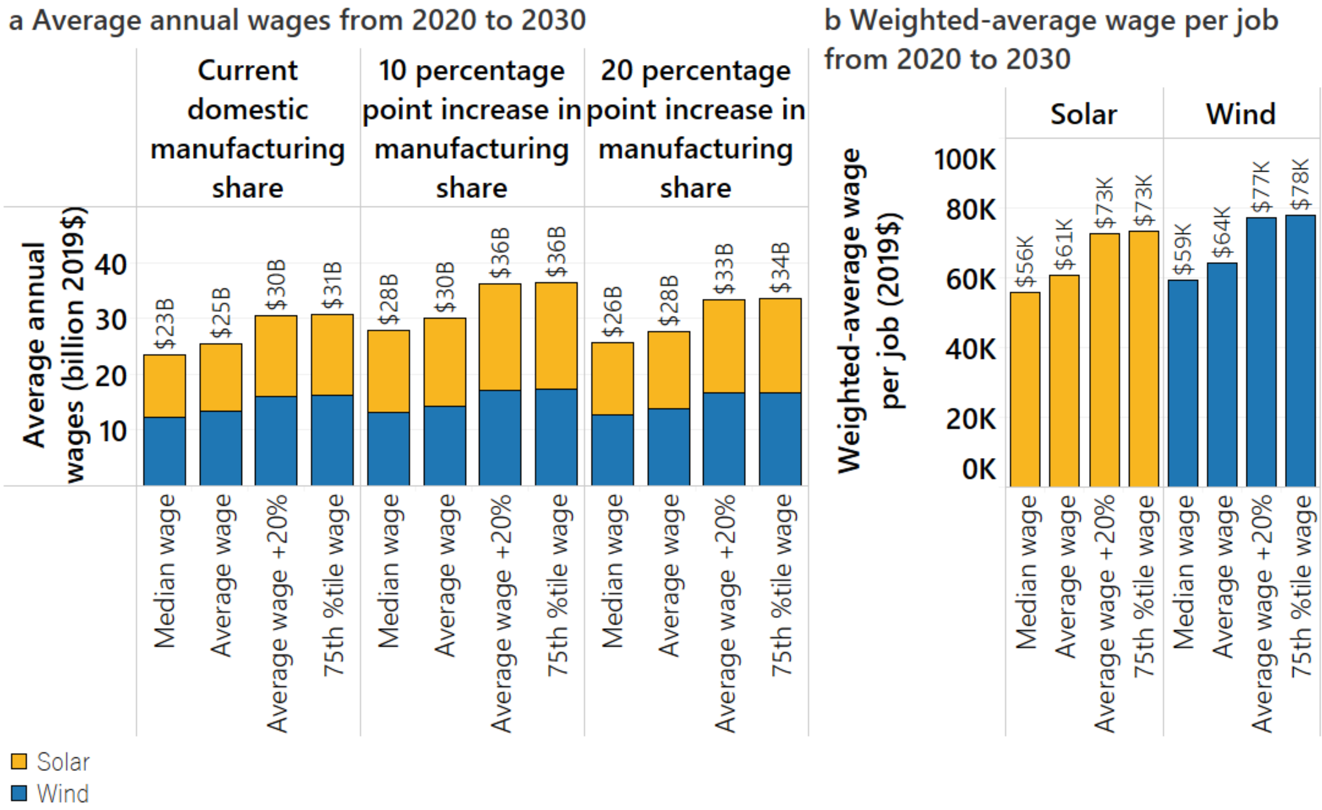

Figure 13. Impact of domestic manufacturing share and wage premiums on wind and solar wages for the U.S. as the energy system decarbonizes to achieve a net-zero emissions goal by mid-century. (a) Annual total wages paid by economic sector and (b) weighted-average annual wages per job by resource sector.

Policy implications

Analysis in the previous sections, including the sensitivity of wind and solar technology costs to increased labor costs and domestic manufacturing shares, are neutral to the policy and market mechanisms that may generate these changes. Prevailing wage or minimum wage standards in government contracting, private sector hiring practices, unionization, business cycles, unemployment levels, labor supply shortages, and the relative competitiveness of domestic manufacturing can all influence labor costs and domestic manufacturing shares in the wind and solar sectors.

Additionally, various public policies such as tax credits, workforce development funding, and other instruments can redistribute the costs of implementing high road labor practices and support both firms and workers. For example, tax credits and similar public policy instruments may support higher domestic content shares across the utility-scale solar supply chain or minimum compensation standards in the solar sector. Based on 2020 capital costs (assuming there are no tariffs on PV modules), a 7% investment tax credit or equivalent subsidy of similar magnitude for installed solar PV systems would fully offset the cost of using 100% domestic content across the full supply chain. A subsidy tied to a requirement to use only domestic cells, modules, and inverters would need to be 4% of the cost of installed solar PV systems to fully offset the increase in average project costs. Similarly, a 20% increase in installation and construction labor costs would increase the installed cost of solar PV and wind projects by only 3% and 1%, respectively, meaning that a nominal subsidy could fully offset the impact of high road labor practices on the cost of installing renewable energy. Wind and solar resources have generally enjoyed public policy support at both state and federal levels. Any tax incentives or policy support to offset the costs of high road labor practices or greater domestic manufacturing could be additive to other policies and contingent upon minimum compensation standards or specific domestic content share, giving flexibility to firms. The level of a future tax credit may be adjusted to account for the changing price spread between domestically and globally manufactured renewable energy products, in addition to interactions with other policies such as tariffs. Furthermore, the durability of a tax credit to support domestic manufacturing, as well as the temporal lag in growing domestic manufacturing capacity, must be considered in the policy design.

Tax incentives and other subsidies alone are not necessarily sufficient to induce high road labor practices, however, given that manufacturing and development decisions are idiosyncratic, influenced by other cost signals and non-cost factors, and vary across product supply chains. Moreover, this study does not model market interactions, and thus, further investigation of the impact of policy on high road practices and net cost impacts for wind and solar installations is needed.

In performing this analysis, there were some notable gaps in availability of data relevant to assessing labor costs and domestic content within the solar and wind supply chains. Our work takes advantage of the best available and most recent public data, but faces limitations and uncertainties. In particular, there were a lack of robust data regarding the price spread between domestic and globally sourced wind products, in addition to labor shares associated with balance of system costs for wind and solar. Absent robust data for several key parameters, we selectively conducted bounding analyses. As the socioeconomic impacts of energy transitions are highly salient to policy makers and stakeholders and can potentially act as accelerants or bottlenecks for the pace of net-zero transitions, additional effort from government statistical agencies and researchers to regularly and accurately quantify and report data on labor costs, employment levels, domestic supply chains, and other pertinent data would facilitate improved decision support and policy design.

Overall, this study demonstrates that high road labor practices and policies have a small influence on wind and solar PV costs as well as the cost and pace of net-zero transitions. Such practices are thus unlikely to impede the pursuit of least-cost decarbonization strategies, while generating substantial benefits for U.S. workers and communities. Tradeoffs and synergies between climate and social equity objectives can be real, but they are context specific and the magnitude of such tradeoffs requires quantification. Within the scope and limitations of this study, we find minimal evidence that climate and high road labor objectives in the wind power and solar PV sectors are in conflict.

Acknowledgements

The authors appreciate comments on earlier drafts from Ryan Wiser, David Feldman, and R. Brent Alderfer. Any errors or omissions are the responsibility of the authors alone.

Funding

This work was funded through a grant from the BlueGreen Alliance.

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Influence of high road labor policies and practices on renewable energy costs, decarbonization pathways, and labor outcomes

Supplementary Information

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Contents

1 Methods

1.1 Baseline technology costs

We estimate baseline capital and operations and maintenance (O&M) costs for utility-scale solar, land-based wind, and offshore wind for circa 2020, using the most recent and publicly available data. We then simulate the effects of high road labor policies and practices on costs by modifying the domestic manufacturing shares and labor costs.

1.1.1 Utility-scale solar capital costs and operations & maintenance costs

Baseline costs for utility-scale solar are based on bottom-up estimates developed by the National Renewable Energy Laboratory (NREL) for Q1 2020 (Feldman *et al.*, 2021), updated to reflect more recent global and domestic prices of photovoltaic (PV) module components and inverters as of Q3 2020 (Feldman and Margolis, 2020a). Table 1 and Table 2 show the capital costs associated with the domestically- and internationally-produced products across the crystalline silicon photovoltaic module manufacturing supply chain, including polysilicon, wafers, cells, and modules, as well as inverters; we update the 2018 capital costs reported by NREL (Woodhouse *et al.*, 2019) based on updated market prices for 2020 (Feldman and Margolis, 2020a). Table 3 includes the capital costs including all system and project development costs incurred during installation (Fu, Feldman and Margolis, 2018; Feldman *et al.*, 2021). Table 4 shows the O&M costs (Walker *et al.*, 2020; Feldman *et al.*, 2021).

Table 1. Average 2020 capital costs for crystalline silicon photovoltaic module supply chains by country.

Parameter	Units	US	Rest of world (except China)	China	Taiwan	South Korea	Malaysia	Philippines	Germany
Polysilicon production[a]									
Labor cost	$/kg	1.1	0.2	0.2	-	-	-	-	-
Non-labor cost	$/kg	13.9	10.5	10.5	-	-	-	-	-
Subtotal	$/kg	15.0	10.7	10.7	-	-	-	-	-
Subtotal	$/W_{DC}$	0.05	0.03	0.03	-	-	-	-	-
Wafer manufacturing (excluding polysilicon)[b]									
Labor cost	$/wafer	0.07	-	0.01	0.02	0.04	0.01	-	-
Non-labor cost	$/wafer	0.10	-	0.09	0.09	0.10	0.08	-	-
Subtotal	$/wafer	0.17	-	0.10	0.11	0.14	0.09	-	-
Subtotal	$/W_{DC}$	0.03	-	0.02	0.02	0.03	0.02	-	-
Cell manufacturing (excluding polysilicon and wafers)[c]									
Labor cost	$/W_{DC}$	0.02	-	0.00	0.00	0.01	0.00	0.00	0.02
Non-labor cost	$/W_{DC}$	0.04	-	0.04	0.04	0.04	0.04	0.04	0.04
Subtotal	$/W_{DC}$	0.06	-	0.04	0.04	0.05	0.04	0.04	0.06
Module assembly (excluding polysilicon, wafers, and cells)[d]									
Labor cost	$/W_{DC}$	0.02	-	0.00	0.01	0.01	0.00	-	-
Non-labor cost	$/W_{DC}$	0.16	-	0.13	0.13	0.13	0.13	-	-
Subtotal	$/W_{DC}$	0.18	-	0.13	0.13	0.14	0.13	-	-

a Values are based on 2018 polysilicon costs, adjusted to 2020 costs using a factor of 0.71 based on the ratio of the November 2020 global spot price ($0.05/W) to the January 2018 global spot price ($0.07/W) (Woodhouse *et al.*, 2019; Feldman and Margolis, 2020a).
b Values are based on 2018 wafer costs, adjusted to 2020 costs using a factor of 0.25 based on the ratio of the estimated November 2020 global spot price ($0.02/W) to the January 2018 global spot price ($0.07/W) (Woodhouse *et al.*, 2019; Feldman and Margolis, 2020a).
c Values are based on 2018 cell costs, adjusted to 2020 costs using a factor of 0.48 based on the ratio of the estimated November 2020 global spot price ($0.05/W) to the January 2018 global spot price ($0.11/W) (Woodhouse *et al.*, 2019; Feldman and Margolis, 2020a).
d U.S. values are based on 2018 module costs, adjusted to 2020 costs using a factor of 0.97 based on the ratio of the estimated Q2 2020 U.S. price ($0.29/W) to the Q1 2018 U.S. price ($0.30/W) (Woodhouse *et al.*, 2019; Feldman and Margolis, 2020a). Values for the rest of the world are based on 2018 module costs, adjusted to 2020 costs using a factor of 0.80 based on the ratio of the estimated Q2 2020 global spot price ($0.12/W) to the Q1 2018 global spot price ($0.15/W) (Woodhouse *et al.*, 2019; Feldman and Margolis, 2020a). Prices for China exclude tariffs.

Table 2. Average 2020 capital costs for inverters.

Parameter	Units	Value
Labor cost	$/W_{DC}$	0.02
Non-labor cost	$/W_{DC}$	0.05
Total	**$/W_{DC}$**	**0.07**

All values are based on 2018 manufactured product costs, adjusted to 2020 costs using a factor of 1.4 based on the ratio of the Q4 2020 global spot price ($0.07/W) to the Q1 2018 global spot price ($0.05/W) (Woodhouse *et al.*, 2019; Feldman and Margolis, 2020a).

Table 3. Average 2020 capital costs for utility-scale solar in the U.S.

Parameter	Units	Value
Manufacturing		
Module price[a,b]	$\$/W_{DC}$	0.25
Inverter price[a,b]	$\$/W_{DC}$	0.07
Development / installation		
Structural Balance of System (BOS)	$\$/W_{DC}$	0.12
Electrical BOS	$\$/W_{DC}$	0.07
Install labor & equipment[c]	$\$/W_{DC}$	0.14
EPC overhead	$\$/W_{DC}$	0.06
Sales tax	$\$/W_{DC}$	0.03
Land acquisition/lease payments	$\$/W_{DC}$	0.03
Permitting fee	$\$/W_{DC}$	0.00
Interconnection fee	$\$/W_{DC}$	0.02
Transmission line	$\$/W_{DC}$	0.01
Developer overhead	$\$/W_{DC}$	0.02
Contingency	$\$/W_{DC}$	0.02
Profit	$\$/W_{DC}$	0.04
Labor costs (development / install only)	$\$/W_{DC}$	0.14
Non-labor costs (development / install only)	$\$/W_{DC}$	0.44
Total	**$\$/W_{DC}$**	**0.90**
Total[d]	**$\$/W_{AC}$**	**1.20**

a Module and inverter prices reflect global and domestic price differentials and import shares, as further detailed in Table 1 & Table 2.
b Assume a wage rate of $26.09/hour, which is the 2019 average wage rate for the manufacturing sector reported by the U.S. Bureau of Labor Statistics (U.S. Bureau of Labor Statistics, 2020).
c Assume a wage rate of $27.46/hour, which is the 2019 average wage rate for the construction sector reported by the U.S. Bureau of Labor Statistics (U.S. Bureau of Labor Statistics, 2020).
d Assume an DC:AC inverter ratio of 1.34 (NREL, 2019).

Table 4. Average O&M costs for utility-scale solar in the U.S.

Parameter	Units	Value
Labor cost	$\$/kW_{DC}/yr$	5.17
Non-labor cost	$\$/kW_{DC}/yr$	11.15
Total	**$\$/kW_{DC}/yr$**	**16.32**

1.1.2 Land-based wind capital and operations & maintenance costs

Baseline costs for land-based wind are based on bottom-up estimates developed by NREL for 2019 (Stehly, Beiter and Duffy, 2020), updated to reflect more recent turbine component market prices (Wiser *et al.*, 2020). Table 5 shows the labor and non-labor capital costs associated with the land-based wind turbine manufacturing supply chain, including blades, nacelles, and towers (Bortolotti *et al.*, 2019; Stehly and Beiter, 2019; Wiser *et al.*, 2020). Table 6 includes the capital costs including all system and project development costs incurred during installation (Stehly and Beiter, 2019; Stehly, Beiter and Duffy, 2020; Wiser *et al.*, 2020). Table 7 shows the O&M costs (Reategui and Hendrickson, 2011; Stehly and Beiter, 2019; Wiser, Bolinger and Lantz, 2019).

Table 5. Average 2019 capital costs for domestically-produced land-based wind turbines.

Parameter	Units	Value
Blade manufacturing		
Labor cost	$/W	0.07
Non-labor cost	$/W	0.18
Subtotal	$/W	0.25
Nacelle manufacturing		
Labor cost	$/W	0.12
Non-labor cost	$/W	0.30
Subtotal	$/W	0.42
Tower manufacturing		
Labor cost	$/W	0.05
Non-labor cost	$/W	0.13
Subtotal	$/W	0.18
Turbine manufacturing supply chain		
Labor cost	$/W	0.25
Non-labor cost	$/W	0.60
Total	**$/W**	**0.85**
All values are based on 2018 manufactured product costs, adjusted to 2019 costs using a factor of 0.84 based on the ratio of the 2018 turbine cost ($1.01/W) and 2019 market price of turbines ($0.85) (Stehly and Beiter, 2019; Stehly, Beiter and Duffy, 2020).		

Table 6. Average 2019 capital costs for land-based in the U.S.

Parameter	Units	Value
Manufacturing		
Turbine price[a]	$/W	0.85
Development / installation		
Development cost	$/W	0.02
Engineering Management cost	$/W	0.02
Foundation cost	$/W	0.06
Site Access and Staging cost	$/W	0.04
Assembly and Installation cost	$/W	0.04
Electrical Infrastructure cost	$/W	0.15
Construction Finance cost	$/W	0.03
Contingency cost	$/W	0.09
Labor costs (development / install only)[b]	$/W	0.09
Non-labor costs (development / install only)	$/W	0.36
Total	**$/W**	**1.30**

a Assume a wage rate of $26.09/hour, which is the 2019 average wage rate for the manufacturing sector reported by the U.S. Bureau of Labor Statistics (U.S. Bureau of Labor Statistics, 2020).
b Assume a wage rate of $27.46/hour, which is the 2019 average wage rate for the construction sector reported by the U.S. Bureau of Labor Statistics (U.S. Bureau of Labor Statistics, 2020).

Table 7. Average 2019 O&M costs for land-based wind in the U.S.

Parameter	Units	Value
Labor cost	$/kW/yr	12.41
Non-labor cost	$/kW/yr	31.59
Total	**$/kW/yr**	**44.00**

1.1.3 Offshore wind capital and operations & maintenance costs

Baseline costs for offshore wind are based on bottom-up estimates developed by NREL for 2019 (Stehly, Beiter and Duffy, 2020). Table 8 shows the labor and non-labor capital costs associated with the offshore wind turbine manufacturing (Bortolotti *et al.*, 2019; Stehly and Beiter, 2019; Stehly, Beiter and Duffy, 2020). **Table 9** includes the capital costs including all system and project development costs incurred during installation (Stehly and Beiter, 2019; Stehly, Beiter and Duffy, 2020). Table 10 shows the O&M costs (BOEM, 2020).

Table 8. Average 2019 capital costs for offshore wind turbines.

Parameter	Units	Value
Labor cost	$/W	0.38
Non-labor cost	$/W	0.92
Total	**$/W**	**1.30**

Table 9. Average 2019 capital costs for offshore wind.

Parameter	Units	Fixed	Floating
Manufacturing			
Turbine price[a]	$/W	1.30	1.30
Development / installation			
Development cost	$/W	0.14	0.17
Foundation cost	$/W	0.82	1.44
Port, staging, logistics, transportation	$/W	0.06	0.04
Assembly and Installation cost	$/W	0.20	0.44
Electrical Infrastructure cost	$/W	0.76	0.98
Lease price	$/W	0.09	0.09
Engineering Management cost	$/W	0.07	0.09
Insurance during construction	$/W	0.04	0.05
Decommissioning bond	$/W	0.06	0.08
Plant commissioning	$/W	0.04	0.05
Contingency cost	$/W	0.29	0.36
Labor costs (development / install only)[b]	$/W	0.38	0.55
Non-labor costs (development / install only)	$/W	2.39	3.48
Total	**$/W**	**4.08**	**5.33**

a Assume a wage rate of $26.09/hour, which is the 2019 average wage rate for the manufacturing sector reported by the U.S. Bureau of Labor Statistics (U.S. Bureau of Labor Statistics, 2020).
b Assume a wage rate of $27.46/hour, which is the 2019 average wage rate for the construction sector reported by the U.S. Bureau of Labor Statistics (U.S. Bureau of Labor Statistics, 2020).

Table 10. 2019 O&M costs for offshore wind in the U.S.

Parameter	Units	Fixed	Floating
Labor cost	$/kW/yr	20.64	21.92
Non-labor cost	$/kW/yr	108.36	115.08
Total	**$/kW/yr**	**129.00**	**137.00**

1.1.4 Domestic manufacturing share

We estimate domestic manufacturing shares of products across utility-scale solar, land-based wind, and offshore wind supply chains, using the most recent and complete data that are publicly available. There is substantial yearly variation and uncertainty in estimates of domestic manufacturing shares, given rapidly changing market and regulatory conditions as well as incomplete or coarse data collection and reporting that may not include information such as stockpiling and end use disposition of manufactured products. Table 11 provides a summary of baseline assumptions.

With respect to solar, we focus on the crystalline silicon photovoltaic supply chain, including polysilicon, ingots and wafers, cells, modules, and inverters. We do not include other upstream materials and products, such as steel, aluminum, flat glass, encapsulants, and backsheets, that may also be produced domestically. With respect to land-based wind, we focus on assembly of wind turbines and components, including nacelles, towers, blades, and hubs. We do not account other parts of the supply chain, such as other wind equipment (e.g., mainframes, converters, pitch and yaw systems, main shafts, bearings, bolts, controls) and manufacturing inputs (e.g., steel).

Table 11. U.S. domestic manufacturing share of solar and wind products.

Product	Manufacturing share	Year	Data source
Land-based nacelles	90-100%	2019	(Wiser *et al.*, 2020)
Land-based towers	65-85%	2019	(Wiser *et al.*, 2020)
Land-based blades and hubs	40-70%	2019	(Wiser *et al.*, 2020)
Land-based turbines	79%[a]	2019	(Stehly and Beiter, 2019; Wiser *et al.*, 2020)
Offshore turbines	0%	2018	(Stehly and Beiter, 2019)
Polysilicon	0%	2019	(Smith and Margolis, 2019; Feldman and Margolis, 2020b)
Wafers and ingots	0%	2019	(Smith and Margolis, 2019; Feldman and Margolis, 2020b)
Cells	15%[b]	2017	(Smith and Margolis, 2019)
Photovoltaic modules	11%[c]	2019	(U.S. Energy Information Administration, 2020)
Inverters	37%[d]	2017	(Smith and Margolis, 2019)

a Cost-weighted average estimate based on average nacelle, tower, and blades manufacturing shares and assuming capital costs of 247, 420, and 185 $/kW for rotors, nacelles, and towers, respectively.
b Estimated based on 0.1 GW domestically produced for domestic consumption and 0.68 GW domestically consumed for reporting year 2017. Data for reporting years 2018-2020 are insufficient for estimating domestic manufacturing shares, but suggest that domestic cell production has declined since 2017.
c Estimated based on the source of photovoltaic module shipments for reporting year 2019 – domestic manufacturing (1,827,178 peak kW) and imports (15,316,877 peak kW).
d Estimated based on 3.1 GW and 8.4 GW of domestic production and consumption, respectively, for reporting year 2017. Data for reporting years 2018-2020 are insufficient for estimating domestic manufacturing shares, but suggest that domestic inverter production has declined since 2017.

1.1.5 Labor costs

We develop baseline estimates of labor costs for each technology as described in Sections 1.1.1 to 1.1.3. We also model the influence of increasing labor costs. While we do not explicitly model the mechanisms that may influence labor costs, increases in labor costs may stem from high road labor practices and policies, such as prevailing wage standards, gender and racial equity standards, local hiring standards, unionization, and training and certification programs.

To contextualize the labor costs in terms of wages, we perform a sensitivity of baseline costs to differences across the wage distribution for the construction and manufacturing sectors and on the basis of unionization. As a base assumption, we use the average wage rate for construction and manufacturing sectors for 2019 reported in the U.S. Bureau of Labor Statistics Occupational Employment Statistics, although there is variation across regions and occupations within in each sector that we do not account for (U.S. Bureau of Labor Statistics, 2019, 2020). Table 12 shows the wage rates used in estimating current technology costs.

Table 12. Wage rates.

	Annual wages		Hourly wages	
	Manufacturing sector	Construction sector	Manufacturing sector	Construction sector
May 2019 BLS Occupational Employment Statistics				
10th Percentile	25,330	28,240	12.18	13.58
25th Percentile	31,460	35,870	15.12	17.25
Mean	54,260	57,110	26.09	27.46
Median	42,560	49,030	20.46	23.57
75th Percentile	63,260	68,690	30.41	33.02
90th Percentile	99,000	96,840	47.59	46.56
2019 BLS Current Population Survey				
Median	48,672	47,268	23.40	22.73
Union Median	50,024	65,364	24.05	31.43
Non-Union Median	48,516	45,136	23.33	21.70

1.2 Technology cost projections

To project capital and O&M costs from 2020 to 2050, we estimate the annual percent change in costs based on the NREL 2019 Annual Technology Baseline mid case, and apply the percent change estimates to the baseline cost estimates (National Renewable Energy Laboratory, 2019). To isolate and bound the effect of high road labor policies and standards, we model two scenarios that vary based on labor costs and domestic content shares: 1) current domestic content share and average wage rates and 2) 100% domestic content share and average wage rates. Cost projections are provided in Figure 1 to Figure 6.

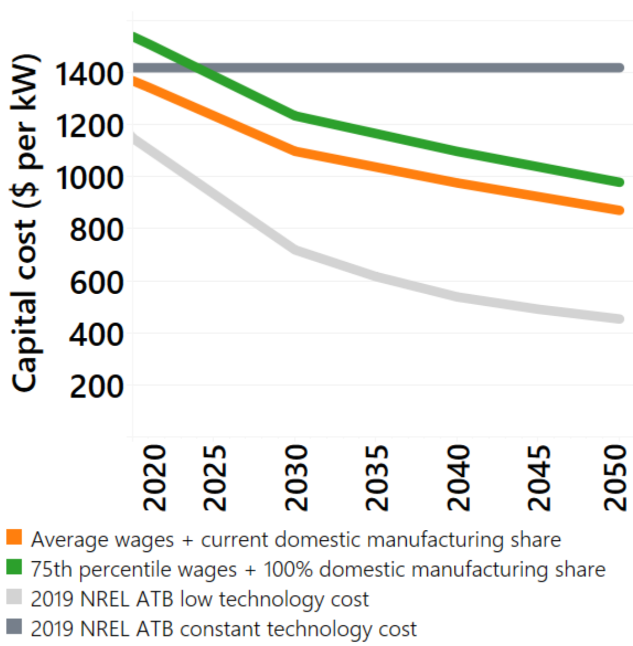

Figure 1. Capital cost projections for utility-scale solar.

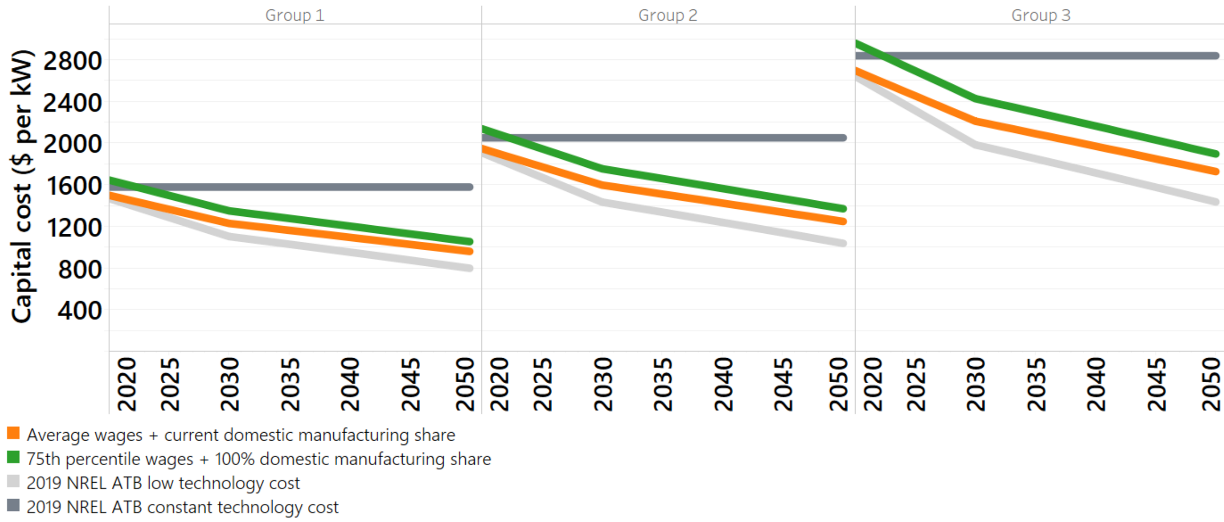

Figure 2. Capital cost projections for land-based wind. Geographically-designated groups, including group 1 (i.e., AL, AZ, AR, CO, FL, GA, IA, ID, IL, IN, KS, KY, LA, MI, MN, MS, MO, MT, NC, ND, NE, NV, NM, OH, OK, SC, SD, TN, TX, UT, VA, WV, WI, WY), group 2 (i.e., CA, OR, WA), and group 3 (i.e., DE, CT, MA, MD, ME, NH, NJ, NY, PA, RI, VT).

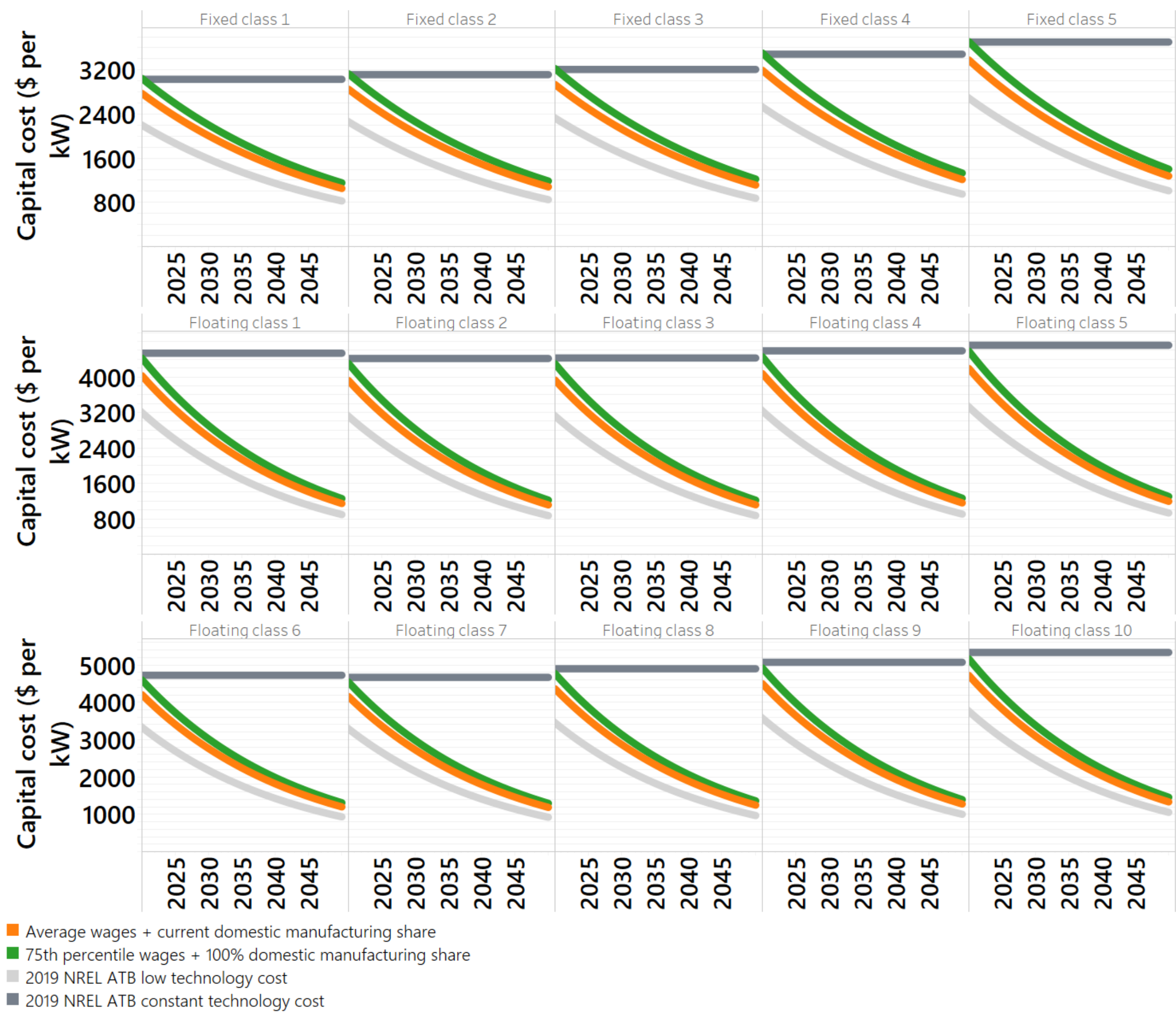

Figure 3. Capital cost projections for offshore wind. Classes indicate different wind speed classes.

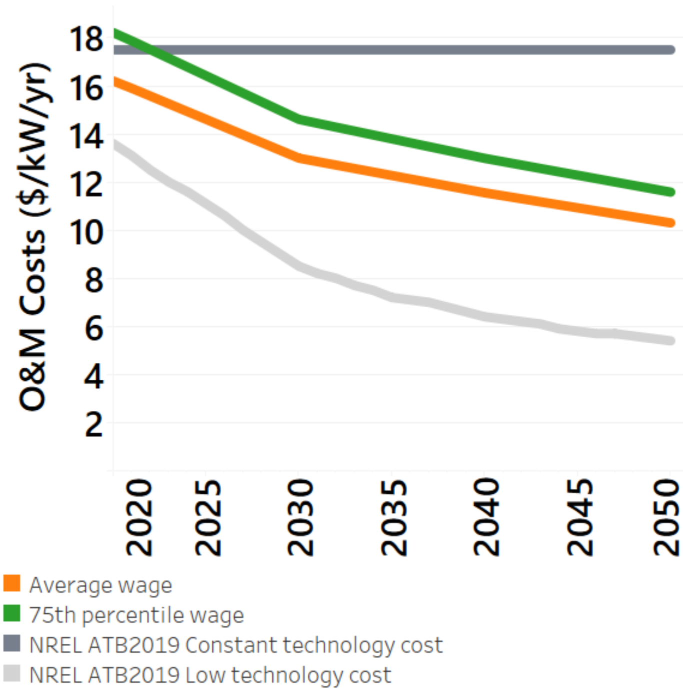

Figure 4. O&M cost projections for utility-scale solar.

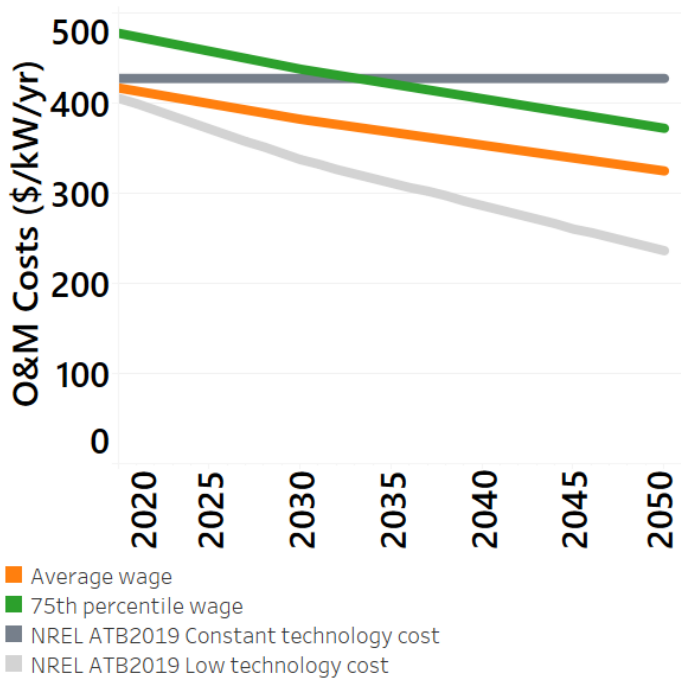

Figure 5. O&M cost projections for land-based wind.

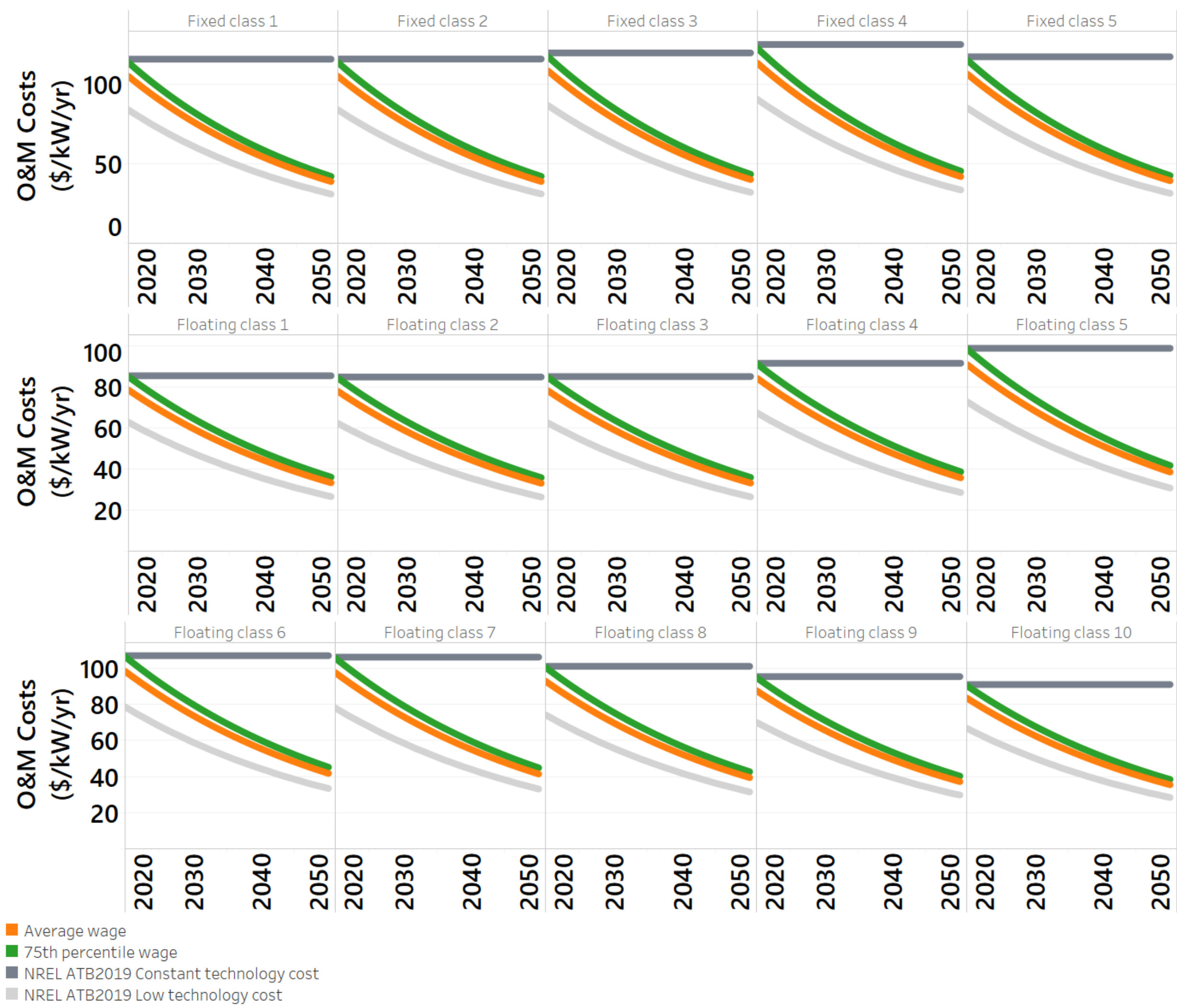

Figure 6. Capital cost projections for offshore wind. Classes indicate different wind speed classes.

1.3 Techno-economic optimization

We simulate the effects of high road labor policies and practices on least-cost pathways to achieve net-zero emissions in the U.S. by 2050. We model alternative techno-economic pathways using the modeling approach and specifications developed as part of the Princeton *Net-Zero America* (NZA) study (Larson et al., 2020). The NZA study implements a macro-energy system modeling framework to select a techno-economic pathway. We use EnergyPATHWAYS, a bottom-up model of future economy-wide electricity and fuel demand, coupled with RIO, a linear programming model that combines capacity expansion with sequential hourly operations over a sampling of representative days to find the least-cost solution for decarbonized energy supply to meet demand over time (Williams and Jones, 2021). We apply a linearly decreasing net-zero emissions constraint over time to require net-zero emissions by 2050. Infrastructure decisions are solved at 5-year time steps with perfect foresight and perfect coordination between supply sectors. Alternative modeling assumptions can be made regarding the rate of electrification and the extent of renewables deployment, among other constraints; the model specification is largely consistent with the

E+ scenario in the NZA report, wherein there is a high rate of electrification and allowable renewable growth rate (up to 10% per year increase in annual rate of capacity additions).

To isolate and bound the effect of high road labor policies and standards, we model two scenarios based on the technology cost projections specified in Section 1.2. Specially, we model scenarios that vary based on labor costs and domestic content shares, which serve as approximate bounds of high road policies: 1) current domestic content share and average wage rates and 2) 100% domestic content share and 75th percentile wage rates.

1.4 Employment and wage projections

We estimate employment and wages associated with utility-scale solar, land-based wind, and offshore wind associated with the techno-economic pathways modeled. We use the Decarbonization Employment and Energy Systems (DEERS) model, which is loosely coupled with the techno-economic modeling described in Section 1.3. DEERS simulates the distribution of employment and wages over time and across economic sectors, resource sectors, occupations, and geography for multi-decadal energy-supply system transition scenarios (Mayfield *et al.*, no date). DEERS is constructed using publicly-available energy activity and labor market data, and applying regression-based and bottom-up estimation approaches to derive marginal employment factors that relate employment and energy activity across fossil fuel and low carbon resource supply chains. We also incorporate time-variant factors, such as labor productivity and wage inflation, which are especially important in the context of emerging labor markets and long-term transitions. The DEERS model is adaptable to different energy system contexts and can be used to explore modifiable workforce and infrastructure planning and policy decisions.

We simulate the effects of high road labor policies and practices on employment and wage outcomes by modifying the domestic manufacturing shares and wage rates. We vary the domestic content shares of manufactured products to alternatively reflect the current shares, an increase in domestic shares by ten percentage points (e.g., if the current share is 15%, then it is increased to 25%), twenty percentage points, and 100% shares. Changes in the domestic content share increase the total number of manufacturing sector jobs and aggregate wages. As a baseline assumption, DEERS projects real (2019$) average wage rates based on historical nominal wages from 2000 to 2019 (adjusted for inflation) for over 1,000 occupations (U.S. Bureau of Labor Statistics, 2020b, 2020e). We also vary the occupational wage rates paid across economic sectors (i.e., average wage, median wage, 75th percentile wage, average wage plus 20%).

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