WORLD SMALL HYDROPOWER DEVELOPMENT

REPORT 2019

Case Studies

TECHNOLOGY, INNOVATION AND SMART SMALL HYDROPOWER

UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

ICSHP

Disclaimer

The *World Small Hydropower Development Report 2019: Case Studies* is jointly produced by the United Nations Industrial Development Organization (UNIDO) and the International Center on Small Hydro Power (ICSHP) to provide development information about small hydropower.

The opinions, statistical data and estimates contained in signed articles are the responsibility of the authors and should not necessarily be considered as reflecting the views or bearing the endorsement of UNIDO or ICSHP. Although great care has been taken to maintain the accuracy of information herein, neither UNIDO, its Member States nor ICSHP assume any responsibility for consequences that may arise from the use of the material.

This document has been produced without formal United Nations editing. The designations employed and the presentation of the material in this document do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations Industrial Development Organization (UNIDO) concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries, or its economic system or degree of development. Designations such as 'developed', 'industrialized' and 'developing' are intended for statistical convenience and do not necessarily express a judgment about the stage reached by a particular country or area in the development process. Mention of firm names or commercial products does not constitute an endorsement by UNIDO.

Suggested citation:

LIU, D., LIU, H., WANG, X., and Kremere, E., eds. (2019). *World Small Hydropower Development Report 2019: Case Studies*. United Nations Industrial Development Organization; International Center on Small Hydro Power. Available from www. smallhydroworld.org.

ISSN: 2406-4580 (print)
ISSN: 2706-7599 (online)

The digital copy is available on **www.smallhydroworld.org.**

Design: TERI Press
Cover Picture: gregbrave -123rf.com

Acknowledgements

The World Small Hydropower Development Report 2019: Case Studies was prepared under the overall guidance of Tareq Emtairah, Director of the Department of Energy at the United Nations Industrial Development Organization (UNIDO) and Deyou Liu, Director General of the International Center on Small Hydro Power (ICSHP).

The Report was headed by LIU Heng, Senior Technical Expert at UNIDO and consulted by HU Xiaobo, Chief of the Division of Multilateral Development at ICSHP. This lengthy, and at times, arduous endeavour was coordinated by Eva Krēmere at UNIDO and WANG Xianlai at ICSHP. The Report is the result of three years of intense research efforts and was backed by a talented and indispensable team of researchers at ICSHP and a vast number of experts in the field of small hydropower.

WSHPDR 2019 team

Head	LIU Heng – Senior Technical Advisor, United Nations Industrial Development Organization (UNIDO)
Coordinators	Eva Krēmere – United Nations Industrial Development Organization (UNIDO), WANG Xianlai – International Center on Small Hydro Power (ICSHP)
Communications	Eva Krēmere – United Nations Industrial Development Organization (UNIDO), Oxana Lopatina – International Center on Small Hydro Power (ICSHP)
Team	**UNIDO:** Eva Krēmere, Sanja Komadina
	ICSHP: Oxana Lopatina, WANG Xianlai, Alicia Chen Luo, Martin Battersby, Jerus D'Silva, Athina Wilson

Authors and Contributors:

Josseline Acuña, Zafar Alam, Ma Biao, Wan Changshun, Ou Chuanqi, José Fábrega, Tokihiko Fujimoto, Xu Gang, Thomas Gross, Eric Guchitta, Shi Hong, Daniela Hurtado, Michela Izzo, Xu Jincai, Łukasz Kalina, Brian Kelly, Karl Kolmsee, Arun Kumar, Sarah Kwach, Rebecca Leaf, David Managadze, Bernhard Monai, Bernard Moulins, Laurent Nahmias-Léonard, Eric Nguchitta Njoroge, Keijiro Okajima, Jose Luis Olivas, Faisal Rahadian, Zhengfu Rao, Raditya Rahmanhuda Rusmiputro, Atif Zeeshan Rauf, Daniel Rea, Alberto Sánchez, Jasper Verreydt, Yoshinobu Watanabe, Wu Xiaoling, Shigenori Yamamoto, Nicola Yurkoski, Li Zhenggui, Cui Zhenhua and Birgit Zraunig.

1. ZAGRODY SMALL HYDROPOWER PLANT: AN IDEA FOR AN OLD MILL

Source: Google Maps

Łukasz Kalina, Enerko Energy

Located in south-central Poland, the small hydropower plant (SHP) Zagrody is built in the conservation zone of an old water mill complex. Although this is the 40th SHP developed in Świętokrzyskie Voivodeship Province, the initiative is amongst a handful projects to use hydro-complex technology in the form of the Archimedes' screw – a relative newcomer to the SHP world having only arrived on the scene over the last decade.

The project developed by Instytut OZE Ltd, the Zagrody SHP is built in the immediate conservation zone of the water mill complex in Markowizna, in Sitkówka-Nowiny commune in Kielce County. The complex comprises the best-preserved mill in the commune, which includes a historic working water system. In this area, water mills are considered monuments of great historical significance given the commune's industrial heritage and Sitkówka-Nowiny alone is home to three mills.

The main river is the Bobrza, which is the longest tributary of the Czarna Nida and flows through the northern, north-western and western edge of the Świętokrzyskie Mountains. Around 50-km in length, the terrain of its catchment area occupies 379 km2. The area in which the Zagrody SHP is located is a protected landscape area. Operating since September 2019, it is only the fourth SHP in the province to use the Archimedes' screw. Equipped with this technology, which was provided by Enerko Energy Ltd, the Zagrody SHP produces 150 MWh of electrical energy each year.

Project works

Initial planning, development and financial identification were conducted over a two-year period. As the SHP project was located in a rural area, an environmental impact assessment was undertaken and a fish pass was designed. The project developers (Instytut OZE Ltd) secured relevant administrative permissions including on water rights and other requirements to enable construction. The SHP development was in the immediate neighbourhood of a technological monument, the old hydro-technological system based around the historic water mill, and pre-existing parts of the monument had to be preserved (Figures 1–4).

More specifically, installation of the Archimedes' screw was designed in parallel to the existing turbine cage where a water turbine used to work for the mill's needs. Moreover, the elevation of the new SHP building was covered with natural limestone to help maintain architectural consistency with the neighbouring building of the historic mill. The space between the channel of the Archimedes' screw and the residential building was used as a recreational terrace. Overall, the site is an attractive example of how to creatively repurpose a historic mill as a new hydroelectric power plant, using new technology, and without losing the site's local charm and its architectural, technological and historical significance. The developers have a significant experience in designing new hydroelectric installations in areas of water mills. The portfolio of the company already includes over a dozen such revitalizations. The company works on complex SHP designs including obtaining necessary administrative decisions based on the proxy granted by the investor.

Technical specifications: the Archimedes' screw

Equipped with an asynchronous generator (Cantoni Group), the Zagrody SHP is able to generate 37 kW. A key feature, which distinguishes this installation from others, is the inverter system (produced by the ABB group), which enables work with a variable rotation speed ensuring maximum use of the potential of flowing water.

The Archimedes' screw was made as a steel construction. The angle of the turbine axis in relation to the level is 22°. The screw itself consists of a steel tube and Archimedes' spirals wrapped on it with a diameter of 2,600 mm that are angularly offset from each other by 90° (Box 1). The hydrocomplex was placed on a concrete steel gutter. Enerko Energy Ltd also uses Archimedes' screws built in self-supporting steel structure and Kaplan turbines in various systems of S, PIT, Z types and of vertical axis. In addition to providing water turbines, the company constructs SHPs.

'Overall, the site is an attractive example of how to creatively repurpose a historic mill as a new hydroelectric power plant using new technology.'

Box 1. Summary list of the main technical parameters of the SHP Zagrody hydropower unit

Type of turbine	Archimedes' screw
Flow rate	2.0 m^3/s
Head	2.5 metres
Runner diameter	2,600 mm
Runner speed	22.3 rmp
Installed capacity of the generator	37 kW
Average annual generation	150 MWh

Source: Enerko Energy

Automatics of SHP

The control and automation system of the power plant is based on the programmable modular PLC (Programmable Logic Controller) and the HMI (Human Machine Interface) panel enabling setting parameters of work of the hydropower complex and updated screening of current electric and mechanical parameters. Moreover, the operating panel is equipped with an Ethernet-standard port and software enabling online view on selected computers connected to the Internet, according to the same rules of access that direct operations. The controller, having modular construction, allows a hassle-free extension of its functionality in additional modules. It is worth highlighting that the controller is powered by constant voltage 24 VDC (Volts DC) by buffer power supply equipped with gel batteries enabling work in case of power failure. Under normal conditions, it functions as an automation system power supply and battery charger. In the case of power failure, it automatically switches off this function and transfers power from the batteries. Once normal access to power is resumed, it charges the batteries.

Further, the controller collects valuable up-to-date signals from a number of installed sensors as well as gauges of network parameters. Some of the most important monitored elements include the rotation speed, temperature, water level before and behind the grille, the logical positioning of equipment, water flow through the turbine, the level of dam opening, energy quality, energy production and the level of hydraulic power.

It should be noted that the power plant uses an inverter system, which ensures a smooth change of rotation speed of the generator. This is important as at particular hydrological parameters, this helps attain higher efficiency of the hydropower complex.

The power plant has also been equipped with the SCADA (Supervisory Control and Data Acquisition) information system for communication, monitoring and the archiving of the exploitation parameters of the power plant (Figure 5). This helps in creating an efficient remote control mechanism to monitor the work of the system. Moreover, the solutions offered allow for more efficient processing through the remote collection of measurement data from the power plant and they enable in archiving as well. In turn, the implemented software enables showing data in the tabular, numeric or graphic form. This increases accuracy and functionality of the installation and enables the optimization of work and increased security and efficiency of the power plant.

Main benefits of project approach

The Zagrody SHP has used an already existing hydro-technological infrastructure for electricity generation, which has kept disruption to the local environment to a minimum. Moreover, the use of the Archimedes' screw and inverter system has boosted the plant's efficiency by making maximum use of the flowing water for local electricity generation. Overall, the initiative can be said to be in support of several United Nations Sustainable Development Goals (SDGs) including SDG 13 to "take urgent action to tackle climate change and its impacts" and SDG 7 to "ensure access to affordable, reliable, sustainable and modern energy for all".

Lessons for future SHP development

Lesson 1: The importance of engaging the private sector

The investment, which revitalized an inactive hydro-technological object, was made possible thanks to the engagement of the private sector. It is a good example of development of formerly functioning water mills using locally available hydropower potential. It is clear that the already existing infrastructure and comfortable terrain can be important factors in securing the high profitability of projects in such areas.

Lesson 2: Potential for further development in the hydropower sector in Poland

It is worth recalling the information about the hydropower potential of Poland provided by the Polish Association for Small Hydropower Development. In the 1950s, around 6,500 hydropower plants were operational in Poland. Today, this number is around 770 and over 81 per cent of technological potential (and approximately 50 per cent of economic potential) is currently not being used in Poland. According to current assessments, there are around 7,500 hydro-technological objects in Poland that are presently not being used for energy purposes. Poland has conductive conditioning for the development of hydropower, especially in the form of SHP, although the pace of activating the new production powers is still far too low. However, given that in Poland, the Renewable Energy Sources Act (RES Act) supports the development of hydropower installations, it is possible that there will be a boom in the SHP industry in the coming years.

Figure 1. Renovated water mill before transformation into SHP

Figure 2. A challenge during the installation of the Archimedes' screw was its transportation from the semi-trailer to the channel because of high trees located in the immediate neighbourhood

Figure 3. Finalized object

Figure 4. Construction area during the installation of the Archimedes' screw. The old hydro-technological system supplemented with the newly built fish pass is visible

Figure 5. View of the SCADA System

2. FISH LIFT SLUICE (AUSTRIA): INNOVATIVE, SPACE-SAVING FISH LADDER

Birgit Zraunig, Bernhard Monai, Der Wasserwirt

The "Der Wasserwirt" fish lift sluice system is a newly developed, versatile applicable fishway. Its compact design makes it particularly suitable for locations where fishways either cannot be built or can only be built with a high financial cost. Moreover, low overall building costs and low water consumption make the system an attractive option even where the state-of-the-art fishways are possible.

The fish lift sluice system is a relatively new, innovative and compact technology, which brings together two existing systems to facilitate fish migration–the fish lift and the fish sluice. Launched by Austrian developers, the technology is based on research and development undertaken with several Austrian stakeholders including Vienna's University of Natural Resources and Life Science and Graz University of Technology.

Previous roll-outs have already served to illustrate the system's adaptability. For example, if the upstream and downstream water levels of a facility are constant, a system with a float as a transport unit is deployed. In practice, the sluice is filled up to the upstream water level and the float with the transporting system rises up for the fish to exit upstream. In the case of variable upstream water levels, a stopper construction for the floating system has been developed, whereas, in the case of high variable downstream water levels, the float is replaced by a cable winch to facilitate transportation.

The system may have particular relevance for developers given the coming into force of the European Water Framework Directive, a framework which commits EU member states to achieve good qualitative and quantitative status of all waterbodies. In light of this legislation, many operators have utilized fish ladders at hydropower plants to re-establish fish migration. Often costly, these state-of-the-art systems need space that is not always readily available, making the innovative fish lift sluice system a practical alternative at such locations.

Development of the project and main concepts

The initial project development dates back to a 2014 feasibility study, which tested whether a combination of a fish lift and a fish sluice could be used as a space-saving fish ladder system for SHP locations. The results demonstrated that the system could be effectively used as a fish ladder. Based on these findings, Der Wasserwirt launched a research project funded by the Austrian Research Promotion Agency (FFG) and the Carinthian Business Development Fund (KWF). In the development of the fish sluice, Der Wasserwirt cooperated with several partners on hydraulic dimensioning of the system and on developing monitoring systems to check the functionality and fish behaviour during migration through the system. Partners included Vienna's University of Natural Resources and Life Science, Graz University of Technology, Profisch and KÖR.

The main concept was to develop a combination of a fish lift and a fish sluice, both of which are already existing systems for fish migration. The primary aim was to develop a space-saving fish migration system without a closed container as a transportation system. The state-of-the-art fish lifts have closed containers that need a powerful hoisting system to transport the container filled with water and fish from the downstream level to the upstream level. Fish sluices do not have any transport systems. The combination works with a swimming transportation system in a shaft. The shaft has two openings, one at the downstream level and the other at the upstream level. Both openings have an electric slide that opens and closes depending on the corresponding operating phase.

In the first year, two pilot projects were developed and implemented in the southern Austrian region of Carinthia. Located in different fish regions, the projects tested the main ideas with two different shaft sizes. Further, during the tests, Der Wasserwirt developed two additional pilot locations, one with a strongly fluctuating upper water level (appr. 2.5 metres), and the other with a flushing pipeline to the upper water level and over-pumping the water in the shaft above the upper water level. During the second year of the project, these two concepts were implemented at the next pilot locations. During the monitoring of hydraulic states and fish behaviour, improvements were made to flow steering, flow variations and installation of structural elements.

The third research year is currently underway – and the primary aim is to optimize the over-pumping system with a further developed transportation system and a different flushing line. To make the entry level in front of the shaft more attractive for fish, installations with a self-cleaning function are being developed. As the system does not constantly release water to the downstream level, it also needs a leading flow water pipe. In future, the water pipe will be equipped with a residual water turbine. As each location has specific requirements, appropriate turbines are chosen to test different conditions.

System components and main benefits

Perhaps, the main benefit of the fish lift sluice is that it is a space-saving system. At locations with no upstream and downstream water-level fluctuations or less water, it can provide a very effective solution for fish migration.

In terms of system components, it consists of a shaft with two openings – one at the tailwater level and the other at the headwater level (Figure 1, Box 1). Both openings have an electric slide. The shaft filling works with a pipeline from the headwater into the bottom of the shaft. The attraction flow at the tailwater is generated by a pipeline from the tailwater. Both pipelines have an electric slide. Inside the shaft is a transport system consisting of a float and a perforated plate with a specific distance between them. Inside the shaft, a stopper system can be installed at the headwater level to always stop the transportation system at the same position. This system is very useful for locations with an unsteady upper stream level.

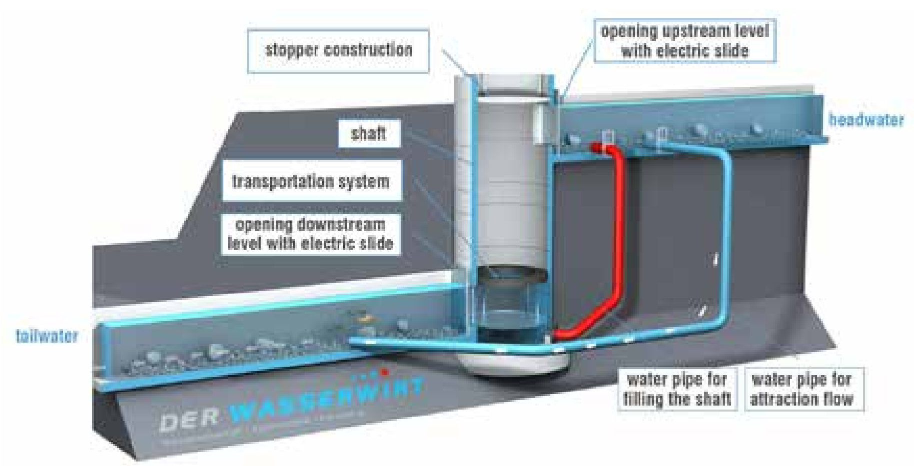


Figure 1. Components of a fish lift sluice
(For animation see "Der Wasserwirt 3D Animation Fish Lift Sluice" available from https://www.youtube.com/watch?v=K1rzygfdssY)

'The main benefit of the fish lift sluice is that it is a space-saving system. At locations with no upstream and downstream water-level fluctuations or less water, it can provide a very effective solution for fish migration.'

Box 1. How the fish lift sluice system works

The four process stages during operation:

Phase 1: Catch stage – Slide at the bottom is open. Fish can swim into the shaft.

Phase 2: Filling stage – Slide is closed and the shaft is filled with water. The transport system with fish is flooding simultaneously with the water level in the shaft.

Phase 3: Exit stage – Slide at the top will be opened. Fish can swim into upstream level.

Phase 4: Emptying stage – Slide is closed and the water in the shaft sinks to the tailwater level.

Depending on the size of the shaft and the height difference between headwater and tailwater, the four phases repeat two or three times per hour, during the operation.

Pilot plant Löllingbach

The pilot plant at Löllingbach (Carinthia) is a typical SHP. The Löllingbach is a small stream with a mean discharge of 497 l/s. The difference between headwater and tailwater is 2.4 metres. The operator has to evolve 60 l/s as residual water to the tailwater in winter and 150 l/s in the rest of the year. This is a small amount for a state-of-the-art fish ladder. The target species is the brown trout (*Salmo trutta fario*) with 40 cm. The shaft has a diameter of 1 metre.

Figure 2. Pilot plant Löllingbach

The implemented fish lift sluice needs approximately 10 l/s depending on the various operational phases. The difference is evolved with the water pipe for attraction flow. Several floods have taken place since the fish lift sluice was built in 2015. However, the system is very compact and the operator only has to initiate the scavenging process after the floods to reactivate the fish lift sluice. Figure 2 shows how well the fish lift sluice has been integrated into the stock.

Pilot plant Möll

The pilot plant at Möll (Carinthia) has an unsteady upper stream level (appr. 2.5 metres). The stream has a discharge of 18 m^3/s. The operator has to evolve 600 l/s as residual water to the tailwater. The difference between headwater and tailwater is, depending on the unsteady upper stream level, between 4.3 and 6.8 metres. The target species is the Danube salmon (*Hucho hucho*) with 80 cm. The shaft has a diameter of 2 m. The implemented fish lift sluice needs approximately 150 l/s depending on the various operational phases. The difference is evolved with the water pipe for attraction flow. The fish lift sluice was built over the winter of 2015–2016. At this location, the camera monitoring system was used to observe the fish behaviour. Figure 3 shows that the fish sluice has been well integrated into the stock.

Figure 3. Pilot plant Möll

Thematic focus and sequencing

Initially, the project team designed the shaft with the openings, the transport system and the operation stages. The second stage saw the development of a small model for testing the transport system, which utilized plastic basins, a transport system and a pump to fill and empty the cone. Following the launch of the pilot project at Löllingbach, the control system was tested. The project team changed sequences and opening times and also installed a flush sequence to use after floods or in autumn when there are a lot of leaves in the stream. To control the function, the system has a remote maintenance tool that highlights which operation stage is active. For bigger and higher shafts, the sequences were optimized and a cost-effective stopper system was integrated for unsteady upper stream levels.

This system contrasts with the state-of-the-art fish ladders, which often need expensive slide structures to balance water-level fluctuations.

Monitoring and optimization process

The implementation of the pilot plants and a comprehensive monitoring during the operation enabled the project to test different types of transportation, filling systems, programme sequences with various dependencies, structural installations and streamings. Moreover, a camera monitoring system was used to observe fish migration through the system and fish behaviour during the four operation phases. This made it possible to identify the impact of various adjustments on fish behaviour such as installations that attract fish. The project also used a fish trap in the headwater after the shaft to control fish migration. The camera records enabled observation of migratory behaviour upstream and downstream, the fish using the system in both directions (Figure 4).

Figure 4. Monitoring with camera, fish mark and fish trap

These two pilot plants have a different exit strategy. The difference from the four other locations is that the water in the shaft is over-pumped above the upstream water level and then the fish are flushed to the headwater through a flushing pipeline. At one of these locations, various systems to scare away the fish to leave the shaft and enter the flushing pipeline were tested (Box 1).

Box 1. Overview of implemented pilot plants

	Location 1	Location 2	Location 3	Location 4	Location 5	Location 6
River	Löllingbach	Gurk	Möll	Traun	Görtschitz	Große Mühl
Maximum length of target species	Brown trout 40 cm	Danube salmon 80 cm	Danube salmon 80 cm	Brown trout (m. *lacustris*) 90 cm	Grayling + Brown trout 50 cm	Danube salmon 80 cm
Difference in water elevation	2.4 metres	3.4 metres	5–7.5 metres	9–10 metres	1.4 metres	9–10 metres
Features	none	Unsteady downstream water levels	Unsteady downstream water levels up to 2.5 metres	Over-pumping + flushing pipeline to the upstream water level, unsteady downstream water levels	Compact system (finished parts)	Over-pumping + flushing pipeline to the upstream water level, unsteady downstream water levels

Lessons for future SHP development

Lesson 1: Flow directions in front of the tailwater influence fish behaviour

The different pilot plants and the intensive monitoring showed that the flow directions in front of the shaft (tailwater) greatly influence fish behaviour. Camera records allowed the project team to optimize flow directions and intensity for every operation stage. The observation of the filling pipeline during the catch stage led to a different form of the pipeline in the shaft to improve the flow inside the shaft. Further, the opening times of the slides affected migration behaviour.

Lesson 2: The value of pilot projects

The implemented pilot plants provided the project with valuable data and real-world experience, particularly during the installation and operational phases of the fish lift sluice for locations with different conditions.

Lesson 3: Improving river continuum as water status

The system can be installed at locations where the state-of-the-art systems reach their limit. The fish lift sluice helps to restore the river continuum. It also helps improve the water status of streams and rivers.

3. TURBULENT: RESILIENT, COST-EFFECTIVE TURBINES DESIGNED FOR RIVERS OR CANALS WITH MINIMAL HEIGHT DIFFERENCES

Daniela Hurtado, Jasper Verreydt, Turbulent

Resilient and cost-effective, the Turbulent small hydropower (SHP) turbines are designed for very low head stream and involve minimal civil works and maintenance. Inspired by nature, they use a vortex system to deliver stable, low environmental impact and cost-effective renewable energy.

In recent years, there has been a revolution in terms of energy production and usage. Old energy solutions are being set aside in favour of options that are sustainable, decentralized and financially accessible. Due to the intermittency and unpredictability of wind or solar power production, hydropower has increasingly been seen as one of the most attractive ways of harnessing energy. However, there can be considerable environmental and economic issues associated with hydropower infrastructure such as large dams; and with significant investment needed upfront for installation, investors and project developers can be put off by the financial commitment associated with hydropower development.

While SHP technologies have been very successfully explored, it has been a challenge to create a solution for low head water channels that would be both scalable globally and financially accessible. This specific issue is the one that Turbulent SHP systems have been designed to address. Designed for streams with very low height differences and involving minimal civil works and maintenance, they use a vortex system to deliver stable, low environmental impact and affordable renewable energy – as evidenced by the company's latest commercial scale vortex turbine, which is currently in operation in real-life conditions in Green School in Bali, Indonesia.

Turbulent technology

Resilient and cost-effective, Turbulent SHP systems are uniquely designed for low head streams specifically those below 5 metres, and generate up to 200 kW per turbine and up to multiple megawatts of energy as a network of decentralized turbines, close to the end user with minimal civil works and maintenance. The design, inspired by nature itself, uses a vortex system based on the natural free Rankine vortex principle (Figure 1) to deliver stable and cost-effective renewable energy through an individual turbine or a network of multiple turbines. The turbine design allows fish (and debris or sedimentation) to pass through unharmed, which also keeps maintenance low, while control software keeps efficiency high. Installation is straightforward and the system can be used anywhere in the world. Whether in an urban setting or as part of a rural off-grid project, this technology offers a practical solution for investors, developers and energy users. It demonstrates how energy production can work together with nature and without damaging the local ecosystems to satisfy growing global energy demands. Overall, costs are comparable to those of other renewable energy technologies and diesel.

'The design, which is inspired by nature itself, uses a vortex system to deliver stable and affordable renewable energy, without damaging local ecosystems.'

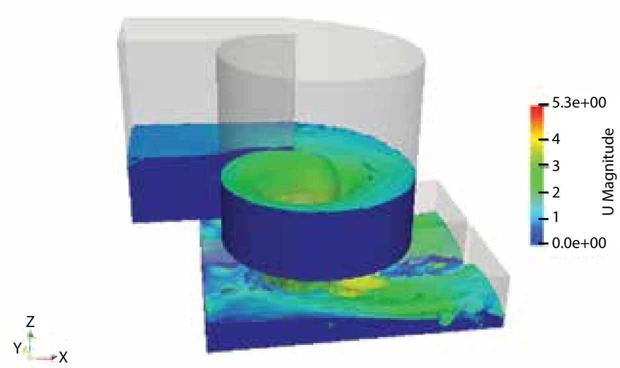


Figure 1. Vortex model 3D, Doñihue, Chile

Case description: Turbulent in Green School Bali, Indonesia

The 13 kW Turbulent installation is located in Green School, on the Ayung River in Bali, Indonesia (Figure 2). Green School Bali owns the site and has the water rights, which are often necessary for SHP installations.

The Turbulent turbine is a fully validated industrial scale vortex turbine operating in real-life rainforest conditions. It is being used to apply all lessons learnt in the previous prototype in Doñihue, Chile.

The installation provides energy to 500 students and a local farm. The main motivation has been to have reliable electricity day and night by finding a robust alternative to the previous SHP installation that was destroyed in a flood carrying debris downstream. Although Green School had made remarkable efforts to fulfil their energy needs with renewable energy sources, their photovoltaic installation could not generate more than a smaller percentage of the school's needs (since the sun's availability is unpredictable and at its peak gives only a few hours on sunny days) and the previous SHP project could not resist the rainforest storms or failed to deliver the estimated energy production from its capacity.

The new Turbulent turbine was designed for a flow of 1.5 m^3/s and a drop of approximately 1.7 m. It provides 13 kW of continuous energy and has been operational since March 2019. The power electronics consist of an induction generator directly coupled to the grid via a soft starter. With a local energy price of 0.08 US$/kWh and an LCOE (levelized cost of energy) of 0.04 US$/kWh (roughly the price to generate electricity with a gas-fired power plant), the total investment cost of the turbine will be paid off within six years (+15 per cent return on investment).

Box 1. Turbulent in Bali – an island of SHP potential

Turbulent's latest 13 kW SHP is keeping Green School Bali powered day and night, 100 per cent by renewables. It provides energy to more than 500 students and a local farm.

With its biodiversity, rice terraces and rainforests, the island of Bali is one of the main tourist attractions in Indonesia and home to one of the most sustainable schools in the world, Green School. Green School is a pioneer in terms of sustainable education and living off-the-grid, preparing global citizens of the future.

The school is situated right next to Bali's longest and most sacred river, the Ayung River. However, it took more than seven years and several tryouts to find a reliable SHP solution in harmony with the surrounding ecosystem but robust enough to withstand the unpredictable rainforest floods. Turbulent offered a suitable technological solution for the location – a resilient and cost-effective low-head SHP system.

In addition, Indonesia's recent net-billing law would now allow Green School to have a new revenue stream selling the excess energy generated with the Turbulent SHP plant back into the grid.

Since the turbine was inserted into an existing basin, all civil works were practically reused (Figure 3). The installation itself was completed in six days and the commissioning lasted for four days. However, future turbines can be installed most likely faster than in Bali, since a significant part of the commissioning time was used to install and test new control features, which will be already implemented for the upcoming projects. Turbulent engineers expect to reduce the commissioning time to less than a day.

Considering that traditional hydropower has a reputation for significative intervention in the local ecosystem, community acceptance for SHP is extremely important. In Bali, the local community did not only accept the Turbulent SHP plant as a reliable energy solution with zero negative impact but also celebrated the project with a blessing ceremony (Figure 8).

Figure 2. A view from above of the turbine in Green School Bali, Indonesia

Figure 3. Civil works of the 13 kW turbine in Green School Bali, Indonesia

Main benefits: scalable, cost-effective and easy to maintain

The Turbulent turbine currently provides more than 80 per cent of the energy for Green School. The turbine was transported mainly using a small truck but the last part of the transportation to the site was carried out with the help of the local Balinese people using a traditional technique of rolling wood beams.

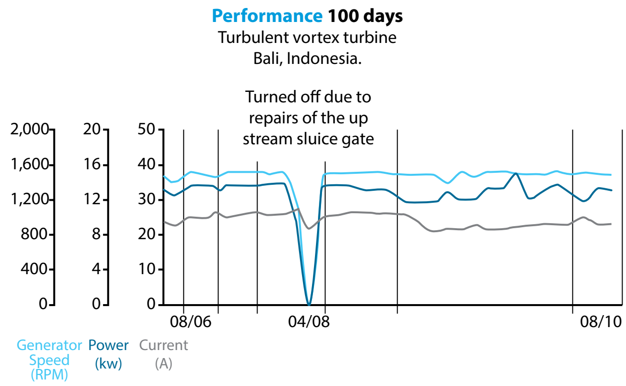


Figure 4. Power output, June–August 2019

Figure 5. Green School's self-made bamboo security fence

Figure 6. Installation and commissioning of the Green School turbine

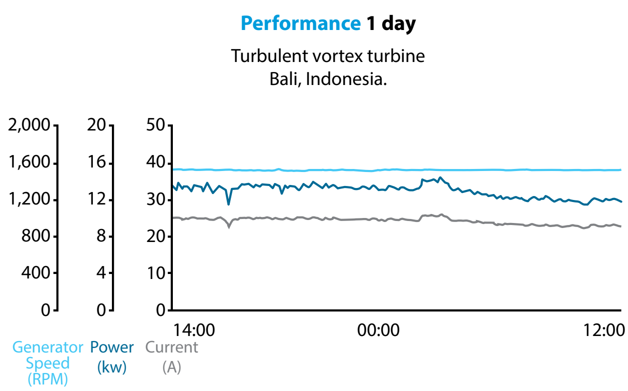


Figure 7. Daily power output in Bali

Figure 8. Blessing ceremony of the turbine in Green School Bali, Indonesia

Figure 9. Bamboo crane, Green School, Bali Indonesia

They also built their own eco-friendly bamboo crane and, together with the Turbulent team, placed the turbine inside the basin. Critically, these local workers have been successfully maintaining the turbine since its installation without any specific knowledge or skills led only by one local engineer from Green School who is in charge of all the renewable energy systems.

This is a major advance in SHP technology as most of the existing turbine solutions require costly components and often on-site expert engineers flying in for routine maintenance.

Having access to hydropower through a Turbulent installation has been a smart economic investment for the community as the return on investment is expected to be rated at over 15 per cent per year and the turbine has been continuously working at a capacity factor of 95 per cent or higher (for reference, the capacity factor of solar installations due to their intermittency is less than 20 per cent and due to fuel availability diesel generation sets are rated at roughly 66 per cent). The initiative has also provided employment to local workers for the duration of the project. Moreover, there are many potential sites around the Green School facilities and all along the Ayung River, so there is a high likelihood of future SHP installations. This means more employment for local workers, less dependency on other sources of non-renewable energy and a more sustainable power infrastructure in the region to enable economic development.

Figure 10. Green School on the map of Bali

Source: Google Maps

In Bali, the engineers from Turbulent were able to successfully implement and validate the lessons learnt from the previous installations, adding design improvements and new components that new projects in Otepää, Estonia, Versailles, France, Ylang, Taiwan and Mindanao, the Philippines will also benefit from (Box 2).

Box 2. Turbulent project improvements and goals

The following are the achieved improvements:

- The installation validated the scalability and industrialization of the turbine;
- A significant cost reduction by replacing the inverter/drive combination with a single soft starter;
- Working with renowned worldwide suppliers to guarantee high quality and provide excellent service on-site;
- For some critical components, especially in bigger projects, it would be best to have spare parts that can be easily used for replacement.

Goals for future projects include:

- A local tactile screen with an easy-to-use interface to operate the turbine;
- Moving towards off-grid projects;
- Scaling and installing projects for more than 200 kW per turbine and multiple megawatts with a network of decentralized turbines.

Turbulent and the United Nations Sustainable Development Goals (SDGs)

SDG 7 Affordable and clean energy: ensure access to affordable, reliable, sustainable and modern energy for all. Turbulent turbines are among the most cost-efficient, robust and easy-to-maintain turbines in the world that can be installed in both remote areas and rural settings in streams that formerly could not be harnessed for energy.

SDG 9 Industry, innovation and infrastructure: build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. The technology offers a new way of thinking in hydropower. It is a resilient, decentralized, scalable and dam-less solution. With minimal civil works, it provides energy right where the energy is consumed.

SDG 11 Sustainable cities and communities: make cities and human settlements inclusive, safe, resilient and sustainable. The technology was designed in view of the remote communities. The company equips local communities with a sustainable, continuous and cost-effective energy source, which allows them to develop at a quicker pace.

SDG 13 Climate action: take urgent action to combat climate change and its impacts. Hydropower is the most consistently accessible renewable resource available to us. Turbulent dam-less plants have a minimal impact at the site, harnessing energy from rivers or canals that cannot be used with traditional hydropower solutions.

SDG 14 Life below water: achieve sustainable development of fisheries, fish stocks must be maintained at a biologically sustainable level. Inspired by nature, Turbulent uses vortex technology to allow fish to pass through unharmed, keeping the ecosystem safe while producing consistent energy.

Lessons for future SHP development

Lesson 1: Be prepared for extreme climate change

In tropical climates, all material must be able to withstand extremely high levels of humidity, therefore, appropriate coating is a must.

Lesson 2: Undertake accurate site review

An accurate site review is necessary to understand project feasibility. In Bali, Turbulent successfully tested a template for future site assessments in order to avoid overlooking important factors or working based on inaccurate information.

Lesson 3: For non-core parts, experienced subcontractors are necessary

One of the major difficulties was to adapt the new automatic system into an existing sluice gate that was not properly dimensioned to work fully automated. This meant a week and a half of extra work for the engineers.

Since components such as sluice gate or trash rack are not part of the core, future distributors, local partners and/or end clients should ensure the correct functioning of these components via experienced local contractors beforehand in order to avoid unnecessary delays during the installation process.

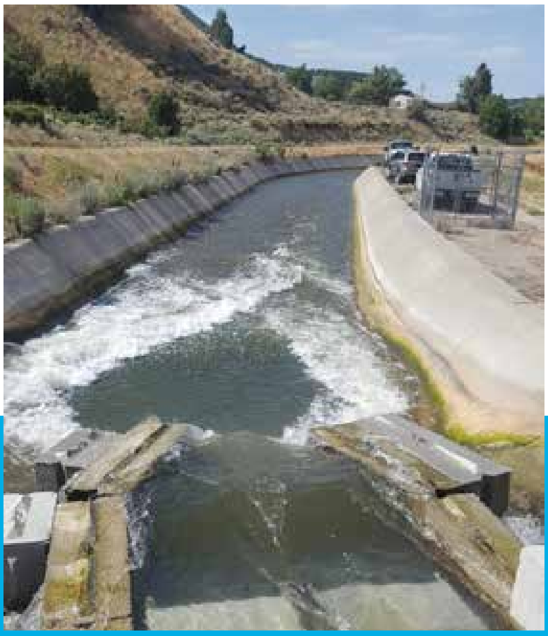
Lesson 4: Flow management on a short notice is essential at sites with flash-flooding

The Bali project experience has equipped Turbulent with a versatile toolset for flow management with a bypass gate right at the turbine and a flow control mechanism at the beginning of the turbine channel.

Lesson 5: Undertake a detailed stream analysis and ensure reliable study data

Any development of an SHP site will require a detailed engineering analysis of the stream. However, there can always be a margin of error due to uncertainty in water supply. The challenge for each hydropower technology is to have reliable study data of the site as well as to consider the margin of error to provide the most suitable solution for the site.

4. KINETIC HYDROPOWER AND COOLING CANALS



Karl Kolmsee, Smart Hydro Power

Smart Hydro Power, a German-based environmental engineering company, has developed what has become known as a 'swimming' hydrokinetic plant. The floating turbine, which works with the flow of water only, requires no infrastructure except a small anchor point. Originally this small 5 kW plant was designed for river use with a view of promoting rural electrification in the areas with poor access to electricity.

Given the seasonality of most rivers, the hydrokinetic turbine is also photovoltaic (PV) in a hybrid system, which allows for a stable power supply throughout the year – making the cost of the technology much lower than that of PV only or diesel generators. Moreover, the 5 kW underwater generator can also be used in existing infrastructure such as canals or water regulation dams.

The more stable flow and lack of debris ensure that the hydrokinetic systems generate electricity for approximately 8,760 hours per year with little or no maintenance and, depending on velocity, low or very low generation costs. Originally designed for river use, kinetic hydropower systems have been installed in canals in Germany, South Africa, the USA and at the NLC Neyveli thermal plant in Tamil Nadu, India.

Kinetic hydropower – light footprint and rural off-grid suitability

Unlike traditional forms of hydropower, which harness potential energy through architectural developments such as dams, Smart Hydro Power hydrokinetic technology projects use the flow of water only. From the development perspective this is a key benefit as no separate infrastructure is necessary other than a simple anchor point. Environmentally, the technology's light footprint also means limited impact on the local environment, wildlife and ecosystems.

Generating sustainable and renewable energy, hydrokinetic initiatives also support several United Nations Sustainable Development Goals (UN SDGs) including SDG 7 to "ensure access to affordable, reliable, sustainable and modern energy for all" and SDG 13 to "take urgent action to combat climate change and its impacts".

‘A typical Smart Hydro Power hydrokinetic project requires one week of preparation and one week of installation, in most countries permits are not necessary as the technology does not require water rights as the natural flow of water is not changed.’

Like traditional hydropower technologies, hydrokinetic initiatives are base load power generation sources and in contrast to solar PV or wind power installations, they can provide a continuous supply of electricity throughout the year. This makes hydrokinetic an attractive technology for off-grid projects, which otherwise suffer the expense of high battery or replacement energy costs.

Moreover, the technology is relatively easy and inexpensive to put in place – a typical Smart Hydro Power hydrokinetic project requiring one week for preparation and one week for installation. The planning and permitting phase is standardized and requires no more than three months. In most countries permits are not necessary as the technology does not require water rights given that the natural flow of water is not changed. Furthermore, as the natural water flow is unaltered there are no unintended cultural or socio-economic consequences linked to the development of hydrokinetic projects.

Figure 1. Smart Monofloat river turbine

Smart hydrokinetic turbines only weigh 380 kg, which means they are also easily transported to remote rural locations by boat or by truck. Importantly, installation can be successfully undertaken using local labour or if necessary using a crane working on two traditional boats. Overall installation costs rarely exceed US$ 1,000 per turbine, and even less when projects utilize several turbines. Even where larger hydrokinetic turbines are used, installation is relatively simple especially compared to the projects that use traditional hydropower technologies or other power generation alternatives.

Technical specifications: Betz’s law and natural kinetic energy

Hydrokinetic energy compares favourably to other renewable energy sources and traditional hydropower options, and it can offer a flexible solution to electricity generation particularly for rural off-grid projects. It should be noted that generation is limited to the natural kinetic energy of the flowing water, which is calculated in the following way: $p_{kin} = \frac{1}{2} \times d \times A \times v^3$ (with p = energy (W), d = water density (kg/m^3), A = area (m^2), v = velocity (m/s)).

Depth and velocity reduce the potential energy harvest with velocity being more important than depth. As is the case with wind turbines, Betz’s law applies to hydrokinetic turbines as well. This means that the turbine can only capture approximately 59 per cent (16/27) of the kinetic energy (the Betz’s coefficient) for the purposes of electricity generation.

Climatic conditions should be taken into consideration. For example, climate in India where the Smart Hydro Power hydrokinetic technology is being used in cooling the canals at the NLC Neyveli thermal plant in Tamil Nadu, is characterized by strong monsoon and a three-month dry season. The technical characteristics of hydrokinetic installations

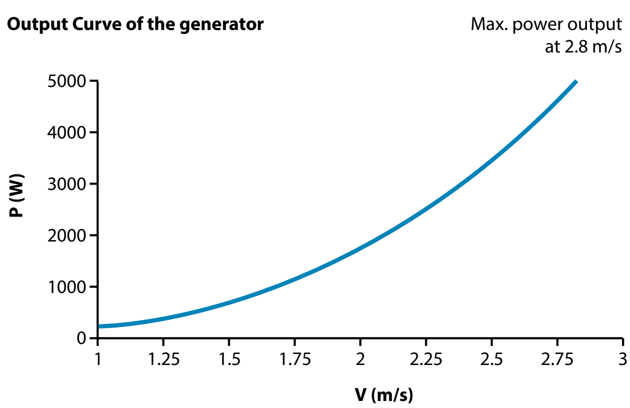


Figure 2. Power curve water velocity to power output

mean that rural off-grid electrification projects should, as suggested, be hybrid with solar PV complementing the hydropower generation. For on-grid projects using rivers as natural resources, this means an on average lower plant factor (defined as given generation output to nominal generation capacity), which increases the economic hurdles.

Using existing infrastructure

It is advantageous for the projects to use existing infrastructure thereby bypassing any limitations caused by the variable flow and velocity of natural water resources. Examples of such an infrastructure might include canals or tailraces associated with traditional hydropower plants or water regulation dams. Given the above circumstances, the plant demands a slightly different design. To adapt to shallow canals (Figure 4) the standard design does not use the diffuser (compare Figure 1 and Figure 3). This design adaptation reduces efficiency by approximately 10 per cent as the diffusor's coefficient of performance is 1.15 (Figure 5).

Figure 3. Smart Free Stream canal turbine

Figure 4. Smart Free Stream in an irrigation canal, USA

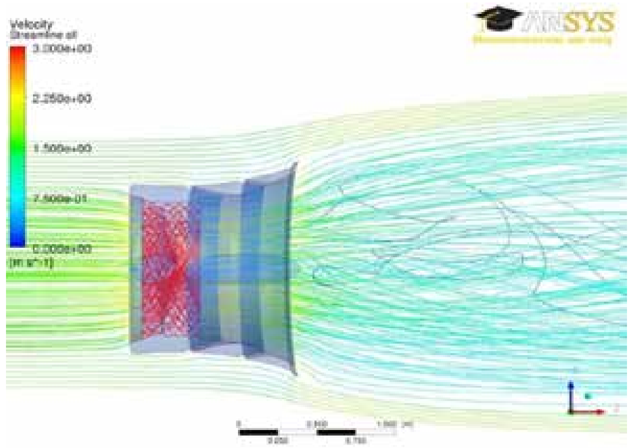


Figure 5. Diffusor of Smart Monofloat turbine simulation

It is also worth noting that although hydrokinetic river turbines, like wind turbines, are limited by Betz's law, canal turbines, by constraining the entire diameter of a structure, show a better output at the same velocity. This is partly caused by the absence of any possible deviation in pressure, whereas in the natural environment, water or air follows the path of least resistance (which is not always past the blades). It is also partly caused by the blockage giving rise to local impounding, which increases the pressure on the blades. While both effects are difficult to calculate, experiments have shown that a total constraint increases the power output at given velocities significantly.

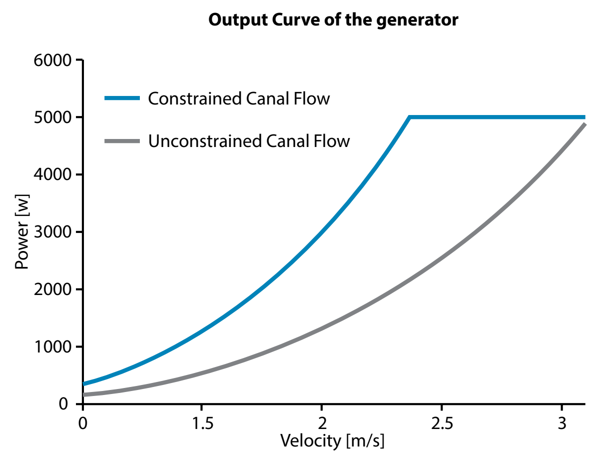


Figure 6. Smart Free Stream with constraint and unconstrained power curve

The unconstrained curve of the Smart Free Stream is less steep compared to the curve of the Smart Monofloat using a diffuser (compare Figure 2 and Figure 6). The fully constrained and unconstrained curves mark the area of measurable generation output given a certain velocity in a canal. While the effects of constraining a canal are difficult to calculate and predict, practical examples offer an interesting insight in canal hydrology.

Box 1. Kinetic hydropower plant in the cooling canal T.P.S –II, NLCIL, Neyveli, Tamil Nadu, India

The cooling canal of the thermal power plant (TPS-III, 1,470 MW) at Neyveli mining site is 5.7 metre wide and 3.5 metre deep. The last section of the main canal carries discharge (36 m^3) collected from four cooling towers. Measurements in the middle of the canal have shown velocities up to 3.1 m/s. Due to friction from the side walls the velocity at the sides is reduced to 2.5 m/s.

The installed plant, which has a nominal capacity of 20 kW and consists of four turbines installed in a row, has been running continuously since its commissioning in October 2017. Output varies between 13 and 15 kW. Electricity is injected into the plant's grid at low voltage level (415 V). While the achieved output is lower than the nominal capacity, detailed analysis of water flow and site hydrology have proven the results to be in line with technical capacities. Being the first installation of its kind, NLC and Smart Hydro Power's local partner IMP Powers Ltd view the installation as having enormous research and development value with many findings offering improvement potential for future hydrokinetic projects. So far research findings have established the following:

- The two turbines in the middle of the plant generate 4 to 4.5 kW each while the two turbines closest to the walls generate 2 to 2.7 kW each. Repeated velocity measurements along the width of the canal show that the velocity decreases significantly due to the walls' resistance (2.5 m/s instead of 2.8 m/s or 10 per cent).
- The frame holding the turbines is designed with flat steel instead of hydrologically optimized rounded steel causing strong turbulence and high installation costs due to the flow resistance.
- The frame structure using a 1.5-metre area below the water surface only results in water deviating from the blades' resistance towards the lower part of the canal and, therefore, causing turbulence behind the turbine.

The design of future hydrokinetic canal plants might be improved by the following:

- Using a diffusor or increased blades to cover the entire area of the structure minus the border of decreased velocities (0.5 metres below the surface, along the walls and over the canal ground).
- Hydrologically improving the frame by using rounded steel.

In this way output per turbine is increased and costs are reduced (mainly installation costs). Even without the changes, the plant generates at approximately US$ 0.051 per kWh (INR 3.5 per kWh), a cost level achieved by other renewable energy sources under ideal conditions only. The targeted annual unit production is 108,000 kWh. Overall, from October 2017 till 31 December 2017 a total of more than 38,000 kWh of electricity was pumped into the grid.

Lessons for future SHP development

Lesson 1: The importance of using existing infrastructure

While hydrokinetic plants are a valuable technology for promoting rural electrification, the seasonality of rivers limits their on-grid use. Using existing infrastructure is an option to make use of this low-cost renewable technology – with an industry grid replacing electricity from the grid or within a standard Power Purchase Agreement (PPA) setting.

Lesson 2: The technology is cost-effective

Initial results regarding the reliability and cost-effectiveness of the technology are encouraging. It is clear that scaling-up this relatively young technology to commercial projects with more turbines will further increase competitiveness.

Figure 7. Neyveli Lignite Corporation kinetic hydropower plant at Neyveli, India

Lesson 3: Low voltage and continuous generation of small hydrokinetic installations can stabilize the grid

Hydrokinetic technology is particularly appropriate for the specific Indian environment, which has relatively high technical grid losses and a widespread need for investment in grid improvement. While renewable energies with strongly variable generation output can destabilize the grid and cause high grid operating costs, small hydrokinetic installations with their continuous generation and low-voltage grid feed-in close to the point of consumption, instead lead to grid stabilization.

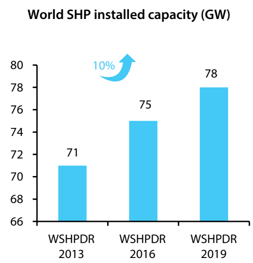
Lesson 4: Increased competitiveness linked to grid stability

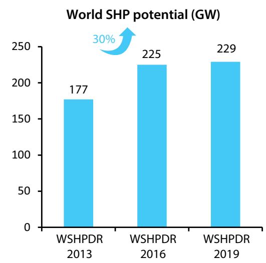
In some energy regimes, such as Germany, the specific positive effect on grid stability is remunerated in addition to the energy volume generated. This would add to the competitiveness of hydrokinetic technology using existing canal infrastructure, which are numerous in India.

UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

World Small Hydropower Development Report

The *World Small Hydropower Development Report (WSHPDR) 2019* is an update of the Report's first two editions in 2013 and 2016. The *WSHPDR 2019* contains **166** national reports and **20** regional reports, with 21 new countries added since its first edition.





A special report with **Case Studies** is added to the *WSHPDR 2019*, showing the different roles small hydropower can play in achieving the SDGs.

- SHP for productive use
- SHP for social and community development
- SHP financing
- Technology, innovation and smart SHP
- Incentive policies for SHP development
- Green SHP

- The Report is available on **www.smallhydroworld.org**;
- More than 230 experts and organizations have been involved;
- Every country report provides information on:
  a. Electricity sector;
  b. Small hydropower sector;
  c. Renewable energy policy and;
  d. Barriers to small hydropower development.

Small hydropower for a better world

Contributing organizations

European Bank for Reconstruction and Development

Energetyka Wodna

HRC Small Hydro

HYCON GmbH

Asociacion de Trabajadores de Desarrollo Rural – Benjamin Linder (ATDER-BL)

Der Wasserwirt

Ping An Bank

Smart Hydro Power

Sarhad Rural Support Programme

Turbulent

Virunga Power

Zhaoheng Hydropower Group

UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Vienna International Centre
P.O. Box 300 - 1400 Vienna - Austria
Tel.: (+43-1) 26026-0
E-mail: renewables@unido.org
www.unido.org

INTERNATIONAL CENTER
ON SMALL HYDRO POWER

136 Nanshan Road
Hangzhou - 310002 - P.R. China
Tel.: (+86-571) 87132780
E-mail: report@icshp.org
www.icshp.org