THE LAST 30 YEARS OF HYDROPOWER IN THE WORLD AND SLOVENIA

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Over the past three decades, the hydropower sector has seen major technological advancements, driven by rising global electricity demand, increasing energy prices, and growing awareness of the environmental impacts of conventional power generation. These factors have strengthened the role of renewable energy sources-particularly hydropower-in building sustainable energy systems with lower ecological footprints. Current research focuses on retrofitting and digitalizing existing hydropower infrastructure, developing next-generation hydro and aero-hydrodynamic technologies, and deploying hybrid systems integrated with advanced energy storage solutions. Given the inherent variability of renewable sources, high-capacity storage technologies are essential for enhancing grid stability, frequency regulation, and overall resilience. Furthermore, the development of advanced smart grid architectures is crucial to enable distributed, multi-nodal power generation, improve demand–supply balancing algorithms, and support the seamless integration of small and medium-scale energy producers. Together, these innovations aim to optimize energy efficiency, support decarbonization goals, and ensure a reliable and flexible power supply in the face of evolving energy needs and climate challenges.

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1 Introduction

The electrical production by source "Our world in data, 2025 "[1] shows that in 2025 the hydropower was the third most powerful source of electricity production after coal and gas, and before nuclear and oil. In 2024, the ratio is similar, only the production is higher by about 50 %

Over the past three decades of energy production development, the developed world has steadily moved toward:

a) The development of smart power grids, towards bilateral operation and protection, distributed energy production, and its optimization according to the energy demand in the network.
b) The combination of different energy systems, in the field of renewable energy sources, mainly the combination of wind and hydropower (reversible hydroelectric power plant).
c) The modernization and upgrading of existing hydropower systems, such as the replacement of Kaplan Turbine and Francis Turbine with the Deriaz turbine, of course, in the mixed field, where both types of classic hydraulic turbines (Kaplan and FT) have been used so far, by placing the powerhouse at an increased pressure in it (high-pressure Pelton systems).
d) The installation or revival of older forms of hydraulic turbines, especially modernized water wheels, improved designs (Steff turbine), screw designs, matrix arrangement of turbines in the watercourse (MATRIX, HydroMatrix), tube designs and derivatives (Saxo, Darrieus designs, ...).
e) Installation of alternative forms of hydraulic turbines (Vortex), mainly in the field of medium and small hydroelectric power plants.

2 Smart networks

The need for smart grids has been established with the increased share of energy obtained from renewable sources. It is known that renewable sources are "volatile" in terms of forecasting production and, of course, subsequent distribution into the grid system [2]. Therefore, the need for two-way communication and automation (regulation + optimization) of the grid has become evident, which will enable monitoring of the amount of energy in the grid in real time (use of sensors, smart meters, control systems that analyse or process data based on which quick decision-making will be enabled (in the future also with the use of artificial intelligence).

Optimization of such a grid system operation will enable automatic switching of energy flows according to current needs, better integration of dispersed energy production (especially from renewable sources), better and balanced supply and demand for energy, and rapid detection of errors and their elimination [3].

Thus, connected users will be able to control their consumption, storage in storage tanks (e.g., batteries), and return energy to the grid (e.g., from a solar power plant) during times of domestic production surpluses.

By using smart grids, we will therefore achieve:

– greater reliability of electricity operation (supply)
– better grid efficiency (higher efficiency and lower losses),
– more straightforward and better integration of "capricious" energy sources,
– greater influence of users (producers and consumers) regarding grid operation and
– greater influence on the price and, above all, on the dynamic determination of electricity prices.

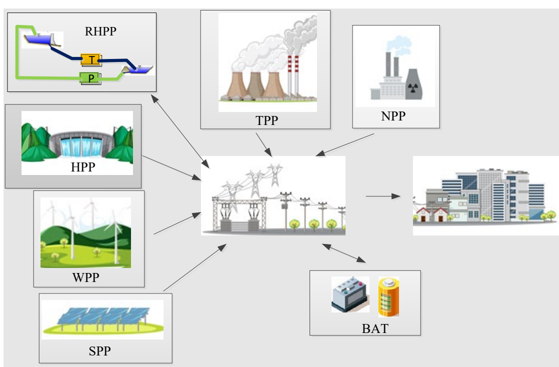


Figure 1: Smart networks.

Europe is at the forefront of renewable energy development, having achieved 24.5 % of its energy supply from renewables in 2023, with a goal of at least 42.5 % by 2030, as specified in European Directive 2009/28/EC.

2.1 Smart grids in Slovenia

In Slovenia, we are significantly lagging behind Europe, as the development of Slovenia's electricity distribution network has only recently begun in terms of greater investment in modernization through the introduction of innovative (smart) grid components [4]. Elektro Primorska, Ljubljana, Gorenjska, Celje, and Maribor promise to invest 150 million euros in upgrading the network by the end of 2026. Approximately 71 million euros should be invested by the national recovery plan, and the aforementioned dispatching companies should invest the rest.

A **smart transformer station** with a power of 15 MW and a capacity of 30 MWh has been installed in Kidričevo since 2021, which is still the only storage station in the Slovenian electricity grid. Near Maribor (in Pekre) and around Ljubljana, two storage stations with a power of 5 MW and a capacity of 25 MWh have been installed.

In total, in Slovenia, in the last 30 years. We have 25 MW of installed power with a capacity of 80 MWh, which is significantly too little for any severe accumulation. However, increases in power and capacity and new installations are planned [5].

3 Combination of Energy Systems

The combination of different energy systems provides a solution for stabilizing the electricity grid when multiple renewable energy producers are integrated. In such cases, significant fluctuations in grid power can occur due to variable wind speeds. The first practical combination involved integrating wind farms (WPP) with reversible hydropower plants (RHE).

The basic principle of parallel operation between a wind farm and reversible hydropower systems is known as the short-circuit operation mode. In this mode, the RHE operates in parallel in the pumped-turbine mode. This means wind energy is used to drive pumps that lift water into a higher reservoir while turbines simultaneously generate electricity from the stored water. Although this operation introduces additional system losses, it greatly enhances the operational reliability of the energy supply during potential power shortfalls from wind farms. In practice, any loss of wind turbine production is nearly simultaneously compensated by the

RHE operating in turbine mode. This results in improved grid stability, making the system less sensitive to fluctuations from renewable energy sources. At the same time, RHE continues to fulfill its primary role of storing excess energy during periods of surplus generation.

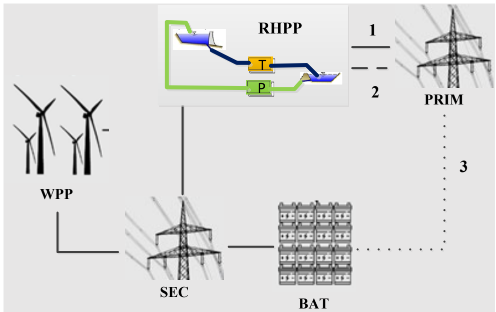


Figure 2: The combination of RHE with WPP.

The integration of RHE with wind systems is organized so that all wind farms within a wind field are first connected to the secondary network (SEC), which is linked to the RHE network. From the RHE, electricity enters the primary (national) grid (PRIM). The RHE maintains a dual connection: directly to the primary grid and indirectly via the secondary network of wind fields. This configuration allows the RHE to operate independently, even when wind production is absent, either as an energy storage system or, if needed, as a direct electricity producer for the primary grid.

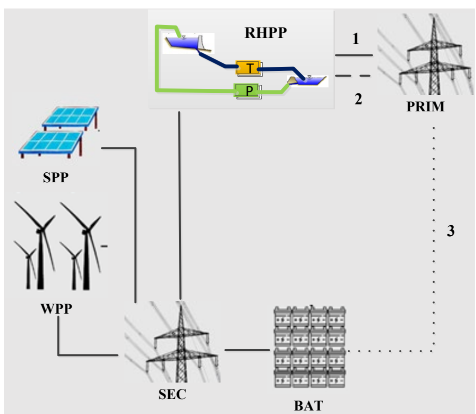


Figure 3: The combination of RHE with WPP and SPP.

In extended combined systems, solar power plants (SPP) are also integrated with RHE. This addition allows the system to balance daily surpluses of solar energy, which would otherwise need to be curtailed to prevent excessive load on the electricity grid.

3.1 Combination of energy systems in Slovenia

In Slovenia, there is currently only one operational reversible hydroelectric power plant: RHE Avče, located on the Soča River, with an installed capacity of 185 MW. This plant is not directly connected to any wind farm or solar power plant in the country. Theoretically, RHE Avče could serve as a compensatory source for the NEK Krško Nuclear Power Plant (NPP); however, this would only apply to the Slovenian portion of the power supply. If Slovenia had followed global or European development trends, this RHE should have been constructed alongside NEK, which began operations 42 years ago.

Several additional RHE projects are planned in Slovenia, with the closest being RHE Kozjak, which is expected to have an installed capacity of 2 × 220 MW. Construction of this project is scheduled to begin in 2027. Currently, Slovenia does not have any operational wind farms, so it is not possible to combine wind power with the existing RHE Avče.

Slovenia does, however, have several solar power plants (SPPs) installed in conjunction with hydroelectric power plants (HPPs). These include installations near HPP Brežice on the Sava River, as well as HPPs at Dravograd, Maribor, Zlatoličje, and Formin. Among these, the largest solar-hydro combination is at HPP Brežice, with the SPP providing an installed capacity of 6 MW. Notably, the solar plant is connected to the 110 kV transmission network as the fourth unit of HPP Brežice, making it the largest solar power installation in Slovenia.

On the Drava River, next to the hydroelectric power plants, we have installed HPPs:

- HPP Dravograd, SPP with an installed capacity of 40 kW,
- HPP Mariborski otok, SPP with installed capacity of 25.5 kW,

- HPP Zlatoličje, SPP with an installed capacity of 777 kW,
- HPP Zlatoličje – segment 5, SPP with installed capacity of 2.5 MW,
- HPP Formin, SPP with an installed capacity of 112 kW.

4 Upgrades and modernizations

As the first direction of upgrades, or modernization in the world, especially in Europe, the direction of upgrades and modernization of hydropower systems is also moving towards replacing the turbine type, e.g., Francis and Kaplan with Deriaz. In the mixed operating range, between Francis and Kaplan, the basic form is successfully replaced by Deriaz. This replacement achieves a higher "yield" of production, because the efficiency of Deriaz is higher at partial loads (when operating outside the maximum efficiency point). The higher yield of Deriaz is possible due to the possibility of operating at a higher available head compared to Kaplan, and the better efficiency of Deriaz compared to Francis, due to better regulation compared to Francis. Deriaz has dual regulation, just like Kaplan.

In terms of efficiency, Deriaz is even better in the partial load range (between 20 % and 50 % of full load) than both compared forms (Francis and Kaplan).

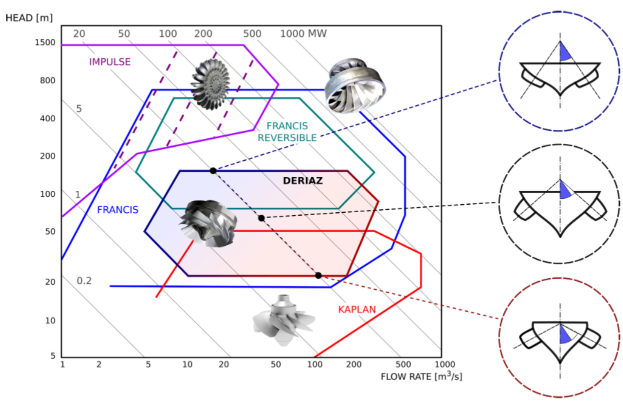


Figure 4: Deriaz pump-turbine.
Source: [8]

By replacing worn-out hydraulic turbines operating in a mixed range between Francis and Kaplan, significantly better production can be expected, especially in smaller, sub-optimal flows. Hence, during times of low water, energy yield is significantly better.

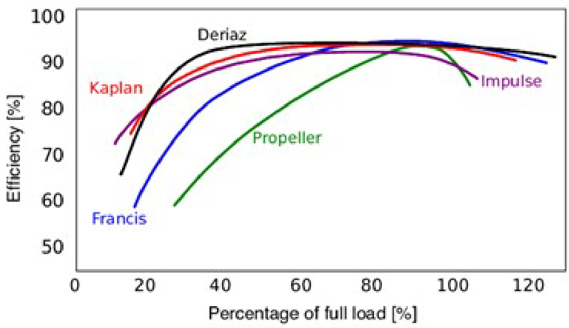


Figure 5: Efficiency comparison.
Source: [8]

Another direction of upgrades is taking place in impulse types of hydraulic turbines Pelton, whereby placing the engine room at a lower level and with increased air pressure in the engine room, production (yield) can be increased, mainly due to the increased head. The engine room is usually placed approximately. 10 m lower, and the ambient pressure (pressure in the engine room) is increased to 2 bar absolutes. That means that we have to maintain the increased air pressure in the engine room with an air compressor system that maintains a constant increased air pressure in the engine room. That is, of course, necessary to place the outlet water angle approximately. 10 m lower, thus ensuring that the Pelton still flows into the air, as the impulse type of turbine requires.

In one such project (KOPS II) [8], we collaborated with the Technical University of Graz, where we tested the impact of increased pressure in the engine room of a Pelton turbine in a laboratory environment. Measurements on the model demonstrated a positive energy yield achieved by increasing the Pelton head, even though a portion of the compressed air in the engine room casing, approximately 3 % to 5 %, was lost through the outflow of the lower water. The increase in power due to the greater head was significantly greater than the energy losses of the compressed head.

The third direction of upgrades or modernization is classic modernization, which replaces older hydraulic turbines of all types with new, more modern ones of the same type and dimensions. Due to better design and better materials, these achieve better efficiency and thus enable greater production than older designs.

4.1 New construction, upgrades, and modernization in Slovenia

Unfortunately, we do not have rivers on which Deriazs and larger Peltons could be installed in Slovenia. Following the example from the neighbourhoods, the upgrade could be installed. Mainly, the upgrade or replacement of older forms of hydraulic turbines with newer ones, with a minimal increase in efficiency, was done.

In the last 30 years, Slovenia has upgraded or modernized six major hydroelectric power plants, namely:

- HPP Boštanj, new construction, built in 2006, as part of the chain of hydroelectric power plants on the lower Sava, average annual production 115 GWh
- HPP Blanca, new construction, built in 2008, as part of the chain of hydroelectric power plants on the lower Sava, average annual production 144 GWh
- RHE Avče, new construction, built in 2009, nominal capacity 180 MW, with an efficiency of 77 %
- HPP Krško, new construction, built in 2012, as part of the chain of hydroelectric power plants on the lower Sava, average annual production 144 GWh
- HPP Brežice, new construction, built in 2017, as part of the chain of hydroelectric power plants on the lower Sava, average annual production 161 GWh;
- HPP Zlatoličje underwent modernization and expansion, including the small hydroelectric power plant Melje. Between 2007 and 2013, a comprehensive renovation of the Zlatoličje HPP, upgrades to the Melje

Dam, and construction of the Melje SHPP were completed. After these improvements, it produces approximately 600 GWh annually, almost 5 % of Slovenia's total electricity production.

5 Renaissance of older forms of hydraulic turbines

Classical water wheel layouts:

a) Undershot Water Wheel Design
b) Overshot Water Wheel Design
c) Pitchback Water Wheel Design
d) Breastshot Water Wheel Design

Add a)

The Undershot Water Wheel Design, also known as a "stream wheel," was the most used waterwheel type and the simplest, cheapest, and easiest type of wheel to construct.

In this type of waterwheel design, the wheel is placed directly into a fast-flowing river and supported from above. The motion of the water flow below creates a pushing action against the submerged paddles on the lower part of the wheel, allowing it to rotate in only one direction relative to the flow of the water.

Add b)

The Overshot Water Wheel Design is the most common type of design. The overshot waterwheel is more complicated in its construction and design than the previous undershot waterwheel, as it uses buckets or small compartments to catch and hold the water.

These buckets fill with water flowing onto the wheel through a penstock design above. The gravitational weight of the falling water in the full buckets causes the wheel to rotate around its central axis as the empty buckets on the other side of the wheel become lighter.

Add c)

The Pitchback Water Wheel Design is a variation on the previous overshot water wheel, as it also uses the gravitational weight of the water to help rotate the wheel. However, it also uses the wastewater flow below it to give an extra push. This type of waterwheel design uses a low head infeed system that provides water near the top of the wheel from an open penstock trough above.

Unlike the overshot waterwheel, which channelled the water directly over the wheel, causing it to rotate in the direction of the flow of the water, the pitchback waterwheel feeds the water vertically downwards through a funnel and into the bucket below, causing the wheel to rotate in the opposite direction to the flow of the water above.

Add d)

The Breastshot Water Wheel Design is another vertically mounted waterwheel design where the water enters the buckets about halfway up at axle height, or just above it. Then it flows out at the bottom toward the wheel's rotation. Generally, the breastshot waterwheel is used when the head of water is insufficient to power an overshot or pitchback waterwheel design from above.

The disadvantage here is that the gravitational weight of the water is only used for about one quarter of the rotation, unlike previously, which was for half the rotation. To overcome this low head height, the waterwheels' buckets are made wider to extract the required amount of potential energy from the water.

5.1 Modern water wheels

Modern water wheels have changed in the last 30 years mainly in two directions:

1) with better hydrodynamically designed blades

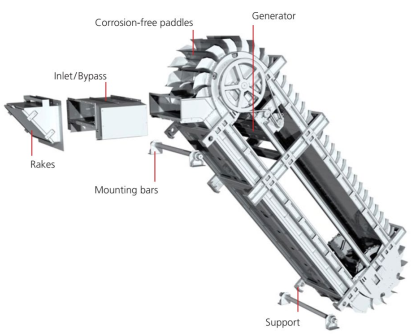
   From 2004 to 2009, the hydrodynamics of water wheel blades were improved, mainly by using CFD. In this way, the total efficiency increased by approximately 3 %.

2) by solving the problem of low water wheel speeds

Modern water wheels eliminate the disadvantage of transmitting torque from the wheel to the generator shaft with a new generator design directly integrated into the water wheel itself. Permanent magnets are installed on the larger radius of the wheel so that the passing speed increases even at low wheel speeds. The stator windings, with a larger number of pole pairs, are also installed on this larger radius, which achieves good generator efficiency even at low speeds. As mentioned, the electric generator is integrated into the water wheel itself, so the transmissions required due to the higher speed of classically designed generators are also eliminated. The solution was patented in 2003, DE 102 18 443, which presents a modular solution of a segmentally placed generator, which enables direct drive with the water wheel.

Steff turbine

The subsequent "modernization" of the water wheel is in the form of the Steff turbine, a turbine developed by the company Walter Reist Holding AG (WRH) from Switzerland. The first physical (concrete) installation was done in 2011. It works on the principle of an "extended path of pulleys", which are attached to a rubber elevation belt on an additional wheel on the other side. The water is fed to the lower part of the belt, which means the water flow is used as in a water wheel with a bottom inlet.



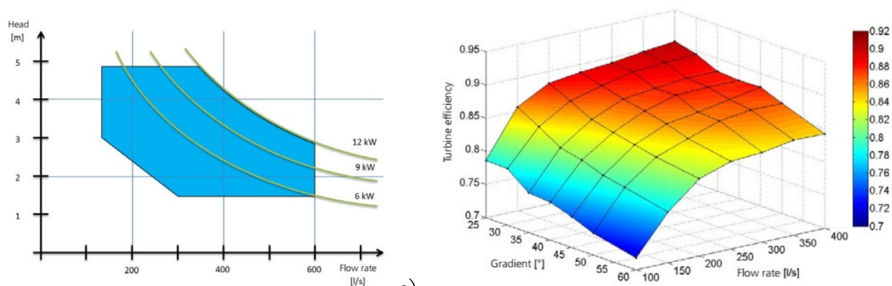
a)

b)

Figure 6: Implemented Steff turbine.

Source: [10]

The application range of the Steff turbine ranges from about 2 to 5 m head and at flow rates between 0.2 and 0.6 m^3/s, up to about 12 kW of power (Figure 7a).



a) b)

Figure 7a: a) Field of use; b) efficiency.
Source: [10]

The efficiency achieved by the Steff turbine reaches somewhere up to 0.9, which is a good efficiency for such a design (Figure 7b). It is also interesting because of its low maintenance and relatively simple installation work. It is also distinguished by its low operating noise level and possible operation even at low ambient temperatures.

Screw turbines

Screw turbines for harnessing the energy of overflow, equalization, or wastewater have emerged in the last 30 years as a cheap and reliable system for harnessing small or small hydro potentials. They can utilize falls from 1.5 m onwards. They are fish-friendly, as the fish survive the passage through the screw rotor. They are relatively undemanding to maintain, even in the case of dirty water. Since they are open, they can be easily cleaned.

5.2 The renaissance of older forms of hydraulic turbines in Slovenia

Is, secondly, only slightly present. As far as the authors know, very few such systems have been implemented in Slovenia, the most famous being the Mill on the Mura River, which was renovated in 2024.

6 Alternative designs and layouts of hydraulic turbines

Vortex turbine

Iis a commercially viable implementation of an alternative hydroelectric power plant. It is intended for small falls and flows and is ideal for implementing small and/or simple hydropower systems (sHPS). Due to its simple design, its use is interesting for smaller watercourses. Flood protection is also well solved, as it can be easily separated from the watercourse flow by closing the inlet gate.

Other alternative forms are mostly still in the development phase, so we do not include them in the comparison.

6.1 Alternative designs and layouts of hydraulic turbines in Slovenia

To the best of the authors' knowledge, no Vortex turbines have been installed in Slovenia. Small hydroelectric power plants employing serial water pumps operating in turbine mode represent the closest alternative. Several such installations exist in Slovenia, particularly in the hilly regions of Gorenjska and Koroška.

7 Conclusions

A comparative analysis with Slovenia's western neighbours, Austria, Germany, and Switzerland, reveals marked disparities in the share of electricity generated from renewable energy sources (RES) (Table 1). Austria leads with over 75 % of its electricity produced from RES, followed by Switzerland (65 %), Germany (55 %), and Slovenia (35 %). When nuclear energy from the Krško Nuclear Power Plant (NEK) is counted as a low-carbon source alongside RES, Slovenia's share rises modestly to around 40 %. Although the figures in Table 1 are drawn from unverified online sources, they nonetheless illustrate a meaningful and indicative trend.

A key structural weakness of Slovenia's power system is its dependence on a single pumped-storage hydroelectric facility, the Avče Plant, commissioned in 2010, with an installed capacity of 185 MW and a round-trip efficiency of 77%. While several pumped-storage projects have been proposed, their development remains stalled. The primary reason is the diversion of financial and institutional resources into economically unsound and environmentally detrimental projects, most notably the Šoštanj Thermal Power Plant Unit 6 (TEŠ 6) and the Ljubljana District Heating Plant. These misallocated investments have significantly reduced the capacity to finance technologically advanced, low-carbon alternatives, limiting progress in expanding flexible generation infrastructure.

The modernization of Slovenia's energy sector has therefore fallen short of the benchmarks set by international environmental agreements, most notably the Kyoto Protocol and the Paris Agreement. The disproportionate allocation of resources to failed or inefficient projects, epitomized by TEŠ 6, has severely hampered systemic progress. This mismanagement has led to the suspension of hydropower development along the lower and middle Sava River and effectively stalled the rollout of new pumped-storage facilities. The RHE Kozjak project stands as the sole partial exception, having advanced only marginally through initial stages of documentation, permitting, and regulatory review.

No major investments have been made in the alternative sector, and unfortunately, none are planned in the near future.

Table 1: Overview of the state of the main (national) grid system.

Year: 2024	Germany	Austria	Swiss	Slovenia
Ratio RES	~55%	>75%	~65%	35% (from NEK 40%)
Main resources RES	Wind, Sone	HPP	HPP	HPP
Storage	Battery + HPP	RHPP	RHPP	Minimal (Avče)
Weaknesses	Medium	High	Very high	Medium+
Excesses	Market, export, shutdown	RHPP modulation	HPP + import	Export + regulation
Flexibility	Medium	High	High	Low

source: various online data for 2024

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