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The Status Quo and Future of Hydropower in Slovenia

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Abstract: Slovenia is a Central European country with a long history of hydropower. This paper gives a brief introduction to the current status of hydropower utilization and informs about some selected successful examples of hydropower plant operation. One such example is fish passage and flood risk reduction on the lower reaches of the Sava River at the Brežice hydroelectric power plant, taking into account a complex of morphological, hydrological, hydraulic, and anthropogenic factors. Future development is considered against the background of the National Energy and Climate Plan, which does not envisage any significant expansion in the capacity or function of the hydropower sector. The envisaged capacity increase is from the current 4430 GWh to around 4580 GWh by 2030. It is shown that the current energy storage capacity of Slovenia's only pumped storage plant will be sufficient to offset the introduction of new non-dispatchable renewable energy sources by 2030. By around 2028, the country will have a need for electrical energy storage from renewable energy sources, reaching a modest total of only 6140 MWh per year. However, by sticking to the unambitious National Energy and Climate Plan, Slovenia will miss the opportunity to remain self-sufficient in electricity generation and significantly increase its share of renewable energy sources. The National Energy and Climate Plan aims to increase the share of renewable energy in total energy generation from 25% in 2020 to 27% by 2030.

Keywords: hydropower; energy storage; energy system model; environmental impact; national energy and climate plan

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1. Introduction

The European Union aims to provide secure, competitive, affordable, and clean energy for EU citizens and businesses. The goals of its approach are security, solidarity and trust, a fully integrated market, energy efficiency, decarbonization and climate protection, and research and innovation to improve competitiveness [1].

The ambitious EU targets will be incorporated into member states' national development plans and laws. The National Energy and Climate Plan of Slovenia (NECP) is the country's general development document until 2030 [2]. It promotes citizens' quality of life, contains sustainable development goals (agreed at the global level), sets strategic orientations, and connects the development goals into a cohesive whole. The country's future development will depend largely on its ability to respond and adapt to trends and challenges in the global environment so that it can cope with major changes, including demographic trends, pressure on ecosystems, competition for global resources, and economic development.

A wide range of software tools are available to researchers, consulting firms, and policy makers to model and analyze energy systems at the national and regional levels. This allows users to identify pathways for transitioning from flexible, and therefore freely dispatchable, coal- and oil-based energy systems to energy systems that include a large share of intermittent and non-dispatchable renewable energy sources (RES). Energy planning software typically simulates the operation of national energy systems on an hourly basis, including the electricity, heating, cooling, industrial, and transportation sectors. The three most common methodological approaches to modeling energy systems are endogenous optimization, exogenous simulation, and equilibrium tools or models that incorporate social and economic factors. For example, the most commonly used software is the free EnergyPLAN software [3].

Raising the share of intermittent RES for power generation inevitably requires a highly flexible power system that can manage high variability in power generation. The system flexibility is provided by increasing the energy storage capacity, where pumped storage hydro power plants (PSHPP) are considered the most cost-effective. This technology features a long lifespan (50–100 years) [4], high trip efficiency (70–87%) [5], and low maintenance costs [6]. Compared to battery storage, which has an assumed lifespan of 15–20 years, PHSPP durability is an evident advantage [7]. Moreover, based on these and other factors regarding economic, performance, technological, and environmental considerations, PHSPP can be regarded as the most sustainable storage technology [8]. On the other hand, wider deployment of PSHPP is limited by several barriers, most typically a lack of support infrastructure (roads and transmission lines), unfavourable topography (low head or head-to-length ratio), land acquisition challenges, water issues, biodiversity loss, high capital costs, public opposition, institutional challenges, long payback periods, and more [9]. In Slovenia, these barriers are also frequently encountered in both PSHPP and HPP development. HPP development, considering both technical and quickly changing socio-economic circumstances, and overcoming these barriers must be given the highest priority.

This paper provides a brief introduction to the recent development of the hydropower sector in Slovenia. Some successful practices in the introduction of hydropower plants will be discussed. In addition, the work aims to determine the viability of the renewable energy expansion proposed by NECP until 2030. The analysis is conducted under the NECP's current assumption that no significant long-term energy storage will be added to the transmission system. The results may prove useful for planning the deployment of RES and energy storage solutions in subsequent decades through 2050.

2. Slovenia and Its History of Hydropower

The Republic of Slovenia is a European country with a geographical position in the north of the Mediterranean and the south of Central Europe. Slovenia borders Italy to the west, Austria to the north, Hungary to the northeast, and Croatia to the east and south. Slovenia lies in a moderately warm zone. The proximity of the Mediterranean Sea and especially the Atlantic Ocean with the prevailing southwesterly winds ensures sufficiently humid air masses that bring precipitation. The transitional location between the Adriatic Sea, the Pannonian basin on the mainland, and the Alps leads to a mixture of different climatic influences.

Slovenia's water bodies were first used as a source of fish and as waterways, but later they were also used for transporting goods or for waterpower to drive (saw)mills. The onset of industrialization drove the need for electrical power. The first private electric lightbulb in Slovenia was lit in Kranj in 1893, powered by a hydroelectric mill and a dynamo. The first public electric light network was first operated in Škofja Loka in 1894, using surplus electricity from a local hat factory [4]. It was powered by a water mill and from 1889 by a 24 hp turbine. The first transmission of three-phase alternating current and transmission of electricity over a distance of 3.1 km from the Fužine hydroelectric power plant to the paper mill in Vevče was achieved in 1896 [10].

The Završnica hydropower plant (HPP) was the first Slovenian public hydroelectric power plant, the construction of which started in 1911 and was completed in 1915. It created an interconnected power system from generation through transmission and distribution to the end user, comprising 50 km of transmission lines, more than 35 substations, and over 50 km of distribution network. Today, the Završnica power plant is a technical cultural monument and a museum.

Fala HPP is the oldest large hydroelectric power plant and was the first power plant on the Drava River. Its construction began as early as 1913, and it was completed in 1918, when the first five turbines were put into operation. The Fala power plant was built to supply electricity to companies and communities in what is now Graz (Austria) and its surroundings, and to meet the energy needs of the carbide and nitrogen production in Ruše during World War I.

In the period before and after World War II, large power plants were built on the Drava, Sava, and Soča Rivers. During this intensive construction of new large power plants, the small hydropower plants were often neglected. In recent decades, the pace of introducing new hydropower plants has slowed down, but still, a few hydropower plants have been built on the Sava and Soča Rivers.

In 2009, the Avče PSHPP (185 MW) was commissioned on the Soča River. To date, it is the only PSHPP in Slovenia.

3. Production of Electricity from HPP and PSHPP

The rivers' energy potential is shown in Table 1. The total annual technically available energy potential is 9145 GWh, of which 41.5% is used. The three most important rivers for energy production are the Sava, Drava, and Soča. Of these, only the Drava River is fully utilized. In addition, the Mura River has significant technological potential, but no power plant has been built yet on it. In the past, the main reason for not building large-scale HPPs on the Sava and Mura Rivers was financial, while in recent decades environmental pressure from various non-governmental organizations (NGOs) has played a role. The locations of large hydropower plants on the Drava, Sava, Soča, and Mura Rivers are shown in Figure 1, both existing and planned. All HPPs are of the run-of-river type.

Table 1. The energy potential of Slovenian rivers [11].

Watercourse	Available (GWh/y)	Technically Available (GWh/y)	Used (GWh/y)	% of Use
Sava and Ljubljanica	4134	2794	512	18.5
Drava	4301	2896	2833	97.8
Soča and Idrijca	2417	1442	491	34
Mura	928	690	0	0
Kolpa	310	209	0	0
other	7370	1114	284	25.5
total	19,440	9145	4125	41.5

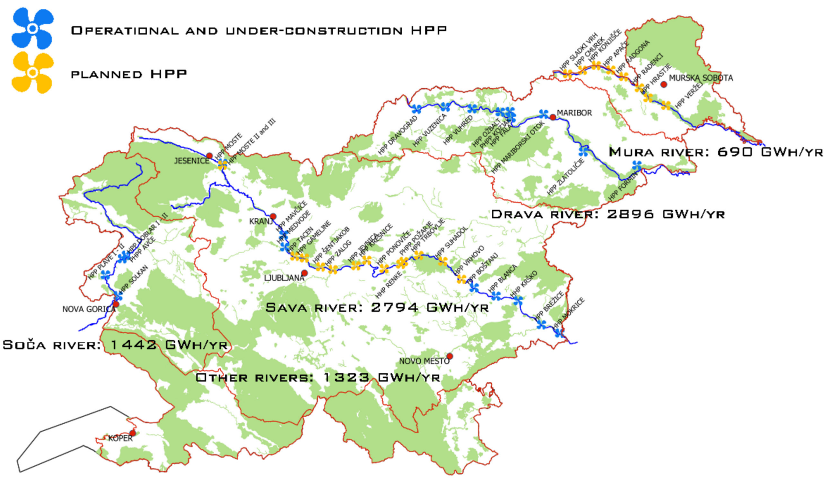

Figure 1. Large existing and planned hydropower plants in Slovenia and the energy potential of the main rivers.

The production of electrical energy from 2000 to 2021 by HPPs is shown in Figure 2. The data are from the annual reports of the National Energy Agency [12]. The figure includes large HPPs feeding the transmission grid and small HPPs feeding the distribution or transmission grid after 2015. Prior to 2015 [12], small HPPs were included in the energy balance as "small producers", so it is not possible to distinguish between generation from HPPs and, for example, generation from small photovoltaic systems. In Figure 2, production from the Avče PSHPP is shown separately, and its share is not included in the total generation from HPPs.

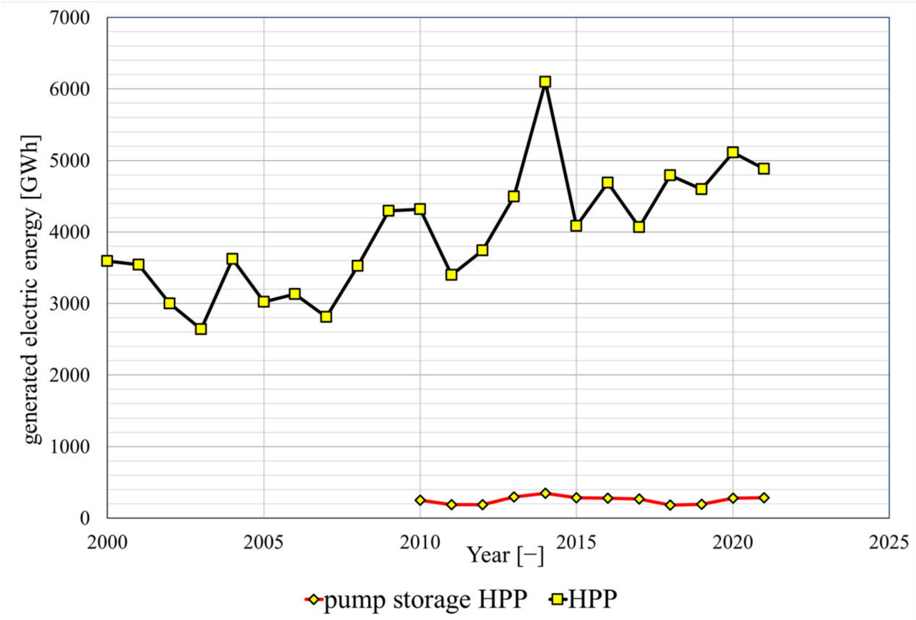

Figure 2. Electricity generation in HPPs in Slovenia per year since 2000.

4. Hydrology and Ecology

4.1. Flood Control and Land Use Change in River Channels and Riparian Areas

The design and positioning of hydropower plants, changes to watercourses and structures important for the operation of hydropower plants, and other accompanying measures are complex challenges because they affect long stretches of rivers and significantly alter the flow regime, habitats, and flood hazards in the area of influence. Therefore, close collaboration between experts from different fields, water management and land use planning agencies, decision makers, flood insurance companies, and other stakeholders is critical in decision making and planning. Such an example proved successful in planning the use of the Save River's hydroelectric potential in the section between the town of Krško and the state border with Croatia, where the complexity of morphological, hydrological, hydraulic, and anthropogenic factors is considerable. In addition to the regulation of the flow regime related to the hydropower plant's operation, it was also necessary to take into account the maintenance or improvement of flood risks, the existing flow regime around the water intake structure for the Krško nuclear power plant and in the area downstream of the confluence of the Sava and Krka Rivers, as well as the preservation of first-category agricultural land and retention areas.

Flood protection measures and other interventions in water and riparian areas are measured with a "design flow", up to which the protected areas are safe (e.g., Q_{100} + freeboard) or a reduction in flood hazard is achieved. Since negative anthropogenic influences on flood hazard management include the inadequate operation of HPPs, maintenance of flood control infrastructure, and uncontrolled changes to land use in retention areas, comprehensive hydraulic and flood risk analyses were conducted during the design of the more recently built HPPs (lower Sava and Soča Rivers). Studies were implemented to identify what happens during exceptional events, such as when flood control measures are slowed down, when operations are faulty or limited, or even when the hydromechanical equipment of hydraulic engineering facilities fails. On the other hand, the reduction of flood risk through the construction of HPPs or other infrastructure, the optimization of their operation during flood events, and accompanying measures lead to a more intensive use of riparian areas and thus to an increase of the damage potential during flood events. From the completion of the measures to their modification or deterioration, land use in the riparian and floodplain areas must be monitored or, if necessary, inappropriate land use in the area of influence must be restricted throughout the structures' lifespans to avoid adverse flood impacts. We have noticed that various NGOs and general public in Slovenia are increasingly aware of the importance of riparian areas in HPP design, construction, and operation. In any case, an effective and comprehensive plan for sustainable development of the riparian area should include systematic management of flood-prone areas that takes into account both temporal and spatial dynamics. Otherwise, the changes in land use will lead to changes in the flow regime, according to the conditions considered in the planning of HPPs, flood control measures, and spatial planning. An illustrative example of the adverse effects of water due to uncontrolled land use in riparian areas is the damage to a water supply channel of the Formin HPP during a flood event in 2012, when runoff exceeded the discharge capacity of the water supply channel of the Drava River and water found another destructive path.

4.2. Sediment Transport

The construction of dams and HPPs alters rivers' natural flow regimes and thus their sediment transport. A reservoir's rate of sedimentation processes and the loss of storage capacity are closely related to the river's flow regime and the amount of incoming sediment, and vary greatly between reservoirs with different characteristics [8]. It is estimated that about 1% of a reservoir's storage capacity is lost annually due to sedimentation [13,14]. This is a major problem because available storage capacity is the backbone of the EU for flood protection, water supply, aquatic environments, and critical infrastructure for human activities and living standards.

Coarse sediments settle first in deltas and, over years of accumulation, pose a significant threat to land use from flooding. Currently, coarse sediments in the EU are mainly removed by mechanical excavation and transported to landfills. There are similar procedures in Slovenia. Since no reliable specific data for Slovenia were found, we give the figures for alpine rivers, where the average amount of coarse sediments are estimated at 40,000 tons/river/year [15].

Suspended sediment settles in a river's shallow or stagnant areas and in the entire reservoir when discharge is low. In most cases, suspended solids are not completely removed and there is no established environmentally friendly removal process. Restoration of the storage capacity of a reservoir lost to accumulated sediments could be partially or even completely achieved by hydraulic flushing, but has significant impacts on the morphology and ecology of the downstream sections of a river system [16–19].

During flood events or during the mechanical removal of accumulated sediments, fine particles pose a massive physical and chemical burden to fish and other aquatic and amphibian life. There is little information on how to set robust guidelines for acceptable sediment concentrations, whether during ongoing washdown or during reservoir emptying. International guidelines for suspended sediment vary because they depend on river basin characteristics. The biodiversity of such rivers is severely affected when elevated sediment concentrations are present. In the Drava River, suspended sediment is transported by mechanical excavation during periods of low flow, causing environmental concerns. When necessary due to dam and mechanical equipment maintenance, the reservoir is completely emptied, as was recently the case in the Soča River. This event released enormous amounts of sediment, which posed a serious threat to the ecosystem downstream and severely affected the habitat in the dry accumulation.

In recent years, Slovenia has also begun to address environmental problems related to the sedimentation of suspended solids and coarse sediments in power plant reservoirs. The main proposed short- and long-term measures are:

- Develop and install new equipment to measure sediment flow rate, turbidity, and water discharge. Harmonized monitoring should be established to provide reliable, continuous, and online data.
- Digitalization, modeling, and analysis of environmentally sustainable scenarios based on available and new data, prediction, and evaluation (according to the criterion "as close to natural as possible") of different scenarios in order to reduce hydromorphological pressure and approach the natural state of the watercourse.
- Improve flood risk management by mitigating fine sediment loading, achieved through successful HPP and sediment management.
- Improve HPP-induced turbidity based on habitat monitoring and analysis of acceptable conditions for fish/water/amphibian populations. Sampling with gill analysis of fish populations to evaluate direct and indirect effects of sediment on fish, e.g., damage to gill tissue, reduction in respiration due to gill clogging, increased susceptibility to infection or disease, mortality, influence on migration patterns, feeding success, and habitat quantity and quality.
- Develop new guidelines for ecological flow Q_{es} and improve water quality during drought. Based on the statistical analysis of hydrologic datasets and the effects of various mass flows on the ecological status of organisms, as well as overall smart HPP operations, improve ecological service downstream of the dam during periods of drought.
- Develop robust guidelines for optimizing HPP operations associated with acceptable fine sediment concentrations.

In addition to environmental problems, sediment transport can also be viewed in relation to its influence on HPP operational safety. HPP operators are obliged to continually measure the reservoir volume and adjust protocols for safe HPP operation. HPP reservoirs' effective storage capacity is more or less insignificant in comparison to the volumes of the flood waves, so it is practically impossible to influence flood wave propagation by operating an HPP, while sedimentation affects only the reservoir's dead volume. Either way, design of reservoirs and spillways must ensure a runoff regime during high water events that have no adverse effects on the surroundings.

4.3. Habitats and Fishways

In addition to disrupting sediment transport downstream, as described above, improperly designed and maintained HPP dams completely prevent fish migration. Fish migration is essential for habitat maintenance and dispersal, spawning, and feeding. Disruption to fish migrations and other aquatic organisms, further affected by the siltation of the reservoir and erosion of the riverbed down to bedrock adversely, damages both habitats and biodiversity. Of the dams built in Slovenia in the previous century, only a few have fish ladders, and almost none of them are fully functional [20]. With the adoption of the Habitats Directive [21] and the Water Framework Directive [22] an initial step was taken towards a policy that introduces obligations to conserve natural habitats, to achieve a good qualitative and quantitative status for all waters, to maintain biodiversity, and to take into account economic, social, cultural, and regional requirements. Based on the above-mentioned directives, nowadays every newly built or reconstructed hydraulic structure in Slovenia (dam, weir, etc.) that leads to river fragmentation and interrupts fish migration routes must be equipped with a fish ladder. Since the goal is to ensure in each river section passage for all fish species, which may have very different characteristics and needs, the design of fishways is very challenging. The importance of effectively designing fishways and their ecological role is evident in a growing body of research recently conducted by various think tanks [23–26].

Remarkable progress in this field has also been achieved in Slovenia through exemplary cooperation between the Fisheries Research Institute of Slovenia, designers of fishways and hydraulic structures, experts in hydraulic modeling, operators of hydropower plants, and other decision makers. In addition to successfully rebuilding smaller physical barriers and improving their passability for aquatic organisms, the collaboration has resulted in two fully functional fishways at the large Brežice and Arto-Blanca HPPs on the Sava River (Figure 3 shows the Brežice power plant fishway (left) in the middle of construction and (right) from a bird's-eye view). The design of these two fishways placed a high priority on all of the facility's extremely important parts. The inflow from the reservoir into the fishways is equipped with hydromechanical devices that allow stress- and injury-free entry and exit from the reservoir/fishway at various water levels. At the downstream end, the outlet was designed to attract fish. Both fishways include a long, natural section that overcomes the difference in elevation between the powerhouse's upstream and downstream water levels. In addition to migration, these sections also provide suitable resting and spawning areas. A fully functional fish ladder is an essential component of a modern and environmentally friendly hydropower plant. With a gross height of the Brežice power plant of 11 m, the entire fish ladder is 930 m long, of which the near-natural part is 830 m long.

Figure 3. An exemplary fishway at HPP Brežice, Sava River.

Regulation of the course of the Sava River downstream of the Brežice power plant and the backwater effect of the planned Mokrice power plant would significantly affect the flow regime of the lower part of the Krka River (see Figure 4). In order to avoid adverse effects, a near-natural regulation of the Krka channel was developed, based on the findings of the Fisheries Research Institute of Slovenia and extensive hydraulic studies with physical and numerical models.

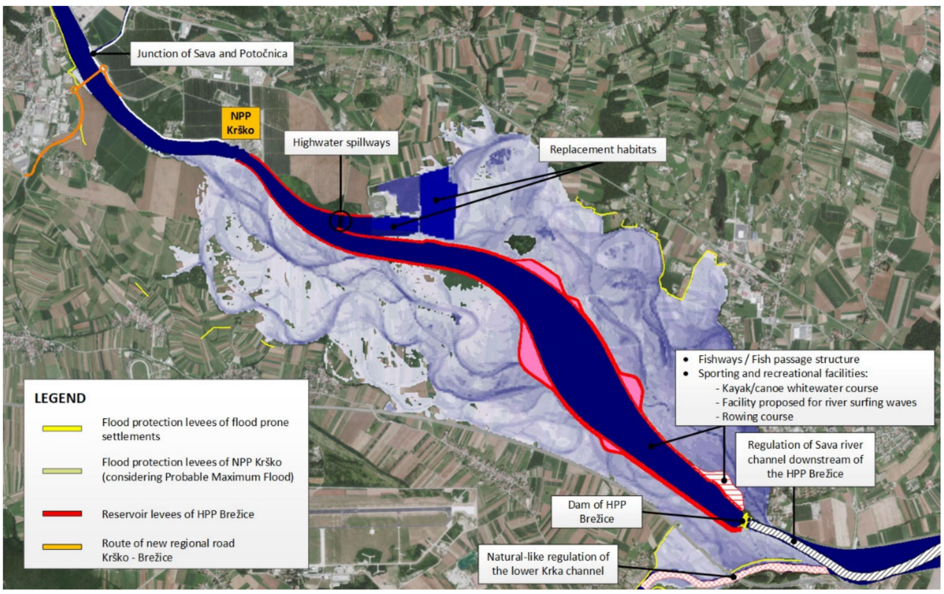

Figure 4. Situation around Brežice HPP, Sava River.

In order to increase biodiversity and preserve existing habitats, several other measures were implemented as part of the planning of the Brežice HPP. To compensate for the gravel pits excavated during the construction of the Ljubljana–Zagreb highway, where habitats for aquatic plants and various animal species have since developed, much larger replacement habitats were created at an alternative site (Figure 4) downstream of the spillways. Several small artificial islands were created to serve a dual function. First, the artificial islands direct stream flow through the reservoir in a manner that prevents the formation of stagnant zones and secondary flows, and thus resulting in sedimentation. By reducing sedimentation and preserving the available reservoir volume, the safety of HPP dam operations was increased and the possibility of flooding hazards was reduced. A second function of the artificial islands is that they provide important habitats for various bird species that require a quiet, aquatic environment. A similar measure was implemented at Ptujsko Jezero, a reservoir at the Formin HPP on the Drava River, which provides a regular resting and nesting area for numerous migratory and resident bird species. To increase social acceptance, sports and recreational facilities were created around Brežice HPP, including canoeing/kayaking/rowing courses and a surf wave.

5. EU and National Energy Plans

Regulation (EU) 2018/1999 [27] on the governance of the Energy Union and climate change requires member states to submit to the European Commission a comprehensive National Energy and Climate Plan (NECP) for the period 2020–2030. The NECP for Slovenia [2] has emerged as a compromise among energy producers, consumers and environmental aspects. The NECP for Slovenia aims at a modest increase in the share of RES in total energy consumption from 25% (EU from 20%) in 2020 to 27% (EU to 32%), assuming a 43% share of RES in electrical energy in 2030 [2]. Figs. 1 and 5 show that the largest producer of electricity from RES is currently hydropower, accounting for about 86% of total electricity generation. The share of hydropower will gradually decrease as more solar and wind power plants are added, both of which are non-dispatchable RES, while hydropower production is expected to remain at about the 2020 level throughout the decade. Future construction of small and large power plants depends critically on project and site planning procedures. These procedures are subject to strict nature conservation and water protection assessments in Slovenia, and require the greatest possible minimization of negative impacts on nature, resulting in the cancellation of most small and large HPP projects. Thus, according to the NECP, few investments in HPP projects are planned for the next decade, as shown in Table 2. Instead, the increase in RES relies on the deployment of solar and wind power. Unfortunately, for the same reasons as for small and large HPPs, the NECP does not include additional PSHPPs to increase the power system's flexibility, for reasons of strict nature and water protection.

As mentioned above, the further introduction of RES in Slovenia is severely restricted by environmental and site planning laws. Future implementation of projects to expand RES by 2030, both for hydropower and wind energy, will only be possible if the need for greenhouse-free energy supply is weighed by RES and subjected to environmental impact assessments with the full participation of all parties involved. Opposition from NGOs and the public to the continued use or expansion of hydropower in Slovenia continues to grow. Many environmental protection initiatives have resulted in various measures such as Natura 2000 (which currently covers about 24% of the country's total area, well above the EU average), parks, nature protection zones, etc., limiting the use of available land for power generation. Therefore, the NECP's modest goal of reaching a 27% share of RES in 2030 cannot be achieved in Slovenia through implementing projects outside Natura 2000 or other protected areas alone. In order to achieve even the arguably not very ambitious targets of the NECP RES, we require even projects whose impact on nature is considered significant. This requires broad agreement between all parties involved or the enforcement of legal procedures that prioritize public energy interests over environmental interests. Effective environmental measures must be taken for future energy projects, taking into account the exemptions provided by EU legislation on water and nature conservation (Figure 5).

Table 2. Basic data on large existing hydropower plants in Slovenia.

River	HPP Name	Net Power (MW)	Annual Production (GWh)	HPP Type
Drava	Dravograd	26.2	142	run-of-river
Drava	Vuzenica	55.6	247	run-of-river
Drava	Vuhred	72.3	297	run-of-river
Drava	Ožbalt	73.2	305	run-of-river
Drava	Fala	58.0	260	run-of-river
Drava	Mariborski Otok	60.0	270	run-of-river
Drava	Zlatoličje	136.0	577	run-of-river
Drava	Formin	116.0	548	run-of-river
Sava	Moste	21.0	65	run-of-river
Sava	Mavčiče	38.0	62	run-of-river
Sava	Medvode	25.0	72	run-of-river
Sava	Vrhovo	34.0	116	run-of-river
Sava	Boštanj	32.5	109	run-of-river
Sava	Arto-Blanca	39.1	148	run-of-river
Sava	Krško	39.1	146	run-of-river
Sava	Brežice	47.4	161	run-of-river
Sava	Mokrice *	28.1	131	run-of-river
Soča	Doblar 1 & 2	70.0	349	run-of-river
Soča	Plave 1 & 2	35.0	196	run-of-river
Soča	Solkan	32.0	105	run-of-river
Soča	Avče **	180.0/185.0	426/553	pumped storage

* under construction; ** turbine/pump mode.

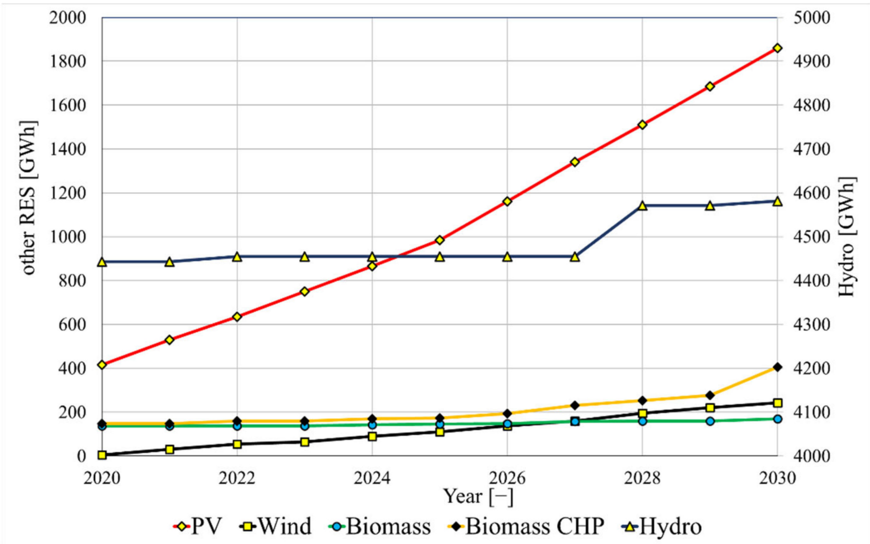

Figure 5. Assumed RES uptake in Slovenia from 2020 to 2030 according to NECP [2].

By 2030, we can assume that most of the new RES production in Slovenia will be from rooftop photovoltaic systems, arguably the most intermittent and least dispatchable RES. Since no new power plants or cogeneration plants are planned within the next decade, it is of interest to see how much the addition of non-dispatchable energy sources will strain the existing energy system. This is examined in the following two sections using the electric power system assessment model.

6. The Model

In this work, we used our own assessment model for electric power systems [28]. The model was created from scratch and was implemented in MS Excel. It considers only the generation and consumption of electric energy, and does not consider any interaction with other energy sources. It is based on balancing the demand and production of electrical energy at hourly intervals for any selected scenario, including those included in the NECP. Electricity consumption is allocated through a series of predefined sequential instructions, similar to other energy scheduling software [3]. First, the electrical energy generated by RES was used to meet the demand. Second, if electrical energy was generated by wind, photovoltaic, or other RES sources, and storage capacity was still available, RES sources were used to fill the empty storage. Third, electrical energy from nuclear sources was used, and fourth, conventional fossil fuel sources were used to meet demand. All RES sources were treated equally, and no preference was given to PV over HPPs or vice versa, for example. It was assumed that the response time of all energy storage sources is infinitely short. Only technical production and demand were considered. This means that financial anomalies were disregarded, e.g., cases where the market introduces a decrease in consumption, or e.g., a delay in storage (waiting for more financially favorable conditions and not using storage capacity immediately), etc.

Historical data of average energy production at hourly intervals throughout the year were used. The model considered independent data sets for generation sources available in Slovenia: wind, photovoltaic, run-of-river, tributary PSHPP, small hydro, other RES sources, fossil and nuclear power plants, river profiles, and environmental minimums [29–32]. Future electricity consumption was adjusted to NECP data while maintaining the daily/weekly/seasonal profiles from previous years. The same procedure was used for all RES energy sources included in the NECP: hydro, solar, wind, biogas, and biomass cogeneration. For example, modeling of the year 2030 technical electricity storage requirements is based on projected electricity consumption for 2030 and projected generation from RES for each energy source according to the NECP [2].

Averaging over several years for both electric energy consumption and generation resulted in a reduction in power system dynamics, but this was considered an acceptable simplification. The ecological minimum and its influence on electricity generation was estimated using the minimum annual electricity output of hydropower plants with run-of-river designs.

HPPs in Slovenia are usually operated as flexibly as possible. Since it is difficult to obtain or collect data in this regard for individual power plants, we set the following assumptions in the model: (1) run-of-river power plants produce electrical energy whenever daytime or nighttime consumption requires, except for the minimum environmental flow Q_{es}, which is mandatory for each river, (2) the minimum environmental flow Q_{es} must always be met and there is no limit to a water body's denivelation rate, (3) the maximum production capacity of run-of-river power plants is limited only by the installed capacity of the turbines, and (4) the average daily production in run-of-river power plants must correspond to the historical daily average values.

Currently, the only PSHPP in Slovenia has a capacity of 180 MW in pumping mode and 185 MW in turbine mode, with a combined efficiency of 77%. The usable reservoir volume and head provide the maximum possible energy of 2.775 GWh. We estimated that the upper reservoir was full at the beginning of the year.

7. Modeling Results

The results of modeling the required storage capacity are shown in Figure 6. The results show that energy storage capacity for excess electricity from RES will be needed only from 2027, while the demand will be highest at the end of the considered period in 2030 and will be around 6 GWh. The value is the sum of all hourly storage requirements spread over the whole year of 2030. The hourly storage maximum power requirement was modeled as lower than 50 MW. One should note that both values are no more than estimations, as it is difficult to predict compliance of RES uptake from NECP, production and consumption almost 10 years ahead.

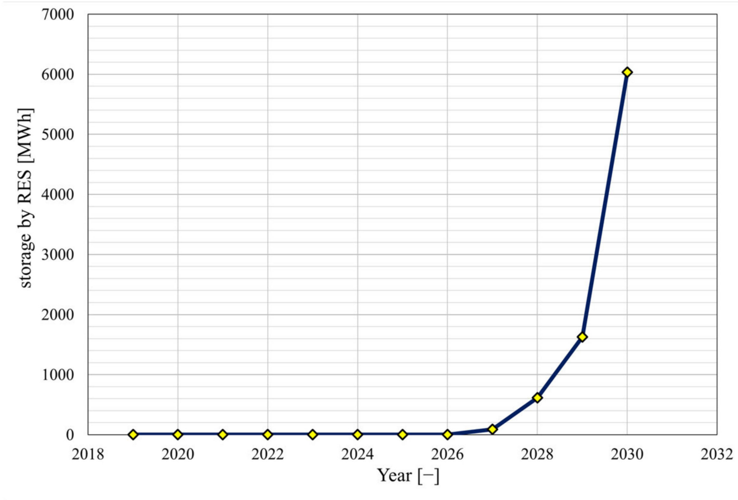

Figure 6. Total annual electrical energy storage requirements generated by RES.

Hourly storage demand events typically occur around midday when energy demand is low and PV production is high. It is important to note that the model does not consider the storage needs that may result from the economic benefits of daily price fluctuations, nor does it consider the energy storage needs that may result. The model also does not account for electromobility requirements that would reduce the requirements from Figure 6.

The modeling results show that from the purely technical perspective of storing electrical energy from RES, no additional PSHPPs are needed through 2030. This, however, does not include flexibility requirements arising from the need for electric energy grid regulation.

The need for additional facilities increases sharply from 2028 to 2030, which is directly linked to increasing shares of RES and the system's inability to balance instantaneous power production and demand. The need for additional PSHPP will also develop soon after 2030. Therefore, it is important to start planning for the additional PSHPP now, because the procedures for placing the PSHPP, obtaining permits, and securing financial resources are lengthy. In this respect, past activities in planning new PSHPPs in the Drava basin can be of great benefit. The project to construct the Kozjak PSHPP (400 MW) was already sited, but was halted in 2013 due to unfavourable electricity prices. Another nine potential locations for PSHPP have been identified on the Drava River, with the main advantages being the existing overhead power lines and the favourable hydrological and energy conditions.

Although the modeling results show (Figure 6) that the current single PSHPP Avče should be sufficient for Slovenia until 2030, we see the reason for self-sufficiency in the unambitious NECP. If Slovenia sticks to it, it will likely miss the opportunity to become self-sufficient in electric power generation and storage. Moreover, the current possibilities for storing electrical energy will not promote an increase in the share of renewable energy sources.

8. Conclusions

An example of good cooperation during the design, construction, and operation of Brežice HPP on the lower Sava River among most involved parties was provided. We sincerely hope that similar activities to address ecological issues, among them improvements in habitats and fishways, will continue for existing power plants with often neglected facilities. We also hope that activities to address environmental problems related to sedimentation of suspended solids and coarse sediments in power plant reservoirs will continue and even intensify.

We believe that the best practices of the Brežice HPP design could be used in restoring fish passages and improving flood protection on the Drava River. Most hydropower plants on the Drava have a similar configuration, while the Zlatoličje and Formin HPPs, the last two on the Drava River, have a derivation channel and the practice should be further improved.

The Sava River has additional unused capacity, and despite the overwhelmingly negative attitude towards hydropower, the construction of additional power plants may be possible. As shown, close cooperation between water management, spatial planning authorities, decision-makers, non-governmental organizations, and other stakeholders is urgently needed.

An overview of the development of the Slovenian hydropower sector through 2030 shows that the proposed increase in installed hydropower capacity from 2020 to 2030 will be modest at 3% according to the NECP. Moreover, no additional PSHPPs are planned by 2030. Installation of other RES will increase RES energy production from 25% in 2020 to 27% in 2030, increasing the need for energy storage.

The results of the electric power system assessment model have shown that the amount of existing energy storage in Slovenia's only PSHPP (Avče) is sufficient for the limited amount of RES electricity planned through 2030. The demand for electric energy storage from RES will start around the year 2028 and will reach an annual total of around 6 GWh in 2030. Due to the rapid increase in electric energy storage demand, we anticipate that new PSHPPs will need to be installed soon after 2030.

Other long-term measures are also possible. These include improving the functionality of the HPPs, such as installing short-term battery storage to improve primary, secondary, and tertiary control capabilities.

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