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SWISS COMPETENCE CENTER for ENERGY RESEARCH
SUPPLY of ELECTRICITY

Swiss Potential for Hydropower Generation and Storage

Synthesis Report

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Innosuisse – Swiss Innovation Agency

Impressum

Publisher
ETH Zurich

Editors
Robert Boes, Benjamin Hohermuth, Domenico Giardini (ETHZ)

Authors
Robert Boes, Paolo Burlando, Frederic Evers, Daniel Farinotti, David Felix, Benjamin Hohermuth (ETHZ), Martin Schmid (Eawag), Manfred Stähli (WSL), Cécile Münch-Aligne (HES-SO), Hannes Weigt (Uni Basel), Francois Avellan, Pedro Manso (EPFL)

Contact
Robert Boes (boes@vaw.baug.ethz.ch)

Editorial and Layout
Barbara Naegeli, Silvia Passardi (ETH Zurich)

Title Image
Planned multi-purpose storage lake at the retreating Trift glacier (Kraftwerke Oberhasli KWO, https://www.grimselstrom.ch/ausbauvorhaben/zukunft/neubau-speichersee-und-kraftwerk-trift/).

Citation
Boes, R., Hohermuth, B., Giardini, D. (eds.), Avellan, F., Boes, R, Burlando, P., Evers, F., Farinotti, D., Felix, D., Hohermuth, B., Manso, P., Münch-Aligné, C., Schmid, M., Stähli, M., Weigt, H. (2021): Swiss Potential for Hydropower Generation and Storage, Synthesis Report, ETH Zurich, 2021.

Date of issue
01.09.2021

SCCER-SoE is financially supported by the Swiss Innovation Agency Innosuisse. The authors thank Oliver Selz, Nico Bätz (Eawag) and Davide Vanzo (ETHZ) for inputs concerning the environmental aspects of hydropower production.

Executive Summary

Hydropower (HP) is the backbone of the Swiss electricity system providing around 60 % (36 TWh/a) of the total electricity generated on a yearly average. With the planned phase-out of nuclear power plants, HP and other Renewable Energy Sources (RES) will need to fill the substantial gap in domestic electricity generation, particularly in the winter season. Because of the intermittent nature of RES generation (mainly solar photovoltaics and wind) and their typically lower production in winter, the need for storage up to the seasonal time scale increases. Such large-scale storage is offered mainly by storage HP. However, maintaining the HP infrastructure will pose significant challenges, mainly due to market and legal conditions. For the latter, partly diverging interests according to the Swiss legislation will need to be fulfilled at the same time.

On the one hand, HP is supposed to be extended in the scope of the Energy Strategy (ES) 2050 and to keep climate goals by reducing greenhouse gas emissions. On the other hand, current negative effects of mainly older HP infrastructure on aquatic ecology will need to be remediated according to the Swiss Waters Protection Act to fulfill biodiversity goals. Meeting all these goals will require to systematically refurbish the existing Swiss HP fleet, to extend it in a smart way with prioritization on large storage HP to foster electricity generation in the critical winter season and to construct new HP schemes, again with a focus on electricity generation in winter.

As to new HP facilities, the retreating glaciers open new opportunities for high-altitude storage plants that, besides generating quasi CO_2-free electricity, have also other benefits like protection from natural hazards and water supply for irrigation. Extending existing storage lakes by heightening of their dams is a complementary option to create additional storage with generally low environmental impact and possibly higher public acceptance.

Both the environmental legislation and economic and market conditions currently hinder investment in HP infrastructure. Regarding legal conditions, certain energy infrastructure has been declared to be of "national interest" in the Swiss Energy Act. However, wetlands of national importance are excluded from this weighing of interest, limiting hence the HP development potential at retreating glaciers that feature such protected wetlands in their forefields. Regarding market environments and general framework conditions, the major uncertainties during typical concession periods of 80 years in combination with long planning and approval procedures do not foster investments in HP.

The target values of the ES 2050 in terms of annual generation by HP can be met only in an upper-bound scenario, which would require more favourable framework conditions for HP than today. Otherwise, an intermediate scenario is more realistic, according to which the annual generation is expected to increase by 0.5 TWh/a until 2050, which is well below the target of 2.6 TWh/a. A lower-bound scenario predicts a decrease by -3.0 TWh/a, mainly due to mitigation measures to fulfill the Waters Protection Act, with reductions in generation primarily from increased residual flow requirements. In terms of energy storage, an effective increase of 1.2 TWh by 2050 is forecast in the intermediate scenario including dam heightening and a few new periglacial storage HP plants. Such an increase would correspond to almost 20 % of today's energy storage capacity of the Swiss HP reservoirs. It is expected that the increase of storage capacity of 2 TWh by 2040 envisaged in the recently revised draft version of the Electricity Supply Act cannot be implemented by HP within this rather short time frame. However, setting such targets is important.

All in all, significant efforts are required to maintain the electricity generation from HP around its current level. Potential increases are very limited because a high share of the Swiss HP generation potential is already exploited. In contrast to generation, the storage capabilities of HP shall be significantly expanded because more large-scale seasonal storage is an essential prerequisite for the efficient integration of a higher share of RES into the electricity supply system.

Acronyms and Abbreviations

BAFU	Bundesamt für Umwelt (Federal Office for the Environment)
BFE	Bundesamt für Energie (Swiss Federal Office of Energy)
CO_2	Carbon dioxide
$CO_{2,eq}$	Carbon dioxide equivalent
EF	Environmental flow
Elcom	Eidgenössische Elektrizitätskommission (Swiss Federal Commission on Electricity)
EPFL	École Polytechnique Fédérale de Lausanne (Swiss Federal Institute of Technology Lausanne)
EROI	Energy Return on Energy Invested
ESOI	Energy Stored on Energy Invested
ES 2050	Energy Strategy 2050
ETH Zurich	Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology Zürich)
GHG	Greenhouse Gases
HP	Hydropower
HPP	Hydropower plant
JASM	Joint Activity Scenarios & Modelling
LCA	Life Cycle Assessment
LoR	Likelihood of realization
PSP	Pumped storage plant
PV	Photovoltaics
RCP	Representative Concentration Pathway
RES	Renewable energy sources
SCCER	Swiss Competence Center for Energy Research
SCCER-SoE	SCCER Supply of Electricity
SFOE	Swiss Federal Office of Energy (→ BFE)
SWV	Schweizerische Wasserwirtschaftsverband (Swiss Water Resources Association)
TSO	Transmission System Operator

AV	Federal Inventory of Floodplains of National Interest, Verordnung über den Schutz der Auengebiete von nationaler Bedeutung vom 28. Oktober 1992 (SR 451.31, Auenverordnung)
BGF	Federal Act on Fisheries, Bundesgesetz über die Fischerei vom 21. Juni 1991 (SR 451.31)
EnFV	Energy Support Ordinance, Verordnung über die Förderung der Produktion von Elektrizität aus erneuerbaren Energien vom 1. November 2017 (SR 730.03, Energieförderungsverordnung)
EnG	Energy Act, Energiegesetz vom 30. September 2016 (SR 730.0)
GSchG	Waters Protection Act, Bundesgesetz über den Schutz der Gewässer vom 24. Januar 1991 (SR 814.20, Gewässerschutzgesetz)
GSchV	Waters Protection Ordinance, Gewässerschutzverordnung vom 28. Oktober 1998 (SR 814.201)
JSG	Federal Act on Chase and the Protection of Feral Mammals and Birds, Bundesgesetz über die Jagd und den Schutz wildlebender Säugetiere und Vögel vom 20. Juni 1986 (SR 922.0, Jagdgesetz)
NHG	Federal Act on the Protection of Nature and Cultural Heritage, Bundesgesetz über den Natur- und Heimatschutz vom 1. Juli 1966 (SR 451)
SR	Systematische Rechstssammlung (Classified Compilation)

kWh	kilowatt-hour
GWh	gigawatt-hour, 1 GWh = 10^6 kWh
TWh	terawatt-hour, 1 TWh = 10^9 kWh

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1 Introduction

Hydropower is a central pillar of the Swiss electricity generation portfolio with a share of more than half. As the fleet of hydropower plants is composed of run-of-the-river, storage and pumped storage plants, the generation is very flexible, enabling to closely follow the demand side, and to compensate to some extent the increasing share of volatile electricity generation by new renewables in the future. In order to compensate the vanishing nuclear generation, hydropower is supposed to grow in the Swiss Energy Strategy 2050. While hydropower shows great benefits and ecological strengths such as high efficiencies and very low $CO_{2,eq}$ per unit of electricity generated, it does have impacts on the aquatic environment.

1.1 Role of Swiss Hydropower

Hydropower (HP) is the most important domestic source of renewable energy in Switzerland. The Swiss net annual electricity production amounted to 63 TWh on average over the last ten years (SFOE, 2019b). Thereof, 57 % (36 TWh) stem from HP (net production after subtracting the consumption of pumps at water adductions), 36 % (23 TWh) from nuclear and 7 % (4 TWh) from conventional thermal power plants and "new" renewable energy sources (RES) (of which 2 TWh from waste incineration, 1.7 TWh from photovoltaics and < 0.2 TWh from wind) (SFOE, 2019b). In the winter half year (October to March), 50 % (15 TWh) of the Swiss electricity was generated from HP and 43 % (13 TWh) from nuclear on average over the last 10 years. Three main types of hydropower plants (HPP) are distinguished:

- Storage HPP with at least one headwater reservoir allowing for flexible production according to the variations of the demand and the production from other sources,
- Run-of-river HPP (without appreciable storage) whose production directly depends on the inflows, and
- Pumped storage plants (PSP) which allow to store large amounts of electric energy by using surplus energy for pumping and releasing energy in times of high demand.

The contributions of the various energy sources and power plant types to the Swiss electricity generation are shown in Figure 1. HP is the backbone of the Swiss electricity supply system and of central importance to Switzerland's economy (Calisesi et al., 2019).

More than 1500 HPP of all categories and power classes are documented in Switzerland as of 2018. Out of these, 658 HPP with an installed capacity (nominal power) of at least 300 kW and an expected production of 36.5 Twh/a were in operation (SFOE, 2019c). 414 HPP with an installed capacity larger than 1 MW deliver about 98 % of Switzerland's HP, both in terms of capacity and generation (Table 1). Depending on the meteorological conditions (precipitation and temperature, snow and glacier melt) the annual production varies by some 10 to 20 %. Out of the mentioned 658 HPP, 85 % are run-of-river HPP, 12 % are storage HPP, and 3 % are PSP. Their shares on the production (10-year averages) are indicated in Table 2, whereby only the natural inflows are considered here in the production of the PSP.

With 56 %, the share of storage HPP on the production is unusually high in Switzerland compared to about one third on the global average. This is favourable for electricity generation in line with the demand, particularly to cover peak demands on short notice. In contrast, run-of-river HPP operate continuously and contribute to cover the base load. Thanks to its storage capabilities (Table 2), Switzerland plays a central role as an on-demand electricity supplier in the European network. PSP are the most flexible plant category of HPP, which is an asset for transmission system operators to assure grid stability.

Until 2004, Switzerland usually exported more electric energy over the calendar year than it imported (SFOE, 2019b). From then on, the export has decreased, leading to occasional net imports of up to 6 TWh/a (Figure 2 a). The annual import / export balance of the last ten years was about even on average.

In the winter half year, however, up to 10 TWh net have been imported since 2002, with an average value of 4.4 TWh per winter half year since 2010 (Figure 2 b), representing 14% of the domestic winter net generation. In the winter 2016/17, when the generation of the Swiss nuclear power plants was pronouncedly below average, the net import of 10 TWh represented even 39% of the domestic net generation in the winter half year (SFOE, 2019b).

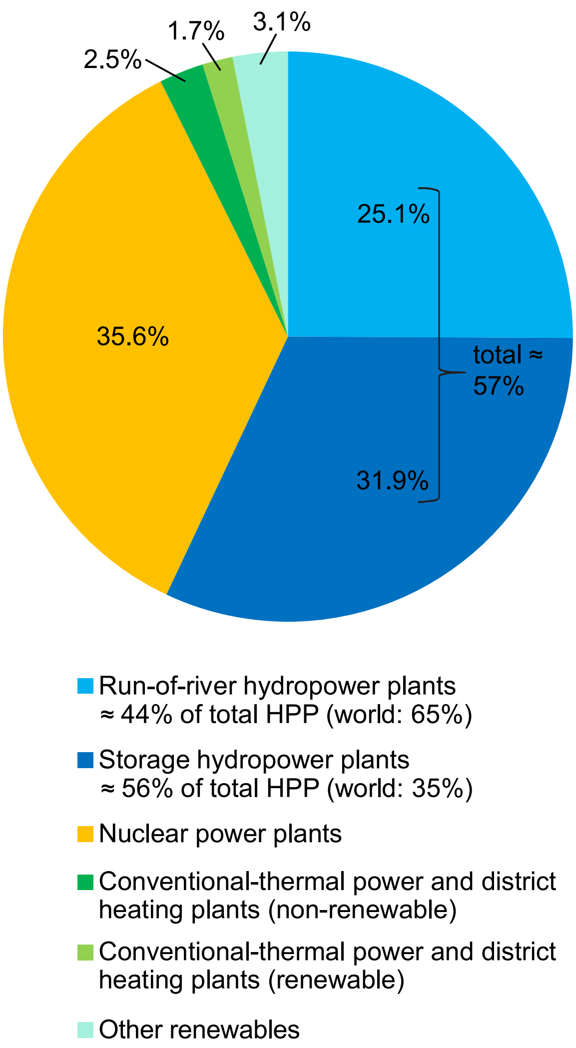


Figure 1: *Switzerland's electricity production according to the type of power plant: average values of the 2010-2019 period (data for thermal and other renewable only from 2013 to 2019). Data from "Schweizerische Elektrizitätsstatistik" 2011, 2013, 2015, 2017, 2019.*

Table 1: *Power and expected annual production share of HPP in Switzerland by power class based on the statistics of the Swiss HPP (SFOE, 2019b) (facilities with nominal power ≥ 300 kW) as well as on the statistics of 'micro HP', (SFOE, 2019b) (facilities with nominal power < 300 kW); *approximate number.*

#	Power class	Installed Capacity (MW)	Share	Expected Production (GWh/a)	Share
186	>10 MW	14'570	93.7 %	32'733	89.1 %
228	1 -10 MW	769	4.9 %	3046	8.3 %
244	0.3 -1 MW	142	0.9 %	670	1.8 %
900*	<0.3 MW*	65*	0.4 %	300*	0.8 %
1558		**15'546**	**100 %**	**36'749**	**100 %**

Table 2: *Power and production of Swiss HPP* (geq *300 kW) by power plant type as per 01.01.2019, considering only natural inflows for pumped storage (adapted from Calisesi et al., 2019).*

Power plant type	#	Installed capacity (MW)	Share	Expected generation (GWh/a)	Share
Run-of -River	559	4133	26.7 %	17'687	48.5 %
Storage	81	8223	53.1 %	17'208	47.2 %
Pumped storage	18	3'125	20.2 %	1554	4.3 %
	658	**15'481**	**100 %**	**36'449**	**100 %**

1.2 Swiss Energy Strategy 2050

After the nuclear disaster of Fukushima Daichii on 11 March 2011, the Federal Council and Swiss Parliament decided a stepwise phase-out of nuclear power plants. Adaptions of the Swiss energy supply system were formulated in the Swiss Energy Strategy 2050 (ES 2050), which targets in the corresponding Energy Act (EnG) a significant extension of the use of RES, particularly photovoltaics. The net HP production should increase to 37.4 TWh/a in 2035 (EnG); a target value of 38.6 TWh/a is foreseen for 2050 (Swiss Federal Council, 2013).

In 2019, the Swiss Federal Government additionally set the goal to reduce its net carbon emissions to zero by 2050 (Zero-Emission goal) (Swiss Federal Council, 2019), which also affects the Swiss electricity supply system.

As per 01.01.2019 (the latest consolidated information available), the expected annual net production from HP was 36.0 TWh/a. This results from both the expected production of the HPP with an installed capacity of at least 300 kW and the expected production of the smaller HPP, minus the average consumption of the pumps in water adductions (SFOE, 2019d). With reference to the 36.0 TWh/a per 01.01.2019 the net HP generation should therefore be increased by a minimum of 1.4 TWh/a (+3.9 %) and 2.6 TWh/a (+7.2 %) by

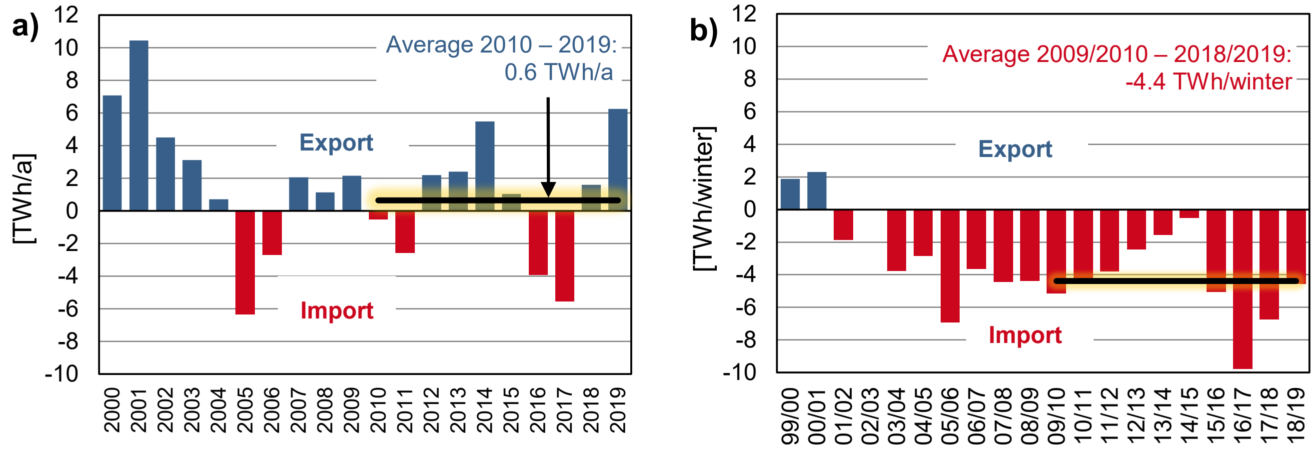


Figure 2: *Switzerland's electricity export balance over the last 20 a) calendar years and b) winter half years, i.e. October to March; both with averages over the last ten years (from SFOE, 2020).*

2035 and 2050, respectively. Note that these numbers are net values, i.e. future generation reductions, which will be treated in Section 2.4, have to be compensated by a further generation increase. Regarding HP generation in the winter half year and storage capacities, no target values were set in the Energy Act nor the ES 2050. However, the Swiss Federal Commission on Electricity (ElCom) sees an increasing risk of winter supply shortages after decommissioning of the two largest nuclear power plants in Switzerland. ElCom has recommended a legally binding target to increase winter generation by at least 5 TWh/(winter half year) until 2035, amongst others (ElCom, 2020).

To promote domestic electricity generation from RES, Art. 12, EnG classifies new and upgraded HP schemes above a certain annual generation to be of national interest. This is relevant for the weighing of interests for HP schemes in federally protected areas according to Art. 6 NHG (Federal Act on the Protection of Nature and Cultural Heritage). In the context of reservoirs, this mainly concerns the Federal Inventory of Landscapes and Natural Monuments of National Importance. According to Art. 12 EnG new RES schemes are excluded from biotopes of national importance (according to Art. 18a NHG, e.g. in wetlands ("Auen"/"zones alluviales") and glacier forefields as given in the annex of the Wetland Ordinance) and from water and migratory bird reserves. Note that with the "Rothenturm"-Article 78 Abs. 5 of the Federal Constitution there is no weighing of interest regarding moors and moorlands, so that the "national interest" on RES in such areas is not relevant.

1.3 The Changing Role of Hydropower

According to the Energy Act the electricity consumption should be reduced by 3 % until 2020 and by 13 % until 2035, compared to 2000. However, with increasing electro-mobility, the increased use of heat pumps in buildings, and the general replacement of fossil resources with electricity, the electricity demand in Switzerland will likely increase in the future (Andersson et al., 2011). The future phase-out of nuclear power (-23 TWh/a and -13 TWh/(winter half year) as mentioned above) will put pressure on electricity generation, particularly in the winter season (ElCom, 2020). Unless combined cycle gas power plants are built or new technologies like the conversion between gas and electricity ("sector coupling") are widely introduced, the demand will likely exceed the electricity supply (Stalder, 2019; ElCom, 2020), despite increasing energy efficiency. To reduce the dependency on electricity imports in winter, the extension of seasonal water storage (reservoirs impounded by dams) is an option to increase the storage capacities of existing HPP and to shift more electricity production from the summer to the critical winter half year.

Switzerland and several EU member states have the intention to further disconnect and decommission their nuclear power plants. The disconnection of these power plants and the rapid development and increasing share of volatile RES – especially in neighboring countries – drastically impacts on power grid balancing, i.e. the capacity of providing regulating power to the grid to ensure the load/generation balance, and challenges the electric power system operations (Piot, 2014). Balancing the power generation with the demand is achieved by reserve scheduling and demand forecast, typically one day ahead. However, the increasing connection of irregular and not well predictable (stochastic) RES to the power system and the upcoming penetration of distributed storage and demand-response mechanisms, are expected to significantly affect the existing power balancing strategy. This will require, in general, an increase of the frequency containment and restoration reserves, i.e. the primary/secondary reserves, to keep safe margins and maintain a high grid resilience. The flexibility of storage HPP and PSP are needed to fulfill these requirements. Moreover, increased storage capacities would allow to better compensate fluctuations in RES production down to the weekly and monthly scales (Felix et al., 2020).

Increasing the flexibility of the HPP fleet through innovation and modernization is fundamental for security of supply, stability in the grid, and for green growth. HP has a lot to offer; in addition to its benefits for electricity production, it can provide water management capabilities and mitigate negative effects of flood and drought events (Section 3.2.2).,

1.4 Ecological Impact of Hydropower

1.4.1 Strengths

Compared to other RES, HP is a favourable technique with respect to energy-payback ratio, life-cycle assessment, greenhouse-gas emissions and water footprint. Adding to that, HP schemes have the highest energy-conversion efficiency and the longest operational life. Nevertheless, HP development has negative impacts on aquatic environments, which need to be mitigated to fulfill the legal requirements.

When looking at the so-called recovery factor or Energy Return on Energy Investment (EROI) of primary energy, which is obtained by the ratio of the total energy produced to the total expense of non-renewable energy (direct and indirect) during a lifetime to operate an installation, HP is unbeatable (Schleiss, 2000). For storage HPP with reservoirs created by dams, the EROI amounts to 78, while for run-off-river HPP it is 58 (Steffen et al., 2018) (Figure 4). These numbers clearly exceed those attained by nuclear power (12) and other RES under Swiss conditions such as photovoltaics (4 to 8) or wind (18 to 20). Regarding the recovery factor for electricity storage technologies, the so-called Energy Stored on Energy Invested (ESOI) parameter is 186 for pumped storage, while technologies such as power-to-hydrogen-to-power, lithium-ion batteries and lead acid batteries currently have values of 23, 7 and 1, respectively (Steffen et al., 2018) (Figure 4).

Recent life-cycle assessments (LCA) confirm that HP can reduce greenhouse gas (GHG) emissions from electricity supply significantly, even by developing only a part of the remaining economically feasible HP potential. Recent studies revealed that for HP the equivalent CO_2 emission is extremely small compared to other electricity generation technologies (see synthesis report on Sources of Primary Electricity Supply Burgherr et al., 2021). According to (Bauer et al., 2017), Swiss HPP emit between 5 and 15 g $CO_{2,eq}$/kWh due to the material production required for construction and maintenance of HP infrastructure. These numbers are backed by a recent study of Basig and Duss (2021). Differentiating the type of HPP, Swiss run-of-river HPP cause about 4 and from 5 to 10 g $CO_{2,eq}$/kWh, whereas storage HPP range from about 6 to 11 and 5 to 15 g $CO_{2,eq}$/kWh according to (Frischknecht et al., 2012) and (Bauer et al., 2017), respectively. In addition, the reservoirs themselves also emit GHG, mainly carbon dioxide (CO_2) and methane (CH_4). The degradation of organic material in reservoir leads to GHG emissions, for which the following parameters are a proxy (Ocko and Hamburg, 2019): ratio of reservoir surface area to electricity generation, maximum water temperature of the reservoir, and erosion rate in the reservoir's catchment area. GHG emissions from reservoirs are highest in tropical regions, moderate in temperate regions and lowest in the boreal climate zone (Harrison et al., 2021). Within Switzerland, reservoirs in the Swiss Plateau region emit specifically more GHG per reservoir surface area than subalpine and Alpine reservoirs. The climate impact of reservoirs in Western Europe is near zero (Ocko and Hamburg, 2019). This is in line with Hertwich (2013) and ecoinvent (2015), according to whom no noteworthy GHG emissions occur from reservoirs in Switzerland. Observed examples are 1.2 g $CO_{2,eq}$/kWh for Klöntalersee or 25 g $CO_{2,eq}$/kWh for Wohlensee (Sollberger et al., 2017).

For comparison, GHG emissions range from 5 to 11 and 10 to 20 g $CO_{2,eq}$/kWh for nuclear power plants depending on the type of reactor (Frischknecht et al., 2012; Bauer et al., 2017). For RES like wind and photovoltaics, average values of 15 g $CO_{2,eq}$/kWh and between 38 and 95 g $CO_{2,eq}$/kWh are obtained, respectively, with the latter strongly depending on the employed technology. Swiss biogas power plants with thermal-power coupling produce between 150 and 450 g $CO_{2,eq}$/kWh. These values are still relatively small compared to the emission of gas power plants

(480 to 640 g $CO_{2,eq}$/kWh) and hard coal and lignite power plants (820 to 980 g $CO_{2,eq}$/kWh). The ranges reflect the variability in terms of site-conditions, technology specification and fuel characteristics. The current Swiss electricity consumption mix includes electricity imports and has a GHG intensity of about 90 g $CO_{2,eq}$/kWh according to the ecoinvent v2.2 database (ecoinvent, 2016).

Generally, HP is producing electricity with a very good environmental profile, i.e. compared to other generation technologies the life cycle burdens of HP are minor (Bauer et al., 2017).

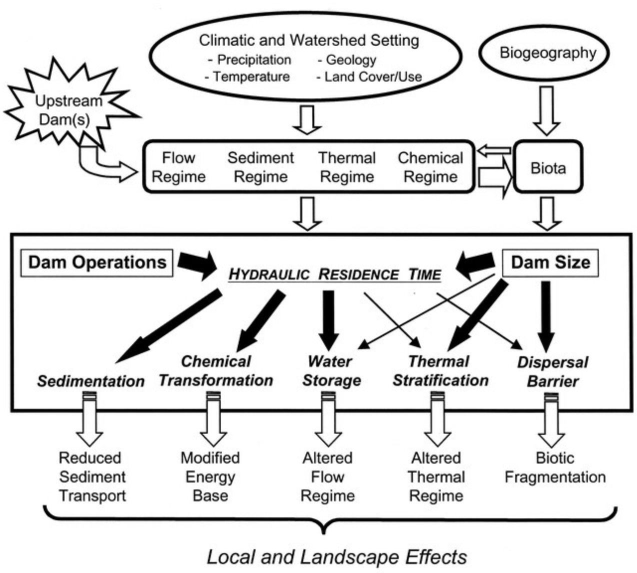


Figure 3: *Flow chart illustrating how attributes of dam–reservoir systems, especially dam size and operations, modify fundamental riverine biophysical processes to cause alterations with local and landscape environmental effects (Poff and Hart, 2002).*

1.4.2 Weaknesses

HP can have negative impacts on aquatic and terrestrial ecosystems that are not assessed with the LCA methodology (Bauer et al., 2017). The LCA methodology builds on abiotic impacts to display the environmental profile of different energy sources, but neglects a number of ecologically relevant biotic and some further abiotic impacts. Such additional impacts can range from local scale to catchment scale, are site-specific, and strongly depend on the (i) climate and watershed setting, (ii) organisms (fauna and flora) present, and (iii) HPP characteristics and operation (Figure 3; Poff and Hart, 2002). Accordingly, environmental impacts need to be evaluated both on a case-by-case basis (i.e. local scale) as well as on a river network basis (i.e. catchment scale). It is important to account for both individual and cumulative effects of HPP due to the spatio-temporal propagation of impacts along a river network. These environmental impacts need to be weighed against the benefits of electricity generation. Also, the negative impact of HPP on the environment and biodiversity can be amplified by climate change. It is therefore recommended that future climate change scenarios are included in the assessment of the impact of HPP (Swiss Federal Office for the Environment FOEN, 2021a; Ecoplan, 2021). Environmental impacts of HPP can be divided into three major groups (Weber and Schmid, 2014), some of which entail to large ($\geq$ 10 MW) and/or small (< 10 MW) HPP.

Interruption of longitudinal connectivity: Dams and weirs represent barriers for animal movement, both in the upstream and downstream directions (Birnie-Gauvin et al., 2017; Wilkes et al., 2019). For instance, fish can be blocked or delayed in their spawning migration and are subjected to injury or mortality when passing turbines, spillways or bypasses, and to mortality due to predation by fish or birds in the impoundments, resulting in cumulative negative impacts on the individual and population levels. Dams capture sediments, possibly leading to sediment starvation and subsequent incision of the river bed downstream. Reservoirs and impoundments transform rivers into lake-like systems, together with a siltation and clogging ("colmation") of the river bottom due to a reduction of flow velocities.

Discharge reduction between water abstraction and restitution ("residual flow reaches"): Residual flow reaches are characterized by reduced discharge dynamics. Depending on the scale of water abstraction and the type of intake (e.g. small weir vs. large dam), a lack of the ecologically relevant seasonal flood pulse may result in the residual flow stretch. The lateral connectivity between water and land is reduced, the longitudinal connectivity can be negatively affected (e.g. due to reduced flow depths), and water temperatures tend to increase in summer and decrease in winter due to the limited water volume.

Artificial rapid fluctuations in discharge ("hydropeaking") and temperature ("thermopeaking"): Intermittent power production can cause abrupt unnatural fluctuations in discharge and temperature downstream of storage HPP. Such artificial, high frequency alterations in environmental conditions can have negative effects on riverine fauna and flora (e.g. drift, stranding, abrasion). Furthermore, seasonal storage of water leads to fundamental shifts in the annual hy-

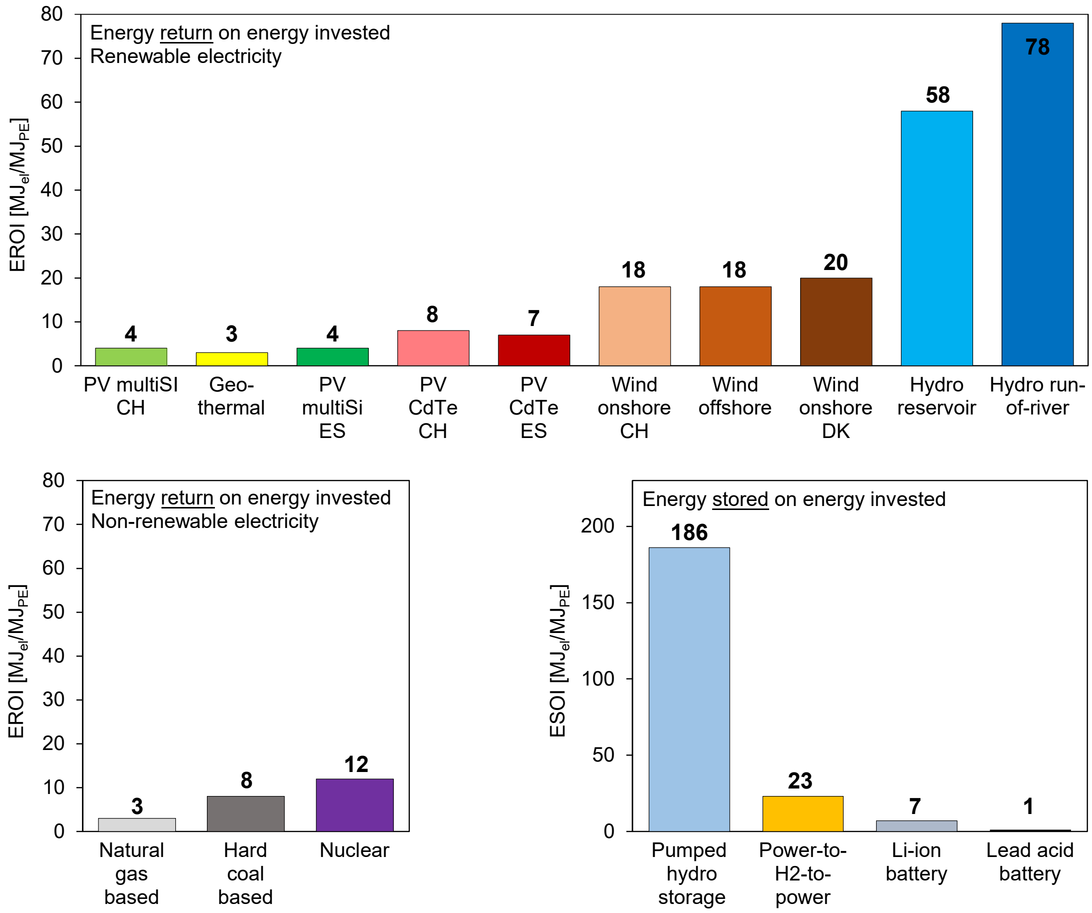


Figure 4: *EROI indicator for (upper) renewable and (lower left) non-renewable power generation technologies; lower right: ESOI indicator for different electricity storage technologies (data from Steffen et al., 2018).*

drograph, with flow increases in winter and reductions in summer. Downstream of reservoirs, temporarily high suspended sediment concentrations due to occasional flushing may occur. When flushing is combined with natural flood discharges, concentrations can however be limited, comparable to magnitudes of natural floods.

2 Potential Changes in Hydropower Generation and Storage

Due to various drivers, particularly the Energy Strategy 2050 and the Swiss Waters Protection Act, there will likely be significant changes in the future hydropower generation and storage, which are detailed in this section. A distinction is made between green-field hydropower schemes and upgrade and extension, as well as renewal and refurbishment of existing hydropower infrastructure. Moreover, climate change effects and the potential role of environmental drivers are discussed. Then, the role of operation on hydropower generation and revenues is treated. Finally, the challenges for hydropower to face the increasing need for flexibility is exposed.

A number of studies have been conducted in the framework of the SCCER-SoE since 2014 to systematically assess the HP potential in Switzerland, for both new constructions and up-grading of existing HP schemes. Furthermore, the effects of the revised Swiss Waters Protection Act (GSchG) on HP generation and the tradeoff among competing uses have been studied, e.g. regarding maximization of generation vs. revenue, environmental flow releases and other ecosystem services. The main outcomes of these projects are described below.

With more than 90 % of its technically and environmentally feasible HP potential already being exploited, Switzerland has not much untapped HP resources available (Hager et al., 2020). SFOE (2019d) gives an update of the Swiss HP potential until 2050, distinguishing between new schemes and upgrading of existing ones. A further distinction is made between small ($\leq$ 10 MW) and large HP (>10 MW). In addition, the generation reductions due to increased environmental flow releases are estimated.

SFOE (2019d) distinguishes two generation scenarios, namely under (i) today's and (ii) modified conditions, the latter being more favorable for HP exploitation. The first scenario accounts for the HP generation options under today's legal, economic and social framework. The second "optimized" scenario relates to positive changes in the economical framework, a more pronounced consideration of HP's utilization interests, and a well-balanced implementation of the ecological regulations according to today's enforcement practice. This would enable an additional, moderate extension of HP development without compromising the goals of the Federal Constitution as to sustainability and environmental protection.

The Swiss Water Resources Association (SWV) conducted a HP potential study in 2012 (with up-dates in 2016), also distinguishing between today's and optimized frameworks for the time frame of 2050 (SWV, 2016b). A study by Andersson et al. (2011) on the future Swiss energy system and electricity generation gives lump estimates for potential future HP generation increases. Herein, no distinction is made between large and small HP. Three time frames until 2020, 2035 and 2050 are specified. The estimated generation increase of 1000 to 2000 GWh/a from 2011 to 2020 was more optimistic than the actual increase of roughly 800 to 1100 GWh/a[1].

2.1 New Hydropower Schemes

New HP schemes use previously unexploited HP potential at new sites. Large and small HP is differentiated, where the latter have installed capacities below 10 MW.

2.1.1 Large Hydropower

For large HP and scenarios (i) and (ii) SFOE (2019d) estimates a production increase by 760 and 1380 GWh/a, respectively. SWV (2016b) estimates 1000–2000 and 3000–4000 GWh/a in the two scenarios, but for large and small HP combined. Given that

[1] SWV (2018) reports on 118 GWh/a of installed generation within the last decade, whereas SFOE (2019d) gives 640 GWh over seven years from 2012 to 2019, i.e. approximately 90 GWh/a.

some 700 GWh/a of additional HP generation have come online since 2012 (SFOE, 2019d), the remaining HP potential for new small and large HPP as per 2020 according to SWV, 2016b amounts to some 300–1300 and 2300–3300 GWh/a for scenarios (i) and (ii), respectively. Boes (2011b) estimated the maximum potential for new small and large HP schemes as 3600 GWh/a in an optimized framework. Converted to today, this would result in a remaining potential of 2900 GWh/a, which is similar to the values in the SWV scenario (ii).

Ehrbar et al. (2018) and Ehrbar et al. (2019) presented an approach for the systematic analysis of the HP potential of the periglacial Swiss Alps, i.e. in regions which have recently or will in the near future become ice-free due to glacier retreat. Their consistent rating of 62 potential sites is based on an evaluation matrix with 16 economical, environmental and social criteria. Ehrbar et al. (2018) and Ehrbar et al. (2019) distinguished three different weighting models (e.g. focus on technical and energy economical aspects vs. focus on public acceptance), the sensitivity of which is not pronounced for some of the best-rated sites, which are rather robust, independent of the weighting model. Various climate scenarios were taken into account in the estimation of future run-off. The eight best-rated sites (average of all three weighting models) and their energy key data are listed in Table 3. The potential of large HP schemes at the 20 best-rated glacier catchments is estimated as 1600 to 1800 GWh/a in an optimized framework (scenario ii). The corresponding new reservoirs would have a total storage volume of 700 up to 760 Mio. m^3 and a total stored energy equivalent of 1400 to 1600 GWh. The latter is defined as the energy that can be generated from one reservoir filling in the new and all existing HPP (if applicable) downstream. The additional stored energy equivalent of these 20 reservoirs would increase the current maximum Swiss energy storage in HP reservoirs of 8.82 TWh (SFOE, 2019b) by 18 to 20 %.

Note that the Trift project belonging to the best-rated sites (Table 3) is currently already in the licensing procedure. Most other sites, however, lie in or upstream of protected areas, likely causing controversial debates on the weighing of interests, the legal feasibility and social acceptance. The numbers given above include sites with protected wetlands according to the Federal Inventory of Floodplains of National Importance (AV), which are excluded from use according to the Energy Act (EnG), Art. 12 (see Section 3.1.2). If these sites are not accounted for, the estimated periglacial generation potential decreases by about one third. The more

Table 3: *Eight best-rated new HPPs (average of all three weighting models) in the periglacial environment in Switzerland.*

Reservoir location	Annual generation (GWh/a)	Stored energy (GWh)	Storage volume (Mio. m^3)
Alalin Glacier	32	47	20
Aletsch Glacier	200	216	106
Gorner Glacier [1]	220	550	150
Oberaletsch Glacier	105	60	30
Schwarzberg Glacier	19	41	19
Trift Glacier [2]	145	215	85
Turtmann Glacier	36	78	36
Unt. Grindelwald Glacier	112	150	84
Total	**869**	**1357**	**530**

[1] after Lehmann (2020)
[2] https://www.grimselstrom.ch/ausbauvorhaben/zukunft/kraftwerk-trift/

realistic numbers then amount to 1000 to 1200 GWh/a for large HP schemes for roughly 12 out of formerly 20 best-rated glacier catchments in an optimized framework (scenario ii). The corresponding new reservoirs would have a total storage volume of about 465 ± 25 Mio. m^3 and a total stored energy equivalent of about 1000 ± 50 GWh.

Based on the results of Ehrbar et al. (2018), SFOE (2019d) gives a periglacial HP potential of 700 GWh/a for scenario (ii), i.e. introduces an additional subcategory of new large HP. There is no potential for scenario (i). Note that in the SFOE (2019d) numbers the potential of the two sites at Gorner and Trift glaciers (Table 3) is already included in the new large HP category, so that they are not considered in the "new periglacial HP" category by SFOE.

2.1.2 Small Hydropower

Of the studies mentioned above, only SFOE (2019d) explicitly lists the potential from new small HP, with 460 and 770 GWh/a for scenario (i) and (ii), respectively. However, as it is expected that many small HPP will be decommissioned for economic reasons after the phase-out of feed-in tariff subsidies, the adjusted estimates are (i) 110 and (ii) 550 GWh/a (SFOE, 2019d).

2.2 Upgrade and Extension

2.2.1 Potential Measures and Overview

Herein, upgrades and extensions of HPP are discussed what comprises measures like

- increasing the hydraulic head (e.g. by deepening the downstream riverbed or increasing the

storage level of low-head schemes),
- heightening reservoir dams, and/or
- tapping of new water resources by new intakes and water transfer systems. Typically, only large HP schemes are considered for economic reasons (economy of scale).

According to SFOE (2019d), upgrading and extension of existing large HP schemes may lead to annual generation increases of 370 and 530 GWh/a for scenarios (i) and (ii), respectively. SWV (2016b) gives ranges of 500 to 1500 GWh/a and 1000 to 2000 GWh/a, respectively. Considering low-head run-of-river HPP on the major Swiss Plateau rivers Aare, Reuss, Rhine and Rhone; Boes (2011b) estimated a potential of about 700 GWh/a for upgrades and extensions. To increase the share of electricity production in winter and increase operational flexibility, existing run-of-river HPP with medium- to high-heads could be transformed to storage HPP by adding headwater reservoirs, e.g at HPP Fieschertal. So far, there are no potential estimates for this option. The feasibility of new reservoirs is currently low under framework (i), unless in high altitudes (see new periglacial HP, Section 2.1.1, which likely applies to existing sites with highly glaciated catchments like HPP Fieschertal).

2.2.2 Extension of Storage Reservoirs by Dam Heightening

A systematic study at ETH Zurich within the SCCER framework explored the potential of extending the storage capacity of existing Swiss storage lakes (reservoirs) by dam heightening. In the study, 38 existing reservoirs in the Alps with a net storage volume of at least 20 Mio. m^3 were investigated. For dam heightening options of 5 %, 10 % and 20 % of the maximum dam height, the required adaptations on the reservoir area, at the dams including their appurtenant structures (spillways, outlets, intakes) and at the corresponding HPP were studied and rated based on eight criteria (Fuchs et al., 2019). For the options that were rated "well-suited" and "moderately-suited", the additional water storage volumes and the additionally storable electricity ("energy equivalent") were estimated.

If 17 or 26 of the reservoirs were heightened, their electricity storage capacity would be increased by 2200 and 2900 GWh, respectively (Table 4, Figure 5). This corresponds to an increase of the existing storage capacity of 8820 GWh by 25 to 33 %. Using the additional storage volumes once every year, 2200 and 2900 GWh year could be additionally shifted from the summer to the winter half year. This would allow to increase the electricity generation of the Swiss storage HPPs in the winter half year from currently 48 % of their annual generation to 59 % or 62 %, respectively (Felix et al., 2020). As shown in Figure 5, two sites (Grande Dixence and Emosson) have an additional storage potential of in total about 1000 GWh. If these options are not realized for various reasons, the storage capacity of the remaining options would be 1200 to 1900 GWh.

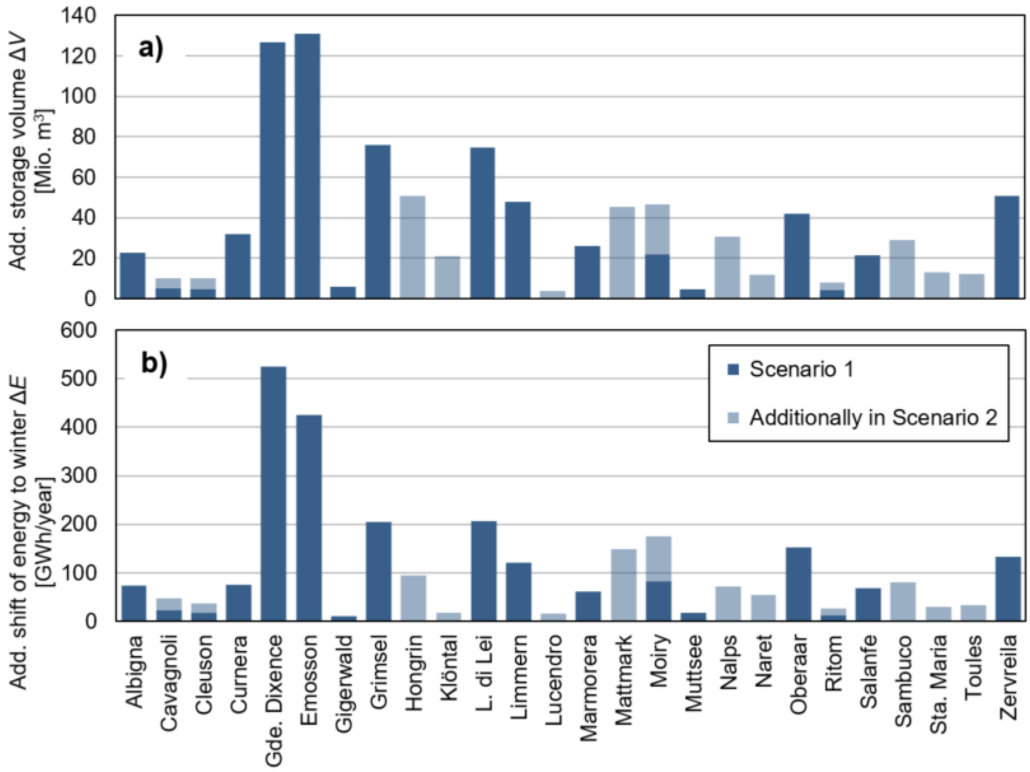
Table 4: *Summary of two Swiss dam heightening scenarios (adapted from Felix et al., 2020).*

	No. of reservoirs with dams heightened ...				**Additional volume**	**Additional energy storage**
... by	**5 %**	**10 %**	**20 %**	**total**	**(Mio. m^3)**	**(GWh/a)**
Scenario 1	1	6	10	17	700	2200
Scenario 2	2	3	21	26	950	2900

It should be noted that dam heightening results in no significant additional generation (< 200 GWh/a) on an annual balance, as the increase in head of the corresponding HPP is negligible ($\approx$ 2 %). The value of dam heightening lies in the production shift from the summer half year (with generation exceeding the demand) to the critical winter semester (with a significant import need, see Section 1.1). It should also be noted that dam heightening further increases the seasonal shift in river discharge already present due to existing reservoirs, with potential ecological impacts (see Section 3.1.2).

2.3 Renewal and Refurbishment

Herein, efficiency increases by modernization of hydraulic and electric machinery, or by reducing head losses in power waterways (e.g. through widening of tunnels) are considered. SFOE, 2019d estimates the potential of renewing and refurbishing existing large HP schemes to 600 and 1000 GWh/a for scenarios (i) and (ii), respectively, while SWV, 2016b lists 500 GWh/a and 500 to 1000 GWh/a. According to Boes, 2011b, the Swiss potential from turbine efficiency increases amounts to about 600 GWh/a. All the mentioned numbers agree quite well, and the differences between scenarios (i) and (ii) are relatively small. This is because hydraulic machinery is renewed at the end of its lifetime as long as the HPP operation is expected to be economic, resulting in better turbine efficiencies and hence a better use of the natural resources thanks to technological progress.



Relative dam heightening $\Delta h/h$

	Scenario 1:	Scenario 2:
Albigna	20%	20%
Cavagnoli	10%	20%
Cleuson	10%	20%
Curnera	20%	20%
Gde. Dixence	10%	10%
Emosson	20%	20%
Gigerwald	5%	5%
Grimsel	20%	20%
Hongrin	-	20%
Klöntal	-	20%
L. di Lei	10%	10%
Limmern	20%	20%
Lucendro	-	10%
Marmorera	20%	20%
Mattmark	-	20%
Moiry	10%	20%
Muttsee	20%	20%
Nalps	-	20%
Naret	-	20%
Oberaar	20%	20%
Ritom	10%	20%
Salanfe	20%	20%
Sambuco	-	20%
Sta. Maria	-	5%
Toules	-	20%
Zervreila	20%	20%

Figure 5: *Additional a) storage volume and b) electricity generation shift from the summer to the winter half year in scenarios 1 and 2 (26 reservoirs with net volumes >20 Mio. m^3) (adapted from Felix et al., 2020).*

2.4 Environmental Aspects

2.4.1 Background

In order to reduce the impacts of HPPs on ecosystems and thus increase its sustainability, the Swiss legislation

- requires minimum residual flows in river reaches downstream of water extraction (GSchG, Title 2, Chapter 2) and Swiss Waters Protection Ordinance (GSchV);
- sets limits to the artificial flow variations (hydropeaking) downstream of storage HPPs (GSchG Art. 39a, and GschV, Chapter 7, Section 2);
- requires measures to facilitate fish migration across artificial barriers and to mitigate HP-related injuries and mortalities, both in the upstream and downstream direction (Federal Act on Fisheries, BGF);
- limits the extent to which the bed load budget of a watercourse can be modified by HPPs (GSchG Art. 43a, and GSchV, Chapter 7, Section 4)

The owners of existing HPPs that do not fulfill the requirements concerning hydropeaking, fish migration or bed load budgets are obliged by GSchG Art. 83, to take appropriate mitigation measures until the end of 2030. The mitigation measures are financially supported by the Swiss Federation. Diversion HPPs that do not fulfill the requirements for residual flows are generally required to do so when their water rights concession is renewed. Compared to the current situation, these mitigation measures may result in reduced hydropower production as discussed in the following sections.

2.4.2 Environmental Flow Regulations

For diversion HPPs, water is diverted from a natural watercourse into a power waterway, from which the flow after passing the turbines is restituted to the same (or in some cases to another) watercourse at some distance downstream. The river reach with less than the natural flow is termed residual flow reach. The so-called environmental flow (EF) is released at the water intake for environmental services such as fish migration, biodiversity and aquatic habitats. The environmental flow release may be used in auxiliary HPPs at diversion structures ("Dotierkraftwerke"). Moreover, water from tributaries between the intake and the point of restitution and ground- and/or seepage water typically adds to the discharge in residual flow reaches. Whenever the natural discharge exceeds the intake design capacity, the surplus water also remains in the watercourse, thus increasing the discharge in the residual flow stretch.

The effect of the requirement to fulfill the environmental flow regulations at concession renewals on HP generation was assessed by SFOE, 2019d as -1900 GWh/a (-5 % of current generation) for the period 2019 to 2050. A detailed study of Pfammatter and Wicki (2018) differentiates four scenarios: (i) business as usual, (ii) consideration of minimum flow depth for migration of brown trout and lake trout, (iii) consideration of flow requirements for wetlands of national importance, and (iv) simultaneous-dynamic environmental flow releases (i.e. 30 % of natural inflow to be dynamically released). The corresponding generation reductions until 2050 were estimated as (i) -2280 GWh/a (-6 %), (ii) -2520 GWh/a (-7 %), (iii) -3640 GWh/a (-10 %), and (iv) -6410 GWh/a (-18 %). The numbers in parentheses indicate the relative generation reduction compared to 2019. It should be noted that this study assumed the relative reduction of power generation for all concession renewals to be similar to that of HPPs whose concessions were already renewed between 1992 and 2017. However, these already renewed concessions encompass only a – not necessarily representative – fraction of the total power generation for which concessions will need to be renewed until 2050 (Figure 6). The estimated generation losses therefore include a high uncertainty.

Investigations carried out in the context of the Swiss National Science Foundation Project "HydroEnv" (NRP70 Project "Optimizing environmental flow releases under future HP operation", Grant 407040_153942) demonstrated that mitigation strategies of streamflow regulation effects due to HPP storage and operation, which are based on the release of constant minimum or EF (as in current legislation), do not represent a sustainable solution. In fact: (i) the current requirements for (constant) EF are not sufficient for the conservation of aquatic biodiversity in alluvial rivers and wetlands; (ii) the streamflow statistics and physical characteristics that are key for the health of riparian vegetation and aquatic fauna do not improve enough with the introduction of EF to get close to the values characterising the natural streamflow regime; (iii) constant EF score worse in terms of impact on HP production and of ecosystem health indicators and non-proportional flow releases can improve the global efficiency of the HP system; (iv) morphogenic floods downstream of dams should also be a target of new EF release strategies, for these maintain the diversity of habitat types across the floodplain; (v) upstream sediment management systems need to be implemented where water is abstracted in order to achieve improvements in stream health of river reaches downstream of glaciated basins if EF benefits are to be realised. The effects of different EF regimes on HP production are discussed in Section 3.1.2 and quantified in the summary Table 6.

2.4.3 Measures to Restore or Improve Fish Migration

The natural behaviour of different life stages of many fish species involves single or recurrent periods of active and passive movement types, such as migration. Movement distances can reach from a few hundreds of meters up to hundreds of kilometres in river networks including connected lakes or the sea. Many different movement patterns can be found both in potamodromous (i.e. freshwater only) and diadromous (i.e. salt-to-freshwater or vice versa) fish species. Due to human-made modifications over the last two centuries, most river networks systems are interrupted by numerous transverse structures such as sills, weirs, dams and HPPs. For HP installations, new fish passages and connections to adjoining water bodies must be erected to support both up- and downstream fish migration. Already existing structures must be reviewed and may have to be adapted if they do not function properly. This may often be the case for facilities for upstream fish migration such as technical or nature-like fish passes, of which many have been implemented in the last years and which have been thought to be quite well established. However, recent upstream fish passage evaluations at many HPPs in Switzerland and Europe show that a majority of implemented upstream fish passes do not have high passage efficiencies for a broad spectrum of fish species.

At diversion-type HPPs, the flow through the fish migration facilities is usually part of the environmental flow that needs to be released to the residual flow

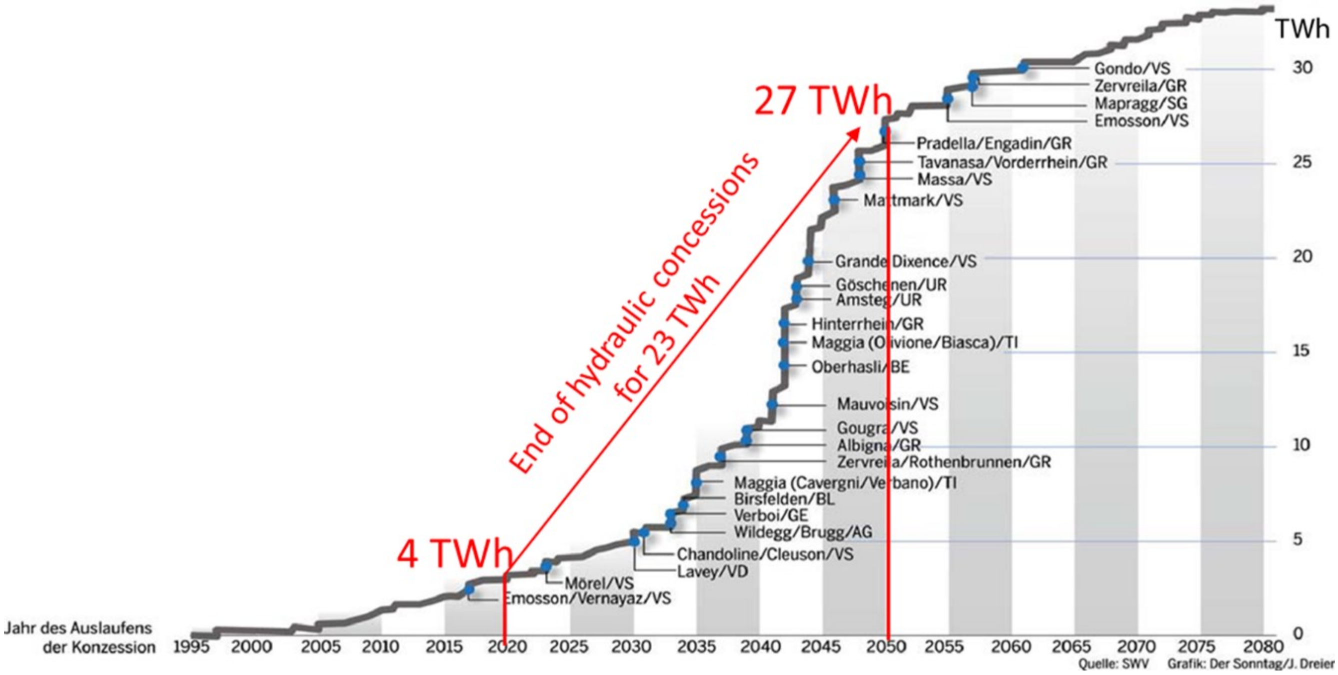


Figure 6: *Time series of HP concessions by expiry date and associated annual power generation in Switzerland (SWV, 2016a).*

reach. At low-head HPPs at rivers without diversion, however, the flow usable for electricity generation is reduced by the discharge in the fish migration facility. Although the flow requirements for fish migration facilities tend to increase, particularly to ensure stronger attraction flows to better guide fish to the entrance of the migration facility, smart solutions such as pumps with low water demand ("Lockstrompumpen") can be applied to reduce water losses for power generation in the main HPPs. Therefore, no major reduction of future electricity generation due to additional measures for upstream fish migration is expected so far.

In recent years, protection of downstream migrating fish has rapidly gained importance in Switzerland. Downstream fish protection poses particular challenges to HPP operators and local authorities due to the current lack of design standards. While there are only a few HP schemes featuring a downstream migration facility for the time being, more than 720 Swiss HP sites, mainly run-of-river HPPs, need to be upgraded with respect to downstream fish migration (Aquarius GmbH et al., 2016). The most promising technical solutions are currently fish guidance racks in front of turbine intakes combined with bypasses to the downstream river reach. Such guidance racks cause additional head losses, and the bypasses need to receive water. Research on various rack configurations for small-to-large HPPs at ETH Zurich has contributed to reduce the head losses, improve the turbine admission flows and showed high protection and guidance efficiencies for several – but not all – of the tested fish species (Beck et al., 2019; Meister et al., 2020; Albayrak et al., 2020b; Albayrak et al., 2020a). Further research is needed to understand how to safely guide whole fish communities past HPPs within a river network. Also, no solutions are available for certain life stages of fish. Passive drift of larvae and passive or active migration of small sub-adult and adult fish species may partially result in entrainment at the turbine intakes, since the physical barrier of racks are not suitable for individual fish smaller than a certain size.

Guidance racks and the corresponding bypasses result in a lower electricity generation due to mostly the bypass flow release. Recent studies at ETH Zurich estimate the generation reductions due to fish downstream migration measures at 196 low-head run-of-the-river HPPs with a total yearly generation of 10’600 GWh/a as 420 GWh/a for an average scenario, with a range from 180 to 1020 GWh/a for lower- and upper-bound scenarios, respectively (Hägeli and Shanmugaratnam, 2019; Huber et al., 2019), representing 4 %, 1.7 % and 9.7 %, of their total generation in 2019.

At large dams and at water bodies not suitable as fish habitats (e.g. very high-alpine regions), no fish migration measures are typically required.

2.4.4 Measures to Improve Sediment Continuity

Rivers transport sediment particles in different sizes. Coarser particles (coarse sand, gravel and stones) are moved close to the river bed, whereas the finer particles (clay, silt and fine sand) are transported in suspension throughout the water depth. HP structures such as dams, weirs, water intakes and power houses in rivers may lead to a reduction of the sediment transport capacity resulting in sediment aggregation. In large Alpine reservoirs (seasonal storage lakes), the sediment deposits usually consist of mainly fine sediment particles, whereas upstream of run-of-river HPPs on the Swiss Plateau the percentage of coarse sediment deposits is higher.

Sediment deposits in reservoirs may reduce the active storage volume and affect the operational safety by blocking low-level outlets. Upstream of weirs of run-of-river HPPs the deposition of fine material on the river bed (colmation) hinders the groundwater exchange and reduces the habitat quality for invertebrates and vertebrates alike. This also holds for residual flow reaches where fine sediments settle due to reduced transport capacity compared to the situation prior to water abstraction. Pronounced sediment deposits in river reaches may also increase the flood risk.

Sediment aggradations lead to a lack of sediment in downstream river reaches. Possible negative consequences are decreasing habitat quality (no moving bed load, formation of an armour-layer) and river bed incision leading to ground water depletion and damages on nearby infrastructure. Art. 43a GSchG stipulates that the bed load budget of a water body may not be changed by installations to the extent that they cause serious harm to the indigenous flora and fauna, their habitats, the groundwater regimen, and flood protection goals. The responsible operators shall take suitable measures to this end until the year 2030.

Typical measures to mitigate negative effects of HPPs on the bed load budget of a river include (Boes et al., 2017):

- Occasional flushing of reservoirs, most efficiently with water level drawdown (e.g. Eberstaller et al., 2007; Swiss Committee on Dams, Forthcoming),
- Creation of controlled morphogenic, so-called artificial floods downstream of dams,
- Dredging (underwater or by dry excavation) and transport of sediment on the road, by boat or via a pipeline to downstream river reaches,
- Dumping of gravel "bed load replenishment") downstream of dams,
- Use of sediment bypass tunnels/channels past reservoir dams (Boes, 2015; Sumi, 2017),
- Use of vortex tubes at headrace channels of diversion-type HPPs to divert sediment to residual flow reaches (Schmidt and Bezzola, 2002)

Sediment flushing from in-stream reservoirs is ideally performed when the river discharge decreases after rain events and the water is naturally turbid. In a series of HPPs, it may be advantageous to coordinate the flushing operations. More frequent flushing operations than in the past may lead to a slight reduction of the electricity production due to water loss.

So far, no estimates of production reductions due to measures to improve sediment continuity are available in the literature. Because Art. 43a GSchG focuses on the bed load budget (rather than fine sediment), mainly measures at the low-head HPPs on the Swiss Plateau are expected. Assuming that all Swiss run-of-river HPPs (with an annual generation of 25 % of 63 TWh $\approx$ 16 TWh according to Figure 1) could not be operated during for example additionally two days per year (approx. 2/365 $\approx$ 0.5 %) due to flushing and refilling of their headwater reaches, the generation loss would be -80 GWh/a. Because the flushing is ideally performed in periods when the natural river discharge is at least as high as the design discharge of the HPPs, the generation loss on such days is higher than the average daily production over the year. However, this does typically not occur in the winter season when electricity demand is highest. This effect may be compensated by the fact that flushing is probably not required at all run-of-river HPPs every year.

The guidelines on future measures to improve sediment continuity at HPPs are being established by the Swiss Federal Office for the Environment FOEN (2021b) and the cantons are elaborating sediment management concepts for the main rivers (Schälchli and Kirchhofer, 2012). The measures to be taken by HPP operators will be defined in the coming years based on further studies and will be adapted according to the operational experience and the monitoring results.

2.4.5 Measures to Mitigate Hydro- and Thermopeaking

The repeated daily and sub-daily sudden water releases related to flexible electricity production are known as hydropeaking. From a hydrodynamic perspective, hydropeaking rivers are exposed to repeated small artificial floods. Depending on river morphology, these artificial flood waves propagate downstream from the turbine release, causing rapid and unnatural fluctuations of water level and quality, near-bed shear stress and flow velocity. The magnitude, duration, rate of change, timing and frequency (see Figure 7) of such sharp artificial discharge variations, have multiple impacts on the fluvial ecosystem:

- The magnitude of hydropeaking influences habitat availability, connectivity and its persistency. As the turbines are activated, the mosaic of habitat characteristics changes in space and time, therefore forcing fluvial organisms to search for new suitable habitats (including refugia). If no new connected habitats can be found, organisms may go into drift, searching for better conditions further downstream.
- The duration of the production cycles, but also of the pauses between two cycles, influence the time-span for which a certain mosaic of habitats is available. This may influence habitat occupancy and connectivity and therefore the time organisms have to pause before changing again habitat or the time they need to resist stress (e.g., drying out of previously wetted areas; high flow velocities during hydropeaking). The duration and magnitude of peak production increase fish stress and may affect their growth and fitness.
- The rate at which the turbines are turned on/off determines the time available for fluvial organisms to search for new suitable habitats or refugia. Fast turbine upramping may lead to involuntary dislodgement of invertebrates (drift) due to the sudden increase of near-bed shear stress. On the other hand, quick turbine downramping has been reported to increase fish and macroinvertebrate stranding on previously wetted riverbanks.
- The timing of production events, i.e. when production peaks occur, shows impacts at both seasonal and sub-daily scale. At seasonal scale, for instance, hydropeaking during the emergence period (snowmelt season) may lead to increased fish larvae stranding. At the sub-daily scale, hydropeaking impacts might be stronger or milder depending on the light conditions (darkness vs. daylight) because fish feeding and migration strategies change with light conditions.
- The hydropeaking frequency affects the overall stress (the sum of the aforementioned points) to which fluvial organisms are exposed. Research shows that repeated hydropeaking affects the abundance, diversity, and recolonization of fish and macroinvertebrate communities. Moreover, also riverbed texture and the vegetation distribution on the river banks may be affected.

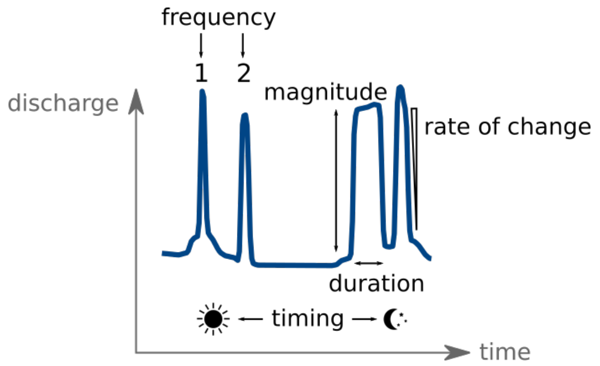


Figure 7: *Main hydrological alterations affecting the river environment caused by hydropeaking (i.e. flexible production)*

When the temperature of the water released from a HPP is different to that in the river upstream of the release, a thermal wave is generated (thermopeaking) which acts as an additional environmental stressor and can cause, for example, increased behavioral macroinvertebrate drift. Moreover, reservoir-induced thermal alterations may affect the timing of fish spawning and hatching.

Different operational and structural mitigation measures have been explored and tested to reduce the ecological consequences of flexible HP production. Operational measures focus on the reduction of streamflow alterations at the source by means of restrictions in turbine operation, e.g., by limiting upramping or downramping rates. Structural measures focus on engineered hydro-morphological modification downstream of the turbine release point such as the creation of retention basins and the usage of PSP systems to reduce the hydraulic alteration, but also river morphological diversifications (e.g. by implementing groynes) to increase refugia availability. Some more recent approaches suggest using large-scale batteries to buffer the loss in flexibility due to operational measures, while decreasing both up- and downramping rates.

The mitigation of thermal alterations is still a challenge. Efforts have been put forward to investigate different operational strategies to mitigate downstream water temperature alterations. In particular, in case of larger reservoirs, selective withdrawals across reservoir depth can not only potentially reduce thermopeaking but also counteract climate warming effects.

Flexible HP plays an important role in sustaining the energy transition to renewable electricity production. Nevertheless, it is essential to also consider the environmental effects that flexible HP systems have on river ecosystems. For the development of this renewable energy source to a truly green technology, it is indispensable to explicitly consider and mitigate the impacts mentioned above in the development of new technologies to increase HP flexibility.

2.5 Climate Change Effects on Hydropower

The Swiss energy transition coincides with a significant change in climate, which results in modified flow regimes and therefore affects annual and seasonal HP generation (Weingartner et al., 2013), alters sediment yield and input into reservoirs (Micheletti and Lane, 2016; Delaney et al., 2018), and modifies the occurrence of natural hazards (Haeberli et al., 2012; Evers et al., 2018). Glacier retreat results in deglaciated stretches of Alpine valleys and may leave newly formed so-called proglacial lakes behind, both offering new perspectives for periglacial reservoirs (see Section 2.1.1).

Schaefli et al. (2019) estimate the Swiss HP generation reduction due to ice mass loss (glacier retreat) as -0.5 TWh/a (-1.4 %) in 2050 relative to the 2019 generation level. It should be noted that the electricity generation had continuously increased since the 1980s due to increased ice melt runoff. Since 1980, 3.0 to 4.0 % (1.0 to 1.4 TWh/a) of the total Swiss hydropower production was provided by the non-sustainable glacier mass loss.

A detailed analysis of eleven representative run-of-river HPPs across Switzerland (SCCER-SoE, 2019) using the most recent climate change scenarios CH2018 suggests no change (with concerted mitigation efforts, RCP2.6) or only a slight decrease of up to 3 % (without mitigation efforts, RCP8.5) in the total annual production by mid-century with the present-day installed machinery and residual water flow requirements (Figure 8). More important is the seasonal shift due to the modified water regimes leading to a > 5 % increased winter production. More winter precipitation will have a positive impact on Swiss HP generation, as more water can be turbined (Savelsberg et al., 2018). In light of the expected higher winter demand, this is a positive trend.

The seasonality of the storage HP production, on the other hand, is expected to continue to be governed by economic factors (or supply shortfall) rather than by the natural water discharge regime. Apart from the above-mentioned glacier melt related loss, climate change will only slightly modify their total annual production as current scenarios predict no significant change in annual precipitation. From a technical perspective, during the winter peak periods with the highest electricity prices, the amount of unused capacity for storage HPPs is practically zero and their full capacity has already been reached. For this reason, more winter runoff does not necessarily mean more electricity production at peak prices for storage HPPs (Savelsberg et al., 2018).

Anghileri et al. (2018a) analyzed how different climate change and energy policies scenarios affect HP reservoir systems in the Swiss Alps, with a focus on glacierized catchments. Their results show that water availability will significantly reduce due to ice melt and that this will translate in a loss in electricity production down to -27 % by 2050 (assessed for the exemplary case study of the Mattmark HP scheme). Though this trend is in agreement with other findings of the relevant literature, the study additionally shows, that the HP operations, even if designed to account specifically for the reduced water availability, cannot compensate for this loss. This reflects a low adaptive capacity of Alpine HP systems to climate change, especially in ice melt dominated catchments.

Schlecht and Weigt (2015) projected even bigger changes for electricity prices both in terms of average price and volatility, which are likely to heavily impact HP operations. If the operations are designed specifically to account for the increase in price volatility in the future, more flexible operating rules can be identified, which allow matching the price peaks and might potentially allow for an overall increase in the revenue of the HP companies. When combining both impacts, electricity price impacts dominate climate change impacts leading to an overall higher revenue compared with historic conditions.

2.6 Increasing Hydropower Generation by Improved Operation

2.6.1 Role of Hydrological Forecasting

Accurate and reliable stream-flow forecasts are important for the management of HPPs. The time-scales of interest for HP production covers forecasts for the next couple of hours (e.g. intra-day market), up to 2–3 days ahead for flood protection, medium-range forecasts up to 7–15 days ahead for the value of the production in the electricity grid, and long-term (months ahead) streamflow forecasts for hydropower optimization, planning, and seasonal water resources management. Whereas the positive impact of short and long-term forecasts has been analysed in many

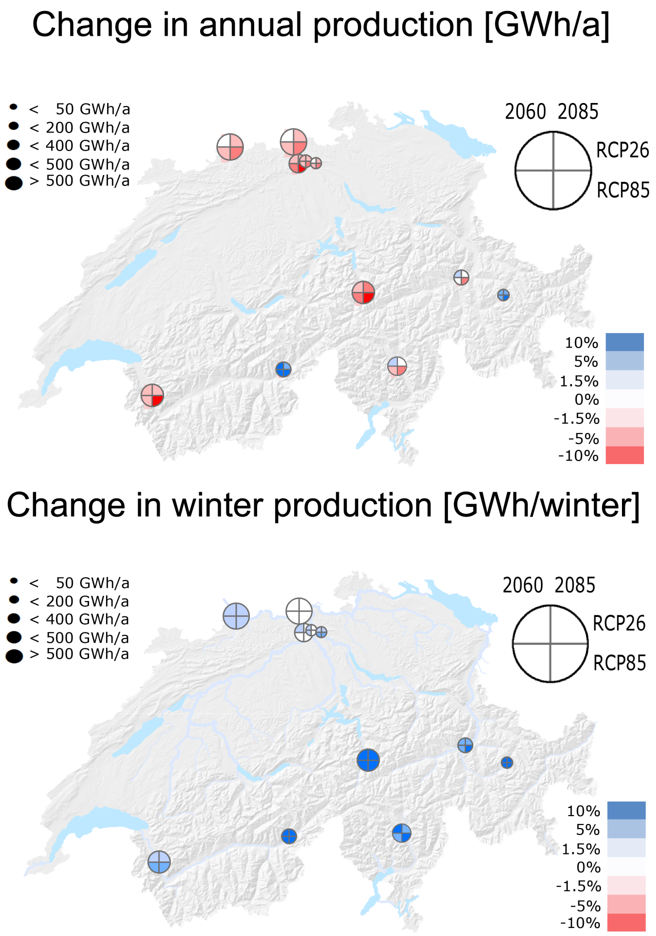


Figure 8: *Expected changes in annual (top) and winter (bottom) production of selected Swiss run-of-river HPPs for the periods 2060 (mid-century, 2045–2074) and 2085 (end of century, 2070-2099) (SCCER-SoE, 2019).*

different studies, the subseasonal forecasts, ranging from weeks to months, have been a grey zone so far. Only recently within SCCER-SoE, several studies have looked at possible gains for the hydropower, that could be achieved using such forecasts (Monhart et al., 2018).

Anghileri et al. (2019) estimated the value, expressed in terms of mean annual revenue and mean annual avoided spilled water volume, of subseasonal forecasts with a maximum lead time of one month. The numerical analysis conducted for the Verzasca HP scheme (Ticino) shows that adopting bias-corrected one-month-ahead forecasts allows for a reduction of nearly 70 % of annual spillage, corresponding to an increased production of approximately 10.4 GWh/a. The increase in mean annual revenue is about 3 %, which, although small, is not insignificant and in line with other studies on Alpine HP systems (e.g., Gaudard et al., 2013). These results are representative for Alpine HPPs with characteristics similar to the one analysed (in terms of catchment size and location) and show that considering subseasonal forecasts to inform Swiss HP operation can be extremely beneficial.

The catchment characteristics and reservoir features, nevertheless, have a strong influence on the hydrometeorological predictability and the corresponding value for HP reservoir operations (e.g., Anghileri et al., 2016; Meissner et al., 2017). For this reason, *ad hoc* studies are recommended for tailoring the hydrological forecasts (in terms of lead time, bias correction, and updating frequency) to suit the requirements of the specific HP system operation under consideration.

2.6.2 Benefits from Real-time Sediment Monitoring

Sediment particles contained in the turbine water of high- and medium-head HPPs at sediment-laden rivers can cause erosion on Pelton and Francis turbine parts. This reduces the turbine efficiency and hence the electricity generation. Kalberer (1988) estimated an efficiency reduction of Pelton turbines in Switzerland due to hydro-abrasive erosion of 0.5 % on average. With an expected production of 13 TWh/a for Pelton turbines, this corresponds to a production loss of –65 GWh/a. For Francis turbines with an expected production of 6 TWh/a in Switzerland, Kalberer (1988) estimated an average efficiency reduction of 1.5 %, resulting in a production loss of –90 GWh/a.

The sediment load and hence the erosion rate are highly variable over the year and depend on single rainfall events. Instrumentation for real-time sediment monitoring is available and has been tested at HPPs on sediment-laden rivers in Switzerland. Such real-time data is an important basis to optimize the operation of erosion-affected HPPs, e.g. to close the water intake and pause the generation in periods of exceptionally high sediment load (Felix et al., 2016). If disproportionate erosion on the turbines can be avoided during flood events, the turbine efficiency decreases to a smaller degree and the turbines need less repairs, resulting in a higher availability. The increased use of real-time hydrologic and sediment data contributes to the cost- and energy-efficient use of the HP potential.

2.6.3 Maximization of Production vs. Revenues

A key question of the future Swiss energy policy is to which extent HP systems can be converted from revenue into production maximizers to support the national electricity demand. Within SCCER, Anghileri

Table 5: *Different timescales of power system flexibility (Harby et al., 2019)*

Flexibility type	Short-term			Medium	Long-term	
Time scale	Sub-seconds to seconds	Second to minutes	Minutes to hours	Hours to days	Days to months	Months to years
Issue	System stability	Short-term frequency control	Fluctuations in supply /demand balance	Operational schedule hours- & day-ahead	Longer periods of surplus /deficit	Seasonal & inter-annual availability of new renewables
Relevance for system operation & planning	Dynamic stability: inertia response, voltage & frequency	Primary & secondary frequency response	Balancing real time market	Day-ahead & intraday balancing	Scheduling adequacy	Hydro-thermal coordination, power system planning

et al. (2018b) analysed the dualism between revenue and production for Swiss HP schemes for the current electricity price scenarios. Simulations show that a production-driven operation might have strong consequences on the HP company income, suggesting that there is a low rate of substitution between the two targets in the current energy market situation. In the exemplary case of the Mattmark HP scheme, an increase in production of $\approx 2\,\%$ would come at a cost of 30 % reduction of the company's income. Specific mechanisms are therefore needed to internalize the negative effects of a shift of HP operations to production optimization in order to create favorable conditions for HP companies to cooperate toward a secure supply based on the increase of electricity production. These mechanisms might include economic incentives in various forms, such as the reduction of the water fees associated with the concessions, which are about to be renewed in future years for most of the companies in Switzerland (Banfi and Filippini, 2010), jointly with the introduction of dynamic fees, where a portion of the tax is linked to the production (Filippini et al., 2002) or the formalization of incentives similar to those adopted for the new renewable energy sources, such as subsidies and feed-in tariffs. We acknowledge, however, that both types of incentives are politically controversial because they would imply considerable regional and national financial consequences (e.g., Banfi and Filippini, 2010) and that a wider perspective should be taken in order to account for social welfare into energy planning (e.g., Zafirakis et al., 2013).

2.7 Increasing Hydropower Flexibility

With the increasing shares of new renewable energy sources in the electric grid and the decommissioning of nuclear power plants, the need for flexibility and storage at different time scales, from milliseconds to seasons, is growing. The role of HP in this context will be crucial in the future as a renewable flexible source of energy to balance the potential mismatch between supply and demand of electricity.

2.7.1 Flexibility needs and ancillary services

The need of flexibility can be categorized according to the time scales as presented in Table 5 from very short-term to long-term (Harby et al., 2019). Services to the grid have been developed to answer the demand with several technologies characterized by different ramping rates, power and energy storage capacities. At short-term, flexibility is expected for power and voltage control, while at longer term, the focus is on energy balance. Swissgrid considers the following ancillary services:

- Frequency control (primary, secondary and tertiary control)
- Voltage support
- Compensation of active power losses
- Black start and island operation capability
- System coordination
- Operational measurement

In the framework of the ongoing Horizon 2020 project XFLEX Hydro, a first report on the "Flexibility, technologies and scenarios for Hydropower" has been published in 2020 presenting the future services to the grid (Moreira et al., 2020) which are summarized below (Figure 9):

Synchronous inertia: This solution is specific to rotating machines which can store and inject their kinetic energy. The service is not yet remunerated but is starting to be contracted by transmission system operators of large-scale islands under specific tenders, as it is the case of Ireland and United Kingdom.

Synthetic inertia: While not providing synchronous inertia, power electronic-interfaced energy sources can provide short-term frequency support through proper control of the coupling interface. They are able to swiftly adapt power output, driven by their control system.

Fast Frequency Response (FFR): FFR is designed to provide an active power response faster than existing operating reserves, typically in less than 2 seconds, in the timeframe following inertial response (typically after 500 ms) and before activation of the frequency containment reserve (which has a maximum delay of 2 seconds).

Frequency Containment Reserve (FCR): formerly known as primary frequency control. FCR aims to contain system frequency after the occurrence of an active power imbalance and must be fully activated within 30 seconds for a period between 15 to 30 min.

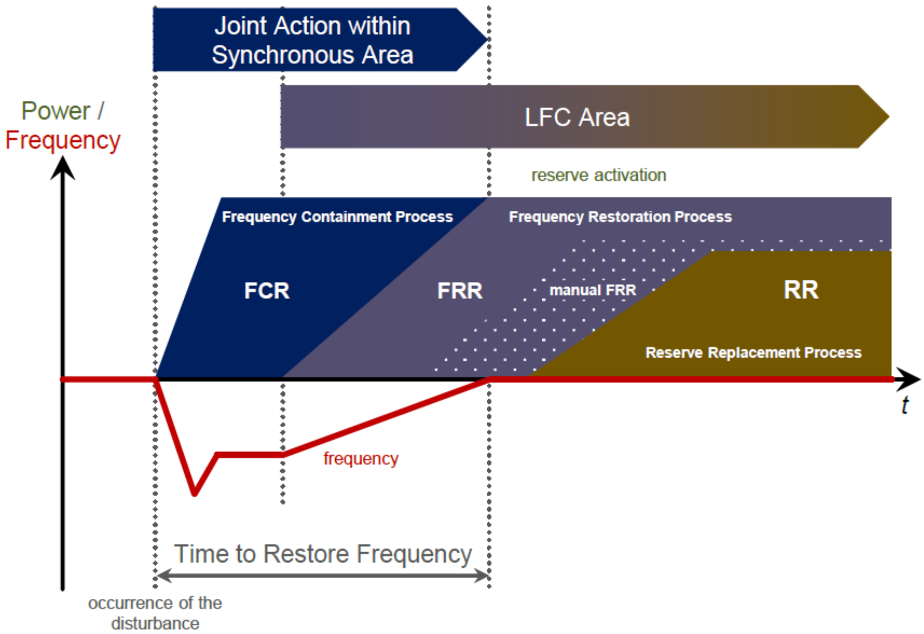


Figure 9: *Load frequency control process (Moreira et al., 2020), definitions see text.*

Automatic Frequency Restoration Reserve (aFRR): formerly known as secondary frequency control aims to restore the system frequency back to its normal value. The aFRR activation delay must not exceed 30 s.

Manual Frequency Restoration Reserve (mFRR): formerly known as direct activated tertiary frequency control, is a frequency restoration process, having therefore similar goals to aFRR. According to EU regulation, mFRR must be fully activated in 15 min.

Replacement Reserve (RR): formerly known as scheduled activated tertiary frequency control, aims to progressively replace and/or support the frequency restoration control process in the disturbed control area, usually performed after the time to restore frequency, in a timeframe between 15 min to 1 h.

Voltage/reactive power control (Volt/var) is implemented by manual or automatic control actions, designed to maintain the nominal set values for the voltage levels and/or reactive powers.

Black start is the process of restarting operation of a power plant during a grid blackout, from a completely non-energized operating state and without any power feed from the network. HPPs are particularly well suited for black start and it will become of crucial importance to guard system security.

2.7.2 Recent results

To face the challenges of electrical grid flexibility in Switzerland, several projects have been set up and realized in the framework of the SCCER-SoE since 2014. The main achievements of those projects are described below.

Hyperbole. The aim of the FP7 European project was to explore the capacity of HPP to be operated on a larger operating time with a faster response time. Transient operation, unsteady numerical simulations (Decaix et al., 2021c; Decaix et al., 2021a), as well as experimental measurements have been carried out to investigate the roots of the operating range limitations for Francis turbines and reversible pump-turbines at model and prototype scales. One of the main achievements of this project was to provide the first economic study of how the profitability of variable speed pumped storage power plants can be assured, considering their role in the provision of a secondary reserve to the grid and in primary frequency regulation.

FLEXSTOR. The FLEXSTOR project aimed to set up innovative tools for flexible operation of complex hydropower schemes. Several actions have been investigated such as concentrating production in less hours, while mitigating negative impacts; managing reservoir sedimentation to expand storage capacity while complying with the Waters Protection Act; addressing mountain slope instability risks in periglacial zone, avoiding non-optimal "preventive reservoir lowering"; identifying the changing demand structure and the required adaptation of the storage management; extending the operating range of hydraulic machinery, whilst avoiding instabilities (Hasmatuchi et al., 2021; Decaix et al., 2018); optimally manage a compensation basin in order to minimize the ecological impacts of hydropeaking in the downstream river reach. All these developments have been validated in the complex system of KWO, which allows later replication to other HP schemes in Switzerland.

RenovHydro. By 2050, roughly 63 % of the HPP hydraulic concessions will end in Switzerland, representing 23 TWh of annual generation. The overarching objective of the RenovHydro project is to support the utilities to smoothly renew these concessions by developing a decision-making assistant to choose the optimal solution taking into consideration all the relevant technical, economic and ecological parameters. The RenovHydro project within the SCCER framework, led by EPFL, partnering with Power Vision Engineering, FMV SA and Groupe E SA, is a multidisciplinary research project targeting the development of a methodology – and its implementation into the existing EPFL SIMSEN software – to assist the decision making for HP projects and refurbishments. Automatic investigation are performed considering civil and electro-mechanical engineering scenarios and evaluating their performances in terms of energy generation, installed capacity and ancillary services to the grid. Numerous scenarios for hydraulic structures, hydraulic machinery and electrical equipment are evaluated by an automated algorithm prioritizing flexible configurations to provide higher production and ancillary services (Landry et al., 2018).

SmallFLEX. Changes in the national feed-in-tariff system challenge small HPP owners by introducing the necessity to produce according to the energy demand, thus opening up new business cases. In this framework, the aim of the SmallFLEX project is to show how small HPPs can provide winter peak energy and ancillary services, whilst remaining eco-compatible (Vogel, 2021; Münch-Alligné et al., 2021; Decaix et al., 2021d). The outcome of recent studies of the project partners are applied to a pilot facility provided by FMV SA with the goal of providing operational flexibility to the small HPPs and therefore harvest additional revenues. The addition of flexibility is provided by testing infrastructure and equipment or operational adaptation measures, while assessing their impact in terms of outflows, electricity output and revenues. Existing structures of the power plant such as the settling basin, the forebay chamber as well as the upper part of the headrace tunnel are used for water retention as "smart storage". Through this multidisciplinary approach, a complete study from the inflow forecast to the hydropeaking effect on the alluvial area downstream of the water restitution point via numerical modelling and field tests of HPP Gletsch-Oberwald has been carried out. A smart storage of 6'200 m^3 has been identified and assessed for this small run-of-river HPP, and primary services of $\pm$ 1.5 MW have been proposed. An economic analysis using the identified smart storage has evidenced the possibility to double winter production, to reduce the number of start-and-stop and to propose ancillary services by integrating HPP Gletsch-Oberwald into a virtual pool.

The present approach could be extended to more than 175 small-medium HPP in Switzerland with an installed capacity between 1 MW and 30 MW.

Penstock Fatigue Monitoring. With ageing of HPPs and the increasing share of flexible operations, penstocks are subjected to fatigue. In the "Penstock Fatigue Monitoring" project, a hydraulic test rig inducing water hammers and pressure fluctuations has been designed at HES SO Valais. This setup will help to predict the speed of crack growth and to convince plant manager to use this monitoring solution for real infrastructures. In parallel, the stress related to pressure oscillations has been measured at the Emosson penstock. After demonstrating that the transient pressures could be accurately correlated with stress variations, four typical days of operations were compared to determine the impact of ancillary services on penstock fatigue. The results clearly highlight the considerable impact of the supply of primary and secondary control services on the penstock service life, with a dominant influence of the secondary control: the fatigue wear rate is about ten times higher when these services are active.

2.7.3 Examples of technical solutions to increase flexibility

HPPs already significantly support electrical power system flexibility in terms of regulation capability, fast frequency control, fast start/stop, fast generating to pumping modes transition, high ramping rate, inertia emulation, fault ride through capacity, etc. However, extending the flexibility capacity of HPPs, while sustaining their reliability and safety and mitigating their environmental impact, is challenging. Therefore, innovative solutions to face this challenge are still under investigations such as unit digitalization, advanced monitoring, predictive maintenance, variable speed, and pumped storage HPP short circuit operation. This flexibilization needs to be scheduled in the cases of run-of-river, storage and pumped storage HPPs and may cover cases of refurbished, upgraded and especially existing HPP to be applied and scaled to any unit size.

Furthermore, for each HPP case the flexibility services that can be provided need to be assessed by considering aspects including investment and operating costs, machine efficiency, wear and tear, as well as environmental impact and revitalization measures.

Some of this innovative solutions are described below through the ongoing activities started in the H2020 XFLEX Hydro project. XFLEX Hydro is an ambitious energy innovation project which aims demonstrating how flexible hydropower technologies can deliver a low-carbon, secure and resilient power system with seven demonstrators in Switzerland, France and Portugal.

Unit digitalization. Unit digitalization by integrating a "smart supervisor" in the general control and monitoring system of a hydroelectric unit as proposed in the XFLEX Hydro project enables to embed in the control system all the engineering knowledge of the unit. Depending on the operating conditions, it is further possible to know the actual physical conditions experienced by the unit and therefore to assess and to predict the impact of these conditions on aspects like machine efficiency, wear and tear, and environmental impact. The engineering knowledge is structured in data base collecting the following results:

- Transient, fluid dynamics and structural simulations;
- Reduced scale physical model tests;
- Prototype commissioning data;
- Operating data time history constantly updated by the advanced monitoring system of key operation parameters.

Meta models of the above results can be cast to build up a so called "hydraulic multidimensional hill-chart" interpolating the machine efficiency, wear and tear, and other parameters as a function of the unit operating points to enable real time monitoring and control. Furthermore, the "smart supervisor" enables to integrate alternate technology components for an enhanced flexibility capacity.

Advanced monitoring. Engineering knowledge of the hydroelectric units enables to develop a digital twin of the unit. Parallel real time operation of the digital twin yields up-to-date data available at each time to evaluate the condition of the unit and to assess future operation scenarios. An example of a digital twin is the Hydro-Clone® system developed by Power Vision Engineering for monitoring of hydroelectric unit transient operations (Dreyer et al., 2019). However, a digital twin can be developed to further mimic physics such as the hydrodynamics, both hydraulic and machine structure dynamics, the unit rotordynamic, and others.

Variable speed. "Variable speed" capacity provides an added degree of flexibility, as operators can vary rotational speed of reversible units and use this for enhanced grid services in both pumping and generating modes. In particular, variable speed pump-turbines enable power regulation and load following even in pumping mode. Variable speed PSP can operate at a wider range, higher efficiency and quicker response time in both modes of operation. There are two types of variable speed currently available: double fed induction machines with a variable speed range between $\pm 6\,\%$ and $\pm 10\,\%$ of the synchronous speed, and full size frequency converters with a full rotational speed range.

In XFLEX Hydro, the Z'Mutt demonstrator located in Switzerland will be equipped with a full size frequency converter for a pump-turbine of 5 MW. The aim is to assess the advantages of the this technology compared to a conventional fixed speed technology for both pumping and turbine modes during start-up, shutdown and fast transitions. A preliminary numerical investigation already shows a considerable potential to mitigate partial damages during turbine start-up using the full size frequency converter technology (Biner et al., 2021; Alligné et al., 2021).

For Alto Lindoso and Caniçada Demonstrators with medium head equipped with fixed speed Francis turbines, the potential of the double fed induction machine variable speed technology to increase the lifetime of the turbine is investigated. A preliminary numerical study shows that at partial load, the possibility to increase the rotational speed by 10 % allows a significant reduction of the pressure pulsation in the runner linked to a modification of the vortex rope in the draftube leading to a decrease of the wear and tear accompanied with an efficiency reduction of 3 % (Pacot et al., 2021).

PSP short circuit operation. Hydraulic short circuit operation means that PSP plants undertake pumping and generating modes at the same time for increased flexibility. Fixed-speed pumping units can be operated to ensure net power consumption from the grid, while in parallel a unit is run in generating mode to regulate the load. This technology is tested in the XFLEX Hydro project at Grand Maison PSP in France equipped with four Pelton and eight pump-turbine units.

The hydraulic short-circuit operating mode leads to a change in the flow paths in the penstocks and junctions compared to the normal turbine or pump modes. Preliminary fluid dynamics simulations have been carried out for several configurations of hydraulic short-circuits to assess the energy losses and possible flow instabilities before any field tests (Decaix et al., 2021b).

3 Challenges and Opportunities

There are both challenges and opportunities for future hydropower. The challenges result from the market framework, the environmental legislation and operational issues like sedimentation. The opportunities are driven by climate-related changes in high-altitude environments, demanding for water resources management and protection against natural hazards, which could be new assets for storage hydropower.

3.1 Challenges

3.1.1 Market situation and regulatory framework

HP plays a central role in Switzerland's electricity system and accordingly also in its electricity market and policy setting. Supplying more than 50 % of Switzerland's electricity, HP is a central pillar of the envisioned electricity transition. It provides both the bulk energy and the needed flexibility for a shift towards a high share of intermittent new renewables. Both, scenario forecast by the JASM framework as well as the Energy Perspectives 2050+ assumes at least a continuation of its 35+ TWh output. However, given the high uncertainty in future developments the envisioned role for HP is subject to uncertainty. Consequently, a survey across a selection of Swiss HP stakeholders at a workshop within the NRP70 project "HP Future" indicated that political and market aspects are among the main challenges for Swiss HP operators (Barry et al., 2015). The main challenges on the market and regulatory side Swiss HP operators are currently facing are summarized below.

Energy Market situation. The Central European market development is the single most important driver for Swiss HP and its profitability (Barry et al., 2019). One could assume that with the expected increasing stringency of climate targets also the carbon prices of the European emission trading system should increase, leading to a subsequent increase in market prices as long as it remains dominated by fossil energies. However, at the same time the increase in new renewables will put downward pressure on wholesale prices. Similarly, the envisioned sector coupling should lead to an increase in electricity demand and subsequent higher prices, but at the same time sector coupling will introduce new flexibility options to the system (e.g. via heat pumps, coupling with thermal systems, and batteries in electricity vehicles) that could dampen price increases and could also pose competition to HP. Consequently, it is not guaranteed that there will be a high price level in the future nor that even if prices would increase in the long run, such a development would not also occur with prolonged low and/or flat price periods (Schlecht and Weigt, 2016).

One central uncertainty element within this market framework is the relation between Switzerland and the EU. Storage and pumped storage plants play an important role in securing the Central European electricity supply (Weigt et al., 2019) and naturally benefit from exporting electricity during high prices hours in neighboring countries. The access to neighboring markets is subject of the still pending electricity agreement. For the time being, Switzerland is not fully participating in the flow-based market coupling regimes in Central Europe and therefore could see limited import and export opportunities in the future. However, the actual impact of such a development is again uncertain. While limited export opportunities reduce income prospects on the European markets, a reduction in import opportunities could lead to higher prices in Switzerland. In short: the future market development is uncertain, low price trajectories cannot be ruled out, and influencing those market dynamics is out of reach for Swiss decision makers. Consequently, companies need to prepare for such developments internally, by maintaining a proper risk and liquidity management.

Uncertainties in Energy policy development. Beside the uncertainty embedded in future market developments also Swiss specific regulation add to the overall uncertainty Swiss HP operators have to face. In addition to the above mentioned negotiations between

Switzerland and the EU, the projected full liberalization of the Swiss electricity market will likely have an impact on Swiss HP companies. Given the current partial liberalization with large consumers (> 100 MWh annual consumption) being free to choose their suppliers, especially companies with a small captive consumer basis are already exposed to the full market risks. However, companies with a captive consumer basis are still (partially) shielded and can more easily refinance high fixed costs or investments. A full market opening would – depending on the willingness of consumers to switch suppliers in case of higher tariffs – also expose those companies to the market risks.

Another regulatory element directly impacting Swiss HP is the envisioned reform of the water fee regime. The current fixed regime is supposed to be replaced by a more flexible system (Swiss Federal Council, 2018). As a flexible regime would partially shift the market risk from producers to resource owners, there is an ongoing debate about whether and how to adjust the system. Betz et al. (2019) investigated the potential impacts of such a regime shift and show that in general the development of electricity prices is the more important driver than the water fee levels or design. However, in a price range from 40 to 60 CHF/MWh, water fee design can indeed make a difference between profit and loss. Whether such a change would be accepted by the cantons and municipalities is a different matter, as their income situation would be significantly altered with a potential for higher income but with a risk of significant shortfalls in low price periods (Hediger et al., 2019).

With the concern about secured energy supply during the winter months after a nuclear phase-out the Federal Council has introduced a so-called "storage reserve" mechanism. The objective is to secure a specific level of HP generation as security against extraordinary situations. Whether and when such a reserve will be implemented and the actual design is still in debate (Swiss Federal Council, 2020). Schillinger et al. (2019) investigated different mechanism designs and showcase the challenges in implementing a design that is not prone to market power abuse while obtaining the envisioned security effect. Furthermore, they show that the overall financial impact of such a mechanism on Swiss HP is rather limited.

In addition to HP specific regulations, the general energy and environmental policy framework is changing due to the envisioned transition towards a carbon neutral energy system. As many policies will directly or indirectly impact the electricity system, they also will have an impact on the prospects for Swiss HP operators.

Amortization Treaties. Given the uncertainty, both with respect to market and policy developments, also investments into new and retrofitting of existing HPPs has become challenging. HP investments usually require a long payback period, due to long construction phase, long lifetime and high capital costs of the assets. This can put HP at a disadvantage in an uncertain market environment compared to more easily scalable and faster investments of other renewable or storage technologies (Gaudard and Madani, 2019). Addressing this disadvantage with adjustments in the investment management process (i.e. by planning modularly) could be one strategy to counter the high uncertainty.

On the regulatory side, support policies have been put in place or are currently discussed. For example, federal investment subsidies were introduced in 2018 for significant upgrades and extensions or renewals of large HP schemes (excluding pumped storage) (Art. 24 and 26 EnG). These contributions are limited to 40 % of the claimable investment costs and the non-amortizable additional costs (Art. 48 EnFV). The investment subsidies are financed with a maximum of 0.1 Rp/kWh from the grid supplement, corresponding to some 50 Mio. CHF annually, so far agreed until 2030 (SFOE, 2019a).

An increase in winter HP generation is also envisioned in the current revision of the Electricity Supply Act (Swiss Federal Council, 2020). In particular, an expansion of seasonal storage capabilities providing 2 TWh of winter generation is to be achieved via specific investment contributions which will be financed with an additional surcharge of 0.2 Rp./kWh. Whether this measure will pass the legislative process is – as of today – unclear, but it clearly indicates the willingness of the Swiss government to increase HP production and provide financial support.

Concession Renewals. In Switzerland, 257 HP concessions, accounting for a generation of 23.4 TWh/a, will expire within the next 30 years (Figure 6). At concession end, the whole HP scheme infrastructure is transferred to the concession granting entity, mostly the canton (so-called "Heimfall"): the "wet parts" like dams, penstock and turbines free of charge, the "dry" parts like generators and control systems against a "low-cost compensation". It is decisive for the future of HP that the "Heimfall" does not compromise HP generation, does not slow down investments and does not further increase HP cost (Piot, 2020).

3.1.2 Conflict of Interest between Hydropower Use and Environmental Legislation

Residual Flow. The Water Protection Act requires increased residual flow releases in future concessions. This will likely cause reductions in HP generation between -1.9 and -6.4 TWh/a (Section 2.4.2). To achieve the ES 2050 targets of +2.6 TWh/a HP generation until 2050, the effective increase by new and extended HP schemes therefore has to amount to +4.5 and +9.0 TWh/a, representing 13 % and 25 % of today's HP generation, respectively. Based on a linear trajectory, this would require an installation of 150 to 300 GWh/a annually until 2050. In view of the specific HP that has effectively come online in recent years of between 91 GWh/a (SFOE, 2019d, 7 year-period) and 118 GWh/a (SWV, 2018, 10 year-period), it seems unlikely to meet these target numbers.

Protection of Wetlands and Floodplains. According to Art. 12 EnG, infrastructure for renewable energy use, in particular storage and pumped storage schemes, is of national interest depending on its size and significance. Nevertheless, in biotopes of national importance according to Art. 18a NHG (Federal Act on the Protection of Nature and Cultural Heritage) and in water and migratory bird reserves according to Art. 11 JSG (Federal Act on Chase and the Protection of Feral Mammals and Birds), new infrastructure for renewable energy use are excluded. In accordance with Art. 18a NHG, the Federal Council designates biotopes of national importance, assesses their situation and sets conservation objectives for them. However, this occurs after the cantons have been heard. As the second federal inventory under Art. 18a NHG , the Federal Council implemented the Federal Inventory of Floodplains (Auenverordnung, AV) with 169 floodplain sites in 1992. It has been expanded in 2001, 2003, 2007 and 2017. Between 1995 and 1997, the Inventory of Glacier Forelands and Alpine Floodplains, a scientific inventory, developed the bases for the first expansion. Currently, 326 objects are contained in the inventory and protected by law.

New reservoirs and heightening of existing dams would cause more areas in the Alpine region to be flooded, resulting in the loss of possibly important Alpine habitats for terrestrial flora and fauna, which causes conflicts between different stakeholders (pro natura, 2015).

Hydrological Effects. With additional storage capacity, the additional shift in production from summer to winter results in a corresponding shift in discharge in the downstream rivers. This shift comes on top of the already existing shift due to the current HP storage, and an additional shift in the same direction resulting from climate change with likely more precipitation in winter and less in summer. In glacial catchments there will be more meltwater in summer until most glacier ice will have disappeared. The impacts of these cumulative changes on the riverine ecosystems have not been sufficiently and systematically investigated so far (Ecoplan, 2021).

3.1.3 Managing the Reduction of Storage Capacity due to Sediment Accumulation

Human-made water storage reservoirs both profit from and interfere with the natural water cycle (IHA, 2019). Water brings along sediment and different types of debris. Water stagnation in reservoirs leads to deposition of large fractions of the incoming sediment, along and across the reservoir, as function of the inflow regime but also of the operation of the HP facilities. In general, the coarser sediment fractions settle at the upstream end of the reservoir, while the finer fractions travel farther, eventually several kilometers until reaching an outlet or an obstacle.

The reduction of human-made storage capacity in Switzerland is not precisely known or monitored. Empirical lumped estimates indicate an annual rate of loss of storage volume of $\approx$ 0.2 to 0.5 % of the total storage capacity in Switzerland and worldwide, respectively (Schleiss et al., 2010; Schleiss et al., 2016; Boes, 2011a; ZeK HYDRO, 2020). Part of such loss concerns directly the reservoir partition areas used for operation (live storage) and for dam safety operations (upper live storage and direct vicinity of the dam), leading to either operational losses or safety losses. A large number of HP operators confirms having had or having continued operational problems related with sediment management (Manso et al., 2018; Swiss Committee on Dams, Forthcoming). The most critical problems are (i) losing the ability to manoeuver dam safety devices, due to sediment blockage; and (ii) the reduction of live storage for both HP production and flood routing. Generally speaking, there is no evidence of sediment issues having an effect on annual production (since there is always the option of operating with constant lake level, i.e. as run-of-the-river HPP). However, this is not the case in terms of annual revenues due to reduced capacity to offset production from the natural water cycle to target time windows with premium energy prices. Therefore, maintaining live storage is paramount to guarantee the medium and long-term viability of the HP schemes using seasonal storage.

Several solutions to mitigate storage loss due to sedimentation are known and deployed globally and across Switzerland, but remain very site-specific (Schleiss and Oehy, 2002; Sumi and Kantoush, 2011; Boes and Hagmann, 2015; Schleiss et al., 2016; Boes et al., 2017, see section 2.4.4). There is no one-size-fits-all solution. Finding a sustainable practice to continuously manage sediment inflows, deposits and outflows requires deep knowledge and monitoring of complex physical processes. Large reservoirs (i.e. seasonal or annual regulation) may end up capturing all incoming sediment, and are often considered with "low permeability to sediment transit", whereas small reservoirs (intra-weekly regulation) have to deal with sediment issues regularly and must be and remain quite "permeable to sediment transit". The different nature of the reservoir regulation role on the natural river catchment, combined with the specific nature of the upstream catchment and its land use (e.g. forest, permafrost) and reservoir operation therefore lead to variable impacts on the sediment transit across the reservoirs. Downstream of large reservoirs the river system typically receives less influx of sediment after reservoir impounding than before. This may result in potentially negative impacts to the downstream river system and coastal areas due to lack of sediment and nutrients.

Sustainable sediment management at reservoirs is currently envisaged by means of regular monitoring of sediment processes and implementation of sediment routing practices allowing to convey sediment fractions downstream. The need to mitigate operational shortcomings and abide by legal requirements to enhance sediment transit has led the technical community to develop mitigation solutions for implementation upstream from the reservoir, within the reservoir, as well as near the dam (Hager et al., 2020). The purpose is generally to allow passing of some sediment fractions, whilst limiting the water losses for hydropower production. From the environmental point of view, coarse sediment are welcome downstream since required for fish spawning, whereas finer fractions are considered more harmful in Alpine areas should they lead to river bed clogging. The transit of bed load can be achieved with sediment routing techniques such as sediment bypass tunnels, particularly suited for small to medium sized reservoirs (Boes, 2015; Sumi, 2017), while fine sediment can be vented, routed or conveyed via dam outlets and intakes (Schleiss et al., 2016).

Swiss seasonal storage reservoirs are vulnerable to the accumulation of fine sediment, mainly close to the dam (Guillén-Ludeña et al., 2018). In contrast to the coarse sediment fractions (i.e. bed load, Art. 43a GSchG), there are no legal requirements (and incentives) to pass fine sediments past dams. Innovative solutions have been conceived in Switzerland to route the fine sediment fraction downstream, using different strategies and hydraulic structures, each with its comparative advantages. The best synergy between fine sediment routing and storage use is to convey fine sediment through the power waterways and turbines at acceptable concentrations (e.g. Felix et al., 2016).

3.1.4 Uncertainties in the Assessment of Hydropower Generation and Storage Potential

The estimated HP potential (in studies like Ehrbar et al., 2019; Felix et al., 2020) depends on forecasts of future precipitation and runoff and a number of assumptions. The longer the time frame of the forecasts, the larger are the effects of deviations in input data and assumptions from reality. The following main sources of uncertainty can be identified:

Assumptions of overall efficiency, the annual full load production hours, etc. were solely determined based on empirical values and experience. They may only partly be applicable for individual sites.

Reservoir volumes at today's glacier sites were estimated using bed-rock topography derived from ground-penetrating radar measurements, which have a horizontal resolution of ± 25 to 50 m and vertical accuracies in the order of ± 10 m. Reservoir volumes, dam heights and installed capacity are therefore subjected to uncertainty (Ehrbar et al., 2018; Ehrbar et al., 2019).

To determine energy storage equivalents of reservoirs, so-called electricity coefficients are needed, expressing the energy generation potential per unit water volume (kWh/m^3). In the study of Ehrbar et al. (2019) the electricity coefficients were simplified as a function of mean elevation of the catchment area according to Schaefli et al. (2019). Considering the actual available heads in upcoming planning phases may lead to different results.

Runoff projections depend on climate change evolution and thus on the chosen scenario. Here, scenario RCP4.5 was chosen, a stabilization scenario that lies between the mitigation scenario RCP2.6 and the non-intervention scenario RCP8.5. For the time period 2017 to 2035, the annual runoff volumes of RCP2.6 and RCP8.5 are 2 % lower and 1 % higher on average, respectively, compared to RCP4.5. These differences are negligible. By the end of the century (2090 to 2099), these differences will be -9 % (lower for RCP2.6) and +2 % (higher for RCP8.5) on average (Ehrbar et al., 2019).

The operation modes of new HPPs depend on the evolution of new renewables as well as on political measures and market conditions. It was assumed that all new HPPs with capacity-inflow ratios > 0.55 operate as seasonal reservoirs to help reduce the deficit in domestic generation during the winter season (Ehrbar et al., 2018, Section 2.1).

In single cases, e.g. at the Roseg glacier periglacial HP scheme, water would be diverted to a different watershed, so that downstream HPPs (e.g. on the Inn river) would feature generation reductions. These were not accounted for in the study of Ehrbar et al. (2019) and therefore constitute another haziness in determining generation numbers.

The attainable additional shift in seasonal HP generation is highly dependent on the feasibility of the dam heightening projects (e.g. hydraulically coupled reservoirs).

Projects in the same river catchment/region need to be mutually coordinated in a spatial planning process. An existing reservoir should for instance not be extended if a new one is built upstream, opportunities for pumped storage plants should be considered, protected vs. HP areas and compensation measures ("Schutz- und Nutzungsplanung" according to GSchG) should be elaborated.

3.2 Opportunities

3.2.1 New Glacier Lakes

Climate change and the associated glacier loss provide perspectives for new HPPs, as suitable reservoir locations might become ice-free due to glacier retreat. In some places, new proglacial lakes have recently formed, e.g. at Unterer Grindelwaldgletscher, Triftgletscher or Gauligletscher (Canton Berne), as well as of Rhonegletscher (Canton Valais) or Vadret da Palü (Canton of Grisons). Potentially, such lakes may be used as head storage of new HPPs, as is planned for the Trift HPP for example (Kraftwerke Oberhasli AG, 2020). Proglacial lakes can either be used for storage in their natural extent, or their storage can be increased by adding an artificial dam. The potential of using areas becoming ice free for HP production has recently been investigated both at the worldwide (Farinotti et al., 2019) and the Swiss scale (Ehrbar et al., 2018; Ehrbar et al., 2019). The latter studies systematically ranked potential locations across the Swiss Alps with 16 different criteria aimed at quantifying economic, environmental, and societal impacts of a possible exploitation. The future runoff evolution of the considered locations as well as the geometry of the subglacial environment were thereby taken into account with model simulations by Huss and Hock (2015) and Farinotti et al. (2016), respectively. For the 20 most suitable locations, taking into account protected areas like floodplains of national importance, the maximal potential amounts to 1.0 to 1.2 TWh/a and the total storage volume to between 0.44 and 0.49 km^3. The latter is equivalent to an energy content of about 1.0 ± 5 % TWh (see Section 2.1.1).

The time frame by which such new sites could become available and attractive is strongly variable. Amongst the most promising sites is Triftgletscher, where the approval and licensing procedure is currently ongoing, and where corresponding research on the potential socio-economic implications has already been performed (Kellner, 2019; Kellner et al., 2019). Other locations, such as the lake expected to form after the retreat of Oberaletschgletscher, are currently at the center of planning activities (New York Times, 2019). Further locations, as could be the overdeepened topography underneath Gornergletscher, are decades away from being exploitable (Farinotti et al., 2016; Farinotti et al., 2019).

Whilst newly emerging glacier lakes can be attractive for HP production in some areas, they can be source of hazards in others. The risks from landslides originating from degrading permafrost (Haeberli et al., 2017) or other cascading processes (Schaub, 2015), for example, have been highlighted (see Section 3.2.3). Taking into account such risks with corresponding analysis frameworks (e.g. Frey et al., 2010; NELAK, 2013) will be important.

3.2.2 Multipurpose-use of HP Reservoirs

Flood Protection, Irrigation, Tourism, Alpine photovoltaics. In the light of climate change, which is expected to have a significant impact on water resources in Switzerland (SCCER-SoE, 2019), the importance of natural and artificial water reservoirs for meeting the total water demand of various sectors is increasing. This is both a challenge and an opportunity for HP operators responsible for large reservoirs.

In the past, the existing HP reservoirs have been used predominantly to generate electricity and, as a second important inherent service, to reduce flooding

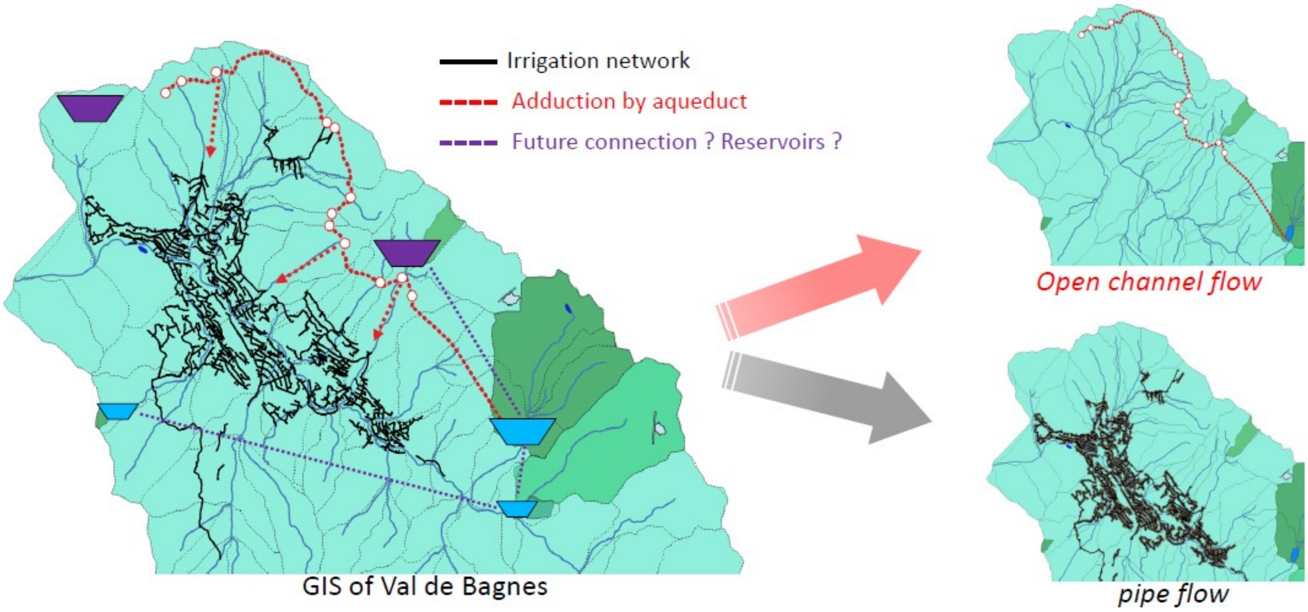


Figure 10: *Water network modelling of Val de Bagnes (Schmid et al., 2019)*

in downstream areas. With a more frequent occurrence of droughts and associated water shortage, the provision of water from HP reservoirs for irrigation, industry or public water supply is probable to become an issue. A recent study (Brunner et al., 2019) has demonstrated that for Switzerland the Aare catchment, which has the most noticeable potential water shortage in the agricultural Seeland region, is also best suited to exploit HP reservoirs for ancillary water supply. However, such a service would request proper regulations for the routing of water to the location where the water is needed and for the financial compensation of HP operators.

A provision of multipurpose-services (for other sectors) could become particularly important when new HP reservoirs (or dam-heightening projects) are promoted or concessions have to be renewed as a convincing argument in the political discussion.

As a test case, in the context of the expected climate change impact in Alpine regions on the availability of water resources, a research project in the Val de Bagnes (VS) is on-going to develop a decision support tool for the management of water reservoirs and a general planning of the irrigation network. Models of the water supply, water transfer and distribution networks for irrigation, artificial snow making, drinking water and energy have been set up (Figure 10).

The study of Schmid et al. (2019) highlights (i) the key role of multipurpose reservoirs for seasonal uses and storage; (ii) the need to connect existing reservoirs or construct new ones seizing the opportunity of melting glaciers; and (iii) a potential future conflict in the concurrent uses of water for irrigation and hydroelectricity.

3.2.3 Contributions to Protection from Natural Hazards (other than Floods)

Reservoirs in high mountain areas are located in a changing environment. The deglaciation holds both risks and opportunities for existing as well as future HP infrastructure (Haeberli et al., 2016). Its periglacial environment is increasingly affected by mass wasting processes. In addition to snow avalanches and glacier break-offs, unstable slopes previously supported by glacier ice and the thawing of permafrost due to rising mean air temperatures pose a risk (PERMOS, 2019). If these very rapid slide masses enter a reservoir, tsunami-like impulse waves are generated (Evers et al., 2019a). Moreover, potential risks also include glacial lake outburst floods, which may be triggered e.g. by slide impact into pro-glacial lakes (Westoby et al., 2014), potentially causing extreme flood loadings multiple times larger than those of seasonal floods on hydraulic structures of downstream reservoirs (Meon and Schwarz, 1993; Cenderelli and Wohl, 2001; Schwanghart et al., 2016). Designed accordingly, reservoir infrastructure can withstand and mitigate these direct and indirect hazards related to mass movements, thereby protecting downstream areas.

Slide-induced impulse wave events involve a process chain of three stages: wave generation, wave propagation and wave-shore/structure interaction (Evers et al., 2019b). All stages need to be quantified in detail to assess the hazard for the shore and adjacent infrastructure (Evers et al., 2018). In reservoirs, the dam structure as the shore segment with the lowest elevation is particularly endangered and can already be overtopped by comparatively small waves (Kastinger et al., 2020). For operational matters it is therefore necessary to take the waves caused by smaller and hence more frequent slides into account for the freeboard dimensioning. While a freeboard set too large would imply a loss in storage volume, overtopping water masses at the dam crest could be the result of a freeboard chosen too small. In proglacial lakes, overtopping of the moraine dam could create an incision channel in the dam crest, initiating a dam breach, i.e. a progressive failure of the embankment leading to an outburst flood (Westoby et al., 2014; Huber et al., 2017). Designed as multipurpose infrastructures, reservoirs may be directly constructed at the site of proglacial lakes to fulfill both flood protection and energy production purposes. In case of reservoirs downstream of glaciers, freeboard and spillway dimensioning need to consider these additional load cases.

4 Conclusions

Herein, the hydropower generation and storage potential in three scenarios, from lower-bound to upper-bound, is summarized. In the upper-bound scenario the expected annual generation of 39.1 TWh/a slightly exceeds the target of 38.6 TWh/a as defined by the Swiss energy strategy 2050. However, in the lower-bound scenario the hydropower generation is expected to decrease to 33 TWh/a, clearly missing any expansion targets. The expected additional winter generation of 2.8 TWh/winter does not meet the recommendations of the grid operator, even for the upper-bound scenario. The main challenges arise from the market conditions and regulatory framework as well as the conflict of interest with environmental needs. Contrary, retreating glaciers and increasing need for multipurpose use such as irrigation present new opportunities for Swiss hydropower. Additionally, on-going research activities help to increase hydropower flexibility, thereby improving grid stability.

The numbers on potential generation and storage changes discussed in Section 2 are summarized in Table 6. To account for the period of the year when electricity is generated, both the annual and the winter semester data are shown (in TWh/a and TWh/winter, respectively). In addition, the energy storage increase in HP reservoirs is given in energy units (TWh) and total volume (Mio. m^3), rounded to 100 GWh and 10 Mio. m^3, respectively. The following assumptions have been made (see annotation in Table 6):

a) Annual generation: Lower/upper bounds according to SFOE (2019d) without accounting for Oberaletsch, Gorner and Trift periglacial HPP, intermediate scenario linearly interpolated; winter generation: 40 % of the annual generation (45 % share for run-of-river and 55 % for storage HP; run-of-river with 1/3 of annual generation in winter semester, 2/3 in summer; storage HP 50/50); storage: negligible additional storage, as mainly run-of-river plants are assumed, storage HP is considered separately
b) Annual generation: upper bound with a likelihood of realization (LoR) of 2/3 of 1200 GWh/a (20 best-rated sites without protected sites, see 2.1.1), intermediate scenario with LoR=1/3, lower bound with LoR=0; winter generation: analogue, 60 % of annual generation; storage: analogue
c) Annual generation: Lower bound according to SFOE (2019d) (see Section 2.2.1), upper bound according to SWV (2016a) (mean value from scenario ii, see Section 2.2.1), intermediate scenario linearly interpolated; winter generation: 40 % of annual generation; storage: negligible additional storage, as mainly run-of-river plants are assumed, storage HP is considered separately
d) Annual generation (see 2.2.2): +2 % for half of all reservoirs (upper bound), +1 % (intermediate scenario), ± 0 (lower bound); winter generation and storage: all additional storage will be turbined in winter; lower bound Grimsel reservoir only, upper bound LoR=2/3 of scenario 1, intermediate scenario linearly interpolated
e) Annual generation (see 2.3): lower bound according to SWV (2016b), upper bound according to both SWV (2016a) and SFOE (2019d), intermediate scenario linearly interpolated; winter generation: 40 % of annual generation; storage: no additional volume, but increase of stored energy is tranferred as %-increase of yearly generation
f) Annual generation (see 2.4.2): lower bound: consideration of flow requirements for wetlands of national importance according to Pfammatter and Wicki (2018), intermediate scenario: consideration of minimum flow depth for migration of brown trout and lake trout (Pfammatter and Wicki, 2018), upper bound: according to SFOE (2019d); winter generation: 40 % of annual values; storage: negligible changes are assumed as the reservoirs will still be filled
g) Annual generation (see 2.4.3): lower and upper bounds and average scenarios; winter generation: 40 % of annual values; storage: negligible, as mainly run-of-river plants are considered

The target of the Swiss ES2050 to increase HP generation by 2.8 TWh/a with reference to 2019 (38.6 TWh/a in 2050 compared to 36.0 TWh/a as of 1.1.2019) will only be met in an upper-bound genera-

Table 6: *Expected changes until 2050 in HP generation and storage for three scenarios. Green = ES target value for annual production met, red = ES target value for annual production not met.*

Increased or reduced generation and storage (with reference to 2019) due to ...	annual generation [TWh/a]			winter semester generation [TWh/winter]			stored energy / storage volume [TWh / Mio m³]						Anno-tation
scenario	lower	interm.	upper	lower	interm.	upper	lower		interm.		upper		
... new small- and large-scale HPP (except periglacial HP)	0.7	1.2	1.7	0.3	0.5	0.7	-	-	-	-	-	-	a)
... new HP storage plants in periglacial environment	0	0.4	0.8	0	0.2	0.5	0	0	0.5	200	1.0	400	b)
... upgrade and extension of existing HPP	0.4	1.0	1.5	0.2	0.4	0.6	-	-	-	-	-	-	c)
... dam heightening	0	0.1	0.2	0.2	0.8	1.5	0.2	80	0.8	280	1.5	470	d)
... renewal and refurbishment of existing HP schemes	0.5	0.8	1.0	0.2	0.3	0.4	0.1	-	0.1	-	0.2	-	e)
... increased residual flow releases according to Waters Protection Act	-3.6	-2.5	-1.9	-1.5	-1.0	-0.8	-	-	-	-	-	-	f)
... fish protection and downstream migration measures at run-of-the-river low-head HPP	-1.0	-0.4	-0.2	-0.4	-0.2	-0.1	-	-	-	-	-	-	g)
Total changes	-3.0	0.5	3.1	-1.0	1.1	2.8	0.3	80	1.4	480	2.7	870	

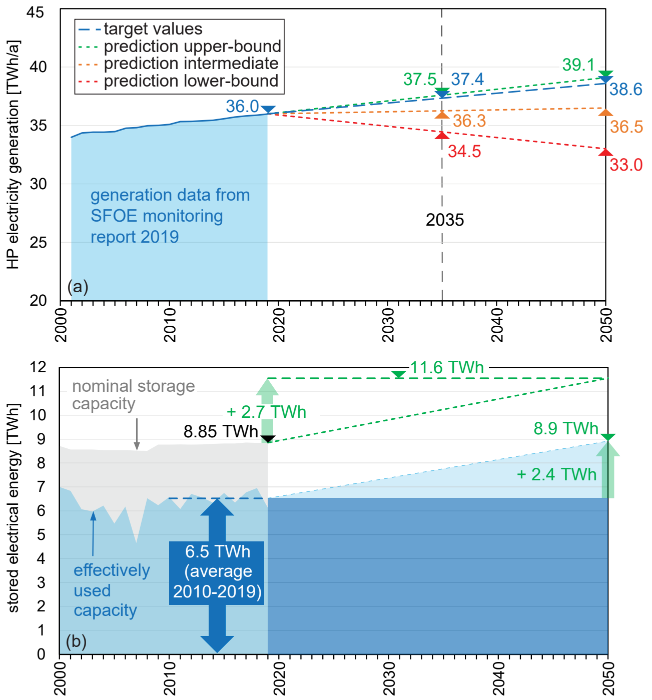


Figure 11: *(a) Hydropower generation: data from 2000 to 2019, target values for 2035 and 2050 (blue) and potential development for a lower-bound (red), intermediate (orange) and upper-bound (green) scenario. (b) Hydropower storage: data from 2000 to 2019 and potential development under an upper-bound scenario for nominal and effectively used capacities*

tion scenario (Table 6, Figure 11a). In a lower-bound scenario, the annual HP generation would decrease by -3.0 TWh/a or approximately -8 % of the 2019 generation. In an intermediate and likely more realistic scenario, the generation potential decrease due to environmental legislation would be countered by extension and new constructions of HPP and – for storage SHP – their reservoirs.

The winter generation is expected to increase by 1.1 and 2.8 TWh/winter in an intermediate and upper-bound scenario, respectively, thus contributing to, but not reaching the target of increased winter semester generation of at least 5 TWh/winter recommended by ElCom (2020) until 2035. The lower-bound scenario would see a decrease of winter generation by 1.0 TWh/winter.

The energy stored in HP reservoirs is likely to increase by 0.3 to 2.7 TWh until 2050 (Table 6). The current Swiss storage potential amounts to 8.85 TWh, of which 6.5 TWh (73 %) have been effectively used in the last decade on average (SFOE, 2019a) (Figure 11b). For new reservoirs such as those of periglacial HP storage schemes, it is assumed that their share of effectively used storage will also be about 73 %, while the new storage volume from dam heightening and HP renewal and refurbishment will be fully usable. The increase of effective storage potential thus amounts to ∼2.4 TWh, resulting in an upper bound of the effective storage of 8.9 TWh (Figure 11b). The above value of 2.4 TWh represents about 37 % of the current effectively used storage energy of Swiss HP reservoirs of 6.5 TWh and would thus represent a significant increase. In an intermediate and lower-bound scenario the share would amount to 20 % and ∼5 % , respectively.

The mentioned potential increases in HP generation and storage as well as flexibility may support the implementation of the ES 2050 in the following ways:

- The extension of existing reservoirs and new periglacial storage HPP would help to increase electricity generation in the critical winter half year and to integrate a higher share of new renewables by providing storage and flexibility.
- New periglacial HP could contribute to reach ES 2050 targets, while allowing the Swiss HP infrastructure to fulfill higher ecological exigencies; new periglacial HP is a new opportunity which could partly compensate the expected future genera-

tion reductions of existing HPP.
- Increased flexibility is an enabler of the integration of new renewables and greatly strengthens the resilience of the Swiss electricity system.
- The upgrading and digitilization of the Swiss HP fleet and its electro-mechanical equipment will help to foster versatility and reduce operation cost.

5 Recommendations for Policy Makers

Based on the studies conducted and experience gained within eight years of research and development in the hydropower domain in the framework of SCCER-SoE, our recommendations to decision makers in terms of priorities and next steps to take are given herein. In short, we see ways to slightly extend hydropower generation and storage in Switzerland while being compatible with the needs of enhanced aquatic ecology in hydropower-regulated watercourses. By extending some existing schemes and implementing new ones, it would be possible to compensate generation reductions of existing hydropower plants to meet stricter ecological goals. Nevertheless, sustaining and possibly extending hydropower generation and storage requires a focused effort from all stakeholders involved.

Thanks to its flexibility and storage options at multiple scales, from milliseconds to seasons, hydropower is the backbone of the Swiss electricity system. Keeping its central role would foster the integration of volatile renewable energy resources like photovoltaics and wind. However, hydropower production strongly affects riverine ecosystems, e.g., by disrupting longitudinal connectivity, modifying discharge and sediment dynamics, and creating residual flow reaches. Environmental legislation aims at mitigating these impacts. Besides that, comprehensive planning of usage and protection (*"Schutz- und Nutzungsplanung"*) is an important tool for setting priorities for both river protection and hydropower development. The renewal, upgrade, optimization and extension of hydropower facilities is fundamental with respect to the ES 2050 and under the constraints of reducing environmental and climate change impacts by the Swiss electricity system. A combination of these hydropower options would allow to meet the targets of the ES 2050 as to hydropower generation. However, additional seasonal storage is at least as important as additional generation, because it compensates fluctuating resources and allows to significantly increase national electricity generation in the critical winter half year, decreasing the risk of import shortages. To reach these targets requires a number of measures:

- Before realizing new green-field projects, which are risky and time-consuming, existing HP plants should be renewed, upgraded and – if possible – extended (including dam heightening) to make optimal use of their generation and storage potentials.
- New hydropower schemes (including reservoirs) at sites of today's glaciers that will disappear in the near future due to ice melt should be studied, and selected projects be realized after careful weighting of sustainability criteria in a participatory process, again on the concept of protection and usage of watercourses.
- As the realization of both new constructions and extensions of existing hydropower facilities may take 15 years or more, it is recommended to further study such projects as soon as possible.
- A combination of renewal, refurbishment, extensions and new hydropower constructions will be needed to reach the ES 2050 goals. To enhance corresponding investments, this will likely require incentives, e.g. by higher tariffs for storage and winter generation, and regulations.
- The mentioned hydropower projects should be realized on a priority scheme based on sustainability criteria. Thereby, the specific ecological footprint of the projects should be taken into account, which tends to decrease with increasing scale.

To achieve the mentioned goals and enhance the sustainability of hydropower, further research and studies are needed on

- effects of climate change on hydropower,
- sustainable sediment management,
- structural adaptations and dam safety,
- multipurpose projects,
- ecological effects of hydropower, especially at the catchment scale,
- effectiveness of environmental mitigation measures,

- energy system modelling,
- feasibility of new technologies and exemplary projects (pilot and demonstration),
- legal aspects of new hydropower/multipurpose schemes in protected areas,
- economic conditions required to realize new projects (with participation of hydropower operators/owners),
- coordination with transmission line capacities.

We also deem further capacity building necessary, as successfully done in other countries with a large hydropower share in the electricity generation portfolio (e.g. Norway), particularly

- to educate and train engineers to cope with the future challenges. This will require high-level education programmes delivered mainly by the two federal institutes of technology, EPFL and ETH Zurich, and a number of universities of applied sciences.
- in the form of long-term competence centers for coordination of research and development and for knowledge transfer,
- to foster exchange with the knowledge of Swiss as well as international industry and engineering consultants.

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