Adaptation of Swiss hydropower infrastructure to meet future electricity needs

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1. Introduction

The Swiss energy transition is defined in the so-called "Energy Strategy 2050" (SES2050) initiated in May 2011 after the Fukushima nuclear accident [*Swiss Federal Council*, 2013]. Swiss electricity production currently essentially relies on hydropower and on nuclear power (Table 1). The SES2050 prescribes a gradual nuclear power phase out and a substantial reduction of greenhouse gas emissions, relying on an increase of energy efficiency and of renewable energy sources, which currently represent a particularly low share compared to neighboring countries (Table 1). To reach the ambitious goal of a complete nuclear power phase out, the Swiss Government is funding a number of competence centers for research on key energy issues (SCCERs), including one on the Supply of Electricity (www.sccer-soe.ch), with the aim to develop fundamental research and innovative solutions in the fields of geo-energies and hydropower.

Hydropower is already the major source of electricity in Switzerland, corresponding to approximately 55% of the total national electricity production, which was 70 TWh in 2014 [*Swiss Federal Office for Energy*, 2014]. The SES2050 foresees an increase of annual hydropower production by 5% to 10% in average hydrological conditions until 2050, in a context where almost all major river systems are already exploited. However, part of this increase is expected to merely compensate for the pending application of recent environmental laws, which will impact (reduce) the hydropower production from existing schemes. An additional decrease of net electricity production is expected from the increase of pumping consumption required for grid regulation. In this context, a net hydropower production increase by at least 1.53 TWh/y under actual usage conditions and 3.16 TWh/year under improved conditions is targeted [*Swiss Federal Council*, 2013]. This hydropower production increase is assumed to effectively contribute to secure the Swiss energy supply, in combination with the planned increased energy production from other renewable energy sources (RES) and with the targeted reduction of country-level energy consumption and increase of energy efficiency.

Table 1: Electricity supply in year 2012 of Switzerland and neighbouring countries (in % and in TWh/y), source: [*Densing et al.*, 2014]; other renewables include biomass, sun and wind.

Country	Fossil		Nuclear		Hydro		Other renewables		Net import		Demand	
	%	TWh/a	%	TWh/a	%	TWh/a	%	TWh/a	%	TWh/a	%	TWh/a
Switzerland	3	2	37	24	61	40	3	2	-3	-2	100	66
Austria	23	17	-	-	63	48	10	7	4	3	100	75
Italy	55	181	-	-	12	41	19	63	13	43	610	34
Germany	10	48	81	405	13	64	5	25	-9	-44	100	497
France	60	361	16	100	4	22	24	147	-4	-23	100	607
All above countries	39	610	34	528	14	214	16	244	-1	-23	100	1573

In this contribution, we present the innovation roadmap of the SCCER-SoE (2014) aiming at unraveling currently non-exploited hydropower potential and reducing energy losses, in particular in river systems that are already used for hydropower production. The resulting better understanding of the current potential is paramount to justify upcoming adaptations of the existing hydropower infrastructure and hydropower usage conditions. Potential adaptations include among other solutions the increase of storage with heightening of existing dams, the increase of the installed capacity at existing schemes, new connections between existing reservoirs by pumped-storage as well as harvesting the potential of new glacier-melt lakes [Nelak, 2013]. The overall goal of these adaptations is to increase the operational flexibility in a highly elastic electricity market and to meet ever more challenging ecosystem protection requirements. Innovative solutions are being devised to harvest new streamflow patterns emerging under an evolving climate and in particular in the context of the ongoing glacier retreat and the ensuing streamflow regime changes. [*Addor et al.*, 2014; *Horton et al.*, 2006].

2. Swiss hydropower infrastructure

Overview

Swiss hydropower infrastructure produces around 37 TWh from the 1450 mm of annual precipitation, leading to 1300 mm average annual runoff of Swiss rivers [*Blanc and Schädler*, 2013]. Storage plants are located in the southern and central mountain regions, whereas run-of-the-river plants are predominantly located on the so-called Swiss Plateau, referring to the lowlands extending from Geneva to Lake Konstanz and in the Jura mountains.

The largest part of the generation capacity is installed in the Cantons of Valais and Grisons, where the sources of the rivers Rhone and Rhine are located. The hydropower generating facilities include 640 power plants [*SFOE*, 2015], 125 large dams and generated on average 37 TWh/a over the period 1997-2014 (with a maximum of 42.3 TWh in 2001 and a standard deviation of 2.7 TWh/a [*SFOE*, 2014]. Table 2 presents a breakdown of hydropower facilities, in terms of average annual production as compared to other types of power plants.

Generally, Switzerland is an annual net exporter of electricity, with few exceptions like the years 2010 and 2011. This has been a source of revenues for the domestic economy, dividends spilling down to a large number of public entities that control the capital of the electricity utilities.

The downside of the picture is that Switzerland is a net importer of electricity during the winter semester: a deficit of 2 to 4 TWh was observed in the past 11 winters (*Swiss Federal Office for Energy*, 2015). Despite not being a major supply issue in itself it raises concerns about the ability of Swiss players to master, if not at least to influence, the supply chain and costs during the winter months and its consequences on the annual balance of external trading and dividend sharing.

Table 2. Swiss electricity power plants: five-year summary of annual production and external trading (source: Swiss Federal Office for Energy, electricity statistics, bulletins 2010 to 2014)

Domestic production (in TWh), civil year	2014	2013	2012	2011	2010
Hydropower	39.3	39.6	39.9	33.8	37.5
Run-of-the-river plants	17.2	17.8	17.8	14.7	16.0
Storage plants	22.1	21.8	22.1	19.1	21.4
Nuclear	26.4	24.8	24.3	25.6	25.2
Conventional thermal and others	3.9	3.9	3.8	3.5	3.6
Total production	69.6	68.3	68	62.9	66.3
Annual balance external trading					
in TWh (-/+; imp/exp)	5.5	2.4	2.2	-2.6	-0.5
in million CHF (-/+; imp/exp)	442	327	771	1018	1328

Top-class asset management with potential for improvement

The Swiss hydropower infrastructure is considered being among the best maintained worldwide [e.g. certified ISO 55’001, *ALPIQ*, 2015]. However, due to the diversity of operation conditions (e.g. young geology, local climate) not all runs perfectly. Some schemes show *waterspills* every summer due to inability to store any further or turbine. For instance, run-of-river schemes have seen, since WWII, a significant increase of the number of storage power plants that modify the natural upstream discharge. Between the 1950's and the 1990's these RoR plants benefited from the increase in winter base flows, increasing their revenues. However, as upstream storage plants started concentrating their production on a few hours per years (typically 2-3 hours and with 3 to 30 turbine starts per day), downstream run-of-river power plants are sometimes not equipped to absorb the resulting discharge peaks and therefore end up spilling occasionally in the winter semester. Installing higher discharge turbine units or additional turbine units is thus under consideration at several locations (e.g. Lavey) and has been done recently in others (e.g. Augst, Hagneck).

Other schemes waste valuable water during non-optimized sediment flushing. Mid-altitude schemes are more exposed to bed load sediment transport and not all of their dams operate properly in terms of *sediment flushing or by-passing*, leading to a reduced live storage volume. On the other hand, altitude reservoirs are silting up at an estimated rate of storage loss of 0.2%/a (Jenzer-Althaus 2011), reducing *live storage*, which is particularly dramatic in smaller (and shallower) reservoirs.

Powerplant *availability* could still be improved with regards to planned maintenance works on waterways and powerhouse units despite top-class practice. Delays for resuming operation after accidental outages could be shortened if supported by the TSO or the regulator. Furthermore, often there is no *redundancy* at waterways or, in the case of smaller schemes at water intakes and turbine units. Maintenance outside low-flow season or renovation means loss of production and revenues. Redundancy implies investment, but secures production and the stream of revenues. Waterway redundancy can even lead to energy recovery, due to reduced friction losses.

Powerplant *flexibility* could also be improved, in particular in high-head storage schemes that play a central role in grid stabilization. These schemes are paramount to regulate the grid but their operation is being limited either the high head losses in the power waterways, limiting the discharge, or by the hydropeaking surge characteristics in the tailrace river reach downstream.

3. The energy strategy for 2050

Swiss domestic strategy and future electricity needs

Similar in general to the European Union's (EU) climate and energy policy, the SES 2050 launched by the Swiss Federal Government is based on the overarching objectives to build an affordable, secure and sustainable energy system, reducing CO2 emissions and reducing the residual risks associated with nuclear power plants (NPPs). The implementation of this strategy consists of a gradual phase out of NPPs, an increase of energy efficiency and of renewable energies. To assist in implementing this strategy, a nationwide research program on energy was launched in 2014, with the creation of eight Swiss Competence Centers for Energy Research (SCCERs), including one specifically for Supply of Electricity (SoE) dealing with hydropower and geothermal issues.

Based on the SES2050, different consulting companies and research institutes elaborated a range of model-based scenarios of future energy demand and future supply mix. According to the review of Densing et al. [2014] none of these studies properly modeled the electricity grid or considered future market configurations. As an example, the study elaborated by Prognos AG on behalf of the Swiss Federal Office for Energy, SFOE [*Prognos AG*, 2012b] considers three electricity demand scenarios (business-as-usual, new energy policy, additional policy measures). The *business-as-usual* scenario assumes that already existing policy instruments and legal constraints remain unchanged or are only slightly adapted to technological progress and that the energy consumption follows the same pattern as today. The *additional measures* scenario considers the quantitative effect of the policy measures describe hereafter [see "Erstes Massnahmenpaket in Kürze", *Swiss Federal Council*, 2013]. Contrary to these two instruments-oriented scenarios, the *new policy* scenario is a target scenario that shows how the target of 20% CO2 emission reduction could be reached (including international collaboration aspects).The resulting assumed future energy demand is summarized in Table 3.

Table 3: Assumed future energy demand in TWh [*Prognos AG*, 2012b]

	2000	2010	2020	2035	2050
Business-as-Usual	215.8	233.6	218.9	196.1	182.8
Additional Measures	215.8	233.6	213.1	177.5	156.9
New Policy	215.8	233.6	203.9	152.5	125.3

On the supply side, Prognos AG [2012b] presents four supply mix scenarios, where nuclear power is replaced at different degrees by renewables (sun, wind, geo-energies, hydro), combined-cycle gas turbines, decentralized combined-heat power plants and imports. The potential of hydropower production increase was assumed to be up to +8.55 TWh/a. (including 3.5 TWh that would be consumed in pumping), [*Swiss Federal Office for Energy*, 2013, Table 12]. Based on the Prognos study [*Prognos AG*, 2012b] and considering all available inventories of large and small hydropower plants and their public acceptance, the SFOE [*Swiss Federal Office for Energy*, 2012] re-evaluated the Swiss hydropower potential and established two consolidated scenarios of net production increase for 2050 with respect to the current expected annual hydropower production (35.3 TWh/a): scenario one considers an increase of 1.53 TWh/a by 2050 in today's usage conditions, scenario two considers an increase of 3.16 TWh/a under optimal economic and socio-political conditions (but without lowering any ecological constraints).

The main challenge in working towards the SES2050 is to overcome the emerging conflict between the energy strategy and the protection of climate on one hand, the protection of the environment and the landscape on the other hand, and this in a context where the vast majority of the hydropower potential is already used. With what is called the first set of measures, the following goals should be reached [*Swiss Federal Council*, 2013] at the horizon 2020:

- Decrease average final energy consumption per inhabitant per year by 16% compared to the reference year 2000, i.e. reach a level of 213 TWh/a at country level in 2020;
- Decrease the average yearly electricity consumption per inhabitant by 3% compared to 2000, which would result in an annual consumption of 59 TWh/a and in a total country-wide consumption of 64 TWh;
- Increase the average annual electricity production from renewable energies other than hydropower to at least 4.4 TWh/a;
- Increase the average annual hydropower production at least to 37.4 TWh by 2035 (note the horizon difference). For pump-storage schemes, only the production resulting from natural water inflows is included.

The measures foreseen by the Federal Council to reach these goals are divided into the fields of energy efficiency (buildings, industry, electrical devices, mobility), renewable energies (taxes, legal aspects, land use planning, approval procedures), optimization of feed-in tariffs (new subsidy system), fossil fuel power plants (favor the development of combined-cycle gas turbine schemes) and electricity grids (legal and administrative procedures, smart meters).

It is noteworthy that the message of the Federal Council also includes the very general intention to examine how the electricity market could be influenced to reach a more appropriate remuneration of the capacity and the flexibility of electricity storage schemes.

European Union 2050 energy strategy and its implications for Switzerland

The EU's strategy for the energy sector has one main drive: the reduction of greenhouse gas emissions [*European Union*, 2011]. The EU has set itself a long-term goal of reducing greenhouse gas emissions by 2050 by 80-95% with respect to 1990 levels. It is explicitly mentioned that the strategy counts on the continuous operation of the existing nuclear power plants. Shutting down French, Spanish, British, Swedish, Bulgarian and other EU member states nuclear power plants is not on the agenda. Also mentioned is the intention to increase penetration of the so-called new renewable energy sources, also on electricity production, such as solar photovoltaic, biomass (including from algae) and maritime plants. In practical terms, the short-term plan is replacing low-efficiency thermal plants (using coal and fuel) by more efficient gas-fired plants.

Swiss hydropower producers are already facing fierce competition from a combination of low-cost nuclear power from France, competitive and reactive gas-fired plants and low cost (due to high rate of public subsidizing) solar power and coal power from Germany and Italy. Among others, the reduction of Italian imports of electricity will put further pressure on Swiss hydropower revenues, so far still positive (Table 2). Not being a member of the EU, Switzerland has limited market access (e.g. *high nominating time*), cannot influence the EU's energy strategy and remains aside closely following the events unfolding next door. In order to increase the chances of remaining a winner, or guaranteeing win-win developments, the Swiss hydropower sector must remain competitive, increase efficiencies, flexibility and availability.

Hydropower in the European Union's energy transition and implications for the Swiss hydropower sector

At EU level policy makers recently agreed on binding targets for 2030 in terms of greenhouse gas reduction, for the increase of the renewable energy share and of the energy efficiency [*European Council*, 2014]. Similar to Switzerland, most of the hydropower potential is already used at EU level, producing roughly 380 TWh/a in the EU-

28 or around 13% of European electricity [*Mennel et al.*, 2015] [1]. Despite this relatively low share, hydropower plays an important role in the European energy transition thanks to its flexibility and its storage capacities. In addition, as pointed out by Mennel et al. [2015], hydropower plays an economic role that is several times higher than what its production share might suggest. And, contrary to the situation in Switzerland, many large hydropower reservoirs are multipurpose reservoirs used for drinking water, agriculture and industry, providing additional benefits to society.

Current EU-wide electricity scenarios assume that hydropower production will remain fairly constant at the horizon 2100, while wind, sun and gas are supposed to strongly increase and represent the biggest electricity source [*Château and Rossetti di Valdalbero*, 2011, Fig. 1.48]. A notable exception are regions that have already a high share of hydropower production, namely high latitude countries and Austria, which shows a setting comparable to Switzerland in terms of hydropower production, with over 50% of annual electricity production produced by hydropower plants and almost 90% of all renewable energy originating from hydropower [*Fruhmann and Tuerk*, 2013]. A special case is Turkey, which will significantly increase hydropower generation in coming years [*Mennel et al.*, 2015].

It is noteworthy that, similar to the situation in Switzerland, the issuing of new hydropower concessions and of pumped-storage concessions is controversial in many EU member states because of the conflicting policies in the field of climate and nature protection, which in the field of hydropower decision-making are namely the Water Framework Directive (2000/60/EC), the Habitats Directive (92/43/EEC) and the Renewable Energy Directive (2009/28/EC).

The foreseen energy transition implies a profound modification of electricity production and grid load patterns, with the disappearance of base load plants, replaced by fast, load following gas power plants. The resulting key challenges are how to handle production security and grid stability. *Hydropower storage* can play a central role in storing electricity from sub-daily to seasonal scales. However, to date there is no general agreement on the potential role of hydropower storage in the future EU energy system. In fact there is not one system but rather a composition of poorly interconnected regional sub-systems, each one requiring frequency and voltage balancing. *Pumped-storage hydropower plants* are generally seen as one of the cheapest and most flexible solutions for these issues, suitable for daily and sub-daily operations, capable of temporarily storing (excess) energy produced by other renewables for later use when this energy provides the highest value for the system.

At a supra-regional level, large Swiss and Austrian Alpine storage reservoirs already contribute to ensure electricity production security during periods of extremely low renewable energy production in Germany [*Kammer et al.*, 2015]. Together with the contribution of Italian hydropower plants, this role is expected to increase in the coming years , due to the increasing penetration of intermittent renewable energy sources like solar and wind [*Mennel et al.*, 2015]. However, assessing the potential role of Alpine storage for international energy exchange, considering today's and tomorrow's climate, economic and grid constraints is still extremely challenging and research in this field is just emerging [*François et al.*, 2014, *Moser et al*. 2014].

4. Swiss hydropower roadmap

The roadmap for the coming 10 years [*SCCER-SoE* 2014] replies to a wide range of challenges: infrastructure ageing, unfavorable market and unsustainable financial margins, non-consensual climate change scenarios, new environmental legislation, concession renewal and the increasing penetration of new renewables like wind and solar. As discussed hereafter, these challenges can either be seen as opportunities or threats to hydropower.

Climate change

State-of-the-art climate projections do not anticipate a significant change of annual water resources availability in Switzerland until 2035, apart from temporary increases of summer stream flows in heavily glaciated catchments [e.g. *Addor et al.*, 2014]. In the long term (by 2085), the available water resources might decrease slightly. The seasonal distribution of runoff (runoff regime) will, however, shift almost everywhere in Switzerland [*SFOEN*, 2012]. The ongoing warming in Alpine areas namely leads to reduced snow accumulation in winter, early snow melt in spring and enhanced net ice melt during summer. These effects are nowadays fairly well understood and monitored. The related discharge regime scenarios are an integral part of the Hydropower Roadmap. On the contrary, climate change effects on sediment loads are yet to be understood, and carrying out research activities on

[1] According to Mennel et al. (2015a), the corresponding numbers for "larger Europe" including the EU-28, Norway, Turkey and Switzerland are 660 TWh/a of hydropower production or 18% of annual electricity production.

this topic is one of SCCER-SoE's priorities. The impact of climate change on hydropower related natural hazards will not be addressed within this project.

Market constraints

In recent years, the selling prices of electricity in the Central European Electricity market EEX have fallen significantly, in general [*Energy Brainpool*, 2013] to values as low as those of 2002 when the EEX was created. Such low prices reduce the financial margin of the share of electricity from hydropower production sold in these markets. Any economic feasibility analysis carried out solely on this basis will conclude with no surprise that new power schemes would be unviable. However, hydropower utilities sell often part of their production directly to end clients (large consumers) using long-term contracts, and provide ancillary services to the grid, which may be remunerated. These two remuneration sources are vital for hydropower feasibility.

The remuneration of long term contract is not immune to the unfolding events in the EEX market. The relative impact of low sell prices on large hydropower utilities is function of their energy placing strategy and market position. Companies with a vertical integration between production and distribution are less exposed to price fluctuations than those without electricity distribution. However, even those producers who sell the most of their production through long term contracts endure the pressure of falling prices, although with some time lag, depending on the tariff revision mechanisms. The time required for any electricity producer, and not only those producing hydropower, to adjust their long-term contracts is in any case short compared to the time required to deploy new hydropower infrastructure projects.

A detailed discussion of the remuneration of ancillary services goes beyond the objective of this paper. In general, hydropower producers might receive additional remuneration for the following services: the availability of installed capacity (MW), its readiness (or its role in primary, secondary and tertiary regulation) or the value of the guaranteed future production in terms of water storage (in TWh) for grid stability and for supply security [*Beck and Scherer*, 2010, *Zucker et al.* 2013]. In particular hydropower storage plants are eligible for the remuneration of such services. Unfortunately *flexibility* has not yet a price at the spot market.

The economic feasibility of the extension and of the rehabilitation of existing storage plants is subject to different constraints to those of low-head RoR. Extension projects represent an increment to an existing running business; accordingly, part of the new facilities will benefit from existing infrastructure, already paid off or accounted for elsewhere. This brings cost prices of extension projects down. For rehabilitation projects no general rule can be identified since every project has very specific characteristics. Their economic feasibility depends largely on the costs of the rehabilitation concept. Limit cases are 1) the rehabilitation with full production stoppage, demolition and reconstruction of new structures, as compared to 2) the sequential rehabilitation without stoppage, with progressive overhaul of key structures and equipment, which, in fact, is similar to multiplying smaller extensions (which are possible if no operation restrictions are necessary).

The market pressure on new small hydropower plants is lower than for the other hydropower plants due to the existing feed-in-tariff (FIT) scheme [*SFOE*, 2015] which remunerates production at cost price levels. The existing framework has recently been modified, having the contract durations been reduced from 25 to 20 years and been compensated for the preferred installed power ranges by a slight increase in remuneration. One of the particularities of the Swiss feed-in tariff policy is that it provides a bonus for previous investments on the water supply facilities (typically the penstock, the weir and water intake), accounted for as new investment in terms of their residual value after 30 years considering a linear depreciation. Despite of such favorable context, small hydropower plant development remains cumbersome. These plants are often in direct competition with many other territorial usages and the promoters with many other riverine stakeholders. The public services are flooded with requests. The minimum power for an eligible application has been raised from 100 kW to 300 kW, as of January 2014.

Renewal of large HPP concessions

Most concessions for large hydropower plants have historically been awarded in Switzerland for 80 years. The first examples of concession renewals took place in the 2000's. When renegotiating concessions the HPPs are being asked to step up and comply with recent legislation (e.g. the Water Protection Act from 1991), in particular in terms of residual (or ecological) flow (this issue is discussed further below) and fish migration, which inevitably leads to additional water releases often without energy production. Concession renewal has also seen the local municipalities recovering control of hydropower companies outpacing the large regional and national electricity utilities (e.g. Fully).

The majority of run-of-river plants were built before the 1950's and their concession terms have already been renewed. In most cases (e.g. Augst, Rheinfelden, Ruppoldingen) increased residual flow in combination with fish migration measures were implemented and the turbine units were replaced, but in some cases the powerhouse was entirely rebuild (e.g. Hagneck, with a production increase of 35%). These schemes are thus most of them compliant with the 1991 law.

Hydropower storage schemes were mostly built after WWII and their concessions end within the period of implementation of the ES2050. The time window available for negotiation is of 25 years before term. The present concessionaires face the double challenge of having to prove efficient use of the concession rights, proposing efficiency gains often through new investments, as well as accepting environmental compliance with modern standards. The present level of implementation of environmental standards is quite varied, as described in the next section. Compliance might come at a high cost if new water releases are not used for electricity production. As an example, in the Canton of Valais/Wallis which has the highest electricity production from storage HPPs (Group I) concessions worth 8 TWh/a will have to be renegotiated between 2015 and 2050 (Cina et al., 2011).

Environmental constraints

At present a significant percentage of the Swiss river network is already influenced in one way or another by hydropower plants operation if not by other industrial uses (e.g. urban and industrial water supply, irrigation). A given number of mountainous streams remains unconcerned by hydropower activities, but it has become difficult to find river reaches without any other anthropic influence. As many other fields of economy and social life, hydropower has been requested over the past 40 years to adjust its practice to comply with legal obligations that reflect societies' growing concerns about the footprint of our activities and their sustainability. In practical terms this means that licensing of new hydropower plants has been subjected to a higher public scrutiny and requested to comply with higher standards, for instance in terms of water withdrawal, water release and interaction with groundwater, as stated in the first edition of the Swiss Waters Protection Act (WPA) from 1991. Nowadays the development of new large hydropower infrastructure is somewhat limited by its potential impact on the landscape and natural reserves, which is regulated by the Nature and Cultural Heritage Act. Opposition to individual hydropower projects may find support on this law but its overall effect on Swiss hydropower production is yet impossible to quantify.

Regarding small hydropower plants, the economic and social/environmental barriers for their development are effectively addressed in Switzerland [*Basso*, In preparation], e.g. through the cost-based feed-in tariff and the involvement of communities in establishing rivers that will be affected by exploitation. A platform promoting dialogue among stakeholders also exists, and research efforts aimed to address rising questions receive support from the Federal authorities. However, conflicts persist between growth of small hydropower, protection of natural creeks and restoration of impaired river reaches required by the WPA [*Federal Assembly of the Swiss Confederation*, 2014]. In particular, the need for a great number of small hydropower plants in order to achieve a significant energy production (due to limited energy generation of single plants) raised public concern regarding local and cumulated ecologic impact on (the remaining) small pristine rivers. However, the conflict seems to concern mainly river in populated areas and not as much the mountainous areas (where landscape and nature issues predominate).

Table 4: Examples of typical operational and structural measures for Swiss HPPs compliance with environmental policy

Issues	Operational measures	Structural measures
Ecological flow release	Quantify present flow releases. Release flows through bottom outlet or other existing outlet.	New outlet for flow release, eventually equipped with small powerhouse to generate electricity.
Fish migration	-	*Upstreamwise:* Contour river, block ramp, fish ladder, fish lift, fish lock or their combination. *Downstreamwise:* Fish-friendly turbine units. Collector channel & gated exit chute. Contour river
Hydropeaking	Sub-optimal turbine scheduling Combined operation of plants for surge mitigation	Compensation basins.
Bed load budget	Bed load dredging and pump outflows. Bed load replenishment. Sediment sluicing (in floods). Drawdown flushing. Monitor-model-mitigate	Bed load by-pass tunnel Gated outlet refurbishment Lowering sill crest levels

Overall the most stringent constraint for HPPs has been the obligation to release a constant minimum flow downstream of the water diversion structures (river intakes or reservoir dam intakes). However, since the majority of existing hydropower production schemes have been built before the Waters Protection Act came into force in 1992, the legal constraints will come into play at latest during their concession renewal or after significant infrastructure modifications.

The latest revision of the WPA in 2014 defines a new framework, which modifies the constraints for hydropower plants in terms of the so-called hydropeaking (variations of river water level due to water release), fish migration, ecological flow releases and bed load budgets. Corrective measures must be implemented within a 20-year deadline. The full implementation of this law is now ongoing. For hydropower schemes this means adjusting to dynamic water and sediment regimes downstream of water withdrawal structures. So far the stakeholders discuss the implementation of operation measures (e.g. turbine sub-optimal scheduling) and structural measures (e.g. fish downstream-migration structures) -

Table 4. Part of the measures are eligible for funding, validated by public authorities but supplying by Swissgrid which is the transmission system operator (TSO).

There is yet no estimation of the cumulated effect of the WPA on electricity generation from hydropower plant, but the sole impact of overall compliance with the minimum water release requirements is expected to reduce the annual hydropower production by 1.4 to 2.0 TWh/a [*SFOE*, 2012] by 2050.

In summary, the changing environmental protection practice is increasing pressure on hydropower producers. From the SES2050 standpoint, pressure can be positive if leading to efficiency gains (e.g. in protection of live storage) but is negative if leading to an overall production (and revenues) reduction from hydropower. Reducing the negative impacts for hydropower production of compliance with the new legal requirements is therefore one main drivers for research within the SCCER-SoE.

Scenarios and targets

The hydropower roadmap of the SCCER-SoE (2015) addresses the main challenges of identifying additional hydropower resources that will lead to a net production increase of up 10% with regards to 2014. This targeted net increase includes the compensation of production losses to be expected from the implementation of the WPA as illustrated in Figure 1 and explained hereafter.

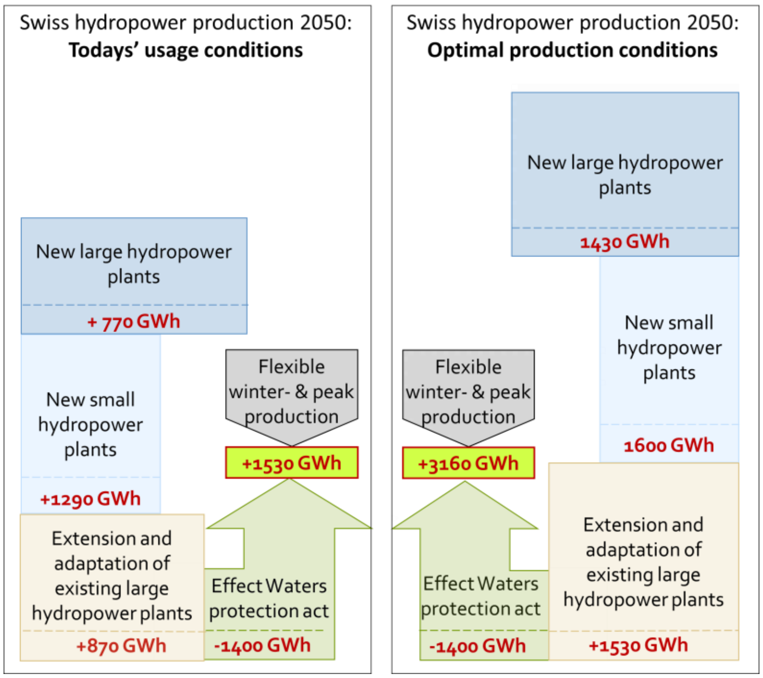

Figure 1: Illustration of the planned net increase of Swiss hydropower production by 2050 under today's and optimal production conditions

In today's usage conditions the adaptation of hydropower schemes may generate an increase in electricity production of about 2.9 TWh/a, out of which 1.4 to 2.0 TWh/a shall be used for the implementation of the Waters Protection Act, leading to a total net production increase of 1.5 TWh/a. This is not enough to guarantee the expected contribution from Hydropower to the SES2050. Should usage conditions be optimized (mainly by reducing inefficiencies) a gross production increase of about 4.6 TWh/a could be reached, which would lead to a net increase of about 3.2 TWh/a considering implementation of the WPA. This is twice the previous result but may still not be enough to achieve the SES2050 main targets if other sources of electricity production do not meet their targets.

New large hydropower plants

The production increase from large hydropower plants should come from a list of few dozen projects identified as being of National Importance (Swiss Federal Office of Energy, 2012), worth between 0.7 and 1.4 TWh/a, depending on the scenarios as presented in Figure 1.

Extension and adaptation of existing large HPPs

This corresponds to the increase of energy efficiency in existing plants, i.e. by decreasing the loss of hydro energy along the entire value chain of hydropower production. In addition to the net annual production increase, the future hydropower production system should also ensure reliable electricity production during winter months (when renewable resources are scarce) and be as flexible as possible to respond to yet unknown, future electricity demand patterns, including climate-related extreme peak demand situations. A more flexible hydropower production focused on peak production requires in parallel the development of innovative measures to reduce adverse effects of hydropeaking on stream ecology and morphology. Strategies to increase production flexibility include (i) the increase of existing storage volume and building of new storage volumes; (ii) the increase of installed capacity by adding new turbine units and waterways; and, (iii), building more compensation basins on the outlets.

Small hydropower plants

The main challenge is the development of site selection methods to ensure optimal production within river networks, with minimal environmental impacts. The potential increase varies between 1287 and 1602 GWh/a [*Swiss Federal Office for Energy*, 2012],of which 60% in five cantons (Valais, Grisons, Uri, Vaud and Bern).

5. Conclusions and outlook

The post-Fukushima decision to embark on an energy turnaround characterized by nuclear power plants phase out is presenting new challenges for the Swiss hydropower sector. The Swiss Energy Strategy 2050 relies on hydro, wind, solar, geothermal, gas-fired plants and demand-side reduction to make ends meet. Switzerland explores already a large share of its hydropower potential and therefore the targeted increase of within 5 to 10% of the multiannual average may seem at first over ambitious in particular knowing that compliance with recently updated environmental standards will generate electricity production cuts. However, positive pressure is making Swiss hydro players change practice and is driving innovation. A new research center has been created to lead research together with the industry. The main goal is to develop innovative procedures, approaches and technologies allowing to maintain and hopefully further increase the present hydropower production level (37 TWh in 2014) by up to 3.1 TWh/a by 2050.

Swiss hydropower stakeholders, private and public, are at a cross roads, facing constraints like infrastructure ageing, enforcement of new ecological standards, unsustainable financial margin in the electricity markets, climate change, market change through grid integration and increasing integration of intermittent renewable plants (solar and wind). Also, part of these changes are taking place abroad in traditional exporting markets for Swiss utilities, which presents the risk of reduced future revenues. Times are challenging. Refraining new investments may represent a danger for the security of electricity supply and would undermine Switzerland's ability to intervene in the European grid. *The existing infrastructure must be adapted such as to guarantee Switzerland's key role in the European electricity grid, both as provider of carbon-free electricity and grid balancing services (a battery with high flexibility)*.

Infrastructure adaptation measures should address first and foremost *storage reservoir* issues. Hydropower storage reservoirs as the main guarantor of electricity supply particularly for winter, considering the variability of climate, market, demand and legal conditions. They are also the most reliable solution to store (excess) energy produced from intermittent renewable plants using solar and wind energy. Secondly, *powerplant flexibility* must be improved, both in terms of turbine operation and mitigation of negative impact of outflow releases to downstream rivers. Turbine operation scheduling must concentrate production on peak hours, which can be facilitated adding new waterways with reduced losses.

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7. References

Addor, N., O. Rössler, N. Köplin, M. Huss, R. Weingartner, and J. Seibert (2014), Robust changes and sources of uncertainty in the projected hydrological regimes of Swiss catchments, Water Resources Research, 50(10), 7541–7562.

Blanc, P., and B. Schädler (2013), Water in Switzerland - an overview, available in English on http://www.naturalsciences.ch/topics/water/ (accessed 18.08.2015)Rep., 28 pp, Bern.

Cina, J.-M., Balet, C., Epiney, S., Escher, R., Favre, M.-H., Métrailler, D., Pralong, J., Truffer, G., Werlen, K., Steiner, M., Zenklusen, I., 2011. Stratégie Forces hydrauliques - Canton du Valais. Objectifs, lignes directrices et mesures.

Château, B., and D. Rossetti di Valdalbero (Eds.) (2011), World and European Energy and Environment Transition Outlook, WETO-T, , 160 pp., European Union, European Commission, Directorate-General for Research and Innovation, Socio-economic Sciences and Humanities, Luxembourg.

Densing, M., S. Hirschberg, and H. Turton (2014), Review of Swiss Electricity Scenarios 2050. Report prepared for the Group Energy Perspectives and the Swiss Competence Center for Energy Research "Supply of Electricity" (SCCER SoE). PSI Bericht Nr. 14-05Rep., 51 pp, Villigen, Switzerland.

European Council (2014), European Council Conclusions on 2030 Climate and Energy Policy, 23-24 October 2014Rep., Brussels.

François, B., et al. (2014), Integrating hydropower and intermittent climate-related renewable energies: a call for hydrology, Hydrological Processes, 28(21), 5465-5468.

Federal Assembly of the Swiss Confederation (2014). Waters Protection Act. Version 01.06.2014. Available at https://www.admin.ch/opc/en/classified-compilation/19910022/201406010000/814.20.pdf (accessed 05.09.0215).

Fruhmann, C., and A. Tuerk (2013), The impact of hydropower generation on river basins in Austria. Case study report of the EU 7th Framework Programme project "APRAISE (Assessment of Policy Impacts on Sustainability in Europe)"Rep., Joanneum Research, Graz.

Horton, P., B. Schaefli, B. Hingray, A. Mezghani, and A. Musy (2006), Assessment of climate change impacts on Alpine discharge regimes with climate model uncertainty, Hydrological Processes, 20, 2091-2109.

Jenzer-Althaus, J.M.I. (2011). Sediment Evacuation from Reservoirs through Intakes by Jet Induced Flow. EPFL PhD Thesis No. 4927: 295 pp.

Mennel, T., H. Ziegler, M. Ebert, A. Nybo, F. Oberrauch, and C. Hewicker (2015), The hydropower sector's contribution to a sustainable and prosperous Europe, Main Report. On behalf of: A European Hydropower Initiative of Hydropower Companies and (supported by) AssociationsRep., 109 pp, DNV GL, Bonn.

Moser, A., Bongers, T., Schuster, R., Lichtinghagen, J., Linnemann, C., Breuer, C., 2014. Bewertung des Beitrags von Speichern und Pumpspeichern in der Schweiz, Österreich und Deutschland zur elektrischen Energieversorgung. http://www.news.admin.ch/NSBSubscriber/message/attachments/36056.pdf (access online 16.09.2015).

NELAK (2013): Neue Seen als Folge des Gletscherschwundes im Hochgebirge – Chancen und Risiken. Formation des nouveux lacs suite au recul des glaciers en haute montagne – chances et risques. Forschungsbericht NFP 61. Haeberli, W., Bütler, M., Huggel, C., Müller, H. & Schleiss, A. (Hrsg.). Zürich, vdf Hochschulverlag AG an der ETH Zürich, 300 S.

Pöhler, F. (2014), Energiewende - eine Erfolgsgeschichte?, WasserWirtschaft, 12, 3.

Prognos AG (2012a), The significance of international hydropower storage for the energy transition. Contracting entity: Weltenergierat - Deutschland e.V. Rep., 81 pp, Berlin.

Prognos AG (2012b), Die Energieperspektiven für die Schweiz bis 2050. Energienachfrage und Elektrizitätsangebot in der Schweiz 2000-2050. Technical report for the Swiss Federal Office for Energy BFE Rep., Basel.

SCCER-SoE (2014), ROADMAP Hydropower, Swiss Competence Center on Energy Research - Supply of Energy, http://www.sccer-soe.ch/opencms/opencms/roadmap/roadmap2014/, accessed on 10 Feb. 2015.

Schleiss, A. J., F. Jordan, and S. Terrier (2013), Potentiel Hydroélectrique, in Neue Seen als Folge des Gletscherschwundes im Hochgebirge - Chancen und Risiken. Formation de nouveaux lacs suite au recul des glaciers en haute montagne – chances et risques, edited by H. Müller, A. Schleiss, M. Bütler, C. Huggel and W. Haeberli, pp. 31-40, vdf Hochschulverlag, Zürich.

Swiss Federal Council (2013), Botschaft zum ersten Massnahmenpaket der Energiestrategie 2050 (Revision des Energierechts) und zur Volksinitiative «Für den geordneten Ausstieg aus der Atomenergie (Atomausstiegsinitiative)» vom 4. September 2013 Rep., 196 pp, Berne,.

SFOE- Swiss Federal Office for Energy (2011), Statistics of the Swiss hydropower facilities, available at http://www.bfe.admin.ch/ (accessed 18. 08. 2015). Rep., 56 pp, Bern.

SFOE - Swiss Federal Office for Energy (2012), Wasserkraftpotenzial der Schweiz - Abschätzung des Ausbaupotenzials der Wasserkraftnutzung im Rahmen der Energiestrategie 2050. Rep., 26 pp, Bern.

SFOE - Swiss Federal Office for Energy (2013), Energieperspektiven 2050 -Zusammenfassung, available at http://www.bfe.admin.ch. Rep., 40 pp, Bern.

SFOE - Swiss Federal Office for Energy (2014), Swiss Electricity statistics, available at http://www.bfe.admin.ch/themen/00526/00541/00542/00630/index.html?lang=en (accessed 29. Nov 2014). Rep., 56 pp, Bern.

SFOE - Swiss Federal Office for Energy (2015). Directive relative à la rétribution à prix coûtant du courant injecté (RPC). Art. 7a LEne. Petites centrales hydrauliques (appendice 1.1 OEne). Version 1.8 du 1er avril 2015.

SFOEN - Swiss Federal Office for Environment (2012). Effects of climate change on water resources and watercourses. Synthesis report on "Climate Change and Hydrology in Switzerland" (CCHydro) project. http://www.bafu.admin.ch/publikationen/publikation/01670/index.html?lang=en (online access 30.08.2015). 76p.

Zucker, A., T. Hinchliffe, and A. Spisto (2013), Assessing storage value in electricity markets. Joint Research Centre – Institute for Energy and Transport. , in A literature review, edited by J. R. C. Transport, Publications Office of the European Union.

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