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Rethinking Pumped Storage Hydropower in the European Alps

A Call for New Integrated Assessment Tools to Support the Energy Transition

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The European Alps are well positioned to contribute significantly to the energy transition. In addition to sites with above-average potential for wind and solar power, the “water towers” of Europe provide flexible, low-carbon power generation as well as energy storage. In the future, hydropower systems are expected to become more than mere electricity generators, serving a key role as flexible complements to intermittent power generators and as providers of large-scale seasonal and daily energy storage. Energy transition on national and European scales can be facilitated by expanding the capacity of pumped storage hydropower (PSHP) plants. Yet the extension of hydropower production, in particular PSHP, remains controversial, primarily due to environmental concerns. Focusing on 2 Alpine countries, Austria and Switzerland, this paper provides a system view of hydropower production and energy storage in

the Alps. It discusses advantages and drawbacks of various assessment tools and identifies gaps and needs for the integrated assessment of PSHP plants. It concludes that instruments that evaluate the impacts and sustainability of PSHP projects need to be developed, elaborated, and applied in a participatory manner, in order to promote public dialogue, increase social acceptance, and, ideally, encourage energy consumers to become advocates of a sustainable energy future.

Keywords: Austria; energy transition; Alps; environmental impacts; pumped storage hydropower; sustainability assessment; Switzerland.

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The energy transition and the Alps: the role of pumped storage hydropower

There is no way around it: pressing issues such as climate change, fossil fuel resource depletion, and the decommissioning of nuclear power plants render the energy transition no longer a political option, but an inescapable necessity. The term “energy transition” describes a set of policies and structural changes aimed at decarbonizing the economy. Toward this end, large economies such as France, Germany, and the United Kingdom took the European lead in implementing national policies (Fabra et al 2015). Austria and Switzerland, the 2 countries this paper focuses on, followed later. Austria agreed to comply with the 2020 targets of the European Energy and Climate Policy (European Parliament 2008) in its national energy strategy (BMWfJ and BMLFUW 2010). In Switzerland, the Federal Council and the Parliament decided in 2011 to phase out nuclear power production and passed the first

package of the Energy Strategy 2050 2 years later (Bundesrat 2013). Despite the increasingly urgent need to achieve climate targets and implement energy strategies, policy-makers as well as society disagree about the best pathway and the speed of the energy transition. Although renewable energy has a positive connotation, hydropower—including pumped storage hydropower (PSHP)—remains highly disputed.

Alpine countries have an advantage when it comes to the production and storage of renewable energy: the capacity for flexible power generation using hydropower plants and their reservoirs. When demand is high, hydropower plants can provide an almost instant supply. When demand is low, they stop production or, in the case of PSHPs, absorb surplus electricity (Smil 2015). Today, hydropower plants are the only available large-scale affordable seasonal energy storage option able to absorb or buffer surplus from intermittent photovoltaic and wind power production. With the further expansion of renewable power generation in Europe, PSHP plants are

expected to gain increasing importance, as has been observed in the past 15 years in countries with wind energy such as Ireland, Portugal, and the United Kingdom. Upon the decommissioning of nuclear power plants, the new energy systems of Switzerland and Austria will rely even more strongly on such services (Hildmann et al 2014).

This prospect could obviously encourage investment in PSHP. But most hydropower companies are reluctant to invest in view of the uncertainties related to electricity market liberalization, grid usage fees, the effect of subsidies for renewable electricity generation on the electricity market, and, in the case of Switzerland, unfavorable currency exchange rates (BFE 2013a; Österreichs Energie 2015; von Hunnius 2015). In recent years, hydropower operators have been challenged by dropping electricity prices that resulted from the increased production capacity of wind, photovoltaic, and lignite-based power units. This increase was initiated by the massive decrease in the value of carbon certificates and by subsidies for promoted renewable power generation. Another barrier to investment in the hydropower sector may be the anticipated impacts of climate change that alter present and future water resources (Björnsen Gurung and Stähli 2014). The future of PSHP will depend on the energy transition pathways outlined in national strategies, as well as on social acceptance, which can accelerate or hamper implementation. To promote public acceptance, a public dialogue is required that makes the costs and benefits of energy options more transparent (Reeds 2008).

This paper aims to support consensus-building on hydropower generation in Alpine regions by providing a basis for goal setting and identifying suitable pathways for the energy transition. Based on a set of tools for assessing the sustainability of electricity production plants, it analyzes the PSHP system in terms of environmental, socioeconomic, and landscape impacts as well as resource availability (Figure 1). It draws on knowledge shared by researchers and practitioners during a workshop on “Sustainability Assessment for PSHP Plants in Switzerland and Austria” held in February 2015 in Bregenz, Austria. Facilitated by the Energy Change Impact Research Program of the Swiss Federal Research Institute (WSL), the Swiss-Austrian Alliance for Mountain Research, the Swiss Center of Competence for Energy Research “Supply of Energy,” and the Vorarlberger Kraftwerke AG, the workshop enabled the expert group to elaborate ideas and to make suggestions for improving sustainability assessment.

Pumped storage hydropower in Austria and Switzerland

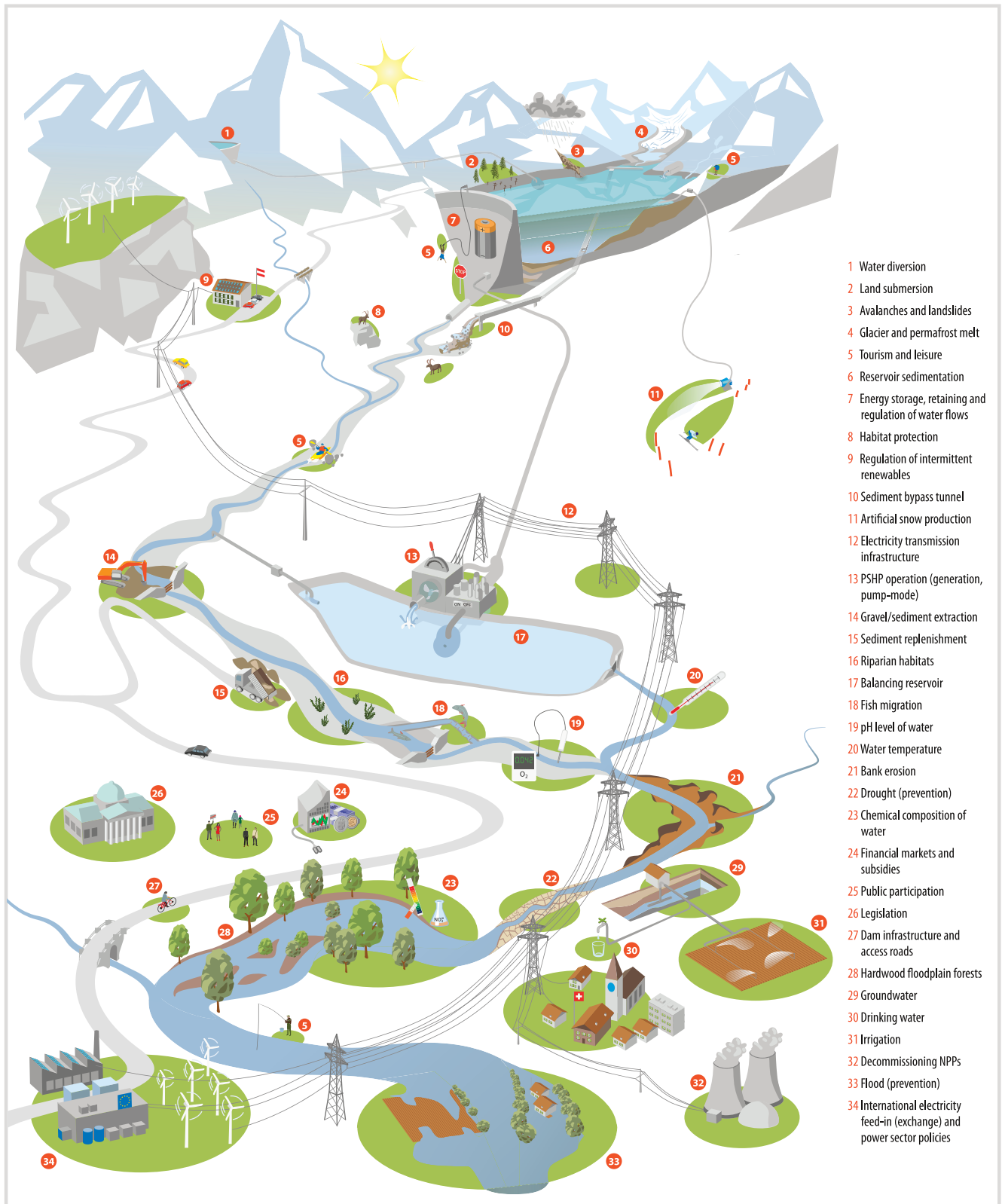
Switzerland and Austria have decided to embark on an energy system transition. The 2 neighboring countries are similar in terms of economic power, technological development, topography, water resource availability, and

total electricity production. Both aim to increase the share of renewables substantially in the near future (BMWfJ and BMLFUW 2010; BFE 2013b; Bundesrat 2013). But they differ in terms of their electricity generation mix (Figure 2). Austria produces most of its electricity with hydropower (64%), and this contribution is expected to grow to 74%; other renewables contribute a small percentage, and thermal fossil fuels supply about one-third. In Switzerland, the energy transition was primarily set in motion by the 2011 decision to phase out nuclear energy by 2034 (UVEK 2011). Nuclear energy now produces about two-fifths of the electricity supply, and hydropower contributes a little over half, with that share expected to increase slightly, depending on the choice of policy and supply scenario as outlined in the Swiss Energy Strategy 2050 (Bundesrat 2013). The anticipated growth, mainly triggered by new construction and improvements to existing plants (Bundesrat 2013), includes new PSHP plants (eg Grimsel 3 and Etzelwerk) complementing 19 existing plants with a combined maximum capacity of 1383 MW (BFE 2015). Three of them (Linth-Limmern, Nant de Drance, and PSHP Veytaux FMHL+) are scheduled to start operating in 2017 (Piot 2014).

For Switzerland and Austria, the expansion of reservoirs and the construction of new PSHP plants are considered a necessity to master the energy transition as they are the only available large-scale energy storage technology capable of operating at time frames from daily to seasonal (AWS 2012a; Österreichs E-Wirtschaft 2013; Hildmann et al 2014; BSMWMET 2015). Despite that need, the economic climate has strongly reduced cash flows in the hydropower sector and has delayed the implementation of existing expansion plans (Table 1). The unfavorable market situation, in particular the uncertainty on the floating margin between electricity sales prices and pumping costs, has led to the suspension of several projects in both Switzerland and Austria.

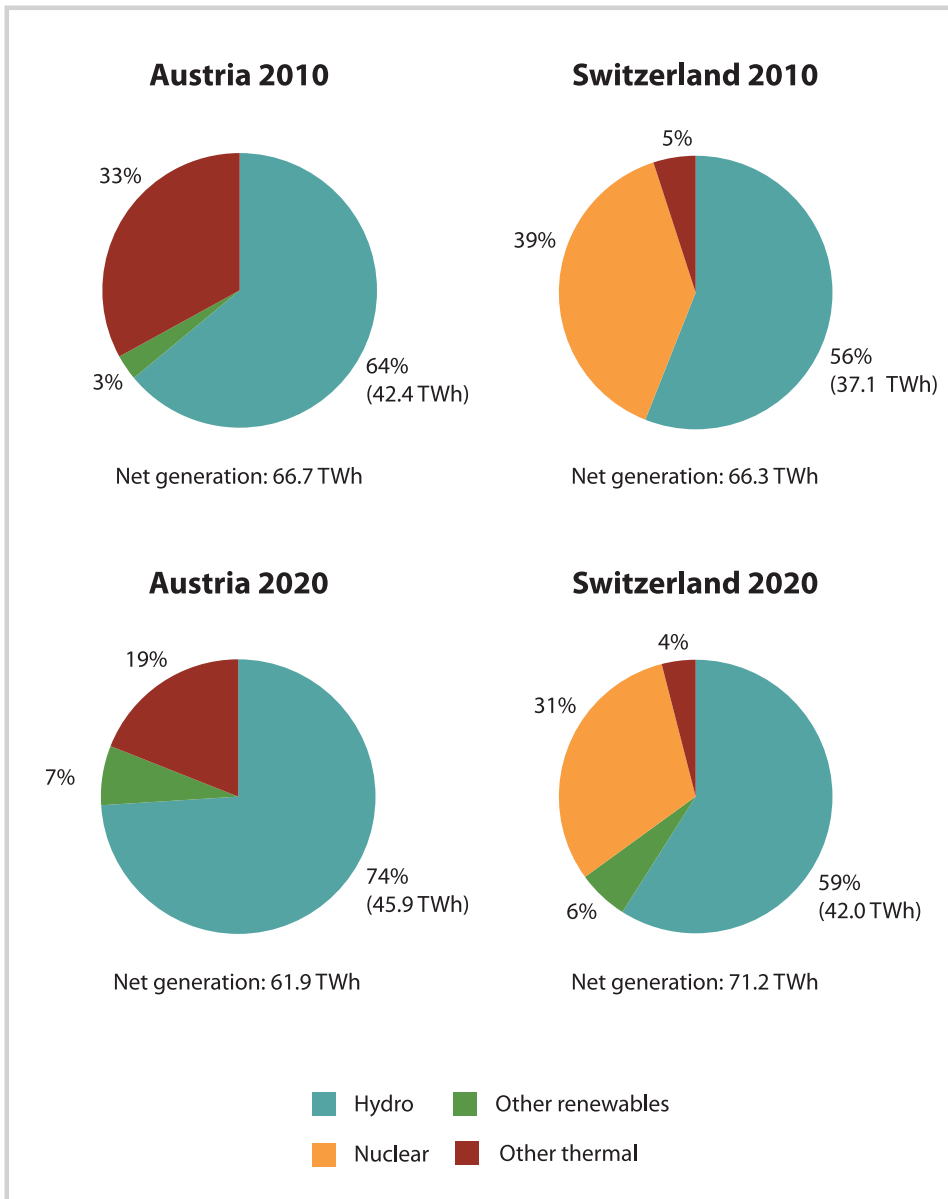
Before the energy transition, when midday peak electricity demands offered attractive prices and revenues for hydropower companies, reliance on electricity generation from PSHP was a valid business model. Today the situation is almost the opposite: surplus energy generated from renewables reduces electricity prices during daytime. As a consequence, the main service of hydropower plants has become the provision of flexible capacity. For Switzerland and Austria, various models indicate that current storage capacities will suffice to integrate the anticipated renewables until midcentury. Thereafter, depending on the scenario, additional storage and/or pumping capacity will likely be required to support integration with the international market (Kirchner 2012; Zach et al 2013; Hildmann et al. 2014; Moser 2014; Bonvin and Jacquod 2015). Due to the strong linkages between Swiss and Austrian PSHPs and the European electricity market, their flexibility and storage capacity are important for the regional and international electricity grid.

FIGURE 1. System view of PSHP operation with environmental, economic, and social relationships. (Diagram by Valentin Rüegg and Astrid Björnsen Gurung, with inputs from workshop participants)



- 1 Water diversion
- 2 Land submersion
- 3 Avalanches and landslides
- 4 Glacier and permafrost melt
- 5 Tourism and leisure
- 6 Reservoir sedimentation
- 7 Energy storage, retaining and regulation of water flows
- 8 Habitat protection
- 9 Regulation of intermittent renewables
- 10 Sediment bypass tunnel
- 11 Artificial snow production
- 12 Electricity transmission infrastructure
- 13 PSHP operation (generation, pump-mode)
- 14 Gravel/sediment extraction
- 15 Sediment replenishment
- 16 Riparian habitats
- 17 Balancing reservoir
- 18 Fish migration
- 19 pH level of water
- 20 Water temperature
- 21 Bank erosion
- 22 Drought (prevention)
- 23 Chemical composition of water
- 24 Financial markets and subsidies
- 25 Public participation
- 26 Legislation
- 27 Dam infrastructure and access roads
- 28 Hardwood floodplain forests
- 29 Groundwater
- 30 Drinking water
- 31 Irrigation
- 32 Decommissioning NPPs
- 33 Flood (prevention)
- 34 International electricity feed-in (exchange) and power sector policies

FIGURE 2 Power generation mixes for Austria and Switzerland in 2010 and projected for 2020. (Sources: BFE 2011; BMWFJ 2010; BFE 2013b [Scenario Political Measures POM/Fossil-central and Renewable Energy C&E])



Assessment tools for pumped storage hydropower

Before a new infrastructure such as a PSHP plant can be built, environmental and social impacts need to be assessed in addition to economic feasibility. Instruments exist to assess hydropower specifically (Table 2) and sustainability more generally (Table 3). To improve sustainability assessment of PSHP plants, it is important to bear in mind that their primary service is the storage and release of surplus electricity and not electricity production per se. This makes it difficult to compare their performance with that of other modes of electricity generation.

Environmental, economic, and social impacts: a systems view

Environmental change

Sustainability in hydropower production is linked to climate change. Recent high-resolution assessments of climate change impacts on hydrology include hydraulic models and detailed plant operating rules to simulate the impact of hydropower plants on the natural discharge of rivers. Simple algorithms have been introduced to estimate water diversion, seasonal storage, and hydropeaking, that is, the rapid increase or decrease in water release from the reservoir when there is a great

TABLE 1 Existing and expected future capacity of PSHP plants with >50 MW capacity in Austria, Switzerland, and Germany.

Pumped storage hydropower >50 MW	Current capacity MW	Under construction MW	Planned MW
Austria	3700	400	2000–3000
Switzerland	1400	2100	1500
Germany	6500	–	–

Sources: Switzerland: BFE 2015, Piot 2014; Austria and Germany: Data compilation from PSHP operators by Markus Aufleger, Innsbruck University, Austria.

fluctuation in the power demand (Fatichi et al 2015; Speich et al 2015). In addition, an impact assessment tool for PSHPs needs to take into account glacier and permafrost melt, shifting snow melt, and hydrological regimes together with the related uncertainties (Bosshard et al 2013). Robust indications already exist, such as increased discharge in winter and remarkable runoff deficits in summer, of likely changes in water resources after 2050 (Hänggi et al 2011; Schädler et al 2011; SGHL and CHy 2011; Addor et al 2014). While run-of-river power stations may benefit from climate change, the impacts on hydropower plants located in some mountain catchments are predominantly negative (eg Kobierska et al 2013; Fatichi et al 2015). Retreating glaciers will increase the sediment yield and reservoir sedimentation, thereby decreasing reservoir volume and energy production (Boes and Reindl 2006; Boes and Hagmann 2015; Raymond Pralong et al 2015) (Figure 3). Increased sediment loads may lead to severe hydro-abrasion of turbines and steel hydraulic parts and result in losses in efficiency and revenue. Potential avalanches, rock falls, icefalls, or landslides into existing reservoirs or newly developing glacial lakes may trigger impulse waves and hazardous flood waves (Heller 2008; Haerberli et al 2013; Linsbauer et al 2013; Gaudard and Romerio 2014). Apart from these hazards, hydropower plants at high altitudes are expected to increasingly compete for water with skiing resorts (eg Weingartner et al 2014).

Time is an essential factor in the assessment of PSHP sustainability. Models and scenarios of future environmental changes can help operators to decide where to build new hydropower plants. While forecasts of several days already make it possible to optimize water use for energy production, decadal forecasts (Smith et al 2010) are an option to be evaluated for glacio-hydrological simulations (Farinotti et al 2012). Furthermore, technologies to decrease reservoir sedimentation (eg sediment bypass tunnels and reservoir flushing) or limit abrasion damage at turbines are currently being investigated and established (Felix et al 2013; Auel 2014; Boes et al 2014; De Cesare et al 2015). New technical and operational solutions are needed to ensure sustainable reservoir operation, improve efficiency and operational flexibility, and help meet environmental regulations.

Ecological impacts

Alpine rivers are extremely dynamic ecosystems (Arcott et al 2002). Their ecological conditions strongly depend on longitudinal, lateral, and vertical connectivity and on the natural variations of flow dynamics. These 4 dimensions determine the existence and spread of animal, plant, and fungal communities in Alpine rivers.

Today few Alpine rivers are in a completely natural state. Most have been severely affected by barriers, regulations, reduced residual flows, or hydropeaking, as well as by flood protection measures, river regulations, agriculture, urban sprawl, and ground sealing. In Switzerland, almost half of the total stream length has been artificially deepened, embanked, dammed, or straightened (Peter et al 2005). Hydropower construction in the last century led to the disappearance of 70% of Swiss floodplain forests (Fischer et al 2015). In Austria, 97–99 % of sinuous or braided rivers have undergone hydro-morphological changes and diminished ecological status (Muhar et al 2000). In rivers with a catchment size larger than 10 km², 32,000 barriers to fish passage have been identified, of which 11% are caused by hydropower plants. Hydropeaking has had a relatively minor impact to date, affecting only 2.4% (779 km) of the Austrian river network (BMLFUW 2014).

Not only aquatic habitats are impacted. Lack of runoff dynamics and debris transport equally affect terrestrial ecosystems that depend on reoccurring disturbances (Werth et al 2014; Werth and Scheidegger 2014). The main impacts from PSHP for downstream river areas include altered sediment transport, water withdrawal, and hydropeaking.

Ecological impacts are assessed by looking at patterns (eg species distribution and composition and population size) or processes (population dynamics, interactions between species and structures, and ecosystem services). The German tamarisk (*Myricaria germanica*), for instance, is an alluvial shrub that has been affected by altered river dynamics. During the last 150 years, it has declined dramatically in Switzerland and Austria, and current populations are threatened (Werth et al 2014; Werth and Scheidegger 2014). Artificial lakes have helped increase river base flows in winter and during droughts and contribute to flood protection in downstream valleys. However, they also limit seed transport by stream, which leads to a reduced spatial dispersal range. Today changes in peak flow and frequency respond to a larger energy

TABLE 2 Hydropower assessment tools.

Tool	Criteria and purpose	Aspects covered	Caveats
Hydropower Sustainability Assessment Protocol	24 criteria for the creation of sustainability profiles for hydropower projects Covers in standalone documents the 4 main stages of hydropower projects: <ul style="list-style-type: none"> • Early stage • Preparation • Implementation • Operation 	<ul style="list-style-type: none"> • Technology • Environment • Society • Economy and finance 	<ul style="list-style-type: none"> • No standard; no replacement for national or local regulatory requirements • No overall rating • Spatial planning not considered
Austrian Water Catalogue	16 criteria for the evaluation of the sustainability of hydropower projects	<ul style="list-style-type: none"> • Energy economy • Environment • Other hydropower-specific issues 	<ul style="list-style-type: none"> • No overall rating • Not legally binding • Socioeconomic aspects not considered
Hydropower Tyrol: Criteria Catalogue	46 criteria for the strategic evaluation of the expansion of hydropower in Tyrol	<ul style="list-style-type: none"> • Energy economy • Hydropower-specific issues • Spatial planning • Ecology • Nature conservation 	<ul style="list-style-type: none"> • No overall rating • Not legally binding • Social aspects not considered

Sources: IHA 2011; Tiroler Landesregierung 2011; BMLFUW 2012.

system of increasing complexity as well as to increased turbine capacity and changes in hydropower plant operations (Pfaundler and Keusen 2007).

Although numerous ecological impacts of hydropower plants are known, essential variables are insufficiently considered in current assessment tools. Biodiversity and abiotic factors such as water quality and quantity, river morphology (Rosgen 1994), dams, and resulting water course fragmentation are not measured satisfactorily, as riverine systems involve complex interactions between different factors that are highly cross-correlated and interdependent (Gostner, Alp, et al 2013; Gostner, Parasiewicz, and Schleiss 2013). In addition, hydrological and ecological impact assessments need to be combined, as demonstrated in the recent assessment of impacts of climate change on water resources, sediment yield, and fish habitat by Junker et al (2015). Ideally, effects caused by hydropower should be disentangled from other anthropogenic pressures.

Socioeconomic impacts

The acceptance of new electricity production units depends on the economic benefits arising for the region during construction and operation. For large hydropower plants, less than 25% of the gross added value generally remains in the region (Ribi et al 2012). However, the hydropower industry has boosted development in Alpine valleys during the last century by creating jobs, providing access to remote places, and channeling substantial funds

into places with limited development opportunities (Borsdorf 2016). The current energy transition again offers opportunities for local and regional economies.

Socioeconomic impacts are not limited to the place of electricity production but reach far beyond national borders. Hence, an assessment tool for PSHP should better reflect its far-reaching multiple services, such as grid regulation ensuring reliable electricity supply as well as flood prevention. In addition, future reservoirs might have to replace disappearing glaciers to store and supply water for irrigation and drinking and to replenish groundwater (Seneviratne et al 2013). Such multiple water uses are seen as likely triggers of new conflicts over resources but reflect the wide transsectoral interest in water and energy storage (AWS 2012b; Weingartner et al 2014). So far there is no satisfactory way to weigh these multiple uses against the costs and benefits of large reservoirs (Smil 2015).

Embedded in the national and international energy system, PSHP operators are important actors in the energy transition but need to respond to the electricity market, oil prices, and market regulations (eg feed-in compensation). Climate targets and the depletability of fossil fuels have created pressure for swift implementation, but current production, storage, and transport technologies have not advanced to a degree that would make it possible to overtake the expansion of currently available forms of renewable energy. The transition needs to be made with proven robust technologies that are readily available to complement the rapid and massive integration of the

TABLE 3 General sustainability assessment tools.

Tool	Criteria and purpose	Aspects covered	Caveats
Environmental impact assessment	<p>Assessment of the environmental impacts of large construction projects and changes to existing infrastructure</p> <p>Explicit consideration of local conditions</p> <p>Mandatory part of the construction permit process</p>	<ul style="list-style-type: none"> • Air • Water • Soil • Flora and fauna • Forest • Landscape • Energy • Noise • Vibration • Radiation • Others <p>Aspects to be considered depend on project scope</p>	<ul style="list-style-type: none"> • Lack of clarity about impacts during early planning stages • Inflexible thresholds that risk exempting projects with considerable impacts
Life-cycle assessment	<p>Detailed ISO-standardized environmental and human health assessment over the whole life-cycle of a technology or process</p> <p>Number of criteria to be determined by the practitioner</p> <p>Overall ranking of options possible but not recommended</p>	<ul style="list-style-type: none"> • Environment • Human health • Resources 	<ul style="list-style-type: none"> • Difficulty evaluating old and future power plants due to missing data • Economic aspects not considered • Energy system aspects not considered • Accidents not considered, only normal operations
Multicriteria decision analysis	<p>Detailed sustainability assessment for problems that include multiple stakeholders and multiple criteria</p> <p>Number of criteria to be determined by the practitioner</p> <p>Stakeholder preferences explicitly taken into account</p> <p>Overall ranking of options encouraged</p>	<ul style="list-style-type: none"> • Environment • Economy • Society 	<ul style="list-style-type: none"> • Subjective choices of options, criteria, and normalization and aggregation algorithms • Exploratory nature that does not yield definitive answer

Sources: Bauer et al 2007, 2012; BAFU 2009; Roth et al 2009; Hirschberg 2010; Flury and Frischknecht 2012; UBA 2012; Treyer and Bauer 2013; UNECE 2015.

new renewable energy production plants to guarantee electricity supply and grid stability. Today PSHP is the only available option.

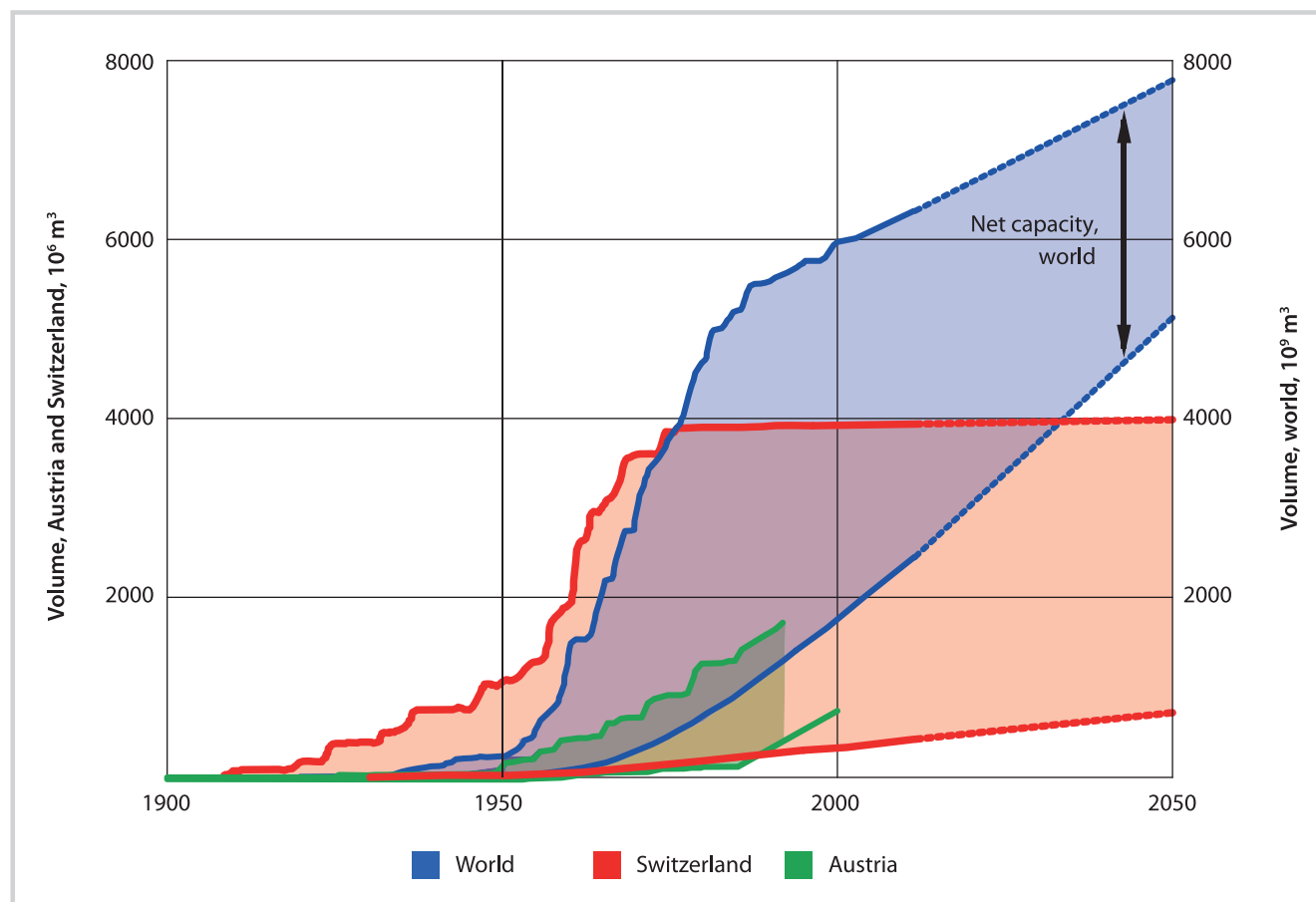
Visual impact

Compared to dams built in the lower reaches of major rivers, hydropower stations in high mountains occupy a relatively small land area (Smil 2015). The tall dams in Switzerland and Austria impound small but deep reservoirs hidden high in Alpine valleys where they cause limited visual blight. If there is a visual conflict, it is limited to areas near roads, tourist areas, and settlements, but not in remote areas (AWS 2012b). However, a recent study using photo experiments of a reservoir enlargement project suggested that the visual impact of hydropower on the nearby landscape and the expected acceptance may be influenced

by the perception that hydropower is not a “green energy.” Hydropower is therefore not unrestrainedly tolerated as an option for the energy transition (Hunziker et al 2014). In particular, the study found that tourists visiting the Grimsel area in central Switzerland associated hydropower with gas and coal rather than with new renewable energy sources. Kienast et al (2014) showed that conflicts related to the expansion of renewable energy production could lead to rejection of many projects, amounting to a 20–80% reduction of the Swiss energy potential.

In order to avoid such losses, research on connotations is needed. This includes the question of whether an impacted landscape is taken as a symbol for sustainability (an “energy landscape”) or as a symbol for technology-driven land encroachment. Such perceptions can change (Lanz Oca 2015), but usually such changes take time. An early and

FIGURE 3 Hydropower production capacity and its reduction by sedimentation in reservoirs in Switzerland, Austria, and worldwide. For each comparison, the upper line represents capacity and the lower line represents sedimentation. (Source: Boes and Hagmann 2015:195, with kind permission of the authors)



well-executed participation process is the likely key to public support for new energy infrastructure. The joint development of landscape indicators to assess the anticipated impacts could provide one tool for the necessary consensus building.

Conclusions

This paper has sought to answer the question: “How can we support the energy transition with a system view of PSHP that makes impacts on the environment, economy, and society more transparent?” Although the ultimate assessment tool is not yet at hand, the system view of hydropower presented here has revealed several blind spots, shortcomings, and research needs to be addressed when developing assessment tools:

- *Environmental indicators:* Biodiversity, water quality, water quantity, and river morphology and continuity should be evaluated adequately.
- *Cumulative effects:* As highlighted in the European Union Water Framework Directive (WFD 2012), for many ecological effects, the cumulative impacts of different

types of power plants (eg hydropeaking, sediment retention, changes in water temperature, and physical barriers to species movement) are important and should be adequately reflected in the assessment.

- *Time:* Reservoir volume, natural hazards, and hydrological regimes change over time, as do management approaches and technologies, in ways that affect the production, efficiency, reliability, and cost of electricity. Thus, sustainability assessment must take time into account.
- *Economic benefits:* The construction and operation of power plants leads to financial benefits for regional, national, and international economies in varying degrees. Assessment tools must make the respective share of gross value added explicit and transparent.
- *Multiple services and water use:* Apart from electricity production, regulatory services need to be valued in the assessment as a contribution to the European Union climate policy’s 20–20–20 targets, that is, cutting greenhouse gas emissions by 20%, increasing the share of energy from renewables by 20%, and increasing energy efficiency by 20% (Council of the European Union 2008). In the same vein, multiple

and far-reaching economic and social benefits, such as natural hazard prevention and water supply, need to be weighed against local environmental impacts.

- **Landscape:** Two established methods could be employed to assess visual impacts of PSHP on landscapes: ecological footprint analysis at the landscape scale including sociocultural information and the “willingness to pay” analysis to establish preferred or disliked landscape developments.
- **Participation:** Assessment needs to be carried out in a way that more thoroughly informs and involves local populations, both before construction and during operation.

Clearly, to be effective, an integrated assessment tool must include multiple indicators and involve public dialogue as well as expert input (Reeds 2008; Schenler et al. 2009). It must also acknowledge that there is no absolute right or wrong approach. The inherent trade-offs of hydropower and the way they are weighted by

different stakeholders have been successfully addressed in the Multi-criteria Decision Analysis tool (Eisenführ et al 2010; Table 3 in this article).

This analysis has drawn from the expertise of researchers and hydropower operators from different backgrounds, allowing an interdisciplinary view on PSHP. Research has much to contribute to the effort to improve management approaches and infrastructure to protect and benefit ecosystems and human societies. For complex systems like hydropower plants, the stimulation and production of collective knowledge with contributions from scientists, operators, administrators, and policy-makers is imperative. To investigate the impacts of the energy transition, it no longer suffices to answer the question “What will happen?” Research needs to address the question “What do we want to happen?” or “What do we want our energy future and our way of life to look like?” Such an approach requires the ability to reach a societal consensus on where to compromise if synergies are not feasible. An integrated assessment tool can help in this respect.

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