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HY:CON: A STRATEGIC TOOL FOR BALANCING HYDROPOWER DEVELOPMENT AND CONSERVATION NEEDS

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ABSTRACT

Hydropower (HP) is an important renewable energy source contributing 65.7% to Austria's national electricity generation. However, HP is also associated with ecosystem degradations jeopardizing the aims of the EU Water Framework Directive (WFD) and Habitats Directive.

Based on the EU Renewable Energy Directive (RED), the Austrian Energy Strategy has defined goals to further increase HP production by 3.5 TWh until 2015. Because national strategies for HP development are widely missing, hydropower plants (HPPs) are planned and approved on a local and regional level, often neglecting the overall optimum for energy supply and ecology. Therefore, a decision support tool (Hy:Con) was developed to integrate the energy-economic characteristics of planned HPPs and conservation needs of ecologically sensible river stretches. Based on 102 planned HPPs in Austria, Hy:Con identified HPPs with high economic attractiveness and low conservation concerns. The results show that owing to the already high HP exploitation in Austria, only a minor number of projects are without conservation conflicts. Upgrading of existing HPPs was associated with least ecological impacts, while HPPs with reservoirs are favoured over run-of-river plants. Cumulated ecological effects of numerous small HPPs are significant, whereas their contribution to overall energy production is comparatively small. Hy:Con represents a strategic instrument that can help decision makers to govern the implementation of the RED and WFD in a transparent way to pinpoint the limitations of future HP development and to avoid conflicts and stranded investments. © 2015 The Authors. River Research and Applications Published by John Wiley & Sons Ltd

KEY WORDS: sustainable hydropower development; renewable energies directive; water framework directive; decision support; strategic instrument

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INTRODUCTION

Hydropower (HP) is an important energy source in Austria contributing 65.7% to the national electricity generation (E-Control, 2013; Wagner *et al.*, 2015). HP is often praised as renewable and environmentally friendly energy source that is crucial to support other volatile renewables such as wind and solar. However, with a high share of Austria's technical/economical HP potential already exploited (i.e. 68% of 56.1 TWh; Pöyry, 2008), a further increase is in conflict with conservation needs.

With regard to the EU Renewable Energy Directive (RED, 2009/28/EG; European Commission, 2009), which aims to achieve a 20% target for the overall share of renewable energy sources by 2020, the Austrian energy strategy (BMWFJ and BMLFUW, 2010) strives for a further HP development of 3.5 TWh by 2015. According to Austria's National River Basin Management Plan (BMLFUW, 2010), there are more than 3000 existing hydropower plants (HPPs) in Austrian rivers with a catchment size ≥10 km^2. Considering also smaller rivers and plants for own consumption, the number rises to over 5000 (Wagner *et al.*, 2015). Since 2009, at least 97 HPPs with an installed capacity of 1479 MW and an annual production of 1220 GWh have been built or are currently under construction. Although HPP is considered as a climate-friendly energy source, HPPs are also associated with ecosystem degradation and cause pressures like water abstraction (Arthington *et al.*, 2006; Huckstorf *et al.*, 2008), hydropeaking (Saltveit *et al.*, 2001; Schmutz *et al.*, 2013), impoundments (Reid, 2004) and fragmentation (Nilsson *et al.,* 2005). Together with non-hydropower-related impacts, these multiple stressors threaten biodiversity (Schinegger *et al.*, 2013; Trautwein *et al.*, 2013; Vörösmarty *et al.*, 2010) and counteract the aims of the EU Water Framework Directive (WFD; 2000/60/EG; European Commission, 2000) and the Habitats Directive (HD, 92/43/EEC; European Commission, 1992). Even under consideration of mitigation measures (e.g. environmental flows), the realization of HPPs will inevitably exert pressure on the aquatic ecosystem (Poff *et al.*, 2010). Especially given the strong conflicts associated with new HPPs on rivers with high conservation needs, integrative approaches are required to allow a consistent assessment of all HPPs on a national scale.

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Hydropower plants can be assessed and compared on the basis of environmental impact assessments (EIAs) or social impact assessments, multi-criteria analysis or cost-benefit analysis. The evaluation of individual projects is usually carried out through EIAs ensuring that at least state-of-the-art mitigation measures are implemented and that the non-deterioration principle is met. However, according to the WFD (Art. 4.7) an overriding public interest, for example, security of energy supply can make the realization of projects possible despite proven ecological impacts. Furthermore, mitigating impacts by fully exploiting the options of alternative sites and/or alternative HPP solutions does not receive sufficient attention in current EIAs.

Multi-criteria analyses integrate economic, environmental and social criteria and are therefore often applied in the context of planning (Supriyasilp *et al.*, 2009; Mourmouris and Potolias, 2013) or ranking of several HPPs (Morimoto, 2013; Barton *et al.*, 2014). The importance of individual criteria can be defined on the basis of expert judgement or stakeholder consultation (Dunn, 2004; Rosso *et al.*, 2014). Thórhallsdóttir (2007) performed a one-dimensional ranking of Icelandic HPPs under consideration of several criteria (e.g. land use, economic/social consequences and technical capacity). Because decision-making is often based on group consensus, this kind of assessment is time-consuming and intransparent. Also Bakken *et al.* (2014) compared several HPPs on the basis of their standardized impacts [i.e. per gigawatt hour (GWh)] on four environmental parameters and concluded that both the quality of affected areas and the quality of energy services should be considered.

In Austria, the first steps towards a sustainable HP development have been set with the Austrian Water Catalogue (AWC; BMLFUW, 2012), which includes criteria related to energy and water management, ecology and other water-related issues. However, the AWC is not legally binding and lacks an approach on how to combine individual criteria ratings into an overall rating. Consequently, it is used either inconsistently or not at all.

The here described approach presents an instrument for applying the principles of the AWC as a supporting tool for decision makers. AWC criteria with regard to energy and water management as well as ecology were adopted, complemented and combined into an overall assessment approach. Other water-related criteria (e.g. effects on floods and tourism) were not considered in this study because of the lack of sufficiently detailed data.

METHODS

Model approach

Hy:Con is a decision support tool for sustainable HP development combining objectives for **hy**dropower development and **con**servation needs. For this study, all Austrian rivers with a catchment size ≥10 km^2 were analysed, while smaller rivers were excluded because of limited importance for HP production and data gaps. Based on information gathered from HP companies, NGOs and online search, current HPP projects and their characteristics were documented in a database to evaluate their HP attractiveness by means of energy-economic criteria.

Furthermore, six conservation scenarios describing possible future developments were defined. Conservation needs were expressed by several ecological criteria, which were collected on a national scale and rated according to the respective scenario.

All data were documented in a geographic information system (ArcGIS; ESRI, 2011), which was used to associate the impact section of each HPP with affected ecological criteria. Depending on the respective scenario and the rating of impacted criteria, each HPP received a conservation value. Finally, HP attractiveness (six classes) and conservation value (five classes) of each HPP were combined graphically (Figure 1).

Data

Hy:Con database. Considering all sufficiently documented projects, the Hy:Con database comprised 102 planned HPPs, representing new projects or upgrading of existing HPPs.

Besides the location, the database contained information regarding the HP type (run-of-river with/without small storage, storage with/without pump capacity and pure pumped storage), annual production (GWh/a), installed capacity (MW) and size (mini: <1 MW; small: 1 to <10 MW; medium: 10 to <20 MW; large: ≥20 MW), reservoir volume (m^3; GWh), pumping capacity (MW), specific investment costs (€/kWh) and local discharge characteristics.

For projects where either the installed capacity or the annual production was indicated (~30 HPPs <10 MW), the missing values were calculated assuming a mean production of 4500 h/year. Furthermore, while investment costs of large projects were well documented, the mean costs of the respective size category (i.e. 5450 €/kW for mini, 3700–5100 €/kW for small (respectively with and without diversion) and 5300 €/kW for medium HPPs) were used for the remaining 53 projects. These values are comparable with the average investments costs of 3484–3986 €/kW for small HPPs stated by ESHA (2010).

The HP database effectively illustrates the current HP development in Austria but does not claim to be exhaustive as especially small HPPs might be underrepresented. Figure 2 illustrates how the number of projects, annual production and installed capacity are distributed among HPP size classes and types.

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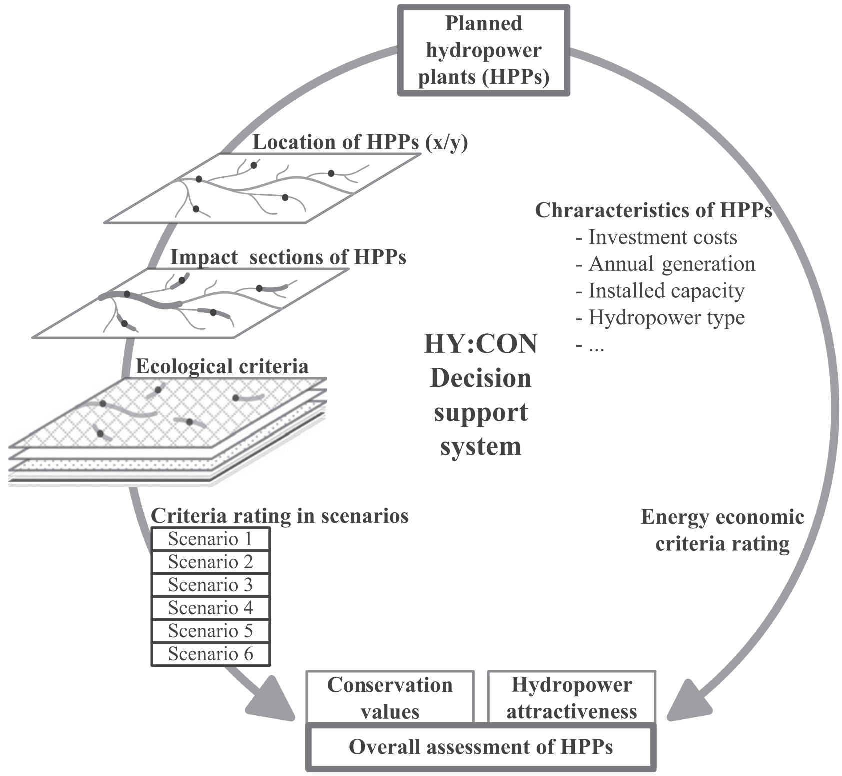

Figure 1. The Hy:Con approach

The river sections directly impacted by the HPPs (e.g. impoundments) were investigated and geo-referenced in the GIS. In case of insufficient data regarding concerned sections, the impact section was estimated under the assumption that the impacted length is related to the river size. Therefore, for locations with catchment sizes of <10, 10–99, 100–999 and ≥1000 km^2 in size, river sections of 1, 2, 5 and 10 km upstream and downstream of the HPPs were defined as 'potential impact sections'. Impact sections were overlaid with geo-referenced information on conservation value to identify HPPs with potential conservation conflicts. Exemptions were only made for 16 upgrading and pumped-storage projects where new impacts were assumed to be negligible. These HPPs were valued with low conservation conflicts in all six scenarios.

Ecological/conservation criteria. In terms of HP-related impacts, conservation concerns may arise from the intrinsic value of a river stretch or its sensitivity to impacts. The integrity and conservation value of a river can be assessed

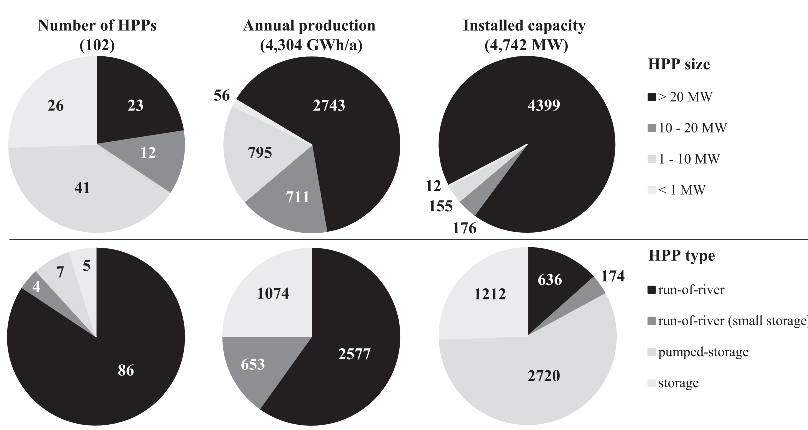

Figure 2. Number, annual production and installed capacity of hydropower plants (HPPs) size classes and types

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using ecological criteria (Willis *et al.*, 2012; Moilanen *et al.*, 2008; Nel *et al.*, 2009; Muhar *et al.*, 2011; Boon and Freeman, 2009). The AWC defines ecological criteria with regard to naturalness, rareness, ecological key functions and spatial extent of negative impacts. These criteria were adopted with minor adaptations according to data availability.

By considering assessment criteria individually, almost all HPPs were in conflict with at least one criterion. Therefore, criteria were combined into eight thematic groups considered as relevant for environmental impact assessments: (1) ecological status, (2) hydromorphological status, (3) key habitats, (4) key species, (5) floodplains, (6) legally binding protection sites, (7) other protection sites and (8) river continuity.

The ecological status is an important criterion reflecting the naturalness of river sections. Only one-third of Austria's river network exhibits a high/good ecological status (13.5% and 20.6% respectively), while 47.2% is rated as moderate (BMLFUW, 2010).

In group 2, river stretches assigned with a high hydromorphological status and >1 km length are attributed the highest conservation needs, followed by sections with the same status but only 0.5–1.0 km length, or stretches with good hydromorphology and ≥ 1 km length. In total, 40.5% of Austria's river network is of high and 24.1% of good hydromorphological status (BMLFUW, 2010). However, under consideration of the minimum length threshold, only 32.8% are rated with high (i.e. ≥ 1 km: 28.5%; 0.5–1.0 km: 4.3%), and only 9.2% with a good hydromorphology and a length >1 km.

Group 3 addresses key habitats, which are considered rare or highly important for certain species. This group includes special river types (e.g. glacial rivers), rare river types (i.e. river types representing <3% of the total river network in Austria and in good hydromorphological condition), specific river sections (e.g. braided/meandering sections with high/good hydromorphological status), the most downstream section of tributaries (as far as passable for fish; 1 or 5 km depending on fish region), potential reproduction areas of lake trout (i.e. passable inflows and outflows of lakes hosting lake trout (*Salmo trutta lacustris*)) and other important reproduction areas for fish (i.e. passable tributaries of rivers with a catchment $>500\,km^2$ and a slope <10%).

The AWC states that all HD-species, red list-species or other sensitive species shall be considered. Therefore, actual and potential habitats of 19 important/sensitive plant and animal species, with sufficient data quality, were included in conservation group 4 (key species). Therefore, five fish species are considered as endangered (crucian carp/*Carassius carassius*, sunbleak/*Leucaspius delineatus*, ide/*Leuciscus idus*, Volga pikeperch/*Sander volgensis*) or critically endangered (*Coregonus* sp.) according to the red list of Austria (Wolfram and Mikschi, 2007). Furthermore, representatives of medium distant fish migrants (i.e. Danube salmon/*Hucho hucho*, common nase/*Chondrostoma nasus*) or other important species (i.e. grayling/*Thymallus thymallus*) were included. For grayling and common nase, actual habitats were graded according to the species' biomass per hectare. For Danube salmon, river sections serving as habitats for populations with an excellent/good conservation status and other stretches hosting this species were distinguished (Schmutz *et al.*, 2010a; Hofpointner, 2013). Furthermore, the white-clawed crayfish (*Austropotamobius pallipes*) and the freshwater pearl mussel (*Margaritifera margaritifera*), two species of the HD (Annex 2) and considered as critically endangered (Petutschnig, 2009, Reischütz and Reischütz, 2007), were included. Finally, the German tamarisk (*Myricaria germanica*), was used as an important representative of pioneer vegetation indicating intact river morphology with regenerating gravel bars (Kudrnovsky, 2013). The fifth group concerns the last remaining connected floodplains, which provide important key functions, especially for species relying on intact lateral connectivity of rivers (Lazowski *et al.*, 2011). Legal protection sites with strong restrictions and other protection sites are covered by the groups 6 and 7. The last group incorporates criteria with regard to river connectivity. The first criterion assesses the length of connected habitat with thresholds depending on the respective fish region. The second criterion assesses the length of the free flowing section, whereby for large rivers (catchment $>500\,km^2$), only the connected length was assessed, while small rivers were classified according to the length of unimpacted sections (i.e. without barriers, hydropeaking and water abstraction). Third, the habitat of medium-distant migrating fish species was included in this group. Overall, 24 criteria with the presence/absence of information and 12 criteria with more differentiated levels (Table I) were mapped in the GIS.

Conservation scenarios. Six conservation scenarios at different levels of conservation intensity were defined to cover possible future developments. The criteria rating per scenario was based on existing documents (AWC (BMLFUW, 2010); World Wildlife Fund (WWF) eco-master plan II (WWF Austria, 2010)) or expert judgement. The highest rating was given to the so-called exclusion criteria, which indicated the presence of conservation values incompatible with HP development. Furthermore, non-exclusion criteria received scenario-specific scorings on the basis of their assigned relevance (i.e. very high (3), high (2), medium (1) or low (0) conservation value).

The scenarios were named 'maximal conservation' (S1), 'WWF energy revolution' (S2), 'moderate conservation' (S3), 'minimal conservation' (S4), 'AWC' (S5) and 'WWF eco-master plan' (S6). The defined conservation needs decreased from S1 to S4, while S5 and S6 represented independent scenarios based on previous studies. S5 only adopted criteria explicitly named in the AWC (i.e.

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Table I. Ecological criteria and their conservation value according to the six conservation scenarios

Ecological criteria (groups)		Scenarios S1	S2	S3	S4	S5	S6
1	Ecological status						
	(a) High ecological status	X	X	X	++	++	X
1.1	(b) Good ecological status	X	++	++	+	~	X
	(c) Moderate ecological status	~	~	~	~	○	~
2	Hy-mo[a] status						
	(a) >1 km with high hy-mo[a] status	X	X	++	+	++	+
2.1	(b) >1 km with good or >0.5 km with high hy-mo[a] status	+	+	~	~	~	+
3	Key habitats						
3.1	Glacial river						
3.2	Large river	++	+	+	+	++	·
3.3	Lake outflow						
3.4	Rare river types						
	(a) >1 km of very rare river type (<750 km in Austria) with good hy-mo[a] status	++	+	+	+	++	·
	(b) >1 km of rare river type (750–1000 km in Austria) with good hy-mo[a] status	~	~	~	~	~	·
3.5	Specific river sections						
	(a) Episodic rivers, braided/meandering sections, groundwater influences sections, marshes with good hy-mo[a] or infiltration sections, waterfalls, gorges and cascades with high hy-mo[a]	++	+	+	+	++	·
	(b) Infiltration sections, waterfalls, gorges and cascades with good hy-mo[a]	~	~	~	~	~	·
3.6	First km[b] or first 5 km[c] as far as passable from river mouth	+	+	+	~	++	·
3.7	Tributary with						
	(a) <5% slope until first impassable barrier	+	+	+	~	·	·
	(b) 5–10% slope until first impassable barrier	~	~	~	○	·	·
3.8	Potential reproduction area of *Salmo trutta lacustris*	X	++	++	++	++	·
4	Key species						
4.1	Actual habitat of *Austropotamobius pallipes*						
4.2	Actual habitat of *Margaritifera margaritifera*	X	++	++	++	++	·
4.3	Actual habitat of *Myricaria germanica*						
4.4	*Hucho hucho*						
	(a) Population with high/good status	X	++	++	++	++	·
	(b) Natural habitat	++	+	+	+	~	·
4.5	Actual habitat of *Carassius carassius*						
4.6	Actual habitat of *Leucaspius delineates*						
4.7	Actual habitat of *Leuciscus idus*	++	++	+	+	~	·
4.8	Actual habitat of *Coregonus* sp.						
4.9	Actual habitat of *Sander volgensis*						
4.10	Actual habitat of *Thymallus thymallus*						
	(a) >20 kg/ha	++	++	+	~	~	·
	(b) <20 kg/ha	~	~	○	○	○	·
4.11	Actual habitat of *Chondrostoma nasus*						
	(a) >20 kg/ha	++	++	+	~	~	·
	(b) <20 kg/ha	~	~	○	○	○	·
5	Floodplains						
5.1	(a) Floodplain with outstanding conservation importance	X	X	++	++	++	·
	(b) Floodplain with very high conservation importance	++	++	++	+	~	·
	(c) Floodplain with high conservation importance	+	+	+	~	○	·
	(d) Floodplain with moderate conservation importance	~	~	~	○	○	·

(*Continues*)

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Table I. (Continued)

Ecological criteria (groups)		Scenarios S1	S2	S3	S4	S5	S6
6	Legal protection sites						
6.1	National park						
6.2	Special protection area	X	X	X	X	·	X
6.3	Wilderness area						
7	Other protection sites						
7.1	Other protection areas						
7.2	Protected landscape	X	+	~	~	·	X
7.3	Natural monument						
7.4	Nature reserve	X	X	++	+	·	X
7.5	Resting area	X	++	+	+	·	X
7.6	Ramsar area	X	X	X	++	·	X
7.7	River sanctuary						
7.8	Natura 2000 area						
	(a) WFD-relevant	X	X	X	++	·	X
	(b) other Natura 2000 area	X	++	++	+	·	X
8	River continuity						
8.1	Connected habitat						
	(a) >5 km[d] >25 km[e] >50 km[f]	++	++	+	+	++	+
	(b) 2–5 km[d] 5–25 km[e] 10–50 km[f]	~	~	~	~	~	~
8.2	Free flowing section						
	(a) >5 km in large river	++	+	+	+	++	·
	(b) <5 km in large river	~	~	~	~	~	·
	(c) >5 km in small river[g] without pressures[h]	+	+	+	+	++	·
	(d) 3–5 km in small river[g] without pressures[h]	~	~	~	~	~	·
8.3	Migration corridor of medium-distance migrating fish species	++	+	+	~	++	·

X (exclusion), ++ (very high), + (high), ~ (medium), ○ (low), · (not included).
[a]Hydromorphology.
[b]Epirhithral.
[c]Metarhithral, Hyporhithral small and Epipotamal small.
[d]Epirhithral, Metarhithral.
[e]Hyporhithral.
[f]Epipotamal and Metapotamal.
[g]Hyporhithral large, Epipotamal medium/large and Metapotamal.
[h]Barriers, hydropeaking and water abstraction.

conservation groups 1–5 and 8) and their respective rating (without exclusion criteria). S6 is based on WWF Austria (2010) and includes only criteria with regard to ecological and hydromorphological status, protected sites and reconnected habitat (groups 1 and 2 and 6–8).

All conservation criteria, their respective classes and conservation values are given in Table I. A detailed description of the conservation criteria and their selection is currently undertaken by Scheikl *et al.* (in prep.)

All HPPs were evaluated by means of the scenario-based conservation values assigned to affected criteria. The presence of one or more exclusion criteria in the impact section of an HPP indicated insurmountable conservation conflicts in the respective scenario. If no exclusion criteria were affected, the criterion with the highest rating represented the overall group rating. The group ratings were subsequently combined to a mean value by dividing the summed group ratings by the number of groups (i.e. eight in S1–S4, six in S5 and five in S6). The resulting values were rescaled representing four levels of conservation conflicts (Table II).

Energy economic criteria. The energy-economic criteria selection was based on the AWC with small adaptions according to data availability. In contrast to the AWC, which suggests a three-stage rating, criteria were rated from 0 (low) to 5 points (high) with four intermediate

Table II. Conservation conflict classification

Ratings	Conservation conflict of the HPP
Exclusion criterion	Outstanding (exclusion project)
2.026–2.700	Very high
1.351–2.025	High
0.676–1.350	Medium
0.000–0.675	Low

HPP, hydropower plant.

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ratings (1–4 points). Criteria were combined in four groups: (1) economic attractiveness, (2) security of supply, (3) quality of supply and (4) climate protection.

The economic attractiveness (EA; group 1) was evaluated on the basis of specific investment costs (i.e. investment costs in relation to revenue potential). The revenue potential highly depends on the adjustability of energy production and is higher for (pumped-) storage HPPs than run-of-river HPPs. Hence, an HP-type-specific assessment was performed. For run-of-river HPPs, the discharge characteristics (summer (Qs) versus winter discharge (Qw)) were investigated on the basis of gauging data. This is important, because the European Power Exchange (EPEX) Spot power prices (for the first semester 2013) and price-forwards of Leipzig's European Energy Exchange (EEX) (for the second semester 2013 and the years 2014 and 2015) indicated that the energy price in the winter season is approximately 10% above, and the price in the summer season is 10% below the annual mean (EPEX and EEX, 2013). The so called baseload fit (Bf) was calculated by Equation 1.

$$Bf = Q_w{*}1.1 + Q_s{*}0.9 \tag{1}$$

Hydropower plants located in rivers with high summer flows and accordingly less revenue potential have a $Bf < 1$. For storage HPPs, where the discharge of summer months can be used for production during winter, the revenue potential is higher. Here, the Bf was assessed on the basis of full-load hours per year (h/a) and the storage capacity (h), and is usually >1. To reflect this fact in the specific investment costs, the investment costs (€/kWh) were divided by the Bf. Finally, pumped-storage HPPs were assessed on the basis of the installed capacity (€/kW).

In accordance with the AWC, the security of supply (SoS; group 2) was evaluated on the basis of the annual production (GWh/a). As a consequence, only run-of-river and storage HPPs scored, while pumped-storage HPPs received no points for this criterion.

The quality of supply (QoS, group 3) was also assessed by HP type. Based on the AWC, run-of-river (R) HPPs were assessed by a comparison of the mean monthly production in December (GWh_{Dez}) and January (GWh_{Jan}) with the mean monthly annual production ($GWh_{\mathrm{year}}/12$). However, because these data were not available, the monthly production had to be estimated by means of the discharge distribution (Q_x). Considering that approximately 20% of the discharge is above design discharge (mostly in summer), the formula in Equation 2 was adapted accordingly.

$$QoS_R = \frac{\frac{GWh_{\mathrm{Dez}} + GWh_{\mathrm{Jan}}}{2}}{\frac{GWh_{\mathrm{year}}}{12}} \rightarrow QoS_R = \frac{\frac{Q_{\mathrm{Dez}} + Q_{\mathrm{Jan}}}{2}}{0.8\ \frac{Q_{\mathrm{year}}}{12}} \tag{2}$$

For (pumped-) storage HPPs, QoS is assessed as a mean value of the ratings for peak performance (i.e. installed capacity) and storage possibility (in hours). Furthermore, if ≥50% of the installed capacity are available as pump capacity, the rating of QoS is raised by one class (maximum rating: 5).

The degree to which an HPP contributes to climate protection (group 4) is assessed on the basis of its CO_2-avoidance (kt_{CO2eq}/a) and its ability to support volatile energy sources. Pumped-storage HPPs without natural inflow do not contribute to CO_2-avoidance. However, to give full consideration to the ability of flexible HP production, HPPs capable of balancing other energy sources by a quantity of more than 100 MW for a continuous time of at least 8 h, scored 2.5 points. Because large storage HPPs usually received the highest rating by means of their CO_2-avoidance, this criterion mostly favoured pumped-storage HPPs.

Because groups 2 and 4 (i.e. SoS and climate protection) both use the annual generation as a main input and show similar results, they jointly received the same weight as the remaining two groups individually (i.e. 33%). The criteria, their weighting and scoring are given in Table III.

RESULTS

With regard to HP attractiveness, 15 small run-of-river HPPs, which almost exclusively scored according to the criterion SoS, were rated as low (0–1 points). Moderately attractive HPPs (>1–2 points) also comprised exclusively run-of-river HPPs, with medium scorings for SoS and EA. The midfield (>2–3 points) included 35 HPPs of different HP types and therefore heterogeneous ratings in the individual groups. Furthermore, 22 HPPs of different HP types were considered as highly attractive (>3–4 points). Only five HPPs (four storage HPPs and one run-of-river HPP with small storage) showed very high attractiveness (>4–5 points), with only one HPP scoring the highest possible rating for all criteria (5 points).

While storage HPPs with additional pump capacity were most attractive (2.2–5.0 points), run-of-river HPPs reached high ratings if they were equipped with a small storage (2.7–4.3 points) or featured less pronounced summer discharges. Although pure pumped-storage HPPs do not contribute to annual production, they reached ratings within the best third. In general, large/medium HPPs tend to be rated higher (>2.1 points) than small/mini HPPs, which are less attractive with regard to the considered criteria (<3.7/<2.7 points, respectively).

The HPPs' ratings based on conservation criteria and their awarded relevance in the six conservation scenarios are as follows: with regard to exclusion criteria, 65 HPPs were considered as exclusion projects in S1, while this number declined to 57 HPPs in S6, 50 HPPs in S2, 34 HPPs in S3 and zero HPPs in S4 and S5. HPPs with very

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Table III. Energy-economic criteria, their weighting and scoring

Group	Criteria	Type	Rating (points)					
			0	1	2	3	4	5
1 – Economic attractiveness[a]	Specific investment costs	R, S	≤0.750	>0.750	>0.875	>1.000	>1.125	>1.250
	(€/kWh for R/S and €/kW for P)	P	≤800	>800	>975	>1.150	>1.325	>1.500
2 – Security of supply[b]	Annual generation (GWh/a)	R, S, P	≤5.00	>5.00	>16.25	>27.50	>38.75	>50.00
3 – Quality of supply[a]	Production characteristic	R	≤0.35	>0.35	>0.45	>0.55	>0.65	>0.75
	Installed capacity (MW)	S, P	≤10	>10	>20	>30	>40	>50
	Storage duration (h)	S, P	≤1	>1	>2	>4	>12	>24
	Pumping capacity	S, P	Upgrade by one class in group 3 if at least 50% of the capacity is installed as pumping capacity.					
4 – Climate protection[b]	CO_2 avoidance ($ktCO_{2eq.}$ p.a.)	R, S, P	≤3.00	>3.00	>9.75	>16.50	>23.25	>30.00
	Renewables support	R, S, P	Upgrade by one class in group 4 if 100 MW can be provided for at least 8 h to support volatile energy sources.					

R, run-of-river HPP; S, storage HPP; P, pumped-storage HPP.
[a]33% weighting in overall assessment.
[b]17% weighting in overall assessment.

high potential conservation conflicts were less frequent and occurred only in S3 ($n=1$) and S5 ($n=6$). With regard to the ecological status, 76% of the HPPs <10 MW were in conflict with the criterion 'high/good ecological status', while this is only the case for 30% of HPPs >10 MW.

Figure 3 shows the combined results of the energy-economic evaluation and conservation needs. The dashed line divides HPPs considered as attractive (≥2.5) with regard to energy-economic characteristics from less attractive projects (<2.5).

Figure 4 shows the rating of HPPs, their annual production and installed capacity for each conservation class and scenario. A comparison of the right (all projects) and the left bar (projects with HP attractiveness ≥2.5) illustrates that although less attractive projects represent half of the HPPs (i.e. 54), they only contribute 2.3% of the installed capacity and 12% of the annual production.

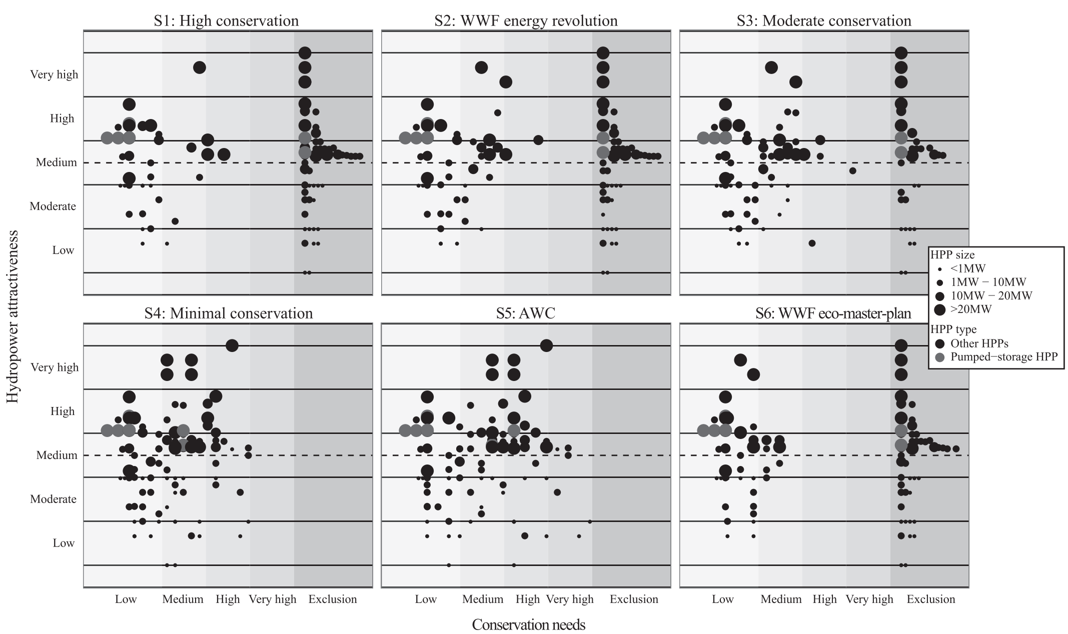

Figure 3. Hydropower attractiveness and conservation needs in six scenarios [hydropower plants (HPPs) located in the conservation-need sectors 'low' and 'exclusion' were displayed with an offset to show all HPPs]

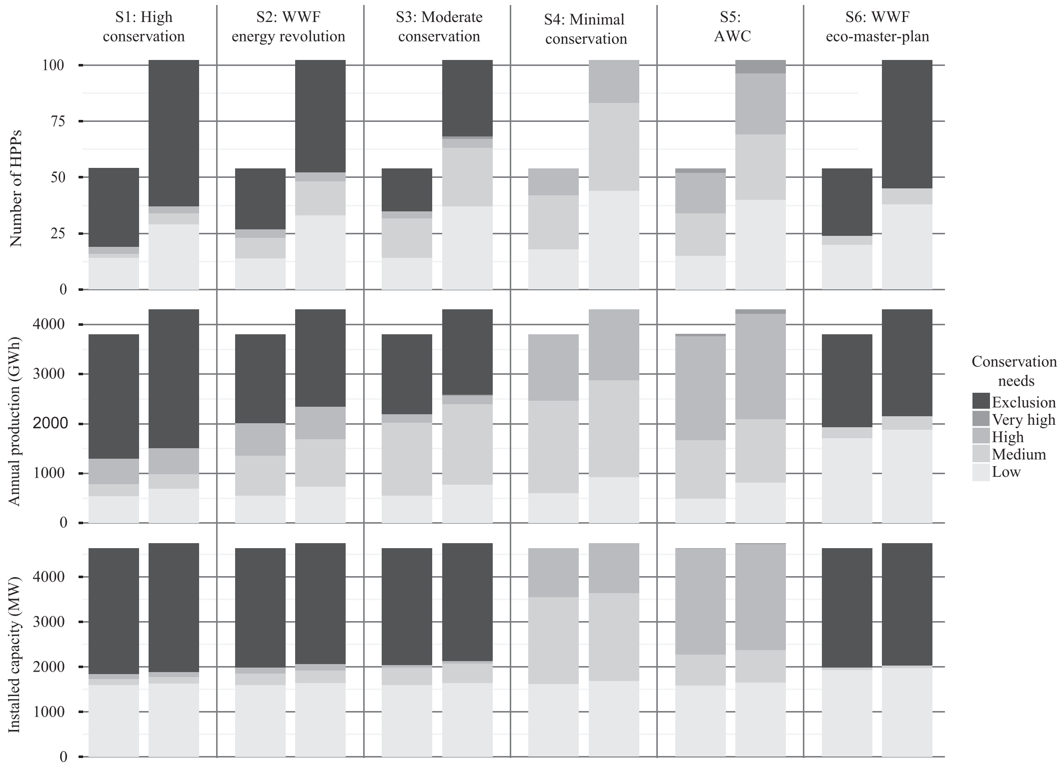

Figure 4. Comparison of number of hydropower plants (HPPs), annual production and installed capacity between attractive HPP projects (energy-economic attractiveness ≥2.5, left bar) and all HPP projects (right bar) within six scenarios and their respective conservation needs

DISCUSSION

Currently, the political goals of increasing energy produced by HP (RED) and achieving/restoring aquatic ecosystems (WFD and HD) are frequently pursued independently, resulting in conflicts between economic and ecologic targets. Nevertheless, the principal need for integrative planning in HP development has been recognized at the EU policy level (CIS policy paper, 2006). At the regional scale, the Alpine Convention (2011) provides common guidelines for small HPPs and the ICPDR (International Commission for the Protection of the Danube River) (2013) promotes guiding principles for sustainable HP development in the Danube catchment. Implementation of those guidelines require strategic and transparent methodologies such as Hy:Con.

Given the already high degree of HP use in Austria (i.e. 68% of the technical/economic potential is already exploited; BMWFJ & BMLFUW, 2010), there is a fierce competition for unexploited and often near-natural river sections. From the vantage point of the present, the timely and simultaneous fulfilment of both the RED and the WFD seems highly unrealistic in Austria. According to our database, 97 HPPs (~1.2 TWh/a) were implemented between 2009 and 2013, representing approximately one-third of the RED target (3.5 TWh by 2015). Considering a moderate scenario as S3, the realization of all attractive non-exclusion projects (i.e. 36 projects; 2.2 TWh/a) would be required to fill the remaining gap. However, this is unrealistic due to logistic, technical and economic challenges. Furthermore, a high share of the analysed projects is in conflict with conservation needs, that is, are classified as exclusion projects or with very high and high conservation needs in almost all scenarios. Only in S4 and S5, where no exclusion criteria were applied, more than half of the projects seem to be ecologically acceptable, that is, with medium to low conservation needs.

With regard to energy balancing services, only storage HPPs are reliable providers of regulating energy that is strongly required to balance other renewable energies (wind and solar). Small HPPs do not provide regulating energy and owing to the low productivity, they marginally contribute to the aims of the RED. However, they significantly counteract the aims of the WFD and HD obligations. This can be demonstrated by the dismissal of less attractive projects (i.e. with an energy-economic rating <2.5), which would cause only a slight production loss (−12% of the annual production and −2% of the installed capacity) but would reduce the number of projects by half. Also Premalatha *et al.* (2014) took a critical view on small HPPs, pointing out that although they are less attractive from an economic point of view, they are

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often promoted by subsidies and unpledged to perform EIAs. This approach has to be critically questioned, because a high share of small projects (<10 MW) is in conflict with the criterion high/good ecological status (i.e. 76% compared with 30% for projects >10 MW) highlighting that especially small HPPs are often placed in pristine sites with high conservation value. Furthermore, Schmutz *et al.* (2010b) demonstrated that small HPPs consume much more river kilometre with regard to the production of 1 GWh/a than large run-of-river HPPs (i.e. 200 m vs 42 m).

Owing to data limitations, Hy:Con had to make use of some simplifications, and some criteria had to be estimated (e.g. the length of the impacted river section or the investment costs) for several (mostly smaller) projects. However, the actual impacts strongly depend on the type and characteristics of implemented HPPs (Schmutz *et al.*, 2010b). Although it is recognized that the implementation of state-of-the-art mitigation measures can minimize impacts, suitable solutions are still lacking for several pressures (e.g. impoundments, sediment transport and downstream fish migration). This is why in Hy:Con, all projects were assessed with equal expected impacts.

With regard to the ecological assessment, Hy:Con did not consider the specific spatial extent of impacts of individual HPPs in the rating, but used a simplified approach by evaluating if conservation criteria were affected within the impact sections. A detailed approach, however, should individually quantify the potential impact of HPPs in terms of intensity and affected river length. Furthermore, cumulative effects of several HPPs are often not taken into account (Schmutz *et al.,* 2010b) and might be larger than the bare sum of projects. Thus, future decision tools should include assessments of cumulative effects based on complete data sets of all existing and planned HPPs.

Following the aim of avoiding vulnerable sites and minimizing impacts, Opperman *et al.* (2015) propose the ‘hydropower by design’ approach by integrating (1) the planning/siting of new dams at the system scale and (2) the design of individual dams at a local scale. Step 1 represents a comprehensive (e.g. nationwide) assessment of HP potential and conservation targets as also described by Šantl and Steinman (2015). Step 2 focuses on sections with high HP potential and low conservation concerns. According to Hartmann *et al.* (2013), dam location is considered the most critical factor for HP sustainability. The potential to find scenarios with lowest possible impacts is largest at exploitation rates between 30% and 70%, while for higher exploitation rates, the options for better solutions diminish (Opperman *et al.,* 2015).

Although an approach like Hy:Con cannot solve all conflicts associated with HP development, it helps in providing more sustainable solutions supporting a wider range of interests (Hartmann *et al.,* 2013).

CONCLUSIONS

Hydropower is an important renewable energy source; however, our results show that the expansion of HP use is often pictured ‘greener’ than it actually is. This is because HP is usually only associated with comparable low greenhouse gas emission or no toxic waste; however neglecting other directly affected ecological factors. Furthermore, HPPs are mainly built on a case-by-case basis without any strategic planning beforehand. Our results highlight that a system-scale approach is required, starting much before specific projects are proposed. Strategic HP planning has to include and integrate environmental, economic and social values. Dam siting is one of the most critical factors for HP sustainability. The identification of no-go areas has advantages for both sides: highly vulnerable river sections receive profound protection, and the risk for delays or stranded investments is reduced for developers. Alternative sites can be explored already at an early stage of planning. Scenarios of different protection levels enable an open but still data-driven discussion. Approaches like Hy:Con should be implemented on a national basis, and concessions should only be given to projects with high energy-economic attractiveness and low conservation concern.

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