HYDROPOWER OPERATION IN A CHANGING ENVIRONMENT

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Abstract:

In Europe hydropower (HP) plays an important role in the energy transition by increasing its generation while at the same time ensure system security by providing back-up and storage capacity and flexibility. However, due to low electricity market prices the profitability of HP is decreased. In this paper, we analyze historic revenue potentials and future market prospects for hydropower taking into account different paths towards the energy future. We develop a short-term HP operation model to capture both the market opportunities of HP companies and the technical and natural constraints of the plants. The model framework is applied to three generic HP plants which should be representative for Switzerland. Looking back into the past, the electricity spot prices strongly decreased over the years. Consequently, the revenues of HP plants in the spot market dropped significantly in the last years. However, in theory balancing markets could provide significant additional revenues for HP plants. Taking into account uncertainties and market characteristics the potential of the balancing markets is reduced but cross-market optimization was still beneficial. Looking into the future, the market price prospects for coming decade are low to modest and the existing EU capacity structure will likely remain stable. The global fuel markets and the ETS will be the decision makers for Swiss HP. The balancing market benefits will be significantly reduced in the future if full Swiss HP aims for balancing. While optimized operation across markets helps Swiss HP to increase its revenues, it is limited in scale.

Keywords: Hydropower, Cross-market optimization, Balancing, Switzerland

1 Introduction

In Europe hydropower (HP) represents an important pillar of the energy system. In 2014, HP was supplying around 19% of the total ENTSO-E generation. This makes HP the technology with the second highest generation output in the ENTSO-E region [1]. With the ongoing changes in the European energy system HP is becoming even more important. In the energy transition, HP is expected to increase its generation while at the same time shall ensure system security by providing back-up and storage capacity and flexibility. However, an increasing share of fluctuating renewable energies such as wind and solar influences the market dynamics [2]. Thus, an increase in renewable energies implies chances as well as threats for HP. One the one hand, flexible technologies such as HP will be needed to balance generation and demand and to provide reserves. This could provide additional income for HP plants. On the other hand, the new renewable energies influence the merit-order and consequently the electricity prices. In addition, low carbon and fuel prices decreased electricity prices in the last years. Thus, HP profitability decreased over the past years due to lower spot prices. In Switzerland for example many HP plants are currently not profitable anymore which is why financial support for HP is discussed in politics. Since the share of new renewable energies will further increase in the future and the development of the carbon and fuel prices are uncertain, HP needs to change its operation strategy to adapt to a changing market environment and new dynamics [3]. In this paper, we analyze historic revenue potentials and future market prospects for hydropower taking into account different paths towards the energy future. The paper is structured in the following way: in the second section, the models and data used in the analyses are explained. In section 3, the historic and future results are shown. In section 4, a conclusion is given and the limitations are addressed.

2 Models and data

2.1. HP operation model

In order to analyze the historic revenue potentials and future market prospects for HP we develop a short-term HP operation model to capture both the market opportunities of HP companies and the technical and natural constraints of the plants. In the model, we take a single plant perspective. The objective of the plant is to maximize its revenues in the spot and the balancing markets (Eq. 1). All Swiss balancing markets, the primary reserve market (PRL), the secondary reserve market (SRL) as well as the tertiary positive and negative markets on weekly and daily basis (TRL^{+}_{w}, TRL^{+}_{d}, TRL^{-}_{w}, TRL^{-}_{d}), are considered in the model.[1] The total revenue *Rev* consists of the revenues of the individual markets.

$$\max\ Rev = Rev_{DayAhead} + Rev_{PRL} + Rev_{SRL} + Rev_{TRL_w^+} + Rev_{TRL_w^-} + Rev_{TRL_d^+} + Rev_{TRL_d^-} \tag{1}$$

In the day-ahead market, the HP plant is remunerated by the hourly Swiss day-ahead market price $p_{t,DayAhead}$ for the amount of energy $G^{+}_{t,i,DayAhead}$ generated in each hour t at each turbine i (Eq. 2).

$$Rev_{DayAhead} = \sum_{t,i} p_{t,DayAhead}\, G^{+}_{t,i,DayAhead} \tag{2}$$

In the reserve markets, the suppliers bid capacity for the underlying time period into the market while some of the capacity can be called up by the TSO if required. If the capacity is called up the suppliers have to generate the required energy or reduce their generation in the case of a negative call-up. In the symmetric PRL market, the weekly capacity bid into the market $Cap_{t,i,PRL}$ is remunerated by the weekly capacity price $p^{cap}_{t,PRL}$. The actual generation or generation reduction is not remunerated (Eq. 3).

$$Rev_{PRL} = \sum_{t,i} p^{cap}_{t,PRL}\, Cap_{t,i,PRL} \tag{3}$$

In the symmetric SRL market, the energy is remunerated in addition to the capacity $Cap_{t,i,SRL}$. If the call-up is positive, the HP plant has to increase its generation while the requested

[1] For details on the Swiss balancing/ reserve markets see e.g. [4] or [5].

energy $G^{+}_{t,i,SRL}$ is remunerated by the energy price $p^{energy+}_{t,SRL}$. If the call-up is negative, the plant has to reduce its generation. For the reduced amount of energy $G^{-}_{t,i,SRL}$, the plant has to pay the energy price $p^{energy-}_{t,SRL}$ (Eq. 4). The energy price in the SRL market represents the spot price +/- 20% based on a rule of thumb of the Swiss TSO [4].

$$Rev_{SRL} = \sum_{t,i} p^{cap}_{t,SRL}\, Cap_{t,i,SRL} + \sum_{t,i} p^{energy+}_{t,SRL}\, G^{+}_{t,i,SRL} - \sum_{t,i} p^{energy-}_{t,SRL}\, G^{-}_{t,i,SRL} \tag{4}$$

The Swiss TRL markets are asymmetric markets. Thus, a positive and a negative market exist. The TRL markets can be traded on a weekly basis or on a daily basis while in the daily market 4 hour blocks are traded. The weekly capacity in the positive TRL market $Cap_{t,i,TRL^{+}w}$ or the daily capacity in 4 hour blocks in the positive TRL market $Cap_{t,i,TRL^{+}d}$ is remunerated by the capacity price $p^{cap}_{t,TRL^{+}w}$ or $p^{cap}_{t,TRL^{+}d}$. In addition, the positive energy which is call up $G^{+}_{t,i,TRL^{+}w}$ or $G^{+}_{t,i,TRL^{+}d}$ is remunerated by the energy price $p^{energy+}_{t,TRL^{+}w}$ or $p^{energy+}_{t,TRL^{+}d}$ (Eq. 5 and 6).

$$Rev_{TRL^{+}_{w}} = \sum_{t,i} p^{cap}_{t,TRL^{+}_{w}}\, Cap_{t,i,TRL^{+}_{w}} + \sum_{t,i} p^{energy+}_{t,TRL^{+}_{w}}\, G^{+}_{t,i,TRL^{+}_{w}} \tag{5}$$

$$Rev_{TRL^{+}_{d}} = \sum_{t,i} p^{cap}_{t,TRL^{+}_{d}}\, Cap_{t,i,TRL^{+}_{d}} + \sum_{t,i} p^{energy+}_{t,TRL^{+}_{d}}\, G^{+}_{t,i,TRL^{+}_{d}} \tag{6}$$

As in the positive TRL market, the capacity in the negative market $Cap_{t,i,TRL^{-}w}$ or $Cap_{t,i,TRL^{-}d}$ is remunerated by the capacity price $p^{cap}_{t,TRL^{-}w}$ or $p^{cap}_{t,TRL^{-}d}$. In the case of a negative call-up, the HP plant has to reduce its output. For the reduced output, the HP plant has to pay the negative energy price $p^{energy-}_{t,TRL^{-}w}$ or $p^{energy-}_{t,TRL^{-}d}$ to the TSO (Eq. 7 and 8).

$$Rev_{TRL^{-}_{w}} = \sum_{t,i} p^{cap}_{t,TRL^{-}_{w}}\, Cap_{t,i,TRL^{-}_{w}} - \sum_{t,i} p^{energy-}_{t,TRL^{-}_{w}}\, G^{-}_{t,i,TRL^{-}_{w}} \tag{7}$$

$$Rev_{TRL^{-}_{d}} = \sum_{t,i} p^{cap}_{t,TRL^{-}_{d}}\, Cap_{t,i,TRL^{-}_{d}} - \sum_{t,i} p^{energy-}_{t,TRL^{-}_{d}}\, G^{-}_{t,i,TRL^{-}_{d}} \tag{8}$$

The objective is being subject to several equations and inequalities. The total positive capacity, composed of the capacity $Cap_{t,i,m}$ bid in to the individual markets m, needs to be smaller equal the maximum capacity cap^{max}_{i}. This accounts for each turbine and any time (Eq. 9).

$$Cap_{t,i,DayAhead} + Cap_{t,i,PRL} + Cap_{t,i,SRL} + Cap_{t,i,TRL^{+}} \leq cap^{max}_{i} \quad \forall i,t \tag{9}$$

To be active in the symmetric reserve markets PRL and SRL or the negative reserve market TRL-, the plant needs to be active on the day-ahead market in order to reduce its generation if negative energy is required. Thus, the capacity on the day-ahead market $Cap_{t,i,DayAhead}$ less the negative capacity on the reserve markets needs to be bigger equal the minimum capacity cap^{min}_{t} (Eq. 10). In our case the minimum capacity is zero.

$$Cap_{t,i,DayAhead} - Cap_{t,i,PRL} - Cap_{t,i,SRL} - Cap_{t,i,TRL^{-}} \geq cap^{min}_{i} \quad \forall i,t \tag{10}$$

In general, only a fraction of the capacity bid into the reserve market is called up. Thus, only a fraction of the capacity has to be physically generated or reduced. The probability $prob_{t,m}$ of getting called up in a balancing market determines the amount which has to be generated in the case of a positive call-up or reduced in the case of a negative call-up (Eq. 11 and 12).

$$G^{+}_{t,i,m} = prob^{+}_{t,m} Cap_{t,i,m} \quad \forall i,t,m = Bal^{+} \tag{11}$$

$$G^{-}_{t,i,m} = prob^{-}_{t,m} Cap_{t,i,m} \quad \forall i,t,m = Bal^{-} \tag{12}$$

The positive energy which is physically generated is determined by the amount of water discharged through the turbine $R^{+}_{t,i,m}$ and the water to energy conversion factor $\alpha_{t,i}$ (Eq.13).

$$G^{+}_{t,i,m} = \alpha_{t,i} R^{+}_{t,i,m} \quad \forall i,t,m \tag{13}$$

Equally, the amount of energy which is reduced is defined by the reduction in the water which is discharged through the turbine $R^{-}_{t,i,m}$ and the water to energy conversion factor (Eq. 14).

$$G^{-}_{t,i,m} = \alpha_{t,i} R^{-}_{t,i,m} \quad \forall i,t,m \tag{14}$$

The water to energy conversion factor gives the amount of energy in MWh obtained per m^3 of water and depends on the density of water ρ, the gravity g, the efficiency of a turbine η_i, and the net head $H^{net}_{t,i}$ (Eq. 15).

$$\alpha_{t,i} = \frac{\frac{\rho g \eta_i H^{net}_{t,i}}{1000000}}{60 * 60} \quad \forall i,t \tag{15}$$

The net head is given by the gross head $H^{gross}_{t,i}$ less the head loss $H^{loss}_{t,i}$ (Eq. 16).

$$H^{net}_{t,i} = H^{gross}_{t,i} - H^{loss}_{t,i} \quad \forall i,t \tag{16}$$

The gross head is a function of the depth $D_{t,r}$ of reservoir r and a constant head $h_i^{constant}$ which does not vary. The parameter $map_{r,i}$ assigns a reservoir to a turbine (Eq. 17).

$$H^{gross}_{t,i} = h_i^{constant} + \sum_r D_{t,r}\, map_{r,i} \quad \forall i,t \tag{18}$$

In order to estimate the relationship between the depth and the storage volume $S_{r,t}$ of a reservoir, we assume a linear relationship between these variables. The slope ($slope_r^{depth}$) and the intercept ($constant_r^{depth}$) are case-specific estimates but verified using real-world data of Swiss HP plants (Eq. 19).

$$D_{t,r} = slope_r^{depth} S_{r,t} + constant_r^{depth} \forall r,t \tag{19}$$

Due to friction (etc.) the gross head is reduced by the head loss which depends quadratic on the net amount of water which is discharged through the turbine $R_{i,t}^{net}$ and the estimated slope ($slope_i^{hloss}$) (Eq. 20).

$$H^{loss}_{t,i} = slope_i^{hloss} R_{i,t}^{net\,2} \quad \forall i,t \tag{20}$$

The net discharge is the difference between the amount of water discharged through turbine *i* at time *t* and the amount of water by which the discharge is reduced (Eq. 21).

$$R^{net}_{i,t} = \sum_m R^{+}_{t,i,m} - \sum_m R^{-}_{t,i,m} \quad \forall i,t \tag{21}$$

As in the case of the depth, we assume a linear relationship between the maximum amount of water which can be discharged through a turbine at a specific point in time $R_{i,t}^{max}$ and the storage volume of the reservoir (Eq. 22).

$$R_{i,t}^{max} = slope_i^{release} \sum_r S_{r,t}\, map_{r,i} + constant_i^{release} \qquad \forall i,t \tag{22}$$

The storage volume of the upper reservoir *r* in period *t* is defined by the storage volume of the previous period, the natural water inflows $i_{r,t}$ into the reservoir, the net amount of water discharged through the turbine and the water which is spilled $Spill_{r,t}$ (Eq. 23).

$$S_{\bar{r},t} = S_{\bar{r},t-1} + i_{\bar{r},t} - \sum_i R_{i,t}^{net}\, map_{\bar{r},i} - Spill_{\bar{r},t} \qquad \forall \bar{r},t \tag{23}$$

Equally, the storage volume of the lower reservoir is defined. However, in the case of the lower reservoir, the discharge and the water spilled out of the upper reservoir need to be considered if they end up in the lower reservoir (Eq. 24).

$$S_{\underline{r},t} = S_{\underline{r},t-1} + i_{\underline{r},t} - \sum_i R_{i,t}^{net}\, map_{\underline{r},i} + \sum_{\bar{r}} \sum_{ii} R_{ii,t}^{net}\, map_{\bar{r},ii} map_{\underline{r},\bar{r}} - Spill_{\underline{r},t} + \sum_{\bar{r}} Spill_{\bar{r},t} map_{\underline{r},\bar{r}} \qquad \forall \underline{r},t \tag{24}$$

The water discharged through the turbine is constraint by the maximum discharge (Eq. 25).

$$\sum_m R_{t,i,m}^{+} \leq R_{i,t}^{max} \qquad \forall i,t \tag{25}$$

In addition, only what is produced at a specific point in time can be reduced. Thus, the reduction in the energy generation needs to be smaller or equal the positive energy generation (Eq. 26). The same accounts for the discharge of water (Eq. 27).

$$\sum_m G_{t,i,m}^{-} \leq \sum_m G_{t,i,m}^{+} \qquad \forall i,t \tag{26}$$

$$\sum_m R_{t,i,m}^{-} \leq \sum_m R_{t,i,m}^{+} \qquad \forall i,t \tag{27}$$

The storage volume of a reservoir is constrained by the maximum (s_r^{max}) and the minimum (s_r^{min}) storage capacity (Eq. 28 and 29). The minimum storage capacity may be defined by regulatory requirements.

$$S_{r,t} \leq s_r^{max} \qquad \forall r,t \tag{28}$$

$$S_{r,t} \geq s_r^{min} \qquad \forall r,t \tag{29}$$

In addition, the storage volumes at the beginning and the end of the optimization period are defined by their start (s_r^{start}) and end values (s_r^{end}) (Eq. 30 and 31). The start and end values can be given by the hydrological conditions or by the management.

$$S_{r,t=t^{start}} = s_r^{start} \qquad \forall r \tag{30}$$

$$S_{r,t=t^{end}} = s_r^{end} \qquad \forall r \tag{31}$$

The smallest time resolution of the model is 15 minutes. However, since the different markets have different underlying time periods, the time *t* can be 15 minutes, hours, 4 hour blocks, days or weeks. To solve the non-linear program (NLP) defined above we first solve a yearly linear program (LP) without considering any non-linear elements. The yearly LP accounts for the seasonality of the reservoir which needs to be considered. Afterwards, we run the NLP model on weekly basis taking into account non-linear elements such as head effects as well as the weekly start and end values of the reservoir given from the yearly LP. The model is coded in GAMS and is based on a modular design. The user can choose among different aspects like markets characteristics, technical characteristics or regulatory issues. Based on the chosen aspects, the model builds up individually.

Since the model presented above is deterministic and thus inflows, prices as well as call-up probabilities are known the resulting revenues are overestimated. In addition, we do not know the real potential of the balancing markets for a single HP plant due to missing data. Thus, we estimate an upper and a lower bound for the balancing market revenues while in reality the balancing market potential will be within these bounds. In order to calculate the upper and lower bound and to take into account specific uncertainties and market characteristics in the balancing markets several cases are considered when looking at the historic revenue potential. The following cases are regarded:

1. Spot only
2. Spot and balancing markets unconstrained
3. Spot and balancing markets security constrained
4. Spot and balancing markets max bids
5. Spot and balancing markets heuristic

In the spot only case the HP plant is participating only in the day-ahead market. In the second case the HP plant is participating in the day-ahead market and the balancing markets. The plant is unconstrained in a sense that the plant operator knows exactly the call-up structure in the balancing markets and the bid size in the balancing markets is only constrained by the TSO's requested capacity. Thus, the result of this case is the theoretical maximum revenue (upper bound) which can be achieved in the balancing market. In the third case, the uncertainty in the call-up of balancing energy is addressed. Since the HP plant can be called up for its offered capacity or a fraction of its offered capacity some water has to be reserved in the reservoir. However, for how many hours the plant is called up during the week or the day is uncertain in reality which is why we run the model several times and vary the duration for which the water has to be reserved in the reservoir. In the fourth case, the fact that the Swiss balancing markets are small and a few bigger HP plants could already satisfy the market is addressed. While in the second case the bid size in the balancing market is only constrained by the TSO's requested balancing amount, we now vary the maximum quantity per bid which can be offered in the balancing markets. Thus, we vary the market share the HP plant can have in the balancing markets. In the fifth case, we assume that the HP operator knows how to optimize its generation in the spot market but has not the ability to optimize its bidding in the balancing markets e.g. due to missing forecasts or modelling tools. This could be the case for smaller companies. Based on the spot market schedule of the HP plant we developed a heuristic which allows the plant to bid into the balancing market such that the weekly generation quantity does not change but the HP plant benefits from periods in which the balancing market prices are high. The basic logic of the heuristic is shown in Figure 1.

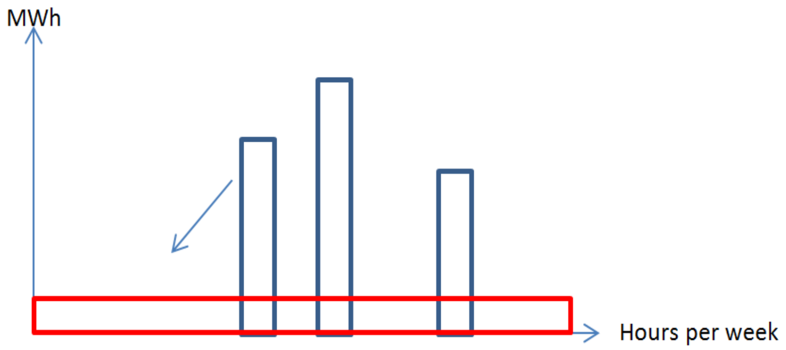

Figure 1: Basic logic of balancing market heuristic.

If the HP plant is only active on the spot market, it would optimally bid into the spot market during a few high price hours in the week (blue bars). Now under the heuristic, the HP plant operator bids its weekly spot market quantity into the balancing. Instead of producing only in high price hours, the HP plant now produces similar to a baseload plant the same amount in every hour such that over a week the generation quantity is the same as under the optimized spot only case (red bars). While the HP plant has to produce in the spot market to be able to bid into a symmetric balancing market in order to increase or decrease its generation, it can decide to produce either on the spot market or on the balancing market in the case of a positive asymmetric market (TRL+). Thus, in the TRL+ market the weekly quantity which is bid into the balancing market is based on the call-up probability. The difference in the weekly spot revenue under optimized spot market only participation and the heuristic can be interpreted as opportunity cost. Thus, the HP plant operator bids into the balancing markets at its opportunity cost plus some profit margin. Every time, the opportunity costs plus profit margin are lower than the balancing market price, the bid is accepted since the markets are designed as pay-as bid. In general, the heuristic can be seen as lower bound for the revenue potential of the balancing markets since the plant is only active on the balancing markets if the prices peak.

2.2. Investment model, Swissmod and scenarios

In order to analyze the future revenues prospects for Swiss HP two additional models are required. To take into account different paths towards the energy future an EU investment model to simulate investments into conventional generation capacities is applied. While the investment in conventional technologies is endogenous, the development of the renewable energies and the development of the demand are exogenously given by [6] as well as national energy strategies. The objective of the investment model is to minimize total generation and investment costs. The model is NTC based while 20 countries (Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Hungary, Ireland, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, UK) are represented. The model is formulated as quadratically constrained program (QCP), coded in GAMS and solved in 5 year steps up to 2050. From the investment model, we take the generation capacity, the demand, the solar and wind generation as well as the costs by technology, year and country for the future scenarios under consideration up to 2030.

The results from the investment model are fed into the Swiss electricity market model Swissmod developed in [7]. Swissmod is a classical dispatch model based on a DC-Load-Flow Approach. It represents Switzerland in detailed spatial resolution while the surrounding countries Austria, Germany, France and Italy are aggregated. Since Switzerland is a HP dominated country, the water flows within Switzerland are defined endogenously in the model [7]. From Swissmod, we obtain the future day-ahead market prices and balancing prices for Switzerland for the individual scenarios which are fed into the hydropower operation model.

Table I illustrates the future scenarios considered in this paper.

Table I: Scenarios considered in analyzing the future market prospects.

Scenario:	***Explanation:***
EU Reference Scenario	as is EU Energy Trends
Base Price 2015 Scenario	what if prices prevail
C+	slow increase of carbon price (35€/t in 2030)
C++	fast increase of carbon price (50€/t in 2030)
F+	slow increase of fuel prices (+50% until 2030)
F++	fast increase of fuel prices (+100% until 2030)
R+	stronger increase in wind and solar (+10% relative to EU Trend)
R-	weaker increase in wind and solar (-10% relative to EU Trend)
Combinations	all combinations of scenarios

The EU Energy Trends by [6] are taken as reference scenario. In the Base Price 2015 Scenario the carbon and fuel prices remain on their 2015 level. In the C+ and C++ Scenarios a slow and a fast increase in the ETS carbon price up to 35€/t respectively 50€/t in 2030 is assumed. The scenarios F+ and F++ take into account a slow and a fast increase in the fuel prices. In the F+ scenario the fuel prices rise by 50% until 2030 while in the F++ scenario the fuel prices rise by 100%. In the R+ and R- scenarios the development of the renewable energies is considered. While in the R+ scenario we assume a 10% higher increase in wind and solar compared to [6], the increase in wind and solar is reduced by 10% in the R- scenario. Beside the individual scenarios all combinations are considered.

2.3. HP data

The HP operation model presented above is applied to three generic HP plants which are shown in Table II.

Table II: Generic HP plants. Data from [8].

	Big	***Medium***	***Small***
Capacity (MW)	100	50	22
Maximum Head (m)	530	530	350
Ratio inflow to storage capacity	2	40	1300
Ratio storage to discharge capacity (h)	1000	72	3
Full load hours (h)	1800	2900	3700

Based on Swiss HP data from [8] three HP categories were defined which should be representative for Switzerland. Using the ratio of inflow to storage capacity and the ratio of storage capacity to turbine discharge capacity as structural indicators, a small, a medium and a big HP category were differentiated. While for the big category the storage is only filed twice during a hydrological year the big reservoir allows to store enough water in the reservoir in order to generate 1000 full load hours. HP plants belonging to this category are typically seasonal storage plants. In contrast, plants belonging to the small category are only equipped with a short term storage which is why they are operated similar to run-of-river (RoR) plants. Thus, the reservoir of the small category is filled 1300 times during a hydrological year while the reservoir is already emptied after 3 full load hours. The medium category encompasses HP plants which lie in between these two extremes. All three generic HP plants have the same simple topology as illustrated in Figure 2.

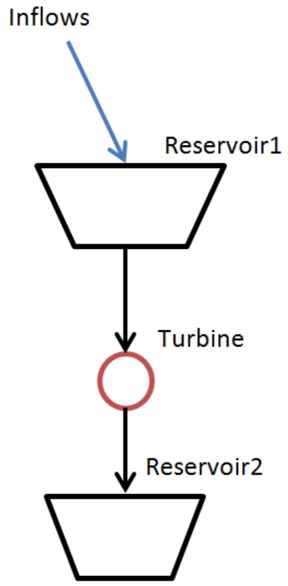

Figure 2: Topology of generic HP plants.

Each plant has an upper reservoir, a turbine and a lower reservoir. While the upper reservoir has natural water inflows, the lower reservoir is regulated solely by the operation of the plant.

2.4. Market data

In addition to the HP data, historic market data are required for the analyses of the HP revenue potential. The average Swiss balancing and spot market prices between 2011 and 2015 are shown in Figure 3.

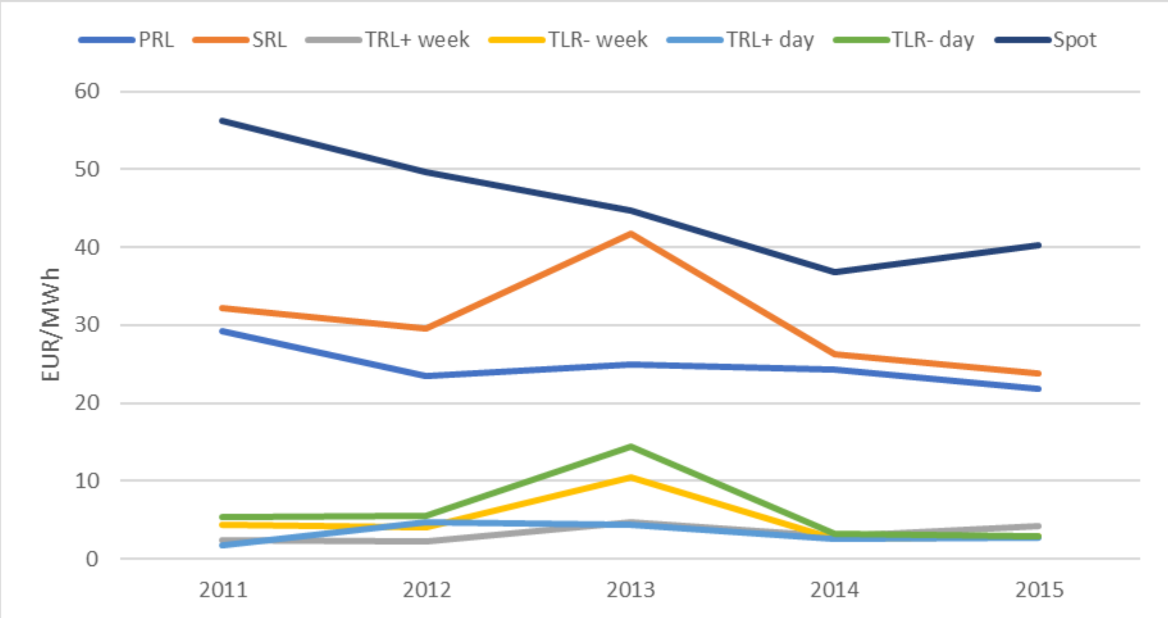

Figure 3: Swiss Balancing and Spot market prices in EUR/MWh. Data from [9] and [10].

The spot market prices decreased in average between 2011 and 2014 and slightly increased between 2014 and 2015. Regarding the balancing prices, the SRL market had the highest prices between 2011 and 2015 compared to the other balancing markets. In 2013, the SRL and the negative TRL prices peaked due to a few high price weeks during that year. In average, the spot prices were higher than the balancing market prices between 2011 and 2015.[2]

The required balancing quantities in Switzerland by market are illustrated in Table III.

Table III: Required balancing quantities in Switzerland by market. Data from [4].

Balancing market	***Required quantity***
PRL	+/- 74 MW
SRL	+/- 400 MW
TRL+	+ 450 MW
TRL-	- 300 MW

The required quantities by market are approximations of the Swiss TSO. While the PRL and SRL market are symmetric, TRL is split into a positive and a negative market. Beside the

[2] The capacity prices in the balancing markets are typically in EUR/MW per week or per 4 hour block. Here, the prices are in EUR/MWh for graphical illustration.

requested balancing market quantities, additional balancing market data like the call-up probabilities or the balancing energy prices are required. These data are taken from [11].

3 Results

3.1. Historic results

Figure 4 illustrates the spot only revenues (blue bars) as well as the revenues from the spot and balancing markets in the unconstrained case (colored bars).

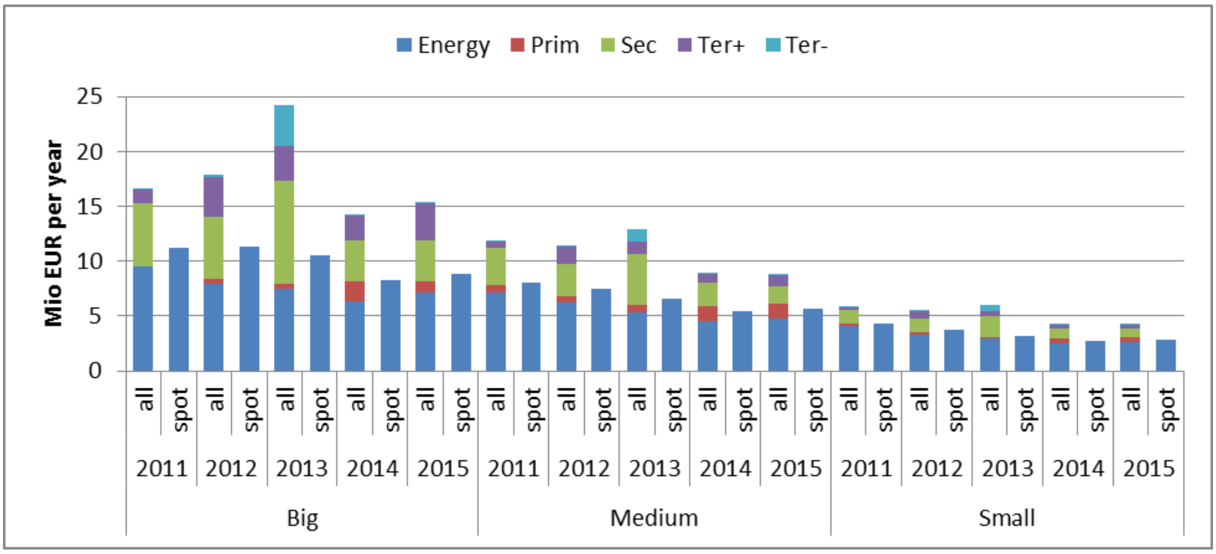

Figure 4: Historic revenues spot only and spot and balancing markets unconstrained.

Since the day-ahead market price decreased in average between 2011 and 2014, e.g. due to an increasing share of renewable energies as well as low carbon and fuel prices, the spot only revenues of the small and medium HP plants decreased during that time as well. While for the big plants the spot only revenues also decreased between 2012 and 2014, the revenues increased between 2011 and 2012. Since the big plants have a higher flexibility due to its large storage capacity, these plants only generate electricity in peak price hours. While the spot prices decreased in average between 2011 and 2012, high price hours were more frequent and more pronounced in 2012.[3] Between 2014 and 2015 all categories could increase their revenues a bit due to a slight increase in the spot prices during that time. Considering the spot and balancing markets, the balancing markets could provide significant additional revenues in the unconstrained case. The big plants could increase their yearly revenues by 50-130% due to balancing between 2011 and 2015, the medium plants between 50-100% and the small plants between 40-90%. In 2013, all categories could increase their revenues most due to balancing since in 2013 balancing prices were extremely high during a few weeks of the year. In general, the big plants benefit most from balancing showing the importance of a larger reservoir when it comes to balancing. Having a look at the individual

[3] In 2012 for example more than 100 hours had a spot price above 100€/MWh while in 2011 only around 10 hours had a spot price above 100€/MWh (see [10]).

balancing markets, the secondary reserve market seems to offer the highest potential across category.

Taking into account uncertainties in the call-up of the balancing energy, the time for which the water has to be reserved in the reservoir is considered in the spot and balancing security constrained case. The number of hours for which the water has to be reserved in the reservoir is varied between 0 and 168 hours in the weekly markets and between 0 and 4 hours in the daily markets. The results for 2015 are shown in Figure 5.

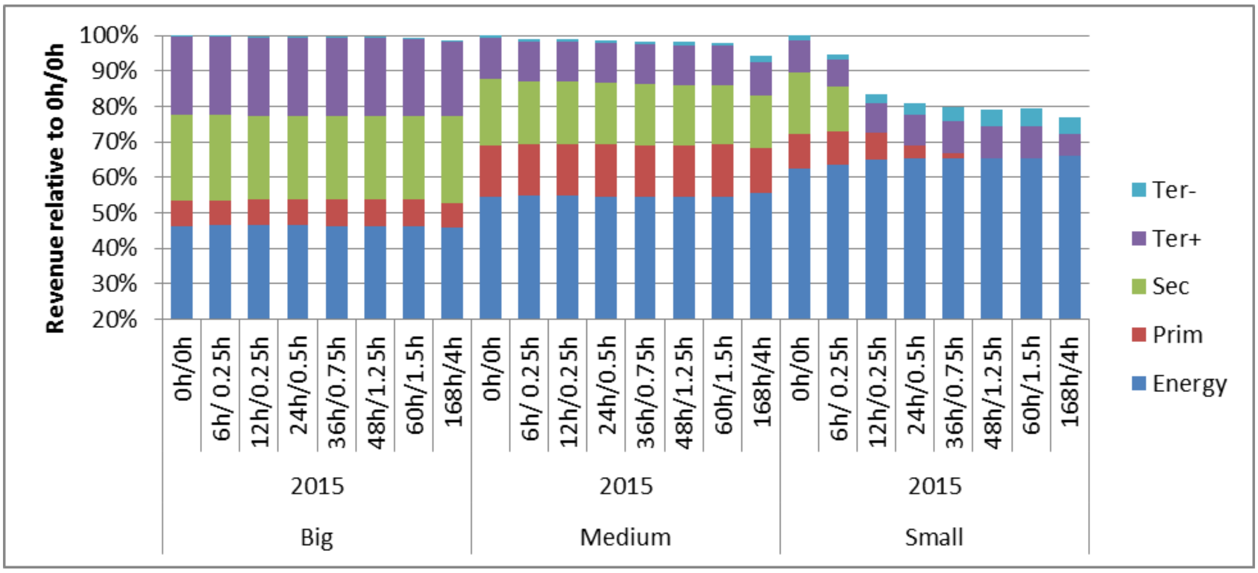

Figure 5: Historic revenues spot and balancing markets security constrained.

The revenue numbers are relative to the unconstrained case (0h/0h). Under the unconstrained case, the HP plant operator has perfect knowledge and knows exactly for how much energy he is call up. Under the 168h/4h case, the HP plant operator does not have any knowledge about the call-up and thus has to reserve the water for the whole time. As shown in Figure 5, the varying number of hours for which the water has to be reserved has only a small effect for the big HP plant. Since the big plants have a large reservoir, reserving the water in the reservoir does only slightly reduce the revenue from the balancing markets. Thus, for the big plants the uncertainty in the call-up of the balancing energy is low due to their large storage capacity. The same accounts for the medium plant. Only in the case in which the water has to be reserved for the whole time period (168h/4h) the revenues are slightly reduced for the medium plants. For the small plants the uncertainty in the call-up of the balancing energy has large impacts. Since the smaller plant has only a small reservoir, the attractiveness of the balancing markets is strongly reduced if the water has to be reserved for a longer time horizon. With increasing time for which the water has to be reserved, the small plant decrease its participation in the weekly symmetric balancing markets (PRL and SRL) and slightly increases its spot participation and its participation in the negative reserve market for which no water has to be reserved. However, revenues from balancing markets are significantly reduced with the increasing security time.[4]

Taking into account the market characteristics of the Swiss balancing markets like the size of the market the maximum size of the accepted bid is varied for each balancing market. As maximum bid size we take the average accepted bid in each market based on data from [9], 10% of the total requested capacity, 5% of the total requested capacity and 2.5% of the requested capacity. The results for the year 2015 are illustrated in Figure 6.

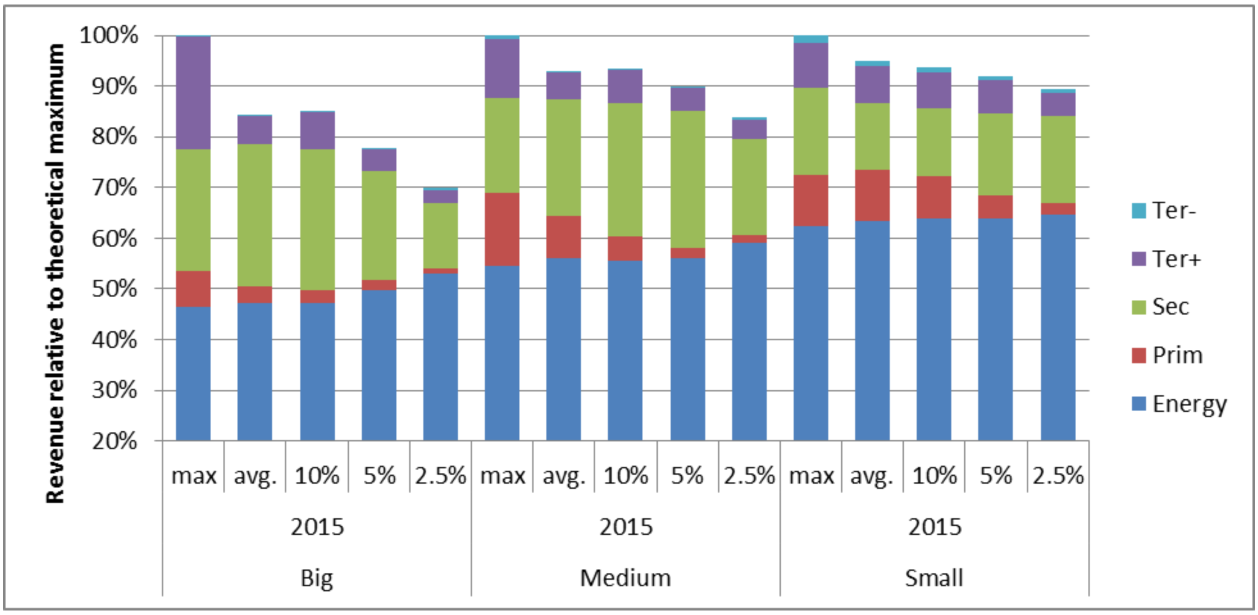

Figure 6: Historic revenues spot and balancing markets max bids.

If the size of the accepted bid is reduced, the revenue in the balancing markets is decreased. For the small category, the size of the accepted bid seems to have only minor impact on the revenue. Because the small category has a lower generation capacity, its balancing market bids are lower as well. However, for the big category, the revenues from the balancing markets are significantly reduced if the sizes of the accepted bids are reduced. If the size of the accepted bid is equal to the average accepted bid in the markets, the revenue is already reduced by 15% compared to the case in which the bid size is unconstrained. If the bid size is further reduced, the balancing revenue is further decreased while the spot market participation is increased. In the case where the big category gets not more of 2.5% of the requested capacity per bid, the revenue is decreased by around 30%. Thus, taking into account that a single HP plant only has a small market share, the reserve market potential is decreased significantly. For the medium plant, the size of the accepted bid also influences its revenues. However, compared to the big category, the reduction in the revenues is lower.

[4] For clarity only the results for 2015 are presented here but the results are transferable to the years 2011 - 2014.

If a HP company does not have the possibility to optimize across markets e.g. due to missing forecasting tools, the company can bid its weekly generation quantity at opportunity cost plus some profit margin into the balancing market. How the revenues are influenced if the three categories act according to this heuristic on the different balancing markets in the year 2015 is shown in Figure 7.

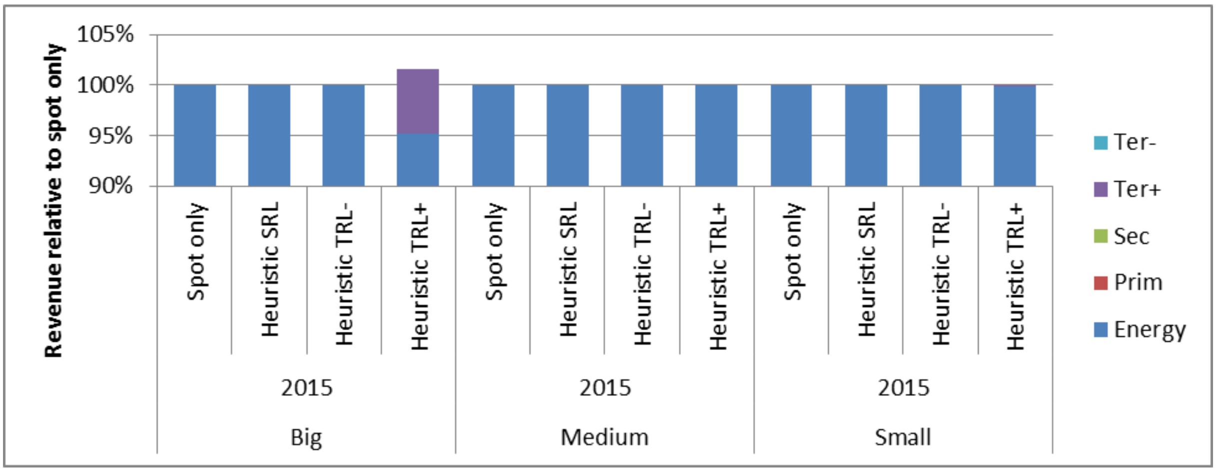

Figure 7: Historic revenues spot and balancing markets heuristic 2015.

While the big category can increase its revenue a little bit compared to the spot only case (1-2%) if it is active in the TRL+ market, the heuristic does not really benefit the HP plants in 2015. How the heuristic influences the revenues of the three categories in 2013 is represented in Figure 8.

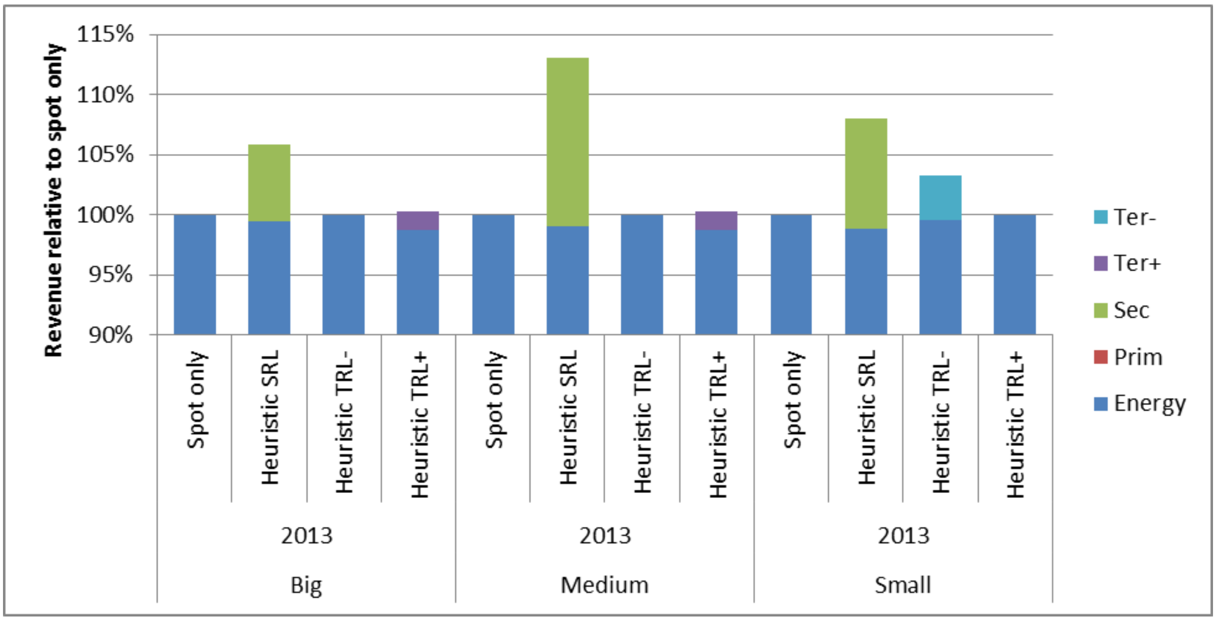

Figure 8: Historic revenues spot and balancing markets heuristic 2013.

While in 2015, the HP plants could not gain acting according to the heuristic, they can significantly increase their revenues in 2013 due to the heuristic. In 2013, the balancing market prices spiked in 2-3 weeks. If the plants act according to the heuristic, they will be active in the balancing markets in these 2-3 high price weeks what will increase their revenues between 4-13%. Especially in the SRL market, the HP plants can increase their revenues. The big plant can increase its revenue by 6%, the medium plant by 13% and the small plant by 8%. In addition, the small plant can increase its revenue by 4% due to the TRL- market. Thus, the heuristic enables HP plants to benefit from balancing in years where the balancing prices are really high while in years in which the balancing prices are normal, the heuristic does not change the revenue. Therefore, the heuristic can be seen as lower bound for the balancing market revenue potential.

In sum, the historic results showed a decrease in the spot revenues due to decreasing spot prices in the past. In theory, the balancing markets could significantly increase the revenue of the HP plants. Since uncertainties and market characteristics are not explicitly considered in this case, the revenues represent an upper bound for the balancing market benefits. Taking into account the uncertainty in the call-up of the balancing energy as well as the size of the balancing market bids, the revenues from the balancing markets are significantly reduced. Our heuristic showed how smaller plants could benefit from high price weeks in the balancing markets. In a normal year, the heuristic will bring no additional money from balancing. However, if the prices peak during a few weeks of a year, the revenues can be significantly increased due to balancing market participation in those weeks. The heuristic can be seen as lower bound for the balancing market revenues.

3.2. Future results

In analyzing the future revenue prospects for Swiss HP different future scenarios have been considered. In this paper, only the results of four of the scenarios are illustrated. The future results show the revenues in the year 2020 and 2030 the respective HP plant could achieve in the spot and balancing markets under a specific scenario. Figure 9 illustrates the yearly revenues by HP category for the EU Reference scenario.

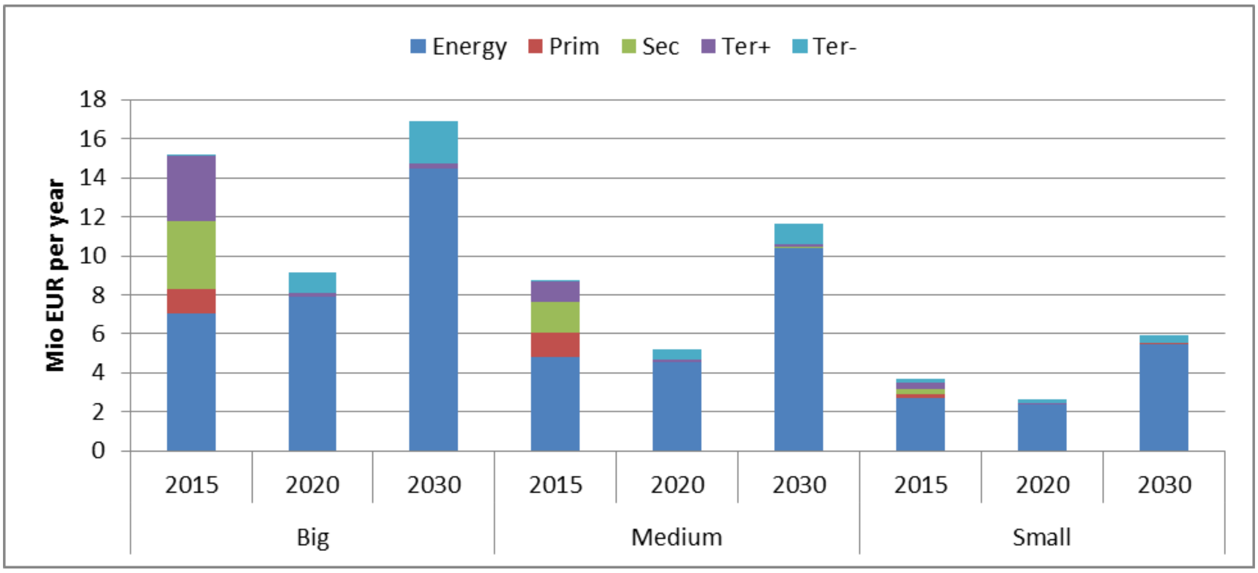

Figure 9: Future revenues spot and balancing markets EU Reference Scenario.

In this scenario, the electricity spot prices further decrease until 2020 due to the carbon and fuel price developments and the consequent development of the generation technologies.[5] In 2030, the prices increase above 2015 levels. The total HP revenues in 2020 and 2030 follow the spot price development. Compared to 2015, the revenues from the balancing market are reduced significantly since the future balancing market prices are lower than the historic balancing prices. While the balancing market prices are determined by many influencing factors, the simulated future balancing prices are solely opportunity cost driven in our model approach. In general, the HP plants can achieve 8-15% higher revenues due to balancing market participation. If the carbon and fuel prices will remain on the 2015 level (Base Price 2015 scenario) the total HP revenues will decrease further due to increased RES generation as illustrated in Figure 10.

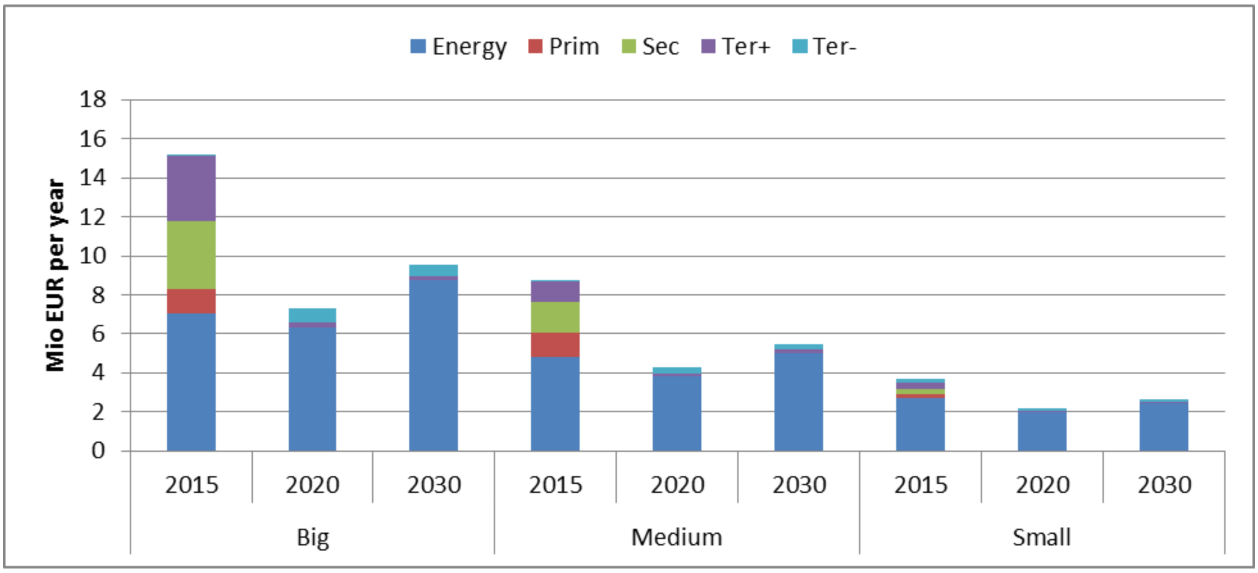

Figure 10: Future revenues spot and balancing markets Base Price 2015 Scenario.

While in the EU Reference scenario the HP revenues recover in 2030, the revenues in the Base Price 2015 scenario remain below the 2015 level in 2030. Thus, the continuous low carbon and fuel prices as well as the overcapacity in the EU are a long-term threat for Swiss HP. In addition, the additional revenues from balancing are significantly reduced. Since in the Swiss electricity market model Swissmod all prequalified HP plants participate in the balancing markets, the future balancing prices are lower. Thus, if all HP plants rush on the balancing markets their current potential is reduced. If the carbon price is slowly increased until 2030, the general revenue situation for HP relaxes a little bit compared to the Base Price 2015 scenario (see Figure 11).

[5] See figures in the appendix for the simulated spot and balancing prices as well as the development of the generation capacities under the individual scenarios.

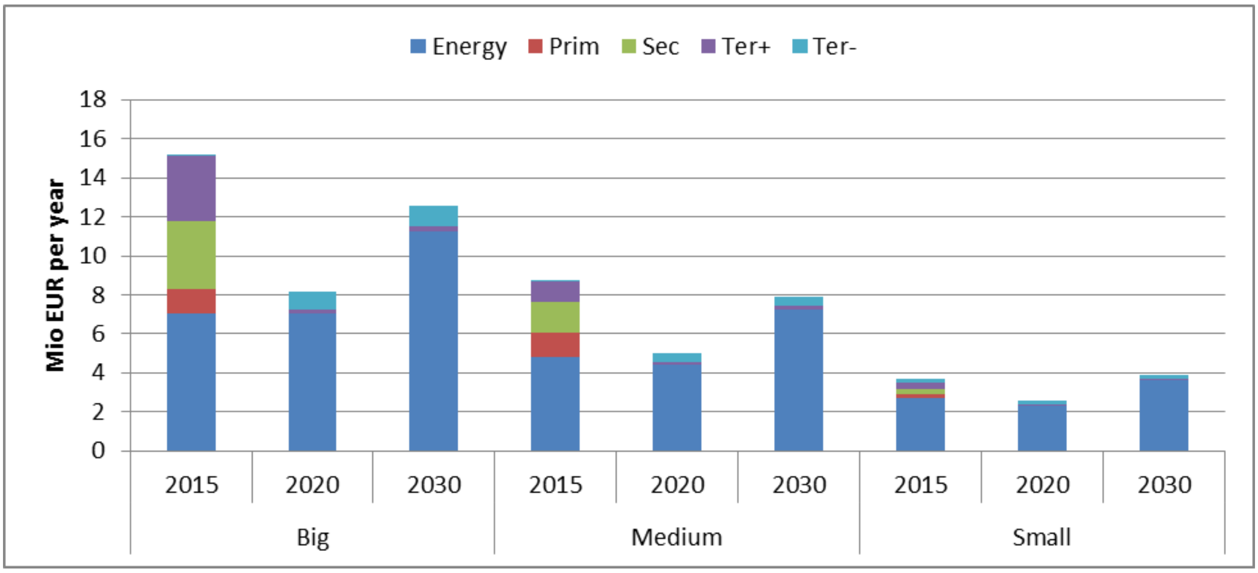

Figure 11: Future revenues spot and balancing markets C+ Scenario.

While the total HP revenues are higher in the C+ scenario than in the Base Price 2015 scenario, the revenues will remain below the 2015 level for the big and the medium category. The increase in the carbon price is less important for large units which are peak price driven. However, the increase in the carbon price is important for the smaller category which is run like a RoR plant in high number of hours during the year. Thus, the total revenues of the small category will reach again the 2015 level in 2030. The revenues from balancing are increased a little bit but the potential remains low. The change in the HP revenues for the three categories under the R+ scenario is shown in Figure 12.

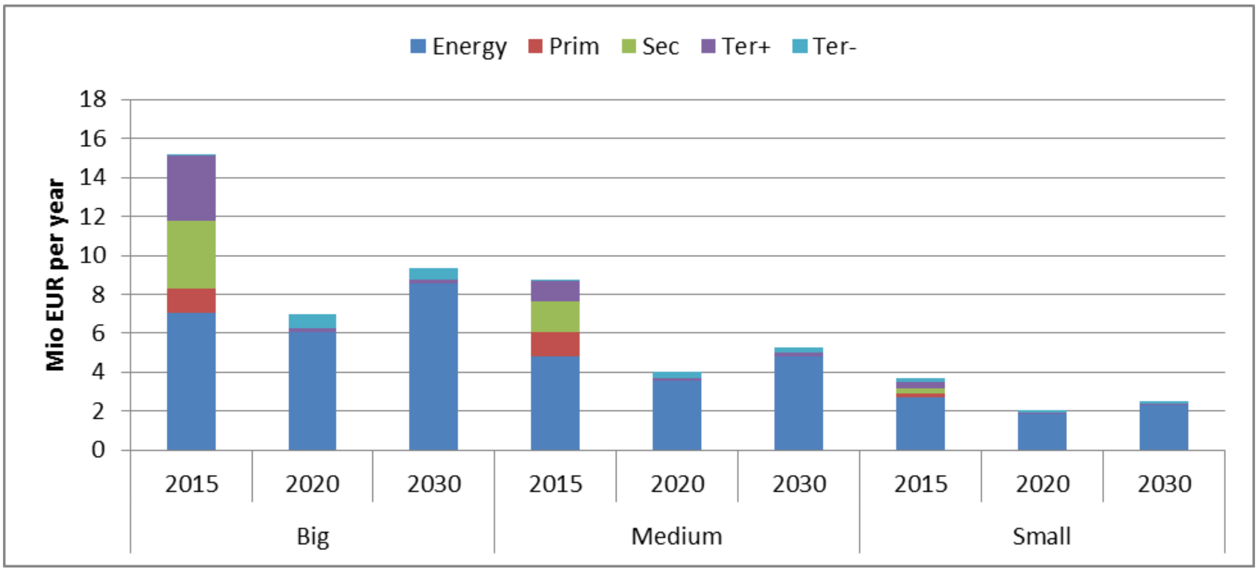

Figure 12: Future revenues spot and balancing markets R+ Scenario.

If the share of RES further increases, the spot market prices will further decrease. Following the spot market price development, the HP revenues are further decreased and will remain below the 2015 level. The potential of the balancing markets remains low since in our model, the required balancing quantities are not increased even if the RES share increases. [6] Thus, balancing prices remain low since many HP plants rush on the balancing market.

In sum, the future results show that the market price prospects for Swiss HP for the coming decade are low to modest since the existing EU capacity structure is likely to remain stable. Thus, the global fuel markets and the ETS will be the decision makers for Swiss HP. In addition, the balancing market benefits will be significantly reduced if full Swiss HP aims for balancing. Since larger plants benefit more from balancing because of their higher flexibility this will be more important for larger units.

4 Conclusion and limitations

Our historic revenue analysis showed that the HP profitability decreased in the last years due to the decreasing spot market prices. Additional revenues from balancing could relax the situation in the past. However, uncertainties and market characteristics need to be taken into account since they reduce the balancing market potential. The analysis of the future revenues showed that the future market prospects for Swiss HP depend on development of global fuel markets and the ETS. However, Swiss HP has no influence their development. The rush on the balancing markets due to low spot prices decreases balancing market potential in the future. In general, optimized operation across markets helps Swiss HP to increase its revenues, but is limited in scale.

Our analysis of the historic HP revenue potential and the future HP revenue prospects is not without limitations. Since our HP operation model is deterministic, the impact of uncertainty in the water inflows and the prices is neglected. To take into account this uncertainty a stochastic approach would be necessary but in the case of a stochastic approach a yearly perspective would not be solvable within reasonable computational time. In addition, we do not regard a single case study in our analyses but three generic HP plants. Since the generic plants are based on average values of real Swiss HP plants the inflows are average values as well. Taking into account more detailed inflow data could lead to changes in the HP plant operation schedule. At the same time, the consideration of three generic HP plants does not take into account specific constraints on residual water flows or other regulations since these factors a case specific. While a real HP plant may have to operate according to specific regulations the three generic plants do not have to consider these factors in their operation. Another limitation of our analyses is the fact that we take the perspective of a single HP plant. Since the balancing markets are small, the bidding strategy of a single HP plant in the balancing markets may already has an influence on the price. In our case, the prices are unaffected by the behavior of the single HP plant. In addition, companies which have a portfolio of generation units need to have a strategy how to bid their portfolio into the balancing market instead of a single plant. Bidding a portfolio may increase the flexibility of the company in bidding capacity and delivering energy. Due to our single plant perspective, this is ignored.

[6] In general it is not clear how the increasing RES share influences the required balancing amount (see e.g. [12]).

5 Literature

[1] ENTSO-E, 2014. Yearly Statistics & Adequacy Retrospect 2014: European Electricity System Data.
[2] Gaudard, L., Romerio, F., 2014. The future of hydropower in Europe: Interconnecting climate, markets and policies. Environmental Science & Policy vol. 37, pp. 172–81.
[3] Barry, M., Baur, P., Gaudard, L., Giuliani, G., Hediger, W., Romerio, F., Schillinger, M., Schumann, R., Voegeli, G., Weigt, H., 2015. The Future of Swiss Hydropower - A Review on Drivers and Uncertainties. SSRN Journal. 10.2139/ssrn.2663879.
[4] Swissgrid, 2015. Grundlagen Systemdienstleistungsprodukte.
[5] Abrell, J., 2016. The Swiss Wholesale Electricity Market. SCCER CREST Working Paper.
[6] European Commission, 2016. EU Reference Scenario 2016. Energy, transport and GHG emissions. Trends to 2050.
[7] Schlecht, I., Weigt, H., 2014. Swissmod – A Model of the Swiss Electricity Market. WWZ Discussion Paper 2014/04.
[8] Balmer, M., 2012. Nachhaltigkeitsbezogene Typologisierung der Schweizerischen Wasserkraftanlagen. Gis-Basierte Clusteranalyse und Anwendung in Einem Erfahrungskurvenmodell. Ph.D. Thesis, Department of Mechanical and Process Engineering ETH Zürich, Zürich, Switzerland.
[9] Swissgrid, 2017. Systemdienstleistungen - Ausschreibungen. https://www.swissgrid.ch/swissgrid/de/home/experts/topics/ancillary_services/tenders.html
[10] EPEX SPOT, 2017. Market data day-ahead auction. www.epexspot.com/en/market-data/dayaheadauction.
[11] Swissgrid, 2017. Energieübersicht Schweiz. https://www.swissgrid.ch/swissgrid/de/home/experts/topics/energy_data_ch.html
[12] Hirth, L., Ziegenhagen, I., 2015. Balancing power and variable renewables: Three links. Renewable and Sustainable Energy Reviews, vol. 50, pp. 1035-1051.

6 Appendix

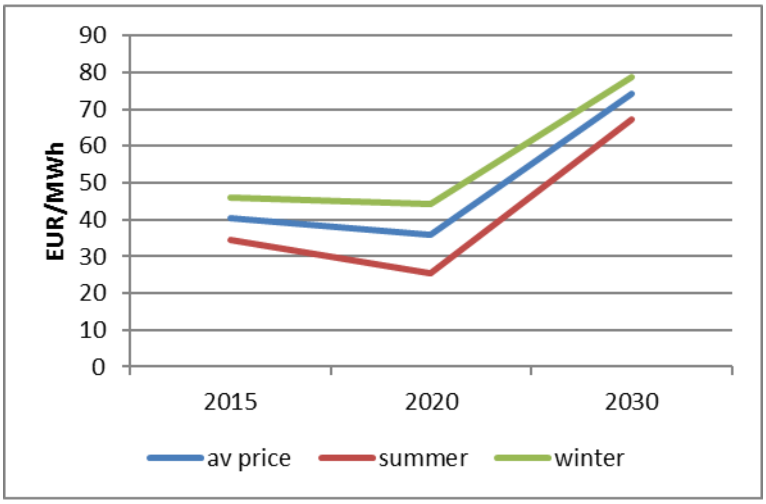

Figure 13: Average spot market prices EU Reference Scenario.

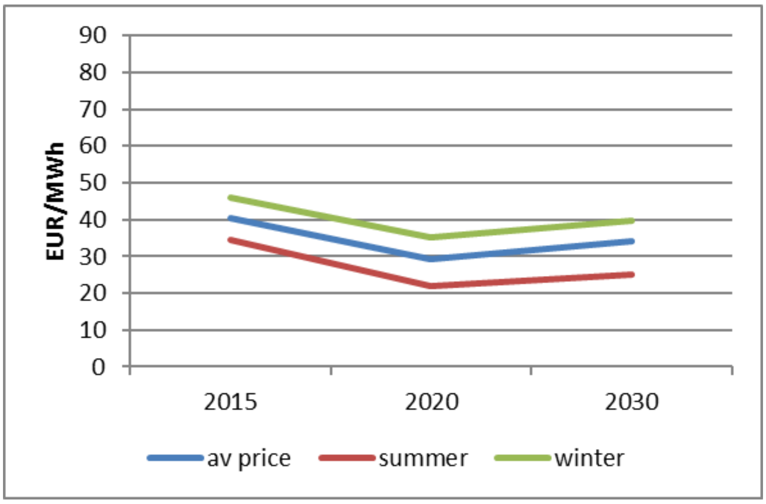

Figure 14: Average spot market prices Base Price 2015 Scenario.

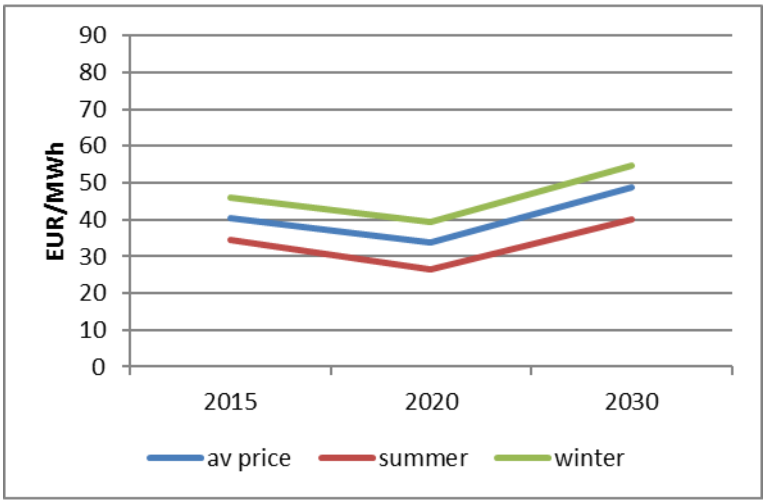

Figure 15: Average spot market prices C+ Scenario.

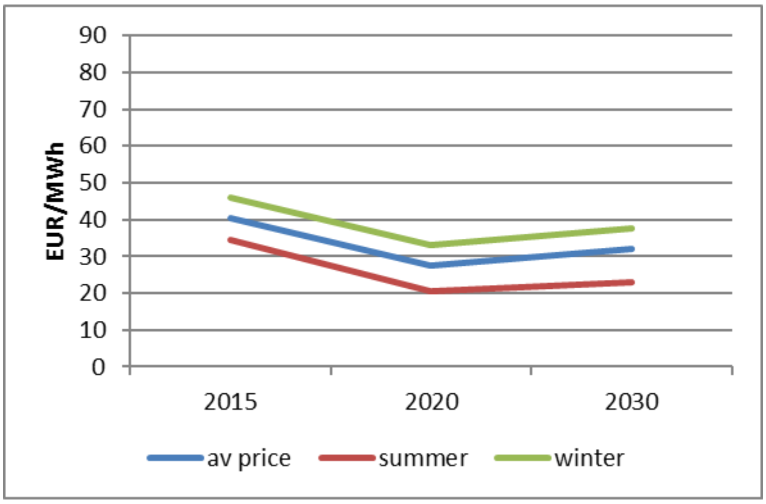

Figure 16: Average spot market prices R+ Scenario.

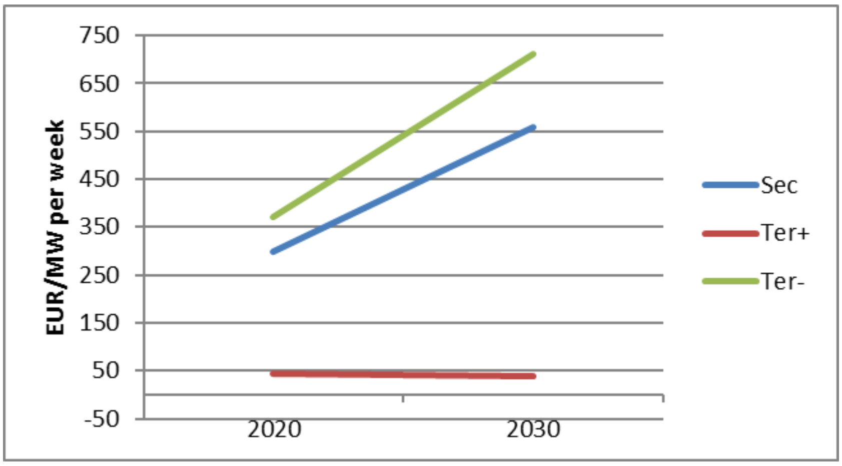

Figure 17: Average balancing market prices EU Reference Scenario.

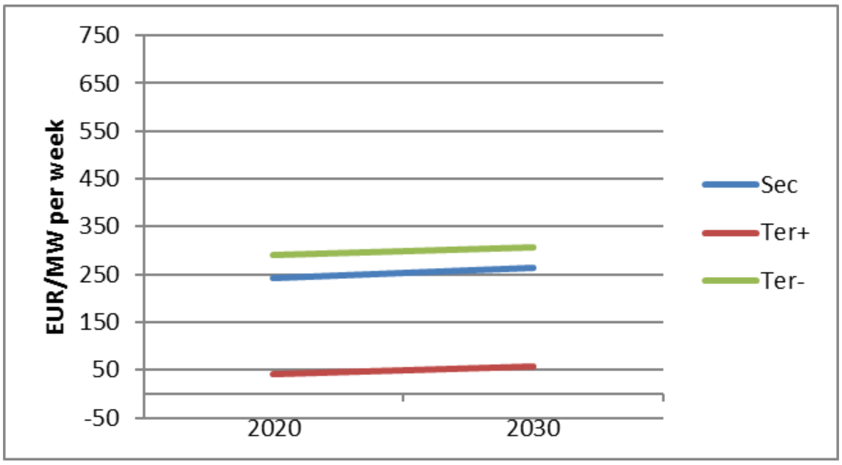

Figure 18: Average balancing market prices Base Price 2015 Scenario.

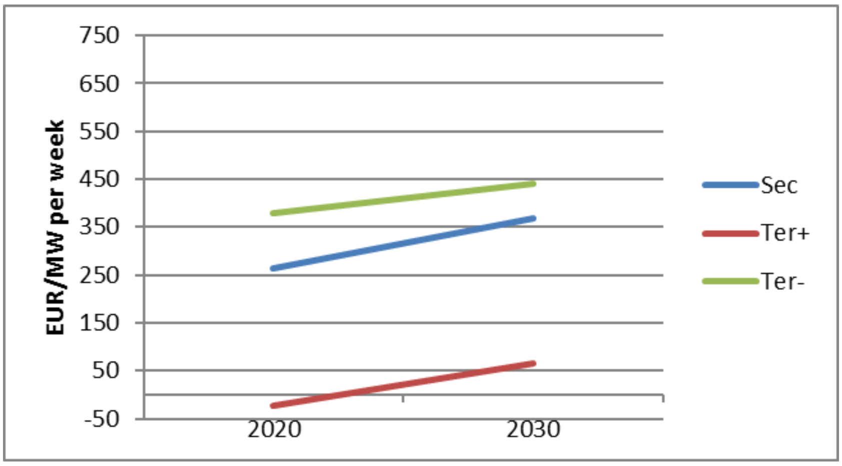

Figure 19: Average balancing market prices C+ Scenario.

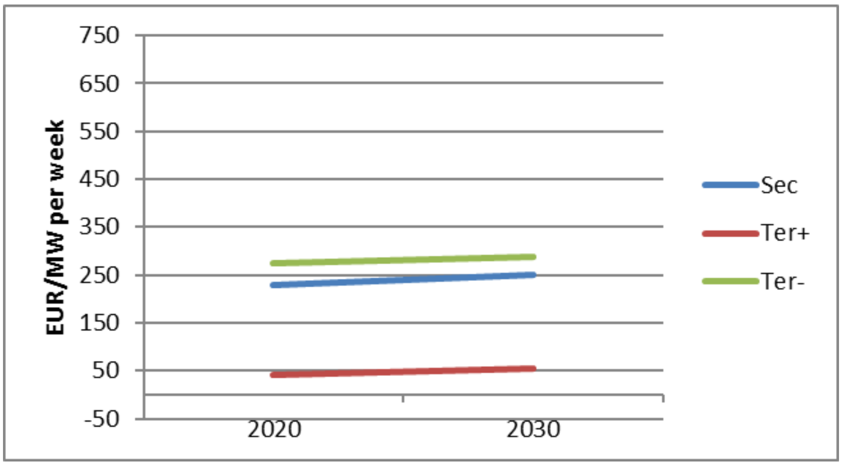

Figure 20: Average balancing market prices R+ Scenario.

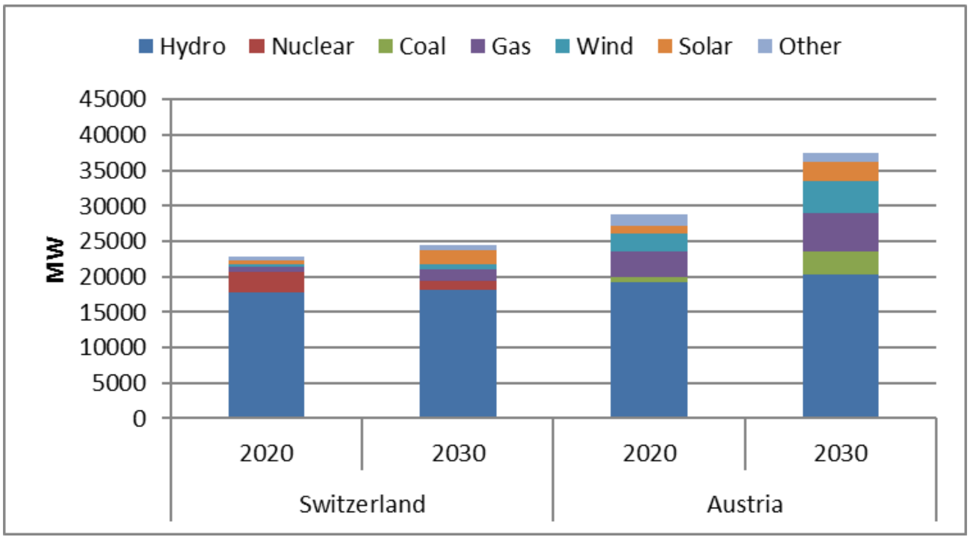

Figure 21: Generation capacity by technology for CH and AT under the EU Reference Scenario.

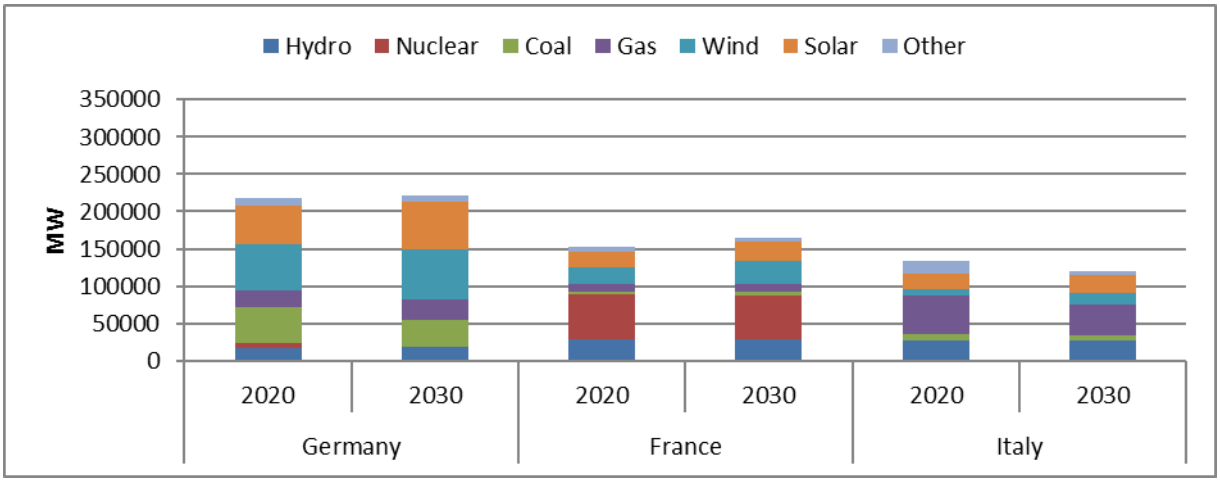

Figure 22: Generation capacity by technology for DE, FR and IT under the EU Reference Scenario.

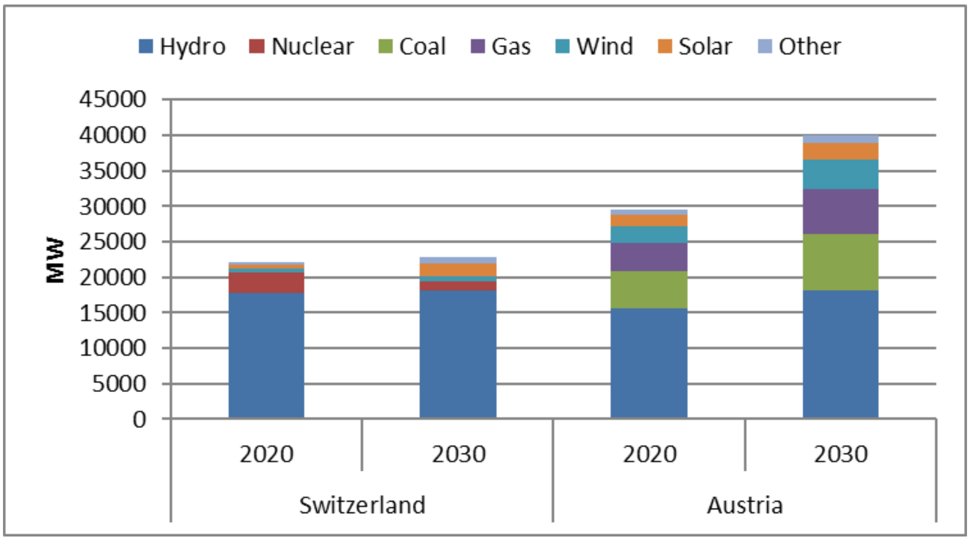

Figure 23: Generation capacity by technology for CH and AT under the Base Price 2015 Scenario.

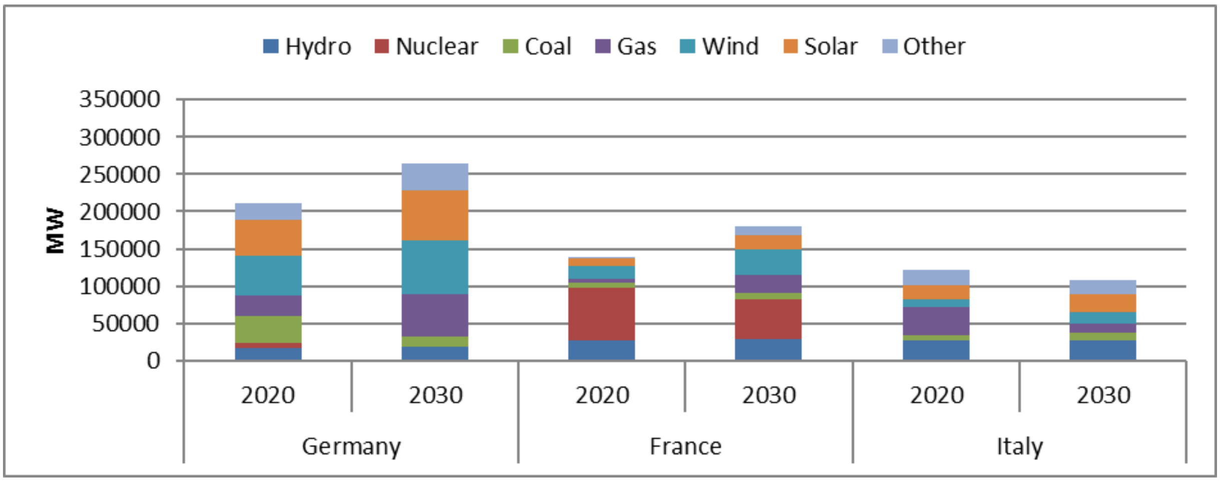

Figure 24: Generation capacity by technology for DE, FR and IT under the Base Price 2015 Scenario.

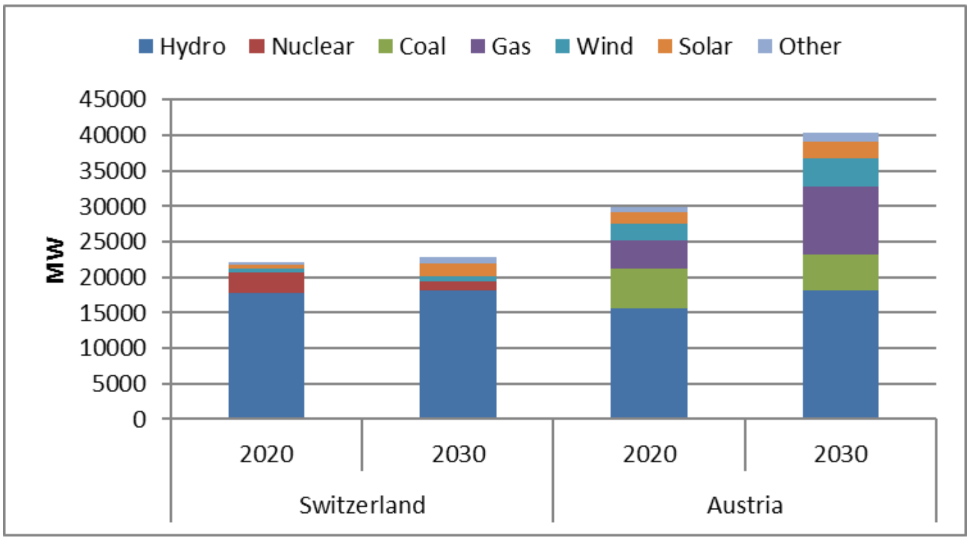

Figure 25: Generation capacity by technology for CH and AT under the C+ Scenario.

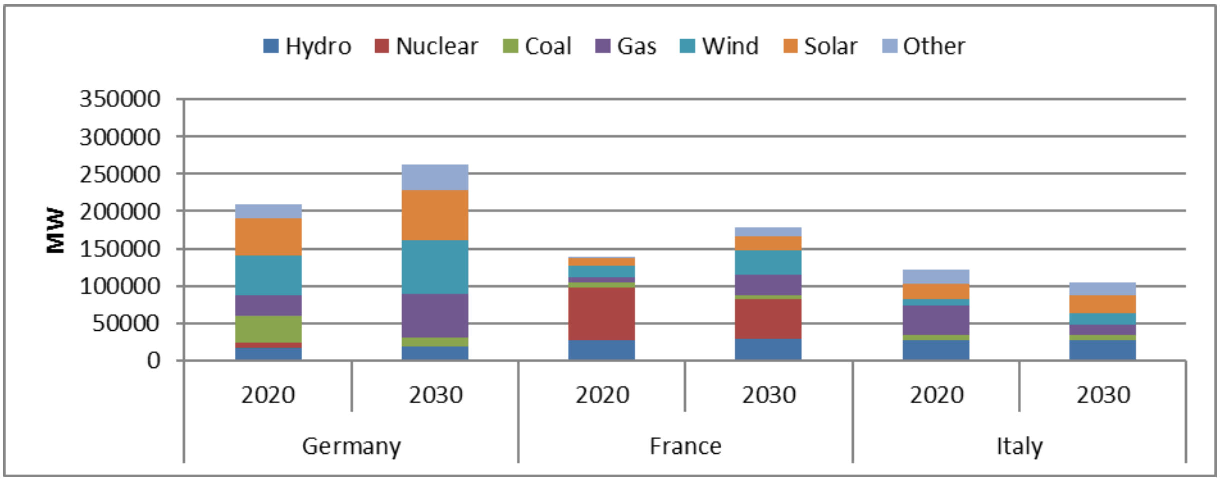

Figure 26: Generation capacity by technology for DE, FR and IT under the C+ Scenario.

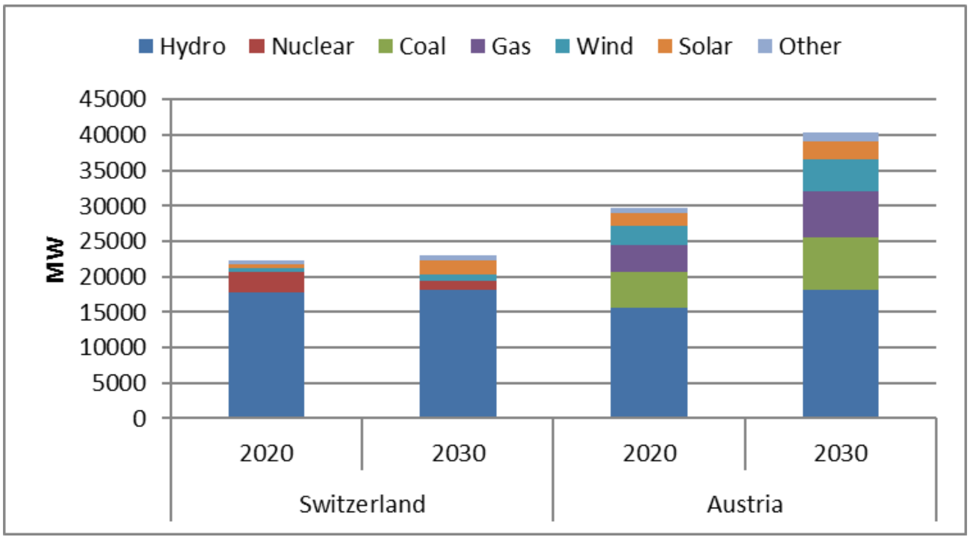

Figure 27: Generation capacity by technology for CH and AT under the R+ Scenario.

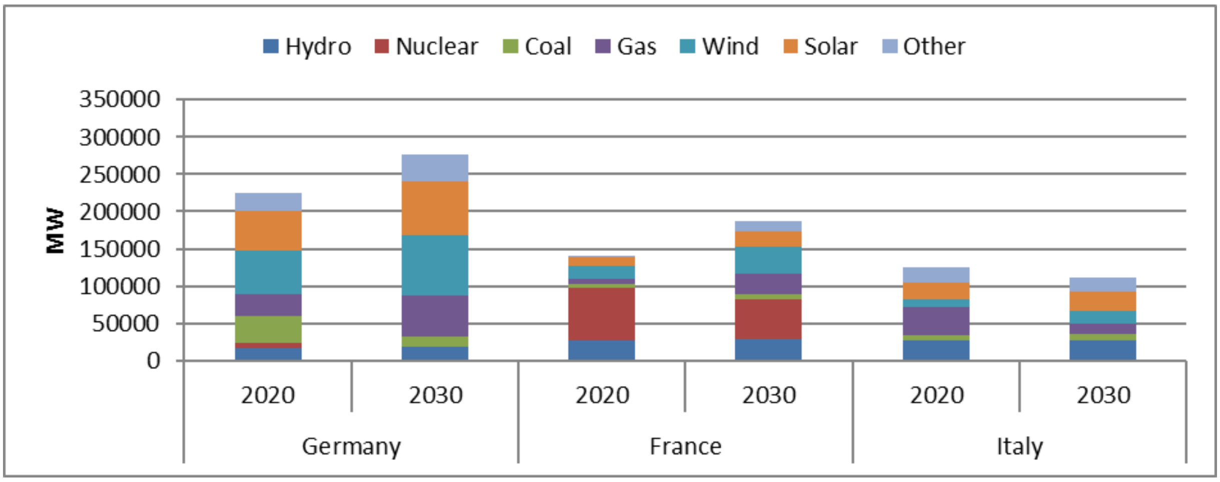

Figure 28: Generation capacity by technology for DE, FR and IT under the R+ Scenario.