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ScienceDirect

Energy Procedia 76 (2015) 49 – 58

Energy Procedia

European Geosciences Union General Assembly 2015, EGU

Division Energy, Resources & Environment, ERE

Modelling the energy future of Switzerland after the phase out of nuclear power plants

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Abstract

This paper evaluates the feasibility of future electricity scenarios drawn in the Swiss Energy Strategy 2050. These scenarios are characterized by a nuclear phase-out and high shares of renewables. We use Calliope, a linear programming model, special to model transition to renewables. Results show that it will be impossible to cover future demand only with domestic production, even if Switzerland reduces the consumption as envisaged. The daily profile of solar and limited capacity of wind lead to scenarios with maximum generation during peak hours. Moreover, we find a need to rearrange generation by flexible technologies to cover future demand.

Peer-review under responsibility of the GFZ German Research Centre for Geosciences

Keywords: electricity model; renewables; Energy Strategy 2050; Switzerland

1. Introduction

In September 2013 the Swiss Federal Office of Energy (SFOE) published the final report of the proposed measures in the context of the Energy Strategy 2050 (ES 2050) [1]. The ES 2050 draws an energy scenario where the nuclear must be substituted by alternative sources. Consequently, we will analyse in depth some of the technical

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Peer-review under responsibility of the GFZ German Research Centre for Geosciences
doi:10.1016/j.egypro.2015.07.843

implications of change in the Swiss electricity mix from a robust baseload power such as nuclear, to an electricity mix with a significant share of intermittent sources.

Implementing the ES 2050 implies difficult challenges, because nuclear power is nowadays the second most consumed electricity source in Switzerland. According to the Bundesamt für Energie (BFE) nuclear accounts for a 39.1% of the electricity production, only behind of Hydropower (54.2%) [2]. Considering that Switzerland has almost reached the maximum of its hydropower capacity, renewables are more likely to be the alternative when the nuclear phase out takes place. Hence, solar and wind power will play an important role in the future Swiss electricity mix, even though currently new renewables account only for 0.9% of the electricity production.

When a country faces the challenge of substantially modifying the electric system, the first commitment to undertake is the evaluation of future situations from varied viewpoints. The current paper analyses the feasibility to cope the electricity demand using the technological potential planned by the ES 2050.

The ES 2050 proposes two electricity scenarios with high levels of renewables:

- Variant C&E. This variant gradually eliminates the imports of electricity out to 2050: Switzerland is to cover its electricity consumption by domestic generation. Increased production of renewable electricity is to make this happen, mainly solar and wind. Renewables are planned to produce 14.3% of electricity in 2035, and 23.7% in 2050. Likewise, the electricity from fossil fuels could reach 24.8% in 2035, and 16.5% in 2050.
- Variant E. This variant includes imports of electricity. They will significantly increase in 2035 regarding the current levels, to return to currents levels in 2050. Net imports are currently 13% of the electricity generated in 2014. Variant E set 30% of imports in 2035, and about 13% in 2050. Exports are equal in both variants. Without counting transit, exports are currently 11% of the electricity generated. In 2035, exports will be 3.3% of the current electricity generated, and 8.2% in 2050. Solar and wind production will increase, up to 12.9% in 2035, and 26.6% in 2050. In this variant, the electricity from fossil fuels will be lower, in favor of imports, up to 7.6% in 2035, and 6% in 2050.

This paper analyses two electricity proposals in the ES 2050, and compares the possible options for Switzerland to supply the energy demand in a future without nuclear power plants. Therefore, we analyse the reliability of the national renewables resources to find an energy mix that cover the domestic demand. The methodology used, a linear programming model, in explained in detail in section 2. Finally, we evaluate the previous scenarios in section 3, and draw conclusions based on the dispatchability of the ES 2050 solutions for Switzerland.

2. Swiss Calliope, an electricity model of Switzerland with high resolution of renewables

The fundamental changes to be done in the Swiss energy system, consequence of the political decision ES 2050, have already been questioned by experts, *e.g.* [3]. Several experts have studied different energy scenarios as possible future options for Switzerland [4,5]. However, the energy supply from renewables sources of power (solar and wind) has still to be studied in a temporal resolution that allows making robust conclusions. In Switzerland, energy modelling has been used by the government [6] and also has significant relevance in academia [7,8,9]. Nevertheless, there is still a gap in the study of the electricity security in Swiss scenarios with higher shares of renewables [10]. One of the most detailed Swiss models of the electricity system, TIMES sectoral model, still uses the wind availability factor based on monthly wind speed [11].

In this paper, we design an electricity model of Switzerland to evaluate the security on electricity supply of the future scenarios. We use an open-source linear programming model with hourly data for wind and solar potentials to account for intermittency. Calliope is a multi-scale energy systems model, it was developed at the Grantham Institute Imperial College at London and Climate Policy group at ETH Zürich [12]. It has been specifically designed to represent high shares of renewable energy. Hence, it is especially suitable to represent the Swiss energy transition with high level of detail.

The novelty of the current model relies in its intra-annual time resolution. Solar and wind resources are modelled in an hourly time step. We calculate the power availability of wind and solar technologies using the hourly weather variables from international recognized reanalysis: European Solar Radiation Atlas (JRC) and National Centers for Environmental Prediction Climate Forecast System (NCEP - CFS) [13,14].

The model here presented optimises jointly renewable and non-renewable electricity sources. Transmission losses per distance, and electricity exports to neighbouring countries are considered, in order to assure the balance of the system. Finally, Swiss Calliope model is free and open.

2.1. Calibration and base model

Swiss Calliope is initially created for 2014 to calibrate it to the existing Swiss electricity output. Additionally, we use the demand and supply power factors for all the technologies of 2014 as load curves in the future scenarios. The supply technologies included in the analysis are presented in Table 1.

Table 1. Technologies and sub-groups modeled in Swiss Calliope.

Technologies by fuel	Sub-groups
Hydro	Run-of-river; dam; pumped storage
Nuclear	2nd Generation: Boiling Water Reactor (BWR); 3rd Generation: Pressurised Water Reactor (PWR).
Fossil	Combined cycle gas turbine (CCGT), combined heat and power (CHP), open cycle gas turbine: steam turbine, combustion turbine
Renewables	Solar photovoltaic (PV); Concentrated Solar Power (CSP); wind

We model the technologies as baseload or dispatchable technologies, according to their flexibility. Nuclear and big part of the capacity of hydro dam are modelled as baseload, since their production is constant over time. The rest of technologies have higher flexibility, as will be detailed later.

The model includes transmission losses of 7%. They are calculated by distance, according to the statistics of the BFE (2014). Likewise, this percentage is the same as calculated by other authors using historic data of Switzerland [11].

The techno-economic information of the different supply and transmission technologies has been mainly set according to two authors [4,15]. Therefore, and according to IEA (2009), the crude oil price is assumed to increase to 116 US$/bl by 2050.

2.2. Future scenarios 2035 and 2050

The aim of the present paper is to study the dispatchability of the scenarios of the ES 2050 that contain higher percentage of renewables, produced or imported. The variants of the ES 2050 to be analysed are Variant C&E and Variant E, under the scenario POM "Measures of the Bundesrat" which reflect the measures adopted by the Federal Council on 18 April 2012. Hence, the time horizon and time period of the model correspond to the full year 2035 and 2050.

Regarding the demand, we have modelled the trend planned in the POM scenario as well. The demand per capita is foreseen to decrease 12.6% by 2035 and 9.7% by 2050 with respect to 2010 [1]. The final electricity demand in 2035 is 62 980 GWh, whereas in 2050 is 65 950 GWh. The total electricity demand per year is hourly distributed according to the hour factors of 2014.

2.2.1. Supply technologies

Nuclear, which is set in the base scenario according to the monthly production of the power plants [2], is not included in future scenarios, because the last nuclear plant, Leibstadt, should close in December 2034 (Table 2).

Hydro is represented by three technologies in the model: run-of-river, dam and pumped storage. The first serves as a baseload technology, *i.e.* it produces constantly the maximum available according to the installed capacity and historic monthly distribution of the production. Consequently, the seasonal oscillations due to changes of the river flows are considered.

We use the monthly production of all hydro as a base data [2]. The resources are assigned to the different hydro technologies according to the expected production per technology detailed in BFE [16]. In order to represent the flexibility of the dam, the resources are adapted to the demand curve. Therefore, the production is higher at the peaks and lower at night. Regarding pumped storage, the model reproduces the behaviour of this technology as a dedicated production to cover demand at peak hours, whereas during night hours, it does not produce any electricity. In this case, the maximum production capacity of hydro resources is not set according to the ES 2050 [1], but to the last predictions of the BFE, published on its website [17]. The efficiencies and the costs of hydro do not change during the model time horizon, because it is a mature technology.

Table 2. Nuclear power plants and their main characteristics included in the Swiss Calliope. Source: [18]*According to ES 2050.

Nuclear	Gross electrical output (MWe)	Net electric output (MWe)	Electric efficiency (%)	Start of operation phase	Finished operation phase*
Beznau I (PWR)	380	365	96.05	01.09.1969	20.08.2019
Beznau II (PWR)	380	365	96.05	01.12.1971	18.11.2021
Mühleberg (BWR)	390	373	95.64	06.11.1972	25.10.2022
Gösgen (PWR)	1035	985	95.17	01.11.1979	19.10.2029
Leibstadt (BWR)	1245	1190	95.58	15.12.1984	03.12.2034
Total	3430	3278			

Fossil fuel is a flexible technology that produces as much as needed, limited by the maximum capacity. The level of fossil production is different according to the variant studied. We set the maximum sources per hour according to the statistics of the monthly production [2]. As shown in Table 1, five fossil fuel technologies are modelled in the base model (2014). According to the variant E, the model for 2035 is formed by 90% combined heat and power (CHP) and 10% of existing combined cycle gas turbine (CCGT). The model for 2050 includes only CHP as fossil fuel technology. The efficiency of the fossil fuel technologies will increase until 2030, but not beyond. Likewise, the costs will decrease until 2030, and then remain unchanged.

The renewable resources are precisely calculated by location, with an intra-annual time resolution of one hour. The locations for solar and wind were selected following the next criteria:

- Existing power plants with capacity of extension.
- Locations already connected to the existing grid.
- Zones excluded from protected areas, and in the case of wind, excluded from especially important bird areas (IBA) [19].

Table 3. Variables used to calculate the power factor of renewables, by technology and by server provider.

Solar variables *Server: JRC*	Wind variables *Server: RDA*	Common variables *Servers: RDA and JRC*
DHR (W/m2)	Wind u vector	Latitude (decimal degree)
DNI (W/m2)	Wind v vector (degrees)	Longitude (decimal degree)
GHI (W/m2)	Wind Velocity	Elevation above sea level (m)
Albedo	Atm Pressure (mbar)	Dry bulb Temp (ºC)

Table 3 shows all variables needed to calculate the power factor of solar and wind. The coordinates, elevation and temperature are variables needed in both cases. We downloaded this data for specific locations with a time resolution of one hour. Due to lack of availability of all the variables for the complete year 2014, we use the data of 2013. We obtain the solar data from the server of the Joint Research Center (JRC), which uses the European Solar Radiation Atlas. The model algorithm of the JRC estimates: direct, diffuse and reflected components of the clear-sky, and real-sky global irradiance on horizontal (GHI) or inclined surfaces (DNI). The total daily irradiation is computed by the integration of the irradiance values at hourly time intervals [13].

Regarding the wind variables, we use the National Centers for Environmental Prediction (NCEP) Climate Forecast System (CFS) reanalysis, available at the Research Data Archive (RDA) [14]. Selected products from CFS time series are available at hourly intervals, as a result of combining different time hour forecasts.

We calculated the power factor for both solar and wind using the System Advisor Model (SAM) developed in the National Renewable Energy Laboratory (NREL) [20]. SAM framework models different renewable technologies in an hourly resolution. It calculates the conversion efficiencies, as well as thermal collector efficiencies for the specific technologies. We used SAM to calculate power factors of solar and wind. However, the integrated Swiss dispatch model was made with Calliope, which allows us to build a complete system. In SAM, the characteristics of single technologies can be adapted to concrete needs, as well as the weather parameters. In our case, a database has been created per each location, using the various variables needed to calculate the power factor.

The solar technology modelled in Swiss Calliope is photovoltaic (PV). Four different locations have been selected, two for solar rooftop, corresponding to the two largest cities in Switzerland (Zürich and Genera), and two for solar farms (Table 4).

Table 4. Modelled locations of Solar

Solar locations			Name	Lat	Lon	m above sea level
Farm	1	SE	Solarkraftwerk Chur	46.85	9.53	700
	2	NW	Mont-Soleil	47.16	6.99	1220
Rooftop	3	NE	Zurich	47.37	8.55	420
	4	SW	Geneva	46.2	6.14	380

In Swiss Calliope, the solar capacity in the northern locations is 14% higher than in southern locations. This percentage is the mean difference of higher ranges of irradiation between north and south regions of Switzerland [19]. We calculate the power factor using different rated power for solar rooftop (4 kWdc) and farms (199.752 kWdc), but in both cases, with a tilt angle of 40º.

Regarding wind, Table 3 shows the variables needed to calculate the power factor for wind turbines. We calculate the power factor of a standard turbine of 70 meter, this was the hub size chosen for the Swiss Wind Energy Concept [21]. Furthermore, 70 meter corresponds to the hight of the turbine at the locations modelled: Callonges (Table 5). The power factor was calculated with a wind turbine Vestas 80.2, with a rated output of 2 MW.

Table 5. Modelled locations of Wind

Wind locations		Name	Lat	Lon	m above sea level
1	SW	Callonges	46.166	7.03	800
3	NW	Tramelan	47.24	7.11	1065

The original data for wind is available only at an altitude of 10 meter above the surface. We derive wind speed (or magnitude) from the component vector magnitudes (u and v) using the Pythagorean theorem (1). Then, we extrapolate the values of wind velocity every 10 meters until an altitude of 40 meters. This is needed to calculate the power factor of the selected turbine. To extrapolate, we use the wind profile power law, due to the difficulties to obtain the surface roughness or stability information of the terrain. We calculate wind direction using the inverse trigonometric function of the tangent (2). We assume the wind direction is the same for the different interpolated altitudes, given the impossibility to obtain these variables in one-hour resolution.

The power factor calculated allows us to model diverse capacities and obtain the consequent power generated for the diverse locations selected. Finally, we obtain the surface needed to satisfy certain amount of power in a year.

$$\mathrm{WS}=\sqrt{v^2+u^2} \tag{1}$$

$$a\tan(v,u) = 2\arctan\frac{v}{\sqrt{u^2+v^2}+u} \tag{2}$$

3. Results and discussion

3.1. Base model scenario

The model of Switzerland for 2014 was build to serve as a reference model for the future scenarios, and as a calibration. The results in Figure 1 show the total annual production of the different technologies included in Swiss Calliope, represented separately for the four seasons, and along the 24 hours of the day. The graph highlights the hours with maximum and minimum production and consumption.

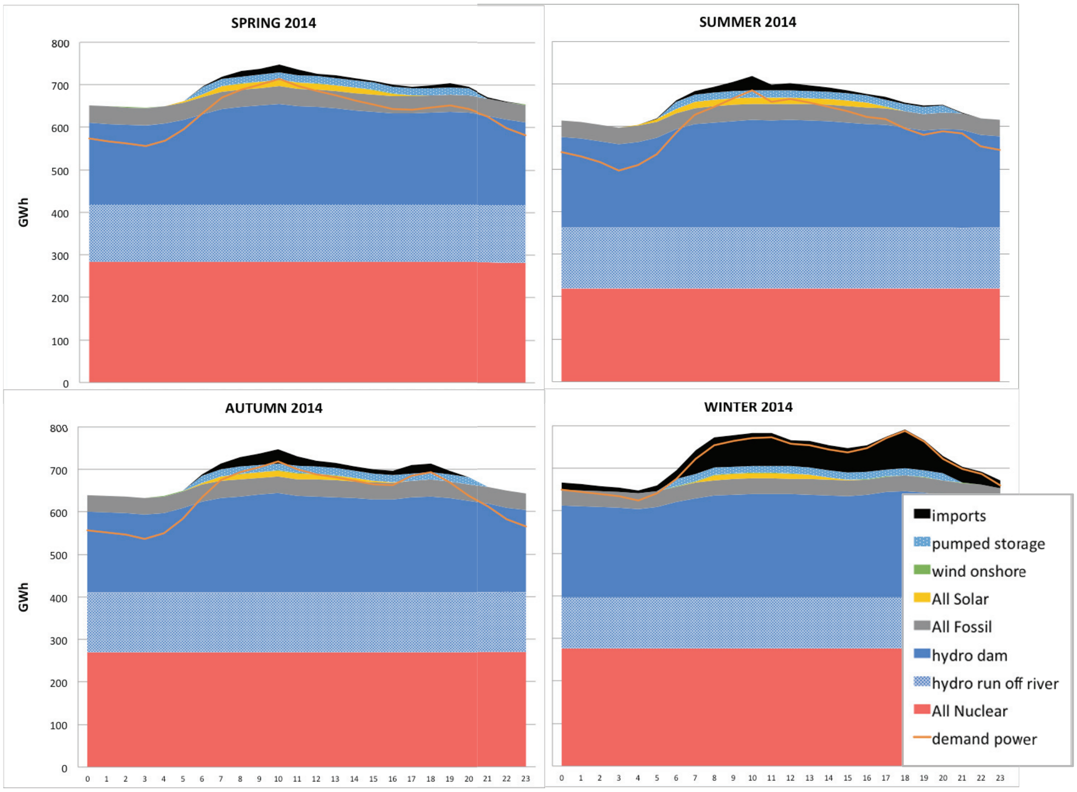

Fig. 1. Results of the model 2014, represented seasonally and in a 24-hour axis.

As can be seen in Figure 1, the nuclear is an important baseload technology, accounting concretely for 39% of the share (26 394 GWh), as specified in Table 6. In 2014, the hours of the day with higher needs of imports are between 7:00 and 11:00, and between 17:00 and 20:00. Those two timeslots correspond to the two demand peaks of the day. In 2014 Switzerland covered all the demand with almost no imports of electricity except in the winter months. It generated about 4 000 GWh more than consumed. Nonetheless, the country acted as transit hub, exporting 32 000 GWh, of which 77% to Italy, 14% to Germany and 9% to France. The 28 000 GWh of imports came from Germany 41%, from France 36% and from Austria 21%.

Winter was the season with greater exports, when the consumption reached its maximums and the hydropower production its minimums. The most critical hours of the winter were a continued fringe from 7:00 to 20:00. In winter, Switzerland was able to consume less than produced only from 2:00 to 5:00 in the morning.

Currently, hydropower technology is not needed as highly flexible technology. Therefore, hydro dams produce mostly as baseload, like run-of-river. The difference between these two technologies is that hydro dams operators adapt their behavior slightly to cover peaks of demand, whereas run-of-river produces always the maximum according to the river inflows. Pumped storage and solar filled the gaps in peak hours during summer, spring, and autumn.

3.2. Scenario in 2035

The results here presented correspond to the variant E, because they include imports. The results for the variant C&E are qualitatively similar, with higher levels of fossil-fuelled electricity replacing imports. The most notorious change in this scenario is the suppression of nuclear (Fig. 2). In its place, run-of-river act as the main baseload along the year. However, run-of-river depends completely on the water flows, which have strong seasonality. Summer is therefore the season with highest electricity production due to melting of the snow, and higher solar production. Thus, hydro reaches a maximum level of production, and Switzerland could depend less on imports.

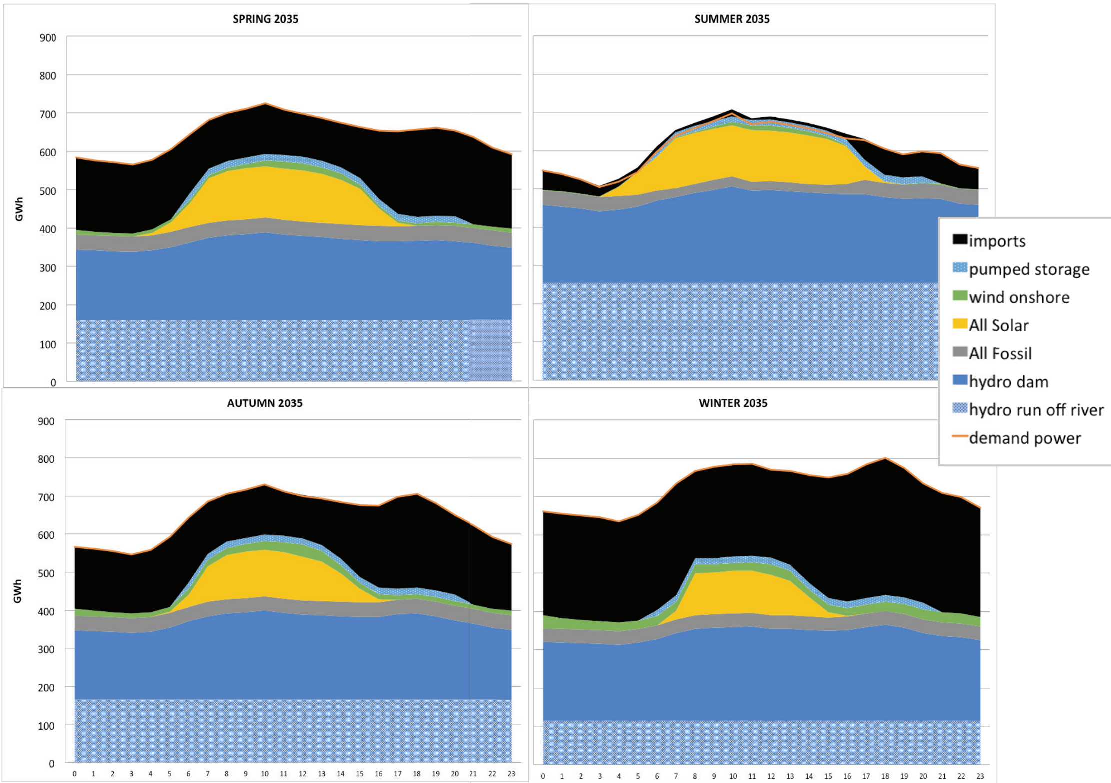

Fig. 2. Results of the model 2035, represented seasonally and in a 24-hour axis.

Solar accounts for 9.3% of the annual production (Table 6), and is exclusively distributed in the central hours of the day. The timeslot of solar production is longer in summer, from 4:00 to 17:00, compared to winter, where electricity from solar is produced only from 7:00 to 15:00.

Wind share accounts for around 4% of the total, and the distribution of its production is quite homogeneous during all the hours of the day. Winter has the maximum wind production, whereas summer, especially in the morning, wind production reaches its minimums.

Fossil production is continuous and stable along the year. Switzerland will therefore have to rely increasingly on the imports to cover the consumption.

According to the ES 2050, the imports will cover up to 30% in the variant E (14 000 GWh), whereas in the model, the imports represent 36.6% of the consumption (17 227 GWh). This difference relies majorly in the production capacity of hydro. Initially, the ES 2050 set on 43 020 GWh the capacity of hydro for 2035, whereas the new expectations published in the website of the BFE, set 37 400 GWh [17].

Finally, the variant E of the 2035 scenario reduces net exports until 2 260 GWh, this represents a decrease of eight percentage points with respect to electricity exported in 2014. However, Swiss Calliope shows a reality where exports will not be possible along the year, except during some hours on summer (11:00 – 16:00).

Table 6. Share of the technologies in the 2035 and 2050 scenarios, in reference to 2014.

Technologies	2014	2035	2050
Nuclear	0.39	0.00	0.00
Hydro	0.54	0.79	0.67
Fossil	0.06	0.08	0.06
Solar	0.01	0.09	0.19
Wind	0.00	0.04	0.07
Total generated	1.00	0.70	0.85

3.3. Scenario in 2050

The results of this scenario are analogous to the previous one, the major difference rely on the increase of renewables. In 2050, the solar production will intensify, up to 19.3% on the electricity mix, and the wind up to 7.4% (Fig. 3). The prominent production of solar, jointly with the rest of technologies, could make possible to cover the need of Switzerland during the central hours of the day. This is achievable in spring concretely from 7:00 to 14:00, in summer from 5:00 to 17:00, and in autumn from 8:00 to 13:00. However, as in the other scenarios, winter remains still with not enough levels of national production to cover the needs. We can observe a direct relation between sunlight hours in a day, and autarky electricity production.

As well as in the 2035 scenario, the model for 2050 contains the revisited capacities for hydro set in the webpage of the BFE [17], and not the capacity initially set by the ES 2050, which was 5 000 GWh higher. The Figure 3 shows the results of setting hydro capacity at 38 600 GWh, whereas the capacity initially planned was 44 150 GWh. The actual capacity of hydro is higher in summer than the electricity produced by the model during central hours. However, solar produces on its place, and as a consequence, the power factor of hydro is low. This could be attributed to the low levels of exports considered in the scenario, that prevent hydro from producing, since there is no demand.

In 2035, the exports are 17% with respect to 2014. Similarly, fossil turbines produce equally distributed along the day, but the total production is 15% lower than the planned in the ES 2050.

Wind produces fairly homogeneously along the day. It plays a special roll in winter, when a higher level of wind production mostly helps to compensate the reduction of hydro. In winter, wind produces 40% of the total annual.

As explained, these scenarios are the result of projecting the current trends of production to the future. The trends reflect production for every technology during the most profitable hours. Nevertheless, considering a general increase of renewables in Europe, overproduction during central hours is likely to happen. Therefore, prices may change consequently, and some technologies may switch the production to timeslots that may result finally more profitable.

The level of imports set in the ES 2050 scenario reaches 12.6% of the production (7 200 GWh), whereas the model under study reflects a need of 30% (17 358 GWh).

If the projections of the ES 2050 are realised, the flexible technologies such as hydro pumped storage, hydro dams, and fossil fuels turbines would have to rearrange their time of production to off-peak hours. So that, a flexible energy mix could contribute to decrease the imports. Nevertheless, it has still to be studied how this relocation can be accomplished profitably, using the capacity of hydro, the larger technology of Switzerland. Finally, the consequent effect on the levelized cost of electricity has to be analyzed as well.

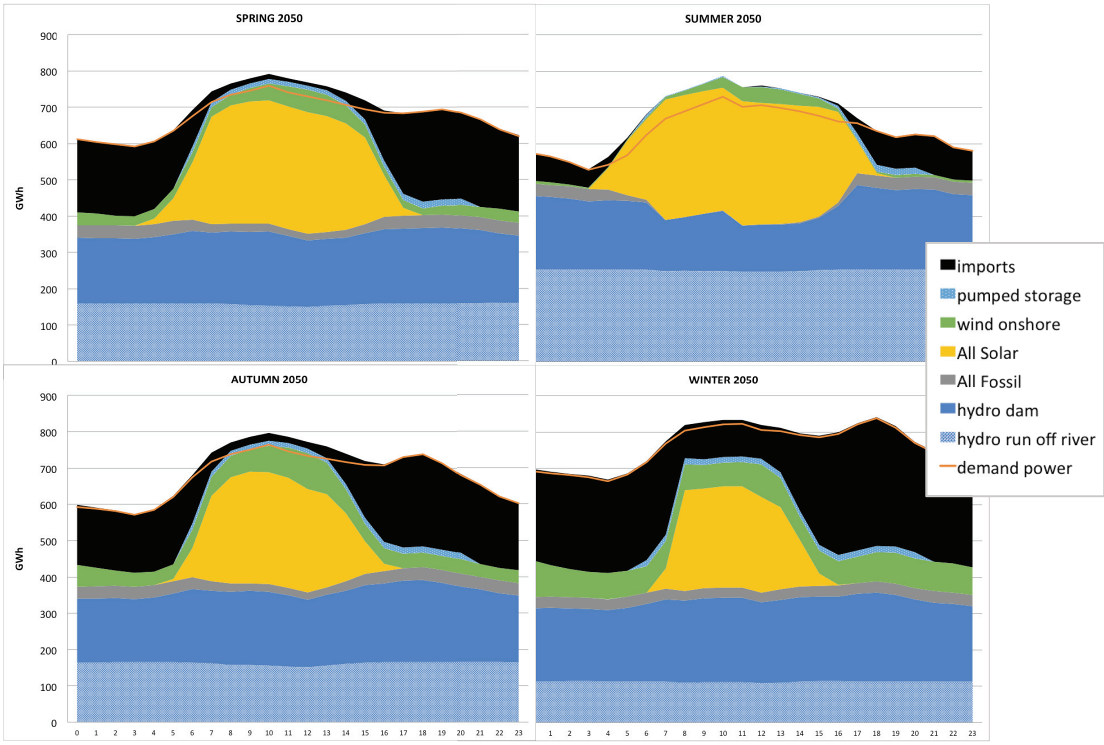

Fig. 3. Results of the model 2050, represented seasonally and in a 24-hour axis.

4. Conclusions

This paper presents a new electricity model of Switzerland with high time resolution. Swiss Calliope, is based on the projections of the ES 2050, variant E and C&E, both committed to a high development of renewables. This responds to the need of analyzing the future situation of electricity generation in Switzerland, after the phase out of its nuclear plants. We use a linear optimisation framework, which has an intra-annual time resolution of one hour. This is necessary to effectively model renewable electricity sources, with accurate precision technologies, such as renewables, which account for high variability. Moreover, Swiss Calliope model and results will be free and open available on the web. Therefore, interested people could benefit from the previous work to elaborate further analysis.

Results show that the variant C&E of the ES 2050, without expected imports, is not possible without expected imports. Although increasing the capacity of solar and wind will increase to 26.7% in 2050, imports of electricity will be needed.

The seasonal analysis shows that summer is likely to be an exporting period, whereas winter will more likely be a high importing period. Imports will play a larger role both in 2035 and in 2050, although larger installed capacity of renewables will contribute to fill the demand on the peak hours, on spring, summer, and autumn. This is projected in case of maintaining the current trends of electricity production. However, this may be subject to changes. Due to overproduction of solar and wind, the capacity factor of some technologies will be considerably low in central hours of the day. Therefore, evening or night hours may seem economically interesting for technologies producing at low factors during the day, such as hydro dam, and fossil turbines. Solutions have to be found to cover the high levels of imports needed during the night, and winter. The authors are currently exploring the possibilities that could bring flexible technologies such as hydro pumped storage. Other solutions to be studied are the flexibility of hydro dam, or new possibilities of storage.

The levels of demand used here presented are taken from ES 2050 projections, which break the increasing trend of last eighty years. Demand will be reduced around 10% per capita in the future, according to the ES 2050. This presents another possibility of future study, where demands consistent with past trends can be included in the model. Likewise, the changes on levelized costs of electricity in future scenarios are being analyzed by the authors, as well as the land needed to increase the share of renewables up to the limits set in the ES 2050.

In brief, we showed the unfeasibility of electricity scenarios with high share of renewables where Switzerland is autarky, and the need of a rearrangement of flexible technologies to cover the demand. In any case, this analysis established a solid base to develop various and more concrete studies in the future.

Acknowledgements

The study was carried out as part of the New Risks project, funded as part of the National Research Program 70 of the Swiss National Science Foundation. The authors would like to thank Stefan Pfenninger and Beat Faas for their invaluable technical assistance. We are also very grateful to several experts, who provide us with generous information and recommendations.

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