Ensuring diversity of national energy scenarios: Bottom-up energy system model with Modeling to Generate Alternatives

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Keywords

Energy scenarios, energy policy, electricity, diversity, energy system models, Modeling to Generate Alternatives

Abstract

Long-range energy scenarios are commonly used to inform national energy policy decisions. Although the scenario approach aims to expand the spectrum of futures considered, in the past energy scenarios have not been diverse enough to include less expected real-world developments. We use a bottom-up energy system model EXPANSE with Modeling to Generate Alternatives (MGA) to assess the diversity of the existing ensemble of multi-organization, multi-model Swiss electricity supply scenarios. We show that both for 2035 and 2050 existing scenarios cover well the various possibilities in deployment of individual electricity generation technologies in terms of installed capacity or produced electricity. When analyzing scenarios as a whole, we find that in 2035 there is a lack of scenarios with high electricity demand and greater deployment of renewable technologies occurring simultaneously, as well as scenarios with a negligible or negative share of net electricity import. In 2050, there is also a lack of scenarios that depict high electricity demand and conservative deployment of new renewable technologies, especially solar PV. We propose six additional scenarios to be included to increase the diversity of the ensemble of Swiss electricity supply scenarios and achieve better understanding of the future possibilities and uncertainties.

1. Introduction

Due to increasing energy demand, climate change and other environmental concerns, multiple countries are currently developing or already implementing strategies for transforming their national energy systems. United Kingdom is putting into practice its legally-binding Climate Change Act [1] that requires reducing greenhouse gas emissions from the energy sector by 80% in 2050, as compared to the levels of 1990. Germany is shifting to decentralized renewable energy and increased energy efficiency as part of the country's strategy, called Energiewende [2]. After the nuclear accident in Fukushima, the Swiss Federal Council and Parliament hasb decided in 2011 to stepwise phase out nuclear power generation by 2035. The Swiss Energy Strategy 2050 [3] and associated analyses in Energieperspektiven 2050 [4] describe options for electricity sector transition without the five existing nuclear power plants in Switzerland that in 2015 have accounted for almost 40% of total electricity production. In this paper we take a closer look at the existing Swiss electricity supply scenarios for the years 2035 and 2050 that underpin analyses for implementing the Swiss Energy Strategy 2050.

Long-range energy scenarios are primary tools in strategic energy decision making in order to assess uncertainties and options for the future energy transition [5, 6]. Such scenarios can be developed by multiple organizations in public administration, non-governmental institutions, industry and academia. Examples of widely-known long-range energy scenarios include International Energy Agency scenarios [7], US Energy Information Administration projections [8], or BP energy outlook [9]. In addition to the Energieperspektiven scenarios [10] that underpin the Swiss Energy Strategy 2050, other Swiss electricity supply scenarios for 2035 and 2050 have been generated too by universities (e.g. ETH Zurich), research institutes (e.g. Paul Scherrer Institute), non-governmental organizations (e.g. Greenpeace), and others. Densing et al. [11] provide an overview. The resulting ensemble of multi-organization, multi-model Swiss scenarios altogether improves understanding of the diversity of future options and uncertainties in the energy transition [6].

Although the scenario approach aims to expand the consideration of future possibilities [5, 12], in the past long-range energy scenarios have been shown not to be diverse enough to include less expected real-world developments, such as increase in energy use efficiency in 1980s or deployment of renewable technologies since 2000 [5, 6, 13-15]. Repeatedly unsuccessful attempts to develop scenario sets that encapsulate

the real-world energy transition led scenario developers to exploring new approaches to scenario development [16]. Schweizer and Morgan [17] have applied so-called bounding analysis in order to estimate the lower and upper bound of US electricity demand in 2050. Their approach, however, has resulted in very large uncertainty bounds, which could be meaningfully reduced by employing energy systems models to exclude internally inconsistent scenarios. Recent advances in semi-quantitative scenario techniques include selection of a small set of diverse scenarios in order to guarantee the variety of futures considered [18, 19]. However, such diversity techniques have been demonstrated for semi-quantitative scenarios only. In energy systems modelling, three decades-old Modeling to Generate Alternatives (MGA) technique has been recently rediscovered [20]. MGA can be used with an energy system model to directly generate a small set of different energy scenarios [21, 22] or to generate a large set of energy scenarios and afterwards select a small set of maximally-different ones [23-25]. In these cases, energy system model is used to account for technology, supply-demand, environmental, economic, other constraints and drivers in order to assure that internally-consistent energy scenarios are generated. MGA enables a systematic extraction of diverse scenario sets to expand uncertainty consideration and forego aforementioned failures of the past, when modelled scenarios do not cover less expected real-world developments.

In order to support the ongoing efforts in Switzerland to implement the Swiss Energy Strategy 2050, in this paper we analyze whether existing multi-organization, multi-model Swiss electricity supply scenarios for 2035 and 2050 are sufficiently diverse in covering the range of possible Swiss electricity supply transitions. Our intention is to assess the diversity of the existing scenario set and, if the current scenarios are deemed to lack diversity, to identify missing types of scenarios that should be added. We use a bottom-up energy system model EXPANSE [23, 24] with MGA [26] (Section 2). First, we generate a large ensemble ($N=520$) of EXPANSE scenarios for the Swiss electricity supply system in 2035 and 2050. Due to MGA, these EXPANSE scenarios are assumed to serve as a benchmark of a diverse set of scenarios. The EXPANSE scenarios are then compared with the existing Swiss scenarios technology by technology and as a whole in order to estimate whether the existing Swiss scenarios are sufficiently diverse (Section 3.1-3.2). Using Distance-to-Selected technique, ten maximally-different EXPANSE scenarios in terms of technology-specific installed capacity or annual electricity supply are selected in order to examine what additional

scenarios would increase the diversity of the existing set of Swiss scenarios (Section 3.3). Electronic Appendix A provides the complete model documentation; Appendix B shows the input data used in Swiss EXPANSE; and Appendix C depicts the newly selected scenarios in detail. Our work thus builds on the previous meta-analysis by Densing et al. [11], who have looked how the existing Swiss scenario set could be reduced to a smaller number of representative scenarios. We analyze whether the existing Swiss scenario set is diverse enough in the first place and whether any scenarios or perspectives might have been systematically missed thus far.

2. Methods and data

2.1. Swiss EXPANSE and MGA

Bottom-up energy system models are a type of widely-used energy-environmental-economic models that support energy and climate change policies [27-29]. Bottom-up energy system models rely on a detailed technology representation of the whole energy system from energy resources, through energy conversion and transmission, to energy end use. Traditionally, these models use cost optimization to generate cost-optimal energy scenarios under technological, resource, environmental and policy constraints. In this paper we also use a bottom-up energy system model EXPANSE (EXploration of PAtterns in Near-optimal energy ScEnarios) [24, 30]. EXPANSE has the same structure as a conventional bottom-up energy system model, but looks beyond cost optimal scenarios only [21-24, 31]. In contrast to D-EXPANSE [24, 32] that models the long-range energy transition and capacity expansion, in this paper EXPANSE focuses on a single year and models the electricity supply-demand dispatch in detail. In contrast to other bottom-up models, in this paper EXPANSE aims to be value-free and cover various diverse perspectives and stakes in the existing Swiss scenarios and beyond. Thus, EXPANSE does not include cost constraints or cost objective function.

Compared to the previous EXPANSE versions, Swiss EXPANSE, described in this paper, includes a detailed electricity dispatch model consisting of 386 time slices per year. A visual representation of the Swiss EXPANSE electricity dispatch can be seen in Figure 1. A year is divided into 50 weeks and 336 hours in such a way that peak and base weeks are modeled on an hourly basis, whereas the remaining weeks are modeled on a weekly basis. Greater time resolution is clearly desirable; however, since Swiss EXPANSE is intended to analyze large numbers of electricity supply scenarios we are faced with a trade-off between temporal resolution for accuracy, computational power

and data availability. This trade-off affects model solutions and could be circumvented by utilizing flexible timeslicing that was introduced in the MARKAL/TIMES model [33, 34], but this would complicate the modelling of pumped hydropower storage as storing of electricity in one time slice and its release during another time slice would be difficult to model. In a low-carbon system, adequate modelling of hydropower is important because it contributes to the deployment rate of weather-dependent wind and solar photovoltaic (PV) technologies.

Figure 1. Graphical representation of the dispatch modelling in Swiss EXPANSE. The weekly load curve for Switzerland in 2015 is depicted; the peak and base weeks are respectively zoomed in at an hourly resolution.

MGA, first introduced by Chang et al. [26], is increasingly used with bottom-up energy system models [22-24, 35]. Traditionally, energy modelers have tended to provide several highly detailed scenarios [24, 35]. Doing so, carries the risk of underplaying the uncertainties and diversity of futures associated with such a complex, socio-technical system as energy system. Generating and analyzing large ensembles of energy scenarios is a means for expanding consideration of uncertainty and diversity [36-39][39-41]. Hence, Swiss EXPANSE includes MGA in order to generate a large number of various electricity supply scenarios that, among other scenarios, also cover the extremes that define the boundaries of the feasible energy scenarios.

Appendix A provides documentation of the Swiss EXPANSE model and MGA used. In brief, by specifying technology, supply-demand, resource and environmental constraints, Swiss EXPANSE defines the space of technically-feasible Swiss electricity supply scenarios for the years 2035 and 2050. Cost constraints and drivers are not accounted for because the primary aim is to develop a value-free model that can account for various existing or possible perspectives. Swiss EXPANSE variables include technology-specific installed capacity and produced electricity in every time slice by each technology, electricity export, import, and hydropower storage. During one MGA run, these variables are assigned a random weight for formulating a random objective function. The weights are sampled from the $\{1, -1\}$ set, assuming uniform distribution. The resulting random objective function is then both maximized and minimized over the set of EXPANSE constraints in order to generate two electricity supply scenarios. This MGA procedure is repeated 20 times for different random objective functions and generates a total of 40 electricity supply scenarios. By combining these MGA runs with 13 assumption sets on electricity demand (Section 2.2), Swiss EXPANSE in total generates 520 electricity supply scenarios.

2.2. Input data and model assumptions

Appendix B provides input data used in Swiss EXPANSE model, e.g. fuel-use efficiencies, technology contributions to peak equation, availability and capacity factors, as well as resource constraints of 24 technologies for the years 2035 and 2050. In this study, Swiss EXPANSE assumes the annual electricity end-use demand and associated load curves exogenously without modelling the demand structure in detail. As in many other models [42], Swiss EXPANSE currently assumes that the future load curves have the same profile as in 2015, but are scaled upwards to result in the total annual electricity demand. Annual electricity demand assumptions from the existing Swiss scenarios are taken for Swiss EXPANSE (Table 1). Annual electricity demand, including losses, in 2035 and 2050 is assumed to follow 13 trajectories, each with different underlying political, technological development, and efficiency assumptions.

Table 1. Electricity demand assumptions in existing Swiss electricity demand scenarios that were reviewed by Densing et al. [11].

No.	Demand scenario	Electricity demand in 2035 (TWh / year, including losses)	Electricity demand in 2050 (TWh / year, including losses)	Average annual GDP growth	Population in 2050 (million)	CO ₂ emission in 2050 (tCO ₂ /person/year)	End-use electricity for mobility in 2050	Efficiency increase	Source
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1	NEP	59.84	57.64	1.1%	9	1.03	41.0 PJ/year	Strong	[10], [43]
2	VSE Szen 3	68.20	60.50	not specified	9	1.4	High	Strong	[44]
3	Green peace	64.32	65.12	1.1%	9	0.2	54 PJ/year	Strong	[45]
4	POM	63.03	66.12	1.1%	9	2.2	31.6 PJ/year	Significant	[10], [43]
5	ETH niedrig	66.00	66.00	not specified	<9	<1.56	<8.5 MtCO ₂ /year	Moderate	[46]
6	Cleantech	72.00	70.01	1.2%	9	0.43	50% efficiency gains within personal mobility, public transport	75%, 20%, and 35% efficiency gains within heating areas, process heating and appliances respectively	[47]
7	VSE Szen 2	72.80	73.00	not specified	9	3.5	Medium	Significant	[44]
8	WWB	70.01	74.80	1.1%	9.04	2.88	23.8 PJ/year	Significant	[10], [43]
9	PSI sys 50	72.10	76.39	1%	9	3.21	Significant amount of hybrid cars	Significant	[48]
10	ETH mittel	75.00	79.00	not specified	9	1.56	8.5 MtCO ₂ /year	Moderate	[46]
11	VSE Szen 1	76.20	81.00	not specified	9	6.1	Low	Moderate	[44]
12	PSI sys noPol	76.79	84.47	1%	9	No climate policy	No battery cars and few hybrid cars	Moderate	[48]
13	ETH hoch	82.00	92.00	not specified	>9	>1.56	>8.5 MtCO ₂ /year	Strong	[46]

Based on the Swiss Energy Strategy 2050 [3], Swiss EXPANSE also assumes that no new nuclear power plants will be built after the end of the lifetime of the current plants. That means, that in year 2035 and 2050 nuclear power share in Swiss EXPANSE scenarios is modelled as 0.

2.3. Selection of maximally-different scenarios to assure diversity

Energy scenario users in policy or industry typically require a small and informative set of scenarios [6]. When choosing which scenarios should be included in this small set, caution is necessary to guarantee that the selected scenarios represent sufficiently diverse futures and exhaust key uncertainties associated with the energy transition [18, 49]. Methods are available for characterizing and filtering a large number of energy scenarios to derive a small and diverse set of scenarios. An overview of some methods can be found in [50]. In Table 2, we summarize the key approaches that have been used or are applicable to energy scenarios. Methods that rely on qualitative or semi-quantitative scenarios typically start with definition of a set of internally-consistent scenarios [49]. In modelling-based scenario development, demonstrated in this paper, this step is not necessary as internal consistency of scenarios is assured through the use of the energy system model.

Table 2. Selected methods for choosing a small, diverse set of scenarios.

Method	Description	Source
OLDFAR (Optimized Linear Diversity Field Anomaly Relaxation)	This method is tailored to qualitative and semi-quantitative scenario construction. The method utilizes robust optimization to locate scenarios that maximize expected value and minimize variance in the diversity score.	[19]
Scenario Diversity Analysis	This method is tailored to qualitative and semi-quantitative scenario construction. In order to locate a small set of diverse scenarios from the large set of internally-consistent scenarios, an optimization technique is used. It locates a scenario set with maximal sum of mean weighted Manhattan distances of all consistent scenarios, when the minimal weighted Manhattan distance is exogenously given as a threshold.	[18, 51]
Local Efficiency Method	This method is tailored to qualitative and semi-quantitative scenario construction. In the large scenario set, consistency score of every scenario is evaluated. Then, several scenarios are selected on the basis of the local maxima of consistency scores, i.e. scenarios whose consistency score is greater than or equal to all its neighbors.	[49]
Max-Min Selection	This method is tailored to qualitative and semi-quantitative scenario construction. In the large scenario set, consistency score of every scenario is evaluated. A small set of most internally-consistent scenarios with a minimum distance from each other is then selected.	[49]
Distance-To-Selected Method	This method can be applied to both quantitative model-based scenarios [25] and qualitative and semi-quantitative scenarios [49]. It searches the large set of modelled or internally-consistent scenarios for other scenarios that are most different in their attributes from the initial scenario, selected based on the scenario developer's preferences. The difference from the initial scenario is defined as the squared Euclidian distance. The distance of the third and further scenarios to the set of already selected scenarios is defined as a harmonic mean of squared Euclidian distances.	[25, 49]
Cluster Analysis	This method can be applied to both quantitative model-based scenarios and qualitative and semi-quantitative scenarios. First, every internally-consistent or modelled scenario is considered to be a separate cluster. The minimal distance between each pair of clusters is calculated using a distance measure of Minkowski distance of order p, Manhattan distance, Chebyshev distance, etc. The two most similar clusters are merged into a new cluster and the procedure continues until only one cluster remains. A small and diverse set is then selected by going backwards through the cluster tree (dendogram). One scenario within each cluster is then chosen to represent the corresponding cluster. The selection of this scenario may be done by looking for the scenario that contributes the least to an increase in the overall variance within the cluster.	[52] [50]
Principal Component Analysis	This method can be applied to both quantitative model-based scenarios and qualitative and semi-quantitative scenarios. This technique helps extract dimensions of a multidimensional space that account for the most in-sample variance. The space of internally-consistent or modelled scenarios X is approximated by a suitable linear combination of orthonormal vectors, subject to minimizing the covariance of X and the approximation. The most distinct scenarios are then defined on the basis of these dimensions that account for the most in-sample variance.	[11]

In this paper, we use the Distance-To-Selected approach. It is simpler and faster than OLDFAR, Scenario Diversity Analysis, Cluster Analysis, or Principal Component Analysis as it relies on calculation of Euclidian distances and their harmonic and does not involve any optimization. Each step can be traced and reasonably justified as explained by Tietje [49]. Compared to the Max-Min-Selection, Distance-To-Selected approach is more controllable as Max-Min-Selection generates different scenarios when

the minimum distance threshold is changed. Although the outcome of the Distance-To-Selected approach depends on the initially chosen scenario and thus on the subjective opinion of the scenario developer, this can also be an advantage. Incorporation of scenario developer's or stakeholder views is not possible with the Max-Min-Selection. In contrast to Local Efficiency and Max-Min-Selection approach, the Distance-To-Selected approach is applicable to modeled energy scenarios [25]. In contrast to Principal Component Analysis applied by Densing et al. [11] in order to reduce the number of existing Swiss scenarios, the Distance-To-Selected approach helps us identify new energy scenarios that are not yet among the existing Swiss scenarios.

In Swiss EXPANSE, the Distance-To-Selected approach relies on squared Euclidian distances and its harmonic means [25, 49]. First, the scenario attributes to be used for selecting maximally-different scenarios are chosen, for instance, technology-specific installed capacity. Second, the initial scenario from Swiss EXPANSE is chosen randomly or by picking a specific scenario of interest. Third, the first maximally-different scenario is selected as the one that has the largest squared Euclidian distance from the initial scenario in terms of the chosen attributes:

$$S^2 = \sup \left\{ S^y \in \mathbb{S}_{all} \left| \sum_{i=1}^n \left[x_i^{cap(S^y)} - x_i^{cap(S^1)} \right]^2 \right. \right\}, \quad (1)$$

where $\mathbb{S}_{all}$ – the set with all Swiss EXPANSE modelled scenarios;

S^1 – the initial scenario;

S^2 – the first maximally-different scenario;

S^y – the scenario y in $\mathbb{S}_{all}$, $S^y \in \mathbb{S}_{all}$;

$x_i^{cap(S^y)}$ – installed capacity of technology i in scenario S^y ;

i –technology indices, $i = 1, 2, \dots, n$.

In order to select the second and further maximally-different scenarios, scenario with the largest harmonic mean of squared Euclidian distances from the set of already selected scenarios is chosen. As pointed out by Tietje [49], the harmonic mean is an appropriate distance measure when the aim is to search for scenarios that are different from an existing scenario set as a whole, since the harmonic mean distance is small as soon as one of the existing scenarios is close to another one. The second and further maximally-different scenarios are selected as follows:

$$S^3 = \sup \left\{ S^y \in \mathbb{S}_{all} \left| \left(\sum_{S^z \in \mathbb{S}_{selected}} \frac{1}{\sum_{i=1}^n [x_i^{cap(S^y)} - x_i^{cap(S^z)}]^2} \right)^{-1} \right. \right\}, \quad (2)$$

where $\mathbb{S}_{selected}$ – the set of already selected Swiss EXPANSE scenarios, $\mathbb{S}_{selected} = \{S^1, S^2\}$;

S^3 – the second maximally-different scenario;

S^z – the scenario z in $\mathbb{S}_{selected}$, $S^z \in \mathbb{S}_{selected}$.

The set $\mathbb{S}_{selected}$ is then updated to add the newly selected scenario:

$$\mathbb{S}_{selected} = \mathbb{S}_{selected} \cup \{S^3\}. \quad (3)$$

The selection process in formulas (2) and (3) is continued until a wanted number of scenarios is selected.

3. Results

3.1. Technology-by-technology assessment of the diversity of existing Swiss electricity supply scenarios

We first present the results of technology-by-technology comparison of existing Swiss electricity supply scenarios and modelled EXPANSE scenarios for 2035 and 2050. As various existing scenarios use different classifications of technologies, we use the same classification as in the previous meta-analysis by Densing et al. [11]. Figure 2 shows the medians, 25th and 75th quartiles, and 1.5 interquartile ranges of the lower and upper bounds for technology-specific annual electricity supply in existing and EXPANSE scenarios for 2035 and 2050. Figure 3 shows the comparison in terms of installed capacity in year 2050; only 20 existing scenarios are included as not all organizations characterized their scenarios in 2050 using installed capacity. As this paper focuses on the implementation of Swiss Energy Strategy 2050, only those existing Swiss scenarios that have no nuclear power in 2035 and 2050 are included in the analysis.

Figure 2. Comparison of technology-specific annual electricity supply in existing Swiss electricity supply scenarios and EXPANSE modelled scenarios for the year 2035 (a) and 2050 (b). The boxplots depict median, 25th and 75th quartiles, and 1.5 interquartile ranges of the lower and upper bounds. Existing scenarios that in 2035 and 2050 do not include nuclear power are considered only.

Figure 3. Comparison of technology-specific installed capacity in existing Swiss electricity supply scenarios and EXPANSE modelled scenarios for the year 2050. The boxplots depict median, 25th and 75th quartiles, and 1.5 interquartile ranges of the lower and upper bounds. Existing scenarios that in 2050 do not include nuclear power are considered only.

If the set of 520 EXPANSE modelled scenarios is considered as a benchmark of a diverse set of electricity supply scenarios, the existing multi-organization, multi-model Swiss scenarios can be judged as relatively diverse to cover various futures. The technology-specific ranges in annual electricity supply and installed capacity are similar for the existing scenarios and the Swiss EXPANSE scenarios. In particular, several outliers in the existing scenarios enable this diversity. Examples include deployment of solar PV and wind power, where organizations, such as Greenpeace or Cleantech, already in 2035 envision high deployment of these technologies. Many of the model-based existing scenarios, however, do not include such scenarios with a significant share of new renewable technologies. Retrospective assessments of energy scenarios have repeatedly indicated such practice as a limitation of model-based scenarios [6, 13, 24]. Swiss EXPANSE model shows that such scenarios could be in principle plausible and thus should be included to guarantee sufficient diversity of a scenario set. Without these outliers, the existing Swiss scenarios in Figure 2 exhibit relatively little variance, especially in 2035, and represent a unified picture for 2035 and 2050. As retrospective scenarios assessments show [5, 6], such a unified picture can be problematic because it hints to too narrow consideration of uncertainties rather than precise judgement about the future. Swiss EXPANSE scenarios thus help to expand the uncertainty consideration.

MGA-based Swiss EXPANSE model generates a variety of technically-feasible electricity supply scenarios without limiting these scenarios to the least-cost ones. Therefore, Swiss EXPANSE scenarios for 2035 in Figure 2a include more scenarios with a significant share of new renewable technologies, such as solar PV, wind, biomass, or geothermal energy. Existing Swiss model-based scenarios, especially those of Swiss Federal Office of Energy (BFE) or Paul Scherrer Institute (PSI), account for cost drivers and constraints of technology build rates. As a result, they include lower shares of costly new renewable technologies in 2035. Assuming such lower shares of new renewables in 2035, the existing scenarios also rely more on net electricity import and fossil fuel-based generation as compared to Swiss EXPANSE scenarios. A similar trend can be observed for technology-specific annual electricity supply in 2050 in Figure 2b, where Swiss EXPANSE scenarios have higher shares of wind, biomass, and geothermal power, and lower net electricity import and fossil fuel-based generation. As solar PV costs are assumed to decrease towards 2050 [53], the share of solar PV in existing Swiss scenarios increases too, nearing the levels in Swiss EXPANSE.

With the focus on diversity, MGA-based Swiss EXPANSE also includes scenarios with negligible shares of renewable technologies, such as solar PV, wind, biomass, and geothermal. These scenarios counterbalance scenarios with high deployment new renewable technologies. In principle, such scenarios with low share of renewable technologies could be technically-feasible and they remind of so-called “business as usual” or “no policy” type of scenarios [5, 54]. However, with currently ongoing energy system transformation worldwide [55], it could be argued that “business as usual” or “no policy” type scenarios will include some new renewable energy technologies already. For the sake of scenario diversity and expanded uncertainty consideration, we still find it reasonable to include scenarios with low shares of renewable technologies too.

3.2. Assessment of the diversity of existing Swiss electricity supply scenarios as a whole

The previous section compared the existing Swiss electricity supply scenarios and Swiss EXPANSE scenarios technology by technology, without analyzing technology combinations. This Section 3.2 compares scenarios as a whole. As there are 520 Swiss EXPANSE scenarios, we use the Distance-to-Selected technique (Section 2.3) to sample 10 EXPANSE scenarios that are maximally different to the set of existing Swiss scenarios. Ten maximally-different EXPANSE scenarios are sampled three times: using technology-

specific annual electricity supply in 2035 (Figure 4a), in 2050 (Figure 4b), and using technology-specific installed capacity in 2050 (Figure 5) as attributes to measure the difference.

Figure 4. Ten Swiss EXPANSE scenarios that are maximally different to the existing Swiss scenarios in terms of technology-specific annual electricity supply in 2035 (a) and in 2050 (b). Empty bars represent cases, when an organization has not published an annual electricity supply scenario for 2035 or 2050, or have included nuclear power.

Figure 5. Ten Swiss EXPANSE scenarios that are maximally different to the existing Swiss scenarios in terms of technology-specific installed capacity in 2050. Empty bars represent cases, when an organization has not published an installed capacity scenario for 2050 or have included nuclear power.

Figure 4 shows that ten Swiss EXPANSE scenarios that are maximally different to the existing Swiss scenarios in terms on annual electricity supply in 2035 and 2050 include several scenarios with total electricity supply above 70 or 80 TWh/year, i.e. high electricity demand scenarios. Although there have been Swiss scenarios with high electricity demand assumptions (Table 1), only the lower or medium demand scenarios have been published in detail by multiple organizations. In the recent years electricity demand in Switzerland has been relatively stable [56], but a significant increase by 2035 and 2050 cannot be ruled out, especially if there is a significant increase in electric mobility, heat pumps and electricity heating in order to decarbonize mobility and heating sectors, or if more electric appliances are purchased by the population. Thus, adding at least one high electricity demand scenario to the existing ensemble of Swiss scenarios would be meaningful to counterbalance multiple low and medium demand scenarios.

Low deployment rates of renewables, such as solar PV, wind, biomass and geothermal electricity, is well accounted for by the existing scenarios in 2035. The maximally-different EXPANSE scenarios suggest including electricity supply scenarios with a greater deployment of these technologies. This finding is similar to what has been already observed in technology-by-technology comparison in Section 3.1. In fact, looking at scenarios as a whole, high demand scenarios among the maximally-different Swiss EXPANSE scenarios tend to include a relatively large share of new renewable technologies. But a combination of high demand and high share of renewables is not

1 represented among existing scenarios in 2035. Interestingly, existing high demand
2 scenarios as a rule tend to have low share of renewables, often because they represent
3 “business as usual” or “no policy” type of scenarios with large shares of electricity
4 import and fossil fuel-based generation. A scenario that has high demand and high share
5 of renewables simultaneously could in principle be possible, for example, with
6 significant deployment of electric transport, electric heating, limited end use efficiency
7 gains, and a successful deployment of renewable technologies.

8 Especially in 2035, but also in 2050, 10 maximally-different EXPANSE scenarios
9 also include scenarios of simultaneously low demand and such a high renewable
10 technology deployment that net electricity import and fossil fuel-based generation has a
11 negligible share. Even more, there are scenarios of negative net import, i.e. electricity
12 export, if the demand is low enough. Although such scenarios are included in the set of
13 existing Swiss scenarios for 2050, namely VSE Scenario 3 or PSI NEP+Imp (Figure 4b),
14 no scenario with low or zero net electricity import and fossil fuel-based generation at
15 the same time is considered for 2035. We, again, argue that it could be in principle
16 possible if rapid demand reduction, end use efficiency increase and renewable
17 technology deployment envisioned in the Swiss Energy Strategy 2050 and beyond could
18 be achieved.

19 For year 2050, maximally-different EXPANSE scenarios in terms of both
20 technology-specific annual electricity supply and installed capacity include scenarios
21 with more conservative estimates of some new renewable technologies, including wind,
22 biomass, geothermal, and especially solar PV. The majority of existing Swiss scenarios
23 include significant shares of new renewable technologies without counterbalancing
24 them with scenarios of lower estimates. As already discussed earlier, the latter type of
25 scenarios would be similar to “business as usual” or “no policy” type of scenarios that,
26 given today’s increasing pace of renewable technology deployment, could be argued to
27 be less plausible. However, if the aim is to have a sufficiently diverse set of national
28 energy scenarios, such low renewable electricity supply scenarios in the long run could
29 also be added.

31 3.3. Additional scenarios to increase the diversity of Swiss electricity supply scenarios

32 We extract additional Swiss electricity supply scenarios that we believe should be
33 added to the existing scenario set to increase its diversity and expand uncertainty
34 consideration. Three new scenarios for 2035 and three other scenarios for 2050 are

chosen conceptually, based on the results in Sections 3.1 and 3.2. We then find respective quantitative scenarios among the 520 Swiss EXPANSE scenarios and characterize them in detail by showing their electricity supply composition and dispatch.

For the year 2035, maximally-different Swiss EXPANSE scenarios in Figure 4a suggest adding scenarios with (i) high electricity demand and very high share of renewable technologies, (ii) high electricity demand and high share of renewable technologies, and (iii) low demand scenarios with negligible or even negative annual net import. Therefore, we suggest including Swiss EXPANSE maximally-different scenarios no. 1, 3 and 4 in Figure 4a to represent each of these viewpoints. We name these scenarios as *High renewables 2035*, *High demand 2035* and *High export 2035* respectively. For the year 2050, Sections 3.1 and 3.2 indicate a need for new electricity supply scenarios with (i) high electricity demand and low-to-medium share of renewable technologies like solar PV, (ii) high electricity demand and high share of renewable technologies, and (iii) one with low share of renewable technologies. We thus suggest adding Swiss EXPANSE maximally-different scenarios no. 1, 2 and 10 in Figure 4b. We name these scenarios as *Low photovoltaic 2050*, *High demand 2050* and *Low renewables 2050* respectively. Annual electricity supply composition for these six new scenarios is shown in Figure 6.

Figure 6. Additional scenarios to be added to the existing ensemble of Swiss electricity supply scenarios in 2035 (a) and 2050 (b) in order to increase diversity of this ensemble.

Swiss EXPANSE models electricity supply in 2035 and 2050 without modelling the electricity supply transition in between 2015, 2035 and 2050. However, the additional scenarios suggested in Figure 6 and those in the existing set of Swiss scenarios link into plausible stories (Table 3). First, the existing set of Swiss scenarios includes multiple cases with high deployment of solar PV, wind, biomass, and geothermal technologies in 2050, but not in 2035. *High renewables 2035* scenario is thus a scenario, where such a high deployment is achieved earlier as envisioned in parts by Cleantech and Greenpeace scenarios for 2035. Second, *High demand 2050* follows from the *High demand 2035* scenario. The deployment of renewable technologies, such as biomass, wind, and solar PV, remains high as for the *High demand 2035* scenario, but we have an additional contribution from geothermal power. Due to its high costs and early technology innovation stage [57], the build rates of geothermal power are slower than the build rates of biomass, wind and solar PV. As a result, geothermal would be deployed in 2050, but not in 2035. *High demand 2050* scenario also continues to include a high share of fossil fuel-based generation to satisfy high demand. Third, electricity export scenarios have been explored among the existing Swiss scenarios for 2050, e.g. *BFE NEP+E* or *BFE NEP + C + E* (Figure 4b). The new *High export 2035* scenario thus provides a link between today and these export scenarios in 2050, when underlying electricity demand remains stable and there is an increase in electricity produced by solar PV, geothermal and biomass. Fourth, *Low photovoltaic 2050* and *Low renewables 2050* scenarios account for more conservative assumptions of renewable technology deployment and thus would be a continuation of existing scenarios for 2035, such as *VSE Szen 1*, *BFE WWB+C*, *BFE POM+C* or *BFE NEP+C* (Figure 4a). The *Low photovoltaic 2050* scenario in particular accounts for a view in which an increase in renewables is caused by other renewables than photovoltaic.

Table 3. Plausible storylines that link six new EXPANSE scenarios and existing Swiss scenarios in 2035 and 2050

2035	2050
<i>High renewables 2035 (EXPANSE)</i>	<i>Greenpeace, Cleantech (existing)</i>
<i>High demand 2035 (EXPANSE)</i>	<i>High demand 2050 (EXPANSE)</i>
<i>High export 2035 (EXPANSE)</i>	<i>BFE NEP+E, BFE NEP+C+E (existing)</i>

VSE Szen. 1 (existing)	Low photovoltaic 2050 (EXPANSE)
BFE WWB+C, BFE POM+C, BFE NEP+C (existing)	Low renewables 2050 (EXPANSE)

3.4. New scenarios in detail

In this section the suggested additional EXPANSE scenarios of *High demand 2035* and *High demand 2050* are characterized in detail; the rest of the new scenarios are depicted in Appendix C. These scenarios are chosen for detailed depiction because integration of high shares of renewable technologies currently receives high interest [58, 59]. Figure 7 shows the annual and weekly electricity dispatch of *High demand 2035*. Run-of-river hydropower, hydropower dams, solar PV, and wind are the primary contributors to the electricity production in the peak week (highest demand week in winter) as well as in the base week (lowest demand week in summer). During the peak week, some electricity is imported, while excess electricity during the base week due to significant solar PV generation is assumed to be exported. Hydropower pumped storage is assumed to operate particularly flexibly during the peak week and at a more constant rate during the base week. The annual operating capacity of hydropower storage is shown in Figure 8. As the electricity demand is high, during the winter months the system relies on significant shares of fossil fuel-based generation. A cautionary remark must be added at this point. The current version of Swiss EXPANSE assumes relatively high flexibility of the electricity technologies, for instance, when the hourly modelling of the peak week includes fast switches between electricity import and use of hydropower dams. On the one hand, such a flexibility is, in parts, an artifact of the current version of Swiss EXPANSE that does not consider ramp rates. On the other hand, it is also a limitation of the MGA because this optimization-based technique by definition generates scenarios that include extreme values of the variables. In the future versions of EXPANSE, this phenomenon could be minimized by adding technology ramp rates and other constraints.

Figure 7. Electricity dispatch in the *High demand 2035* scenario during a year on a weekly basis (a), in the peak (highest) demand week on hourly basis (b), and in the base (lowest) demand week on hourly basis (c). The black line depicts exogenously given electricity demand, including losses. Note: the current Swiss EXPANSE version does not consider technology ramp rates, whereas MGA generates scenarios that are comparatively extreme (see Section 3.4 for further discussion).

Figure 8. Operating capacity of hydropower pumped storage during the year in *High demand 2035* and *High demand 2050* scenarios.

Figure 9 shows the annual and weekly electricity dispatch of *High demand 2050*. As before, run-of-river hydropower, hydropower dams, solar PV, wind power, biomass and geothermal power are again used to cover the electricity demand in the base week, with excess electricity being exported. As the demand rises during the winter months and the peak demand week in particular, *High demand 2050* relies on significant shares of fossil fuel-based generation and import. Annual operating capacity of hydropower pumped storage is shown in Figure 8. The aforementioned cautionary remark on overly optimistic flexibility of technologies also applies here.

Figure 9. Electricity dispatch in the *High demand 2050* scenario during a year on a weekly basis (a), in the peak (highest) demand week on hourly basis (b), and in the base (lowest) demand week on hourly basis (c). The black line depicts exogenously given electricity demand, including losses. Note: the current Swiss EXPANSE version does not consider technology ramp rates, whereas MGA generates scenarios that are comparatively extreme (see Section 3.4 for further discussion).

4. Discussion

Retrospective assessments of energy scenarios in the past have showed that multi-organization, multi-model scenarios ensure the vastest consideration of uncertainties [6]. We confirm this view in our diversity assessment of the existing Swiss electricity supply scenarios in 2035 and 2050. Existing model-based scenarios, such as

those of the Swiss Federal Office of Energy (BFE) or Paul Scherrer Institute (PSI), alone would include only a limited diversity of scenarios. This diversity is increased by other institutions, such as Cleantech or Greenpeace, with more extreme viewpoints. MGA-based Swiss EXPANSE model, in fact, can systematically generate a large ensemble of electricity supply scenarios (N=520 in this paper) that are able to encapsulate the variety of existing scenarios and perspectives. Trutnevyte [24] has previously demonstrated with a retrospective modelling of the UK electricity sector transition in 1990-2014 that MGA-based EXPANSE could anticipate some real-world electricity sector developments that would be typically overlooked by conventional bottom-up energy systems models without MGA. In line with previous research [21-24], we thus again show that MGA is a valuable tool to expand uncertainty consideration for long-range energy scenarios. In fact, in this paper MGA-based EXPANSE was stripped from cost considerations in the objective function or model constraints, leading to generation of technically-feasible electricity supply scenarios that may be costly. Adding such scenarios to an ensemble is still important to increasing diversity and better understanding the range of choices. As a result, MGA-based EXPANSE scenarios can be considered close to being value free as they can represent even more extreme perspectives, such as high-renewable futures by 2035 suggested by Cleantech or Greenpeace. Ability to generate alternative scenarios that represent various stakeholders by using a single model is an advantage that allows for a systematic comparison of these scenarios and associated perspective. Meta-analyses typically face difficulties when comparing multi-organization, multi-model scenarios, c.f. [11]. MGA-based EXPANSE can thus be useful here.

Although the ensemble of existing Swiss scenarios is relatively diverse already, we suggest adding three additional scenarios for 2035 and three for 2050 in order to expand uncertainty consideration and increase diversity of scenarios. These new scenarios that were derived from MGA-based EXPANSE using Distance-to-Selected technique, indicate particular perspectives that no current stakeholder group represents. For example, the most prominent lack of a specific perspective is highlighted by the scenarios *High demand 2035* and *High demand 2050* that combine high electricity demand with high share of renewable technologies. The majority of existing scenarios with high electricity demand (*ETH/ESC*, *VSE Szen 1*, *BFE WWB+C*, *PSI-sys no ClimPol*) are “business as usual” or “no policy” type of scenarios that assume high demand and very low share of renewable technologies. These scenarios are then counterbalanced with

1 normative scenarios of increased electricity use efficiency, demand reduction, and fast
2 renewable deployment at once (*VSE Szen 3, BFE NEO+C, Cleantech, Greenpeace, PSI-sys*
3 *NEP+Imp*). A plausible scenario with both high electricity demand growth and
4 renewable technology deployment simultaneously is, however, missing.

5 The current version of Swiss EXPANSE model is not without its limitations that
6 should be considered, when interpreting results of this study. First, Swiss EXPANSE does
7 not model cost drivers and constraints. This is both an advantage for increasing the
8 diversity of scenarios modelled as well as a limitation as some of the scenarios may be
9 realistically more difficult to achieve due to high costs. As a result, Swiss EXPANSE has a
10 bias towards greater deployment of renewables in the near-term than existing models.
11 In the future, cost constraint could be added to EXPANSE to avoid modelling of very
12 costly scenarios [23, 24]. Second, Swiss EXPANSE is an electricity dispatch model that
13 models only a single year (2035 or 2050) without modelling the transition from today
14 into the future, for instance, 2015 to 2050. Swiss EXPANSE thus in the short run
15 overestimates the deployment of technologies with a slow build rate, such as
16 geothermal. But this bias corrects itself in 2050, since the build rate becomes less
17 important when the modeling horizon increases. In the future, the dynamic version D-
18 EXPANSE [24] should be developed for the Swiss electricity sector too. Third, the
19 current version of Swiss EXPANSE models only the Swiss electricity sector and its
20 interconnection with other European countries without accounting for future
21 developments in these other countries. *High Demand 2035* and *High Demand 2050*
22 scenarios currently assume that in the base week excess electricity from solar PV would
23 be exported abroad. Germany, for example, already has a significant and increasing
24 share of solar PV, meaning that there is excess electricity during the base week too and
25 no import would be needed. Such country interactions should be addressed better in the
26 future Swiss EXPANSE model. Fourth, the current version of Swiss EXPANSE is
27 deterministic and does not account for parametric uncertainty, for example, in
28 electricity demand or weather-dependent electricity generation. Future EXPANSE could
29 also include Monte Carlo runs as already demonstrated in [24, 32]. Fifth, the current
30 version of Swiss EXPANSE models the Swiss electricity supply on an aggregated level
31 without spatial detail. Including the locations of power plants would be important in
32 order to specify the regional implications of the electricity supply scenarios. MGA
33 application for the spatially-explicit EXPANSE, as shown in [25], would improve the
34 exploration of alternatives that meet the views of various stakeholders.

5. Conclusions

Our assessment of the diversity of the existing multi-organization, multi-model Swiss electricity supply scenarios for 2035 and 2050 shows that several perspectives are missing, leading to a limited consideration of future uncertainties to support Swiss energy policy. In 2035, there is a lack of scenarios with high electricity demand and greater deployment of renewable technologies occurring simultaneously, as well as scenarios with a negligible or negative share of net electricity import. In 2050, there is a lack of scenarios that depict high electricity demand and conservative deployment of new renewable technologies, such as wind, biomass, geothermal, and especially solar PV. We thus suggest six new scenarios that we believe should be added to the set of existing Swiss scenarios to increase the diversity. In this way, a more exhaustive and diverse set of scenarios as well as increased understanding of the future possibilities and uncertainties would be achieved.

From the methodological perspective, application of MGA-based EXPANSE model is helpful to expand uncertainty consideration and forego some of the past mistakes, when the long-range energy scenarios have been repeatedly shown not to be diverse enough to include less expected real-world developments. In fact, MGA can help systematically generate a large ensemble of energy scenarios that represent various stakeholder perspectives, including organizations that use energy-environment-economic models and those that rather represent strong environmental views. In the future, we envision an increased implementation of methods, similar to MGA-based EXPANSE, in order to broaden our understanding of choices and uncertainties in implementing ambitious energy policy goals aspired worldwide.

Acknowledgements

This study was prepared as part of the Swiss National Science Foundation Ambizione Energy Grant No. 160563.

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