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Inter-comparison of spatial models for high shares of renewable electricity in Switzerland

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HIGHLIGHTS

- Inter-comparison of three electricity system models with subnational detail.
- Analyzing three targets for renewable electricity in Switzerland in 2035.
- Robust results on the high importance of solar PV and import for electricity supply.
- Differences between the three models on spatial distribution of renewable capacity.
- Improvement of models through lessons learned from inter-comparison.

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ABSTRACT

This study presents an inter-comparison of three structurally different electricity system models (EXPANSE, Nexus-e, and OREES) with sub-national spatial resolution in Switzerland in 2035. We analyze technology and regional implications of three targets for electricity generation from new renewable sources (17 to 25 TWh/year from solar PV, wind, biomass, and waste incineration) and compare results at a national level as well as at a higher spatial resolution of Swiss cantons and municipalities. All three models align on high capacities of solar PV in 2035 as the key technology for reaching the three targets, but there is flexibility where PV can be placed to achieve the targets: either on roofs and facades or also on land. Electricity interconnection with Europe remains of key importance in Switzerland because any increases in electricity demand or lower deployment of new renewable generation are compensated by import. For the rest, the three models provide internally-consistent storylines of future strategies for Switzerland: a future with a diversified range of technologies (EXPANSE), a future with the focus on decentralized rooftop solar PV with batteries (Nexus-e), and a future with the prioritization of most productive areas for wind and solar PV, including open-field PV (OREES).

1. Introduction

Model-based analyses are an established method to study the transition to a decarbonized electricity system with high shares of renewable technologies. A multitude of modeling tools exists with different spatiotemporal resolutions, technological details, economic, and other features [1,2]. This leads to a vast array of resulting scenarios [3] due to differences in model structure, underlying assumptions, input data, and uncertainty analysis. On the one hand, divergences in model-based scenarios from multiple models reveal structural uncertainties that are inherent to future electricity system transitions. On the other hand, these differences often make it hard to crystalize consensus and hence reduce the usability of model results for decision-making [4,5]. Thus, assessing the impact of specific model approaches and characteristics on the

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results is essential to distinguish between robust and diverging findings across models.

Model inter-comparisons have been widely used in the modeling community for the evaluation of integrated assessment models of climate change [6] and energy transition [7,8]. The implicit assumption in model inter-comparisons is that all models are valuable, and the inter-comparisons help understand the strengths and unique contributions of each model as well as allow to identify the points of consensus and divergence for policy making. Methodologically, the evaluation of models usually covers their inputs, outputs, structure, and behavior [8,9], where comparability is assured by the harmonization of the selected key scenarios and parameters [6]. Overlap of the results from different models increases confidence in these results, whereas the analysis of divergences is essential to identify how differences in model structures and inputs explain the diverging results. A better understanding of what causes diverging results is an important basis for interpreting the model findings and for further improving the models. Large model inter-comparison projects with integrated assessment models, such as the AMPERE [10,11] or the ADVANCE projects [12], have proved to increase understanding of behaviors and outcomes of integrated assessment models, leading to the development of diagnostics indicators to assess models [11,13] and eventually underpinning high-level policy reports, such as those by the Intergovernmental Panel on Climate Change.

With respect to electricity and energy system models, recent inter-comparison studies have focused on the German power system [14,15], the balancing of variable power generation in Central Europe [16], the European Union's emission trading system [17], variable renewable electricity in the US electricity system [18], storage in the North American system [19] and whole-system decarbonization scenarios from macroeconomic perspective in Switzerland [20]. Appendix A1 provides a summary of these previous inter-comparisons. Based on MODEX project outcomes that compared 40 diverse modes, Gils et al. [16,21] classify energy system model inter-comparisons into theoretical comparisons (with a focus on benchmarking model properties), inter-comparisons with a technological focus (to examine specific model differences in depth), and inter-comparisons with a harmonized model application (systemic comparisons in harmonized scenarios). Although some previous inter-comparison studies considered models with a subnational spatial resolution [15,18], none of the aforementioned studies included a detailed spatial analysis of results at a subnational level. Spatially refined analyses are key to the understanding of distributed technologies, such as solar PV or wind power, whose potentials and uptake spread unevenly across a country [22,23]. Further, model inter-comparisons in the energy and electricity sector generally used higher degree of harmonization of data and scenario assumptions, hence putting higher emphasis on methodological conclusions. By contrast, inter-comparisons of integrated assessment models follow an approach with less harmonization, hence enabling stronger focus on identifying policy-relevant consensus from models that are allowed to preserve their original rationale.

The present study contributes to the literature on model inter-comparisons by demonstrating a methodology to investigate the spatial distribution of renewable electricity technologies that are endogenously modeled in electricity sector models at high temporal and spatial resolution [cf. [15,24]] and by applying inter-comparison methodology from integrated assessment community to allow sufficient space to preserve the identity of each model with only minimal harmonization defined by the guiding question. We focus on scenarios with high shares of renewable generation and consider the case of Switzerland for the year 2035 because no model inter-comparisons of spatially-explicit models have been done in this country. We perform the model inter-comparison by analyzing the technology mixes in terms of installed capacities and dispatch in three structurally different electricity system optimization models (EXPANSE, Nexus-e, OREES), both on a national system level and the level of 26 cantons and 2′148 municipalities. We identify results that are robust across all models and provide insights into how diverging results can be explained. Consequently, we aim to gain a better understanding of the specific strengths of the three models and, thus, increase the credibility and usability of the modeling results to inform decision-making for the energy transition in Switzerland.

2. Study design

Our model inter-comparison is guided by a policy-relevant question: what are the technology and regional implications of achieving high shares of domestic renewable electricity generation in Switzerland in 2035? We compare three spatially-explicit electricity system optimization models, all of which have previously been applied to study the transition in Switzerland (Section 2.2). To do so, we define a set of scenarios (Section 2.1), in which the renewable electricity targets and the annual electricity demands are harmonized among the three models.

2.1. Harmonized scenarios

We consider three base scenarios, which represent the Swiss electricity system in the year 2035 and reach three different targets for renewable electricity generation (Fig. 1): i) a target of 17 TWh/year of electricity generation from new renewable sources of solar PV, wind power, and biomass (the RES scenarios); ii) a more ambitious target of 25 TWh/year of electricity generation from new renewable sources (the High RES scenarios); and iii) a solar PV-specific target of 25 TWh/year (the High Solar scenarios). The target of 17 TWh/year in the RES scenarios is based on the latest version of the Swiss Energy Act (German: 'Energiegesetz, EnG') [25,26]. The High Solar scenarios are based on a proposition [27] to install a total of 50 GW of solar PV in Switzerland by the year 2050, which could approximately correspond to the annual generation of about 25 TWh/year in the earlier year of 2035. For the High RES scenarios, the same value of 25 TWh/year is chosen for the sake of comparability but instead of achieving this target with only solar PV this target is achieved with a mix of new renewable technologies.

In the three Base scenarios, we harmonize the assumptions for annual electricity demands (Fig. 1) between the three models and utilize the same hourly electricity profiles. The electricity demand assumptions are based on the Swiss Energy Perspectives 2050+, a report that presents government-mandated scenarios for a net-zero emissions system in Switzerland by 2050 [28]. In terms of regulatory assumptions, all models assume full nuclear power phase-out by 2035, which is in line with the current federal strategy. No other federal or regionalized assumptions on regulation are included in EXPANSE and OREES, while Nexus-e accounts for local prices and subsidies. The remaining model assumptions and model features are left as native to the three models, to preserve as much of each model's features and strengths as possible. As the models use different initial years, the assumptions on existing capacities are also not harmonized.

Three dimensions of uncertainty are included in addition to the three base scenarios (Fig. 1): i) high and low assumptions on electricity demand, covering high and low adoption levels of electric vehicles, heat pumps, and energy efficiency measures (DemHigh, DemLow) [28,29], ii) high and low levels of battery system installations (BatHigh, BatLow) [30,31], and iii) complete independence from fossil fuels for domestic electricity generation in Switzerland in 2035 already in light of the ongoing war in Ukraine and the Swiss long-term goal of net-zero emissions (No Fossil). We model each of the three dimensions of uncertainty separately, to assess the models' responses to each uncertainty and keep the manageable number of model runs to a total of 18.

2.2. Three models

Three existing electricity system models are compared in our study: EXPANSE, Nexus-e, and OREES. All these models comprise the whole

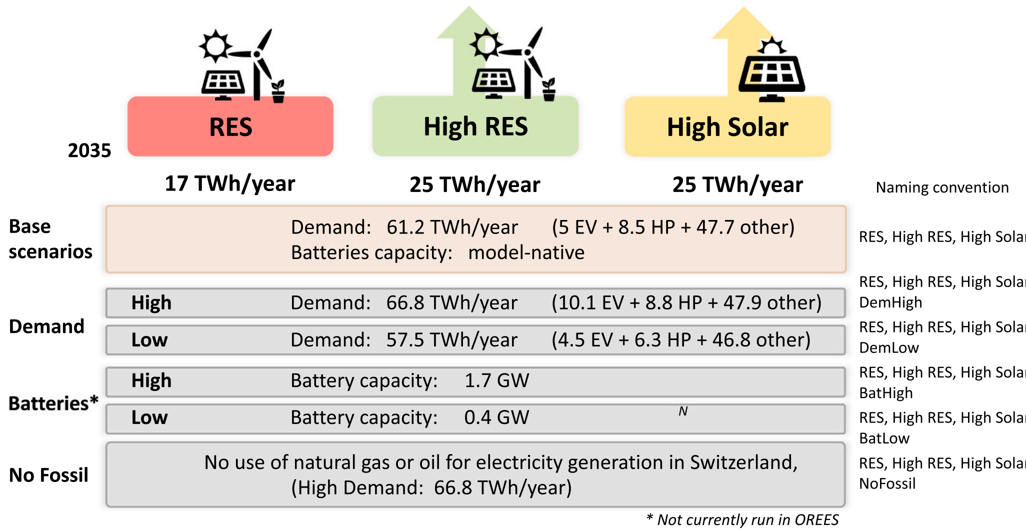

Fig. 1. Matrix of 18 harmonized scenarios, depicting the three main groups of scenarios (RES, High Solar, and High RES) and the three dimensions of uncertainty that are investigated (the levels of electricity demands, battery system adoption, and a strict ban on fossil fuels for electricity generation in Switzerland). EV: Electric vehicles, HP: Heat pumps, other: the rest of the electricity demand that is not for electric vehicles or heat pumps.

Swiss electricity system, can implement national renewable electricity generation targets, are characterized by subnational spatial resolution and high temporal resolution, and have previously been applied to study the Swiss transition. All models are run for the year 2035, considering multiple power system nodes for transmission analysis, the import of electricity from neighboring countries, and a wide set of technology options for electricity generation, storage, and flexibility. Table 1 gives an overview of the main characteristics of the three models and Appendices A2 and A3 document the most important constraints and input parameters. In order to quantify realistic electricity scenarios for Switzerland in 2035, all three models follow a brown-field approach which assumes that existing capacities of technologies that are currently promoted in Switzerland cannot be unbuilt and will not decrease below existing levels (e.g. hydropower, solar PV, wind power, biomass, waste

Table 1
Overview of main characteristics of the three electricity systems models used in this study.

	EXPANSE (reduced version)	Nexus-e	OREES
General			
Model type	Linear optimization	Linear optimization	Evolution strategy (optimization) with optimal power flow
Objective	Total costs minimization (investments and dispatch)	Total costs minimization (investments and dispatch)	Revenue maximization
Decision variables	Installed capacity and operation of generation, storage, and transmission	Installed capacity and operation of generation, storage, and transmission	Installed capacity and operation of generation, storage, and transmission
Model environment	Python	Matlab, Python	Matlab
References	[32–34]	[35,36]	[37–39]
Spatial/Temporal			
Spatial resolution	Municipalities	Central: Nodes; Decentral: Cantons (Municipality *)	1.6 × 2.3 km (PV); 1.1 km (Wind)
Time resolution	6 h (optimized in sensitivity analysis)	1 h	1 h
Temporal scope	2035	2035	2035
Grid			
Power system nodes	8	165	169
Grid expansion	Yes	No*	No
Power flow constraints	Yes	Yes	Yes
Power reserves	Yes	Yes	No
Neighboring countries modeled	No*	Yes	No
Import/export modeled	Hourly cost profile for import and export	Market-based dispatch of electricity in Switzerland and neighboring countries	Imports more expensive (on average) than inland generation
Technologies			
Solar PV	Rooftop, facades	Rooftop (alpine, open-field*)	180 W/m^2, optimized geometry (tilt, azimuth), any location
Wind	Onshore wind turbines	Onshore wind turbines	Onshore wind turbines
Hydro (generation)	Hydro dams, run of river	Hydro dams, run of river	Hydro dams, run of river
Biomass	Woody biomass, biogas	- *	–
Waste incineration	Waste incineration	Waste incineration	–
Fossil fuels	Natural gas without carbon capture and storage	Natural gas with and without carbon capture and storage; (lignite, coal and oil in neighboring countries)	–
Power-to-X	Electrolyzers, hydrogen storage, fuel cells	- *	–
Storage	Pumped hydro storage, batteries	Pumped hydro storage, batteries (decentralized and grid batteries)	Pumped hydro storage

* Implemented in the model, but not utilized for the model runs in this study.

incineration). Interconnection capacities also stay at least the same as currently or can be increased, whereas natural gas-based plants can be fully closed and all nuclear power is closed by 2035. The load factors and electricity generation outputs per technology are then optimized.

The EXPANSE model is a single-year bottom-up linear optimization model that considers investments and dispatch in the electricity system. Typically, EXPANSE is used with the MGA method (Modeling to Generate Alternatives), which is a main feature of EXPANSE to account for uncertainties and decision options [40]. For direct comparability with the other two models, EXPANSE is used here in its reduced form, where it minimizes total system costs only. We apply a version of the EXPANSE model with a spatial resolution of 2′148 Swiss municipalities (the highest spatial resolution for all key technologies in this inter-comparison) and that considers electricity imports and exports to and from neighboring countries. The chosen temporal resolution of 6 h was derived from a sensitivity analysis, optimizing between the accuracy of the results and computation time, given the very high spatial resolution [38]. The model includes technology ramping and start-up constraints, power reserve constraints, power flow and voltage constraints, and energy storage balances. In contrast to the other two models, EXPANSE also includes an estimation of the Swiss biomass potential for woody and non-woody biomass [41] as well as power-to-x. Previous versions of the model have been applied to study the regionally equitable and cost-efficient allocation of renewable electricity generation in Switzerland [32], Central Europe [33], and Europe [34].

The Nexus-e model is based on five modules that combine bottom-up and top-down modeling approaches and can evaluate the mutual impacts of large-scale centralized and small-scale decentralized electricity generation. The modeling framework includes a general equilibrium module for electricity; two modules that optimize generation investments and operational decisions on the transmission system level and of distributed energy resources, respectively, (both formulated as mixed integer linear programs); an electricity market module that simulates market-based clearing of supply and demand bids; and a system security and network expansion module. For this study, a version of the Nexus-e model that includes the modules for centralized and decentralized investment and operational decisions was used, formulated as a linear programming problem. A detailed description of the Nexus-e modeling framework and its application to study future scenarios for the Swiss electricity system is presented by Gjorgiev et al. [35], and its comparison with other models by Granado et al. [36].

The OREES (Optimized Renewable Energy by Evolution Strategy) model is an electricity system model that optimizes the placement of solar PV and wind power installations based on the evolution strategy. OREES finds the optimized generation mix and locations of solar PV and wind power in Switzerland while considering the high-voltage transmission grid, connections to neighboring countries, production from hydropower facilities and water inflow, and spatially distributed time series of electricity consumption and electricity generation from solar PV and wind power. For this study, we use a version of the OREES model that maximizes the revenues of solar PV and wind power capacities. OREES has previously been used to study the optimized market value of alpine solar PV in Switzerland [37], and the optimal mix of solar PV and wind power in the Swiss system to minimize electricity import [38].

2.3. Inter-comparison analysis

For the three models, selected input parameters and model outputs for all 18 scenarios were reported in a harmonized template. We consider outputs, such as the installed capacities or annual generation of electricity technologies, in the modeled year 2035. In addition to comparing the whole Swiss electricity system, we analyze the spatial distribution of solar PV and wind power capacities at a cantonal resolution for all three models and on a municipality level for EXPANSE and OREES. The results on the system, cantonal and municipal levels are assessed in terms of similarities and discrepancies between the models, where model characteristics, electricity system set-ups, and key input parameters, such as cost assumptions or resource potentials, are used to understand the reasons for diverging results (Appendices A.2 and A.3). We conduct two iterations for the model inter-comparison. After the initial model runs and the first analysis of the inter-comparison results, the modeling teams could modify their models and input assumptions, if they wanted, according to the lessons learned from the first iteration. The second iteration of model runs is considered final and is presented here.

3. Results

3.1. Results at the national level

For all scenarios, the three models meet the predefined targets for renewable electricity generation (17 TWh/year or 25 TWh/year from all new renewable technologies or 25TWh/year from solar PV only), indicating the technical feasibility of these targets. The electricity demand in the models is largely supplied by generation from solar PV, hydropower (already installed in the Swiss system), and net annual electricity imports (Fig. 2a). While Switzerland remains an electricity exporter in summer and importer in winter like today, the presence of net annual electricity imports in all models and scenarios suggests that a Swiss system without nuclear power in 2035 would depend on excess electricity in neighboring countries more than today. The highest levels of net imports of electricity are found by all models in the RES scenario that has the lowest target of 17 TWh/year on domestic renewable electricity. It should be noted that for the same electricity demand assumptions (Fig. 1), the OREES model has lower values of domestic generation plus net import because it makes a lower assumption on transmission losses (10%) than Nexus-e and EXPANSE models (14%).

Despite this consensus, the models differ in the rest of the technology mix to meet the renewable electricity targets in the base scenarios (see also Appendix A4). In the High RES scenario, electricity is supplied by a combination of solar PV, biomass, waste incineration, and wind power in EXPANSE, by solar PV, waste incineration, and existing wind power in Nexus-e, and by a mix of solar PV and wind power in OREES. This underlines the sensitivity of model results to the portfolio of technologies considered, where EXPANSE is the only model to consider woody and non-woody biomass. To fulfill the specific PV target in the High Solar scenario, both EXPANSE and OREES models must deviate from the respective optimal technology mixes with wind power and biomass in the High RES scenario. The highest solar PV capacity in the High Solar scenario is installed in the Nexus-e model, while OREES finds the lowest solar PV capacities across the models (Fig. 2b). For both EXPANSE and OREES, this illustrates well the implications of having different assumptions across the three models. Capacity factors for solar PV are modeled with a higher spatial resolution in the OREES model as compared to the EXPANSE and Nexus-e models. This allows OREES to place PV in the best locations without averaging out the capacity factors of these locations. Therefore, capacity factors are on average substantially higher (considering an average of all timesteps of the year and all 26 Swiss cantons) in OREES than in the EXPANSE and Nexus-e. Having said that, EXPANSE and Nexus-e adopt the rationale of capacity factors like in real-world systems, where it is unrealistic to build PV in the most productive locations only [22,32], necessitating capacity factors that are closer to the real systems at municipal or cantonal scale.

Another clear difference is the large installed peak battery capacity in Nexus-e as compared to zero or nearly zero in the other two models (Fig. 2c). In Nexus-e, batteries are connected to PV systems to increase self-consumption. OREES does not model batteries. EXPANSE, on the other hand, includes batteries and power-to-X in the model, but in cost-optimal scenarios balances supply and demand practically without batteries (the installed capacity is negligible), only by means of pumped hydropower storage, import and export, and existing natural gas power plants for supply-demand balancing. Nexus-e also has natural gas

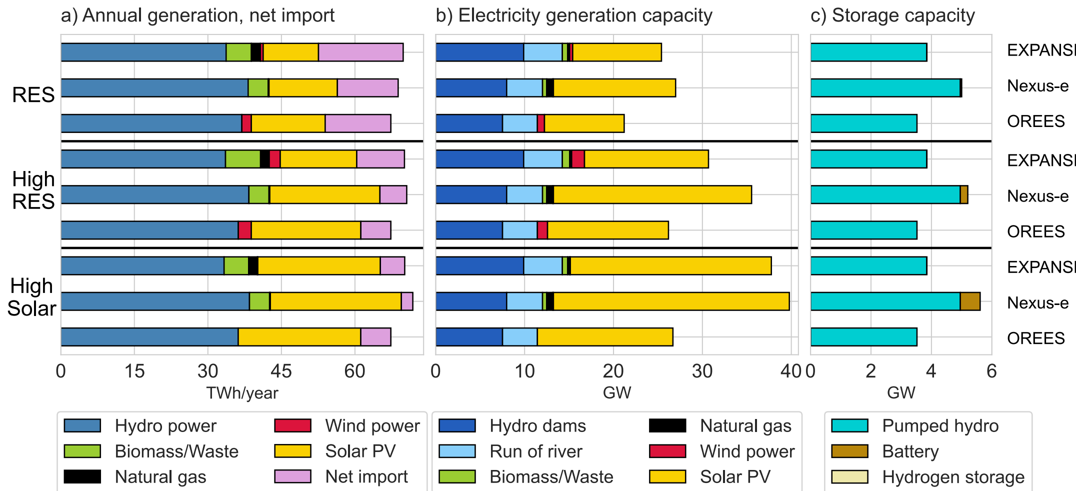

Fig. 2. (a) Annual generation and net imports, installed capacity of (b) electricity generation technologies, and (c) storage technologies in the base scenarios (the RES, High RES, and High Solar scenarios), for all three models EXPANSE, Nexus-e, and OREES. Note: Nexus-e and OREES already include the Nante de Drance pumped storage plant (900 MW), leading to a higher capacity than EXPANSE. OREES excludes small pumped hydropower storage plants.

capacity installed, but uses it at a very low capacity factor or does not use it at all, whereas EXPANSE assumes that any installed large power plants need to operate at least at a certain percentage to be viable from the business perspective. In parallel to installed capacity, estimates of stored electricity could not be analyzed because the three models use too different definitions of what is accounted for in stored electricity, e.g. whether melt water intake is included for pumped storage plants as storage or as generation. In all three models, larger generation from solar PV in the High RES and High Solar scenarios, as compared to the RES scenario, results in lower net electricity imports (Fig. 3a). The EXPANSE model shows the largest technology diversity in the High RES scenario, and therefore increases the generation from wind power, biomass, and waste incineration and reduces the generation from natural gas, as compared to the RES scenario. The increase in generation from solar PV and consequent replacement of imported electricity in the High RES and High Solar targets are common results among all models. In sum, the differences in the technology mixes of the three models can be mainly explained by the portfolios of available technologies, the assumptions concerning their operation, such as fixed and variable cost or capacity factors, and the maximum potential for renewable electricity generation (cf. Appendix A3). In Appendix A4 additional results on the annual generation and installed capacities in the remaining model runs are found, as well as the net imports for all scenarios and the whole year, summer and winter.

In terms of demand uncertainties and the flexibility to match supply and demand, higher electricity demand in the HighDem scenario is in all

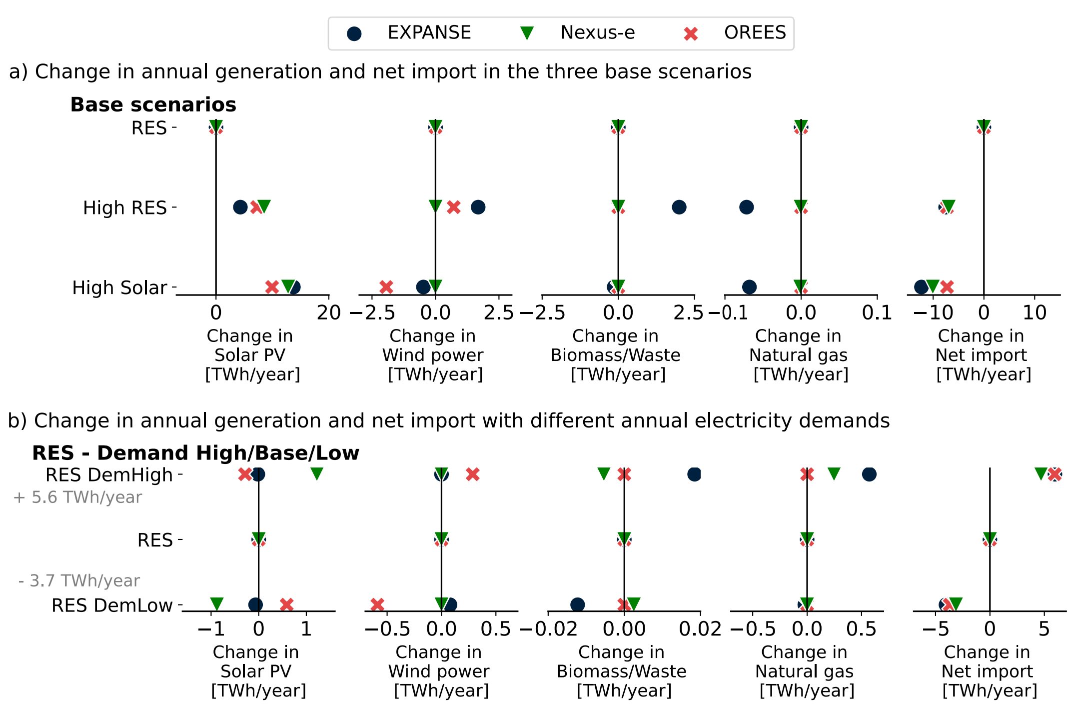

Fig. 3. Change in annual generation and net imports in scenarios with (a) different targets on renewable electricity generation (High RES and High Solar as compared to the RES scenario) assuming base demand, and (b) different annual electricity demands (the RES scenarios with high and low electricity demands, respectively, compared to the RES scenario). The values on the x-axes are adapted to the suitable values for each technology.

three models met by increased net import rather than by an additional increase in the uptake of new renewable technologies above the targets (Fig. 3b). Higher annual demand also means higher demand in winter when Switzerland is a net electricity importer. While the three models include multiple flexibility options of pumped hydropower storage (all models), batteries (EXPANSE and Nexus-e), power-to-x (EXPANSE), and natural gas-based generation (EXPANSE and Nexus-e), we find that import and export are nonetheless the most important providers of flexibility. All these findings emphasize the importance of electricity imports and exports in Switzerland, and of the corresponding modeling assumptions, when assessing future electricity system scenarios. After the net imports, the response of the three models to different assumptions for electricity demand varies. The OREES model adapts the wind power generation in scenarios with high and low electricity demand assumptions. A possible explanation is the prioritization of wind power for covering the winter demand, as well as better exploitation of locations with good conditions for wind power, with the higher demand being met via local wind resources. In Nexus-e, which models the cost-competitiveness of solar PV on a decentralized level, the generation from solar PV is adapted in response to different electricity demands. In both EXPANSE and Nexus-e, a higher demand is covered by increased, yet relatively small generation from natural gas.

In terms of uncertainties around the batteries, the availability of a fixed battery capacity (0.4 GW in BatLow and 1.7 GW in the BatHigh scenarios) hardly impacts the remainder of the electricity generation system in the EXPANSE and Nexus-e models (OREES does not include batteries in the model runs for this study). In Nexus-e the consideration of decentralized solar PV and battery systems entails the usage of batteries in all scenarios and, thus, the fixed capacities of the BatLow and BatHigh scenarios do not further impact results. In the EXPANSE model, only in the scenarios with high targets of renewable generation (High RES), the availability of 1.7 GW of battery systems increases PV installations by 1 GW, as batteries help to reduce curtailment from solar PV and make it more cost-competitive than electricity generation from biomass. Having said that, the original cost-optimal scenarios in EXPANSE without enforced battery capacity do not foresee such extensive uptake of batteries as they tend to rely more on wind power and biomass.

In terms of fossil fuels availability, scenarios with no electricity generation from fossil fuels in Switzerland (No Fossil) hardly differ from the other scenarios, indicating a limited impact of this uncertainty. The small amounts of natural gas power generation in the reference scenarios are replaced by a combination of solar PV and electricity import in EXPANSE and Nexus-e models (fossil fuels are not included in the technology mix of the OREES model).

3.2. Technology distribution at a high spatial resolution

Here we focus on solar PV and wind power at a cantonal or municipal resolution because the key spatial differences among the models emerge

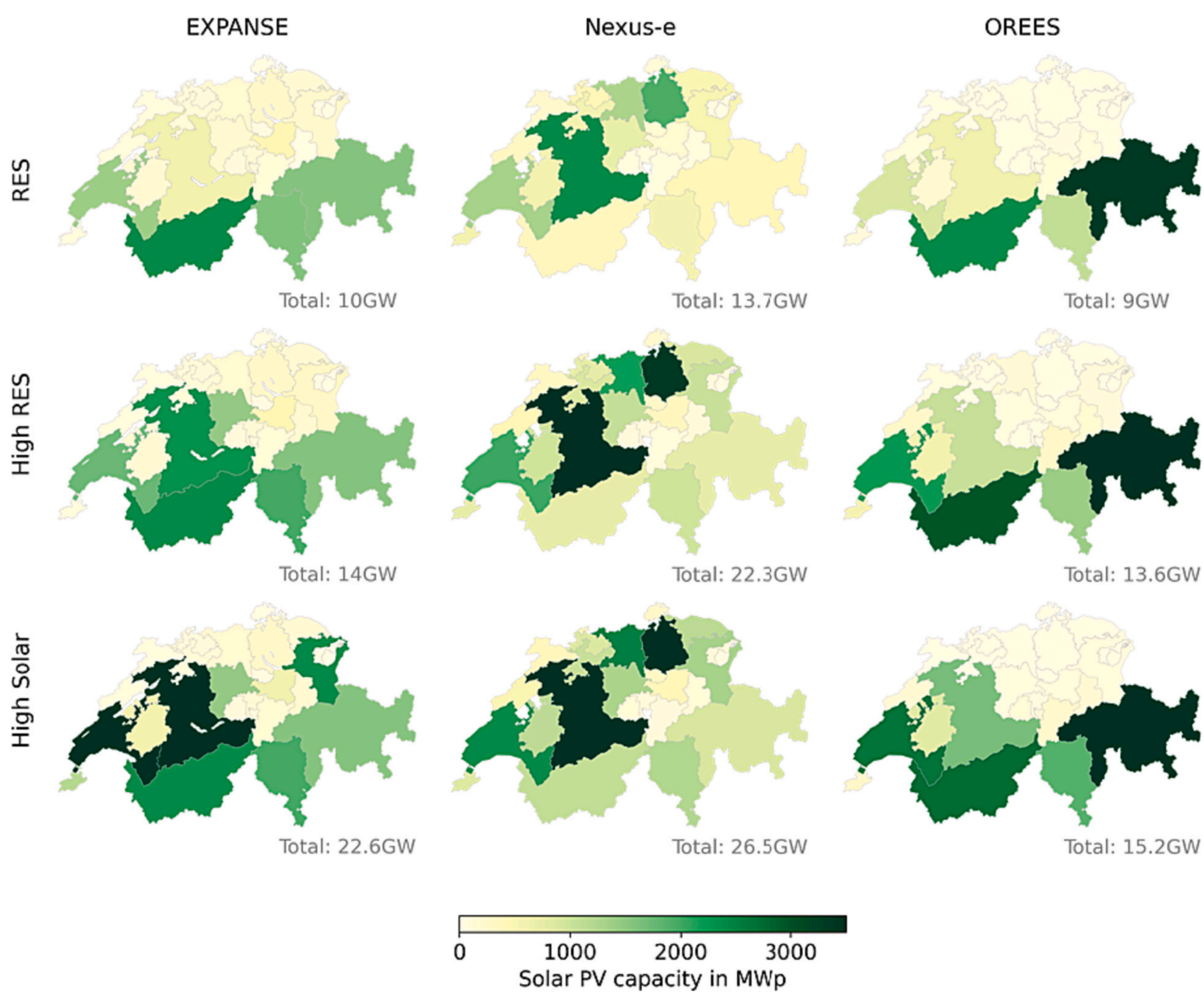

Fig. 4. Spatial distribution of solar PV capacity with a cantonal resolution, for the three base scenarios (i.e., RES, High RES, High Solar) and the three models EXPANSE, Nexus-e and OREES.

for these two technologies (Table 1). The solar PV capacity is distributed very differently over the 26 Swiss cantons in the three models and the three base scenarios RES, High RES, and High Solar (Fig. 4) and none of the models reach the maximum PV potential in these scenarios. In the OREES model, the largest solar PV capacity is found in the Alpine region in the East as OREES allows open-field PV. This illustrates the emphasis in OREES to model in detail the potential for alpine PV installations, as compared to the focus of the Nexus-e and EXPANSE models to represent decentralized PV installations at a household level. In the Nexus-e model, a large share of the PV capacity is placed in central and northern Switzerland, which are regions with higher population, demand, and rooftop areas. Nexus-e also takes into account PV profitability in terms of electricity prices and feed-in tariffs, which are unevenly distributed throughout Switzerland [25]. In EXPANSE, the cantons with the largest PV capacity are in the South in the RES scenario, as rooftop and facade PV is more productive there. In addition to technology-specific assumptions, the distribution of solar PV capacities in the three models is impacted by the resolution of representing transmission grid and whether the potential grid extension is modeled. A higher number of power system nodes in the Nexus-e and OREES models

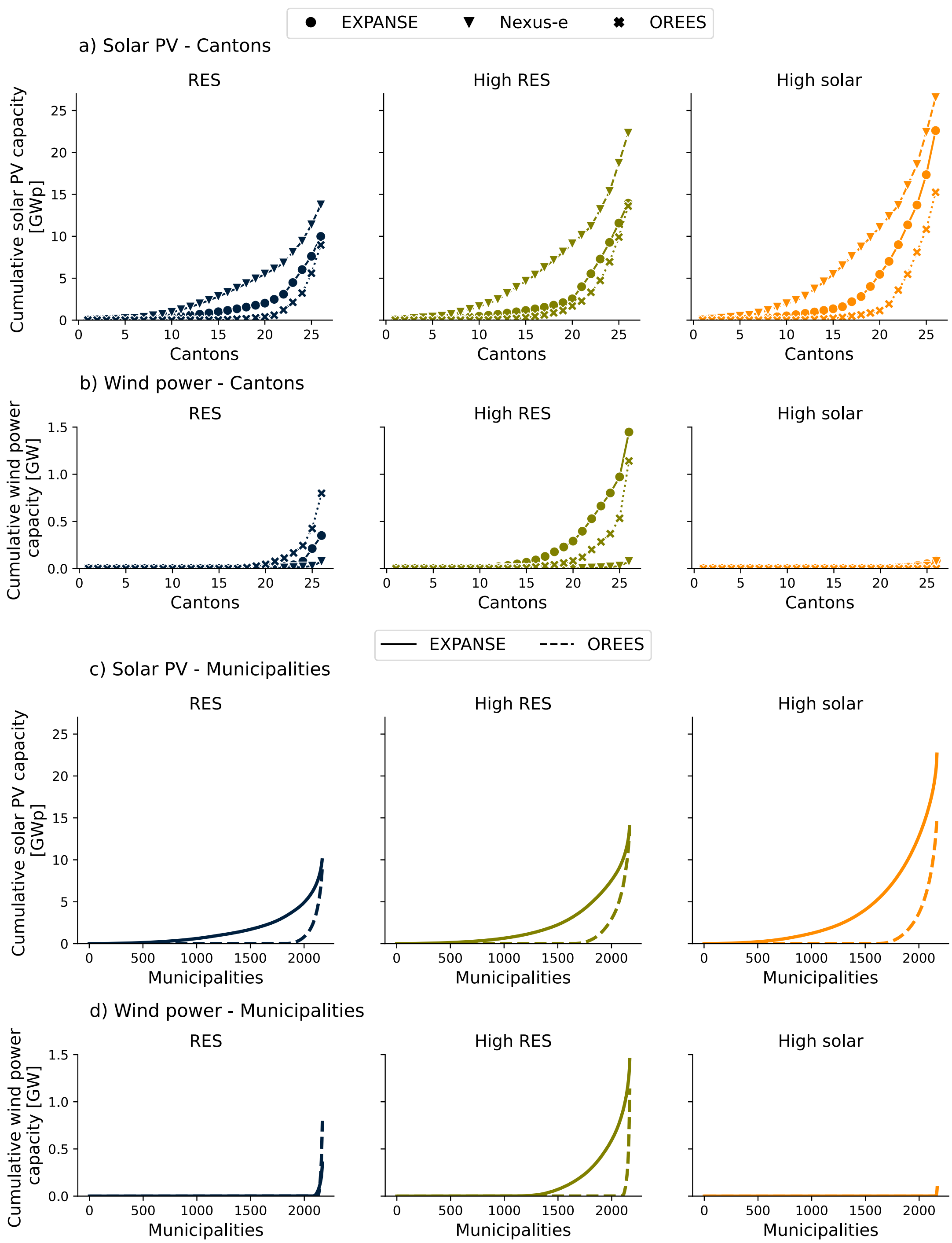

Fig. 5. Curves of cumulative capacities of (a) solar PV and (b) wind power for the 26 Swiss cantons and the EXPANSE, Nexus-e, and OREES models, and of (c) solar PV and (d) wind power for the 2148 Swiss municipalities and the EXPANSE and OREES models. Cantons and municipalities are summed in ascending order of their installed capacity. A straighter curve corresponds to a more even spatial distribution.

entail a larger number of power lines on which congestion can occur and, thus, tend to concentrate PV generation capacities to areas with transmission lines that are less loaded. This is different from the EXPANSE model because EXPANSE, if needed, endogenously models transmission grid expansion to overcome grid bottlenecks to accommodate higher shares of PV. Going from the RES to the High Solar scenario, more even spatial distributions are observed across all the models, especially EXPANSE and Nexus-e, because cost-efficiency driver diminishes once more and more PV is enforced in the models.

The distribution of wind power capacity over the 26 Swiss cantons is found in Appendix A1. In brief, the western part of Switzerland is preferred for wind power installations in all three models, because of its higher wind potential. In the Nexus-e model hardly any wind power is installed in all three scenarios. The EXPANSE and OREES models utilize most wind power when high amounts of renewable generation are targeted (High RES). In EXPANSE, wind power installations are found also in the North of Switzerland in the High RES scenario. In OREES wind power is also installed in the alpine regions in the East, both in the High RES and in the RES scenarios. As compared to the other models, higher resolution in OREES identifies good locations for wind power from the technical perspective, but these locations are not visible in EXPANSE and Nexus-e which are closer to the real-world implementation patterns, where technologies are built not only based on technical considerations. As described in the previous paragraph for solar PV, the modeling representation of the grid and its extension matter too for the uptake of wind power.

Fig. 5 illustrates how evenly solar PV (Fig. 5a) and wind power (Fig. 5b) cumulative capacities are distributed over all 26 cantons in all three models; a straighter curve corresponds to a more even spatial distribution. In all three models, wind power capacities are much smaller than solar PV ones. One wind power plant is also larger than one solar PV unit. Thus, wind power capacities are distributed more unevenly across the cantons, with many cantons having essentially no wind capacity installed. In the OREES model, a large share of the solar PV capacity is distributed to cantons in the alpine regions, which are characterized by higher capacity factors in OREES and explain the more uneven distribution of solar PV in OREES as compared to the two other models. The overall potentials per canton in OREES are also higher. In Appendix A1 additional results are presented for the cumulative capacities of solar PV and wind power plotted over the cumulative population for the 26 Swiss cantons.

With respect to municipal resolution (Fig. 5c and d), the difference between the EXPANSE and OREES models in the distribution of installed capacities is most pronounced in the High Solar scenario for solar PV and the High RES scenario for wind power (Fig. 6). In both models, solar PV installations are found in alpine regions in the east and south of Switzerland. In the EXPANSE model, solar PV is also placed in municipalities in central and east Switzerland in the High Solar scenario. The distribution of solar PV is more even in EXPANSE as compared to OREES in all three base scenarios (Fig. 5c) because EXPANSE accounts only for rooftop and facade PV and hence prioritizes low-cost and built-up areas of Switzerland. OREES, however, covers open-field and alpine PV installations, hence concentrating PV even more in a fewer number of most productive municipalities. In terms of wind power, the higher assumed potential in the alpine region in the OREES model is visible in the distribution of wind power in Fig. 6. While in both models wind power is located in the mountainous areas in the West in the High RES scenario, in OREES a large share of the wind power is also placed in the alpine regions because of the higher capacity factors. The EXPANSE model also assumes a smaller total wind potential, especially in the Alps, than OREES. A larger difference in the distribution of both solar PV and wind power in municipalities of the same canton in the OREES model as compared to the EXPANSE model can be explained by the spatial resolution, grid modeling, and input assumptions, such as capacity factors, as discussed before. The distribution of solar PV and wind power capacities in the base scenarios that are not shown here are found in Appendix A1.

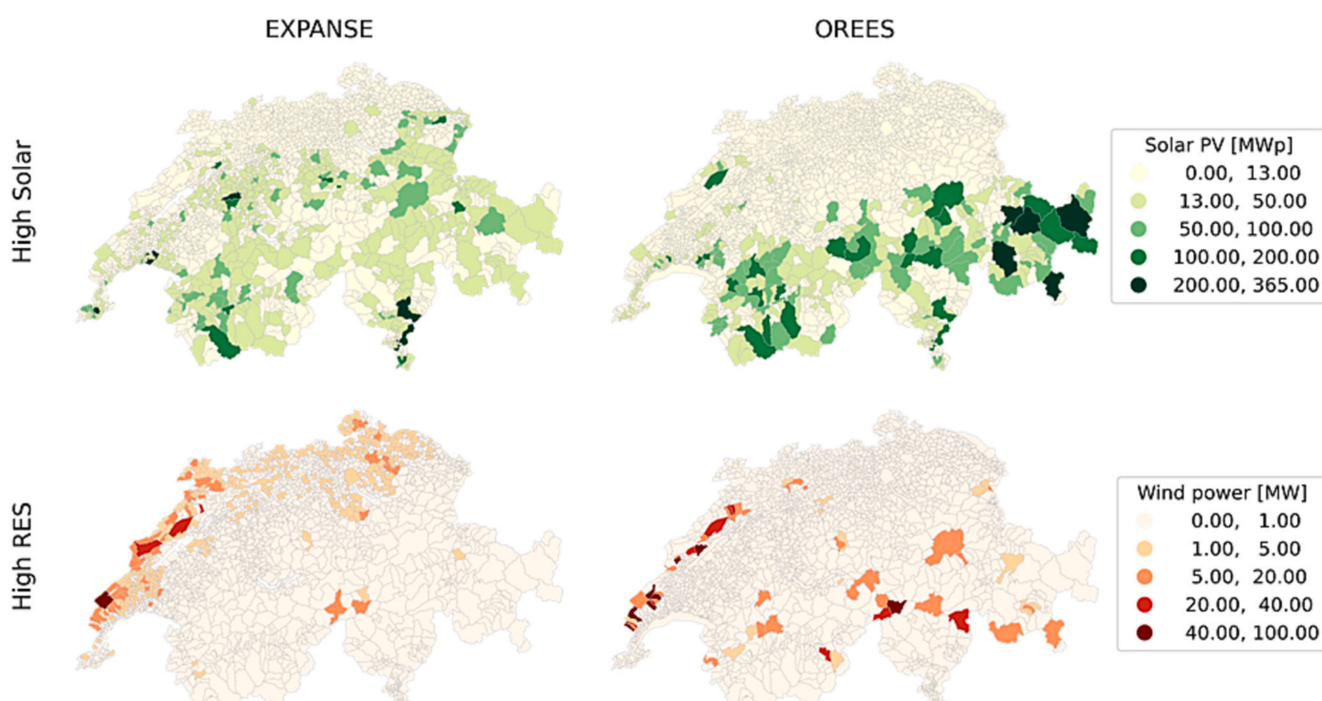

Fig. 6. Spatial distribution of solar PV capacity in the High Solar scenario (a) and wind power capacity in the High RES scenario (b), both with municipal resolutions and for the two models EXPANSE and OREES.

4. Discussion

4.1. Similarities, divergences, and lessons learned from Swiss model inter-comparison

In this model inter-comparison, we focus on electricity system scenarios for Switzerland with high shares of renewable electricity generation and at a high spatial resolution. This is not only the first model inter-comparison of spatially-explicit model in Switzerland [cf. 20], but it also stands out internationally for its high spatial resolution [8,18]. We find that in all models, the different renewable electricity generation targets in 2035 (17 TWh/year and 25 TWh/year supplied by renewable sources and 25 TWh/year supplied by solar PV) are feasible and result in high solar PV capacities. These converging results are identified even though the models differ substantially in assumptions on solar PV: EXPANSE includes the solar PV potential for rooftops and facades as well as their costs in the whole system but does not consider retail price structures and spatially-explicit subsidies, such as feed-in tariffs. Nexus-e only includes solar PV on rooftops without facades but accounts for the installer's perspective, including local prices and subsidies, assuming the continuation of current policies. OREES does not restrict the installation of solar PV on available rooftops or facades but also on some land based on high-resolution analysis of the terrain and the type of land cover. The spatial resolution and grid modeling capabilities also differed among the models. Another convergence of model results is the importance of import and export to cover various in annual electricity demand as well as to provide flexibility. Even though wind power potentials are higher in the OREES model as compared to the EXPANSE and Nexus-e models and the cost assumptions differ too, the installed wind power capacities in all scenarios and all three models are at least ten times lower than the installed solar PV capacities. In all three models, neither solar PV nor wind power deployments reach their maximum technical potentials, meaning that technical potential constraints do not limit the uptake of these technologies in the scenarios. This makes a focus on solar PV expansion in Switzerland a clear recommendation of this inter-comparison study, even more so given that we applied an inter-comparison methodology with comparatively little harmonization effort.

Despite this high convergence of the models at a national scale, the main difference in the results is the spatial distribution of solar PV and wind power installations, which becomes especially visible in our inter-comparison due to high spatial resolution. One explanation for divergences is the different rationale of models. In EXPANSE, the spatially-explicit investments and dispatch of all electricity generation units are determined by a total system cost minimization with underpinning data at a resolution of Swiss municipalities. In OREES, the revenues from solar PV and wind power installations are maximized by considering different possible placements and the interplay of solar PV and wind power with the dispatchable generation from hydropower dams and pumped hydro storages. Thus, OREES allocates PV and wind power installations according to their best possible locations at a higher resolution (i.e., taking the perspective of individual project developers), while EXPANSE considers a path closer to the real-world deployment (i.e., where the absolute best locations from the national perspective cannot be always realistically used because a compromise needs to be met between technical and economic profitability, public acceptance and real-world messiness of the decision making [22,40]). EXPANSE also considers the impacts of solar PV and wind power installations on the remainder of the electricity supply system (i.e., taking the perspective of a national energy planner). Nexus-e follows a hybrid approach where the investments and dispatch of centralized units (e.g., nuclear, hydro, wind) are determined by a total system cost minimization, while investments in decentralized units (e.g., rooftop PV, battery storage) depend on the investment profitability, including spatial differences in feed-in tariffs and retail electricity prices. In EXPANSE and Nexus-e, solar PV is modeled for rooftops, while OREES includes a detailed representation of open-field PV. These differences in model rationales and technology assumptions are the main reasons for the larger placements of solar PV capacities in urban regions in EXPANSE and Nexus-e, and the larger capacities in the Alps in OREES. In addition, OREES considers a higher spatial resolution for solar PV and wind power placements and for the assumptions on capacity factors, which results in a greater unevenness in the distribution of solar PV and wind power capacities. The spatial resolution with which the three models represent the electric power grid, as well as the grid expansion capability in EXPANSE, is another factor that impacts the spatial distribution of installed capacities.

Despite convergence on solar PV, the three models also differ in technology diversity (this tendency has been noticed in previous inter-comparisons elsewhere too [e.g. 14, 15]). While both the EXPANSE and the Nexus-e models include a larger set of technology options, we find a larger diversity in the electricity generation from biomass and waste incineration, wind power, and natural gas in the EXPANSE model and a larger difference in installed battery capacities among different scenarios in the Nexus-e model. Explanations for these differences are the higher potential for electricity generation from biomass and waste incineration in EXPANSE as compared to Nexus-e, which only considers waste incineration and no biomass for this study, and the representation of batteries on a decentralized level in Nexus-e as compared to EXPANSE.

Despite these divergences that can be explained through the different rationales and assumptions of the three models, this model inter-comparison provides robust insights for the Swiss energy transition. The 2035 aims of 17 or 25 TWh/year of new renewable electricity or 25 TWh/year of solar PV are technically feasible. While all models include a mix of multiple technologies to supply the Swiss electricity needs, solar PV emerges as the most important technology. Until very recently [e.g. 28], modeling-based scenarios with considerable share of solar PV were lacking in Switzerland [4,42], even without high spatial resolution. In fact, in our inter-comparison we are also able to show that there is flexibility where PV can be placed to achieve the targets: either on roofs and facades (EXPANSE and Nexus-e models) or also on land (OREES model). In addition to solar PV, one model includes biomass (EXPANSE) in their scenarios, indicating that a technology-specific policy with a focus on solar PV only could lead to sub-optimal solutions and higher system costs. For solar PV and especially for wind power, there is also a tradeoff between placing plants in fewer most productive locations or accounting for the more realistic paths of technology deployment where not only the most productive locations are prioritized. Electricity interconnection with Europe remains of key importance in Switzerland because any increases in electricity demand or lower deployment of new renewable electricity are compensated by electricity import. For the rest, the individual scenarios from the three models can provide a more detailed look into different strategies or options for the future in 2035: a future with a more diversified and complete range of technology and grid extension options to keep the system costs low (cost-optimization version of EXPANSE), a future with the focus on decentralized uptake of solar PV with batteries, and a future with the prioritization of most productive areas for wind and solar PV, including open-field PV (OREES).

Through this model inter-comparison, several aspects of the three models could be improved. Comparing the results and input parameters reported in the first iteration of the model runs, before the second iteration that is used for the final results in this publication, allowed modeling teams to review models and assumptions based on the exchange with other modelers. Thus, assumptions on power reserves, electricity demand profiles, and technology costs, as well as the representation of electricity imports and exports, natural gas, and nuclear power were reviewed by some teams. Additionally, further developments to the models are planned as a result of the lessons learned from this inter-comparison, such as the representation of batteries in the OREES model, advancements in the Nexus-e model to analyze results with a higher spatial resolution on the municipality level, and extension of EXPANSE to further refine the modeling of storage and flexibility. Thus, all models are better equipped to study the energy transition in Switzerland as an outcome of this work.

4.2. Insights for model inter-comparison studies

For future model inter-comparisons in Switzerland or elsewhere, a main takeaway from this study is that inter-comparisons, as an approach to model evaluation, improvement, and extraction of robust insights under uncertainty [5], are possible and useful also with spatially refined and structurally different electricity system models. In line with the well-established methodology of inter-comparisons with integrated assessment models of climate change [6,7], we choose to guide our harmonization by the policy-relevant question (and not solely by modeling interests) and hence we only harmonized two input parameters: the targets for renewable electricity generation and the annual electricity demands. Given that all three models are already well established and peer-reviewed with own justifications of internally-consistent structural and parametric assumptions, the methodology from integrated assessment modeling enabled us to preserve each model's specific rationale and strengths. Structural and conceptual differences of the models (Table 1) are an asset to adequately account for the deep uncertainty that surrounds the future electricity sector transition [5], whereas too much harmonization can lead to underestimated uncertainty and overconfidence in the model results for policy [43]. This inter-comparison approach, inspired by integrated assessment models, gives greater weight to common and hence robust policy findings among the models (such as the large solar PV capacities employed in all models or the importance of import and export) and enables learning between the models without forcing these models to give up their earlier work. For example, the case of solar PV potentials is a good example: EXPANSE and Nexus-e use external data on PV potentials, while OREES estimates these potentials endogenously. Forcing all models to take just one source would mean that either OREES would skip its endogenous calculation and hence loose a part of its identity, or EXPANSE and Nexus-e will need to take another data source that is inconsistent with the rest of their assumptions and rationale. In the end, the inter-comparison scenarios and even the three models more broadly should be interpreted as options or storylines of strategies for the future electricity mix in Switzerland: a technically and regionally balanced strategy from EXPANSE scenarios, a strategy with high reliance on solar PV with batteries in populated areas from Nexus-e, and a strategy of primarily focusing on high-efficiency locations for wind power and solar PV, including open-field PV. For now, a model that combines all these strategies in one balanced assessment is not available, but in fact, it may not even be needed. Each of these three strategy options are associated with many non-modeled considerations, like land use and landscape impacts, involvement of different actors as investors, and so on. It is therefore valuable to pose all three strategy options for policy and societal decision making rather than to make an explicit recommendation between them from a narrower techno-economic perspective.

The focus of this work is to study scenarios for supplying the future Swiss electricity demand with a high share of new renewable generation, in addition to the existing hydropower. Future model inter-comparison studies could address other policy questions on the future Swiss electricity supply and, possibly, define the harmonized scenarios differently. One possibility for further work is to explore scenarios with set limits on the levels of import and export to Switzerland since we find that all three models respond to different renewable electricity targets by a change in net imports. Even more ambitious renewable electricity targets, especially in the longer run, could be analyzed. All three models used in this work consider the electricity system only. Thus, a continuation of this study could further involve extended versions of these models or other models to assess implications from future developments in the transport, heating, and industry sectors of the Swiss energy system. Finally, the methodological frontiers could be further pushed with spatial models to also develop and demonstrate inter-comparisons with large scenario ensembles [5] or with an even larger diversity of models at various spatial scales [44].

5. Conclusions

Model inter-comparisons, where models are assessed with respect to converging and diverging results for a set of harmonized scenarios, are useful for three reasons: for understanding the impact of models' structure and assumptions on the key results, for helping modeling teams to learn from each other, and for enhancing the robustness of main findings for policy. Our model inter-comparison identifies the common and diverging results from three spatially-explicit electricity system models for future Swiss scenarios with a high share of renewable generation in the year 2035. We find high capacities of solar PV in all models and scenarios, pointing to the importance of this technology for the future electricity supply in Switzerland. The spatial distribution of the solar PV capacities differs between the three models, with a larger focus on solar PV in the OREES model including alpine and other open-field applications, with a larger focus on decentralized solar PV installations with batteries in the Nexus-e model, and with a diverse mix of the renewable sources of solar PV, wind power and biomass in the EXPANSE model. In the case of higher electricity demand, all models respond with increased net imports, highlighting the importance of the interconnection with Europe in Switzerland.

From the methodological perspective, we show that an inter-comparison of high-resolution electricity system models can work well with relatively low level of harmonization, driven by the policy-relevant guiding question. With this high degree of freedom, even structurally different models can point to the points of consensus for policy and then indicate divergences as different options for future strategies. For example, EXPANSE demonstrates a technically and regionally balanced technology strategy, Nexus-e illustrates a strategy with high reliance on solar PV with batteries in populated areas, and OREES covers the strategy of primarily focusing on high-efficiency locations for wind power and solar PV in Switzerland, including open-field PV in the Alps and elsewhere. Now, even previous findings or ongoing work with these models can be interpreted in a light of how each model compares to its peers in Switzerland. Finally, the model inter-comparison also reveals the importance of spatially refined analyses for both outputs and key input parameters of the three models. Analyzing results with a high spatial resolution enables additional insights into model differences, but requires all models to document results on the same spatial scale, such as cantons or municipalities in this study. The adequate representation of electricity imports and exports in models to study the energy transition in Switzerland is essential too due to the high importance of interconnection for the future electricity supply.

CRediT authorship contribution statement

Verena Heinisch: Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Jérôme Dujardin:** Writing – review & editing, Software, Investigation, Conceptualization. **Paolo Gabrielli:** Writing – review & editing. **Pranjal Jain:** Writing – review & editing, Software, Investigation. **Michael Lehning:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Giovanni Sansavini:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Jan-Philipp Sasse:** Writing – review & editing, Software, Investigation, Conceptualization. **Christian Schaffner:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Marius Schwarz:** Writing – review & editing, Software, Investigation, Conceptualization. **Evelina Trutnevyte:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare no competing interests.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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