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Review of model-based electricity system transition scenarios: An analysis for Switzerland, Germany, France, and Italy

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ABSTRACT

Policymakers currently face the challenge of supporting a suitable technology mix to decarbonize electricity systems. Due to multiple and interdependent technologies and sectors, as well as opposing objectives such as minimizing cost and reducing emissions, energy system models are used to develop optimal transition pathways towards decarbonized electricity systems. Research in this domain has increased in recent years and multiple studies have used energy system modeling (ESM) to shed light on possible transition pathways for national electricity systems. However, in many cases, the large number of model-based studies makes it difficult for policymakers to navigate study results and condense diverging pathways into a coherent picture. We conduct an in-depth review of ESM publications covering Switzerland, Germany, France, and Italy, and analyze the main trends regarding electricity generation mixes, key supply and storage technology trends, and the role of demand developments. Our findings show that diverging solutions are proposed regarding technology mixes in 2030 and 2050, not all of which meet current climate targets. Additionally, our analysis suggests that natural gas, solar, and wind will continue to be key actors in the electricity system transition, whereas the role of storage remains opaque and calls for clearer policy support. We conclude that due to diverging targets and the current energy landscape in each country considered, different options appear as prominent transition pathways, meaning that individual sets of policies are necessary for each case. Nonetheless, international collaborations will be essential to ensure a swift electricity system transition by 2050.

1. Introduction

1.1. Background

The decarbonization of energy systems is one of the most critical tasks in our efforts to reduce CO_2 emissions and mitigate the effects of climate change. [1,2]. Electricity systems are expected to play a crucial role in achieving national and global climate targets in accordance with the Paris Agreement [3]. In the European Union (EU), the last few decades have seen a rapid increase in shares of renewable energy (RE) generation[1]: from 14% in 2000 to 37% in 2018 [4], mostly due to wind and hydro power; nevertheless, many electricity systems still rely heavily on fossil fuels, and further efforts are needed to boost the integration of renewable sources.

In this context, policy- and decision-makers are tasked with identifying the optimal technology mix and the necessary support mechanisms to sustainably transform electricity systems, while also ensuring reliable electricity supply access for everyone [5]. However, making the right decisions is challenging, given the large number of stakeholders involved and the high degree of uncertainty associated with future electricity demands and technology trends — for instance, driving the increased coupling of other sectors such as transportation and buildings with the electricity system.

Given the complexity of modern energy and electricity systems, ESM is widely used to inform, guide, and support policy- and decision-makers in their efforts to orchestrate the energy transition [6–8]. More specifically, energy system models — and in particular technology-rich, bottom-up models [9], which represent the different components of an energy system and their interactions in a computational environment, can be used to identify future patterns of energy supply and demand, develop strategic long-term plans for the transformation of energy systems, and simulate the impact of policy and technology choices [10].

1.2. Literature review

In recent years, a wide array of energy system models have been developed with different features, scopes, and aims, fueled by current

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[1] Includes all EU member states in 2021 plus the United Kingdom (UK) as a former member state, which was still part of the EU in 2000.

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Terms and Abbreviations

BESS	Battery Electric Storage System
CAES	Compressed Air Energy Storage
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CH	Switzerland
CHP	Combined Heat and Power
DE	Germany
ESM	Energy System Modeling
EV	Electric Vehicle
FR	France
GHG	Greenhouse Gas
IT	Italy
PtG	Power-to-Gas
PHS	Pumped Hydro Storage
PV	Photovoltaics
RE	Renewable Energy

energy challenges [11] and supported by the advances in computational power [9]. Current directions of ESM focus on the challenges of identifying the right level of complexity to accurately represent the problems they examine [12], representing social and behavioral factors in models [13,14], and enhancing model relevance and impact for policy making [15]. In parallel, a plethora of studies have applied these models to generate long-term transformation scenarios for national and multinational energy and electricity systems. These developments, in turn, have motivated a series of review studies to summarize the current state of ESM and provide perspectives for different research dimensions. These review studies can be broadly grouped into two categories.

The first category concentrates on energy system models and their technical characteristics, offering valuable summaries of methodological trends, challenges, and future research directions. As a result, these studies are mostly targeted at a technical energy modeling audience. The most relevant studies published since 2010 are summarized in Table A.1, further divided into two sub-groups. The first sub-group comprises studies that provide general overviews of different models [6,9,11,16,17]. These studies typically present and compare models in terms of their scope, capabilities, and features; identify common modeling needs; outline directions for future research; and help modelers to identify suitable models for their needs. One example is the study by Ringkjøb et al. [16], in which the authors compared 75 modeling tools in terms of their general logic, spatio-temporal resolution, and technological and economic properties. The studies in the second sub-group focus on specific key dimensions and challenges of ESM, and review different methodological approaches used in the literature to address them. For instance, Koltsaklis et al. [18] analyze the approaches taken by previous ESM studies to address aspects such as the role of risk assessment, the interdependence between electricity and natural gas infrastructure, and energy storage and demand-side impacts.

While this first category of studies condenses valuable ESM information, their focus is limited to technical and methodological details. As ESM literature addresses real world problems, a second broad category of review studies has been developed that focuses mainly on the transition scenarios and results generated by studies that apply ESM to different energy and electricity systems. Their target audience includes policy- and decision-makers in addition to the modeling community. The rationale behind this targeting can be described as follows: Typically, in almost any context in which energy and electricity systems are examined, policymakers have access to a plethora of studies that use ESM to generate diverse, long-term energy system scenarios that rely on different technology sets to meet energy and climate targets. On the one hand, the availability of multiple model-based scenarios can be deemed as positive, since it enables a more comprehensive view of the problem and can also uncover the full range of potential options. On the other hand, all these studies use highly complex models that might employ different methods, parameter values, and initialand boundary conditions for their analyses. The lack of model transparency further exacerbates this aspect of complexity, as many model assumptions and data are not clearly reported in the studies [19]. As a result, policymakers often find themselves in a quandary about how to navigate the results of multiple studies and how to further proceed with synthesizing all the available information and transforming it into effective policy.

Therefore, review studies in the second category, by collecting energy and electricity system scenarios from multiple studies, seek to highlight key trends, similarities, and differences among scenarios, allowing policymakers to interpret the main pathways forward and the potential risks hidden in them, without having to weave through complex model-based studies.

Review studies of this type, though, are far less frequent in the literature compared to technical ESM reviews. A summary of the most relevant publications of the second category is given in Table 1. Out of those, one prominent example is the study by Densing et al. [22], in which the authors collect and review multiple model-based scenarios for the Swiss electricity system. After comparing the various dimensions of the models used to generate these scenarios, the authors apply quantitative methods to identify the most representative and most extreme scenarios, with the aim of informing policymakers about the main transformation avenues for the Swiss electricity system. Xexakis et al. [24] also examine model-based scenarios for the Swiss electricity system and compare them with preferred scenarios defined by different stakeholders (uninformed and informed citizens, and energy experts) through online surveys and workshops. Their findings highlight important differences between the two scenario sets, with model-based scenarios, for instance, favoring fossil fuel-based generation and stakeholder scenarios prioritizing domestic renewable generation for the Swiss electricity system.

While both previous studies focus on the electricity system of a single country, the study by Candas et al. [20] provides first insights into energy system decarbonization scenarios for 15 countries that are electrically connected to Germany. While the authors investigate many countries, they only use one to three studies per country, and focus primarily on overarching trends without linking country-specific developments to individual scenario assumptions. A multi-country perspective is also retained in the study by Kondziella et al. [23], which compiles the findings from multiple studies regarding the flexibility requirements for different shares of RE in the German and European electricity systems. However, the authors' study does not consider flexibility requirements for different scenarios, but instead aggregates the results to general trends. Finally, motivated by the widely varying projections in different studies regarding the storage needs for electricity systems in the USA, Europe, and Germany, Cebulla et al. [21] collect these study findings and develop empirical relationships for the storage power and energy capacities as a function of the RE shares in the different systems. While the authors do consider the scenarios underlying the results, the study only analyzes storage systems, and omits an investigation of the transition pathways for the whole electricity system.

1.3. Motivation

The reviewed studies of the second category, particularly those that carry out multi-country analyses, have investigated the results of scenario-based energy and electricity system models from several different angles — for example, by focusing on the variability found in country-specific scenarios [22] or by investigating storage demand

Table 1
Summary of reviews drawing insights from energy system scenario results.

Publication	Title	Characteristics	Approach[a]
Candas et al. [20]	Meta-analysis of country-specific energy scenario studies for neighboring countries of Germany	Indicator-based summary of national discussions on energy transition for 15 neighboring countries of Germany	Qual.
Cebulla et al. [21]	How much electrical energy storage do we need? A synthesis for the U.S., Europe, and Germany	Review of 17 storage expansion studies for the U.S., Europa and Germany analyzing the dynamics between increasing intermittent RE shares and electrical energy storage capacity	Qual.
Densing et al. [22]	Meta-analysis of energy scenario studies: Example of electricity scenarios for Switzerland	Taxonomy-based classification of energy system models and assessment of the variability between 28 Swiss energy system scenarios	Qual. + Quan.
Kondziella et al. [23]	Flexibility requirements of renewable energy based electricity systems — a review of research results and methodologies	Classification of scientific approaches determining future flexibility demands in Germany and Europe	Qual.
Xexakis et al. [24]	Models on the wrong track: Model-based electricity supply scenarios in Switzerland are not aligned with the perspectives of energy experts and the public	Comparison between electricity supply pathways developed from expert interviews and 82 Swiss electricity system transition scenarios for 2035	Qual.

[a] Qual. = Qualitative: Interviews or non-numerical discussion of scenario results. Quan. = Quantitative: Analysis of scenario results using statistical methods or modeling.

across different countries [21]. Nevertheless, to the best of our knowledge, no study has investigated multiple aspects related to the energy transition across multiple countries, focusing not only on local changes, but also on cross-country trends. Furthermore, the reviews of the second category have only selectively condensed the diverging results of ESM studies into understandable implications for policymakers and lack a cross-country perspective — even though providing such clarity is a crucial input for policymakers to better orchestrate energy system transitions.

Therefore, with this paper, we aim to contribute to the nascent but growing body of review studies that seek to provide clarity for policymakers on key challenges in the electricity system transition. To this end, we analyze the findings from multiple model-based scenarios on the electricity systems of four European countries: Switzerland, Germany, France, and Italy.

The key contributions of this study are:

1. We present a detailed analysis of multiple model-based scenarios for the Swiss, German, French, and Italian electricity generation mixes for 2030 and 2050.
2. We conduct an in-depth cross-country analysis of technology trends and their projected developments until 2050.
3. We derive general relations between policies and future electricity system developments that apply independently of the examined country.

With these three contributions, we aim to highlight how electricity system could change in different countries with unique policy landscapes, depending on the pathways they take and targets they set. Furthermore, our contributions facilitate a better understanding of the role that key technologies will play and, thus, elucidate the relevance of policy support. Finally, by aggregating the results, we illustrate how policies might accelerate the electricity system transition.

The paper is structured as follows: In Section 2, we first introduce the case studies that will be the focus of this paper. Then we outline the steps that we apply to perform our review, and introduce the scenarios from which we will draw for our analysis. In Section 3, we present the results of the analysis for each country (Section 3.1), then discuss several trendsregarding specific technologies (Section 3.2) and electricity demands (Section 3.3). In Section 4, we present the resulting implications for policymakers (Section 4.1) and derive additional insights for modelers (Section 4.2), after which we highlight some limitations of the study (Section 4.3). Finally, we present our concluding remarks and suggestions for further research in Section 5.

2. Case studies and methods

In this section, we first discuss our motivation to focus on the electricity systems of four European countries, and introduce each country's key electricity and energy system goals. In the second part, we describe the scenario collection and filtering processes that are used to obtain a final set of model-based scenarios for the transformation of each country's electricity system, and the scenario comparison approach that we follow for this study.

2.1. Current electricity system states and energy goals of the case studies

For this study, we focus on the electricity systems of Switzerland, Germany, France, and Italy. Our motivation behind this choice is threefold: First, although all four countries aim to decarbonize their electricity systems, they each have very different starting points in terms of their current electricity generation mixes and available resources, and, thus, might face different obstacles along the path towards achieving their goals. Second, the findings for each of the four countries can also offer insights for other countries with similar characteristics, allowing policymakers to consider generation technology trends beyond the limits of one specific country.[2] Third, since all four countries are electrically interconnected, the selection supports the discussion of electricity import and export projections between the countries.

Table 2 summarizes the countries' current electricity supply and demand, the yearly CO_2 emissions from fuel combustion, each country's major electricity sources, and the share of RE and low-carbon technologies in their current electricity generation mix. Therefore, by comparing model-based electricity system scenarios for each country, in addition to providing country-specific insights, we also aim to examine the degree to which the different starting points for each country might influence the actions needed for the transformation of its electricity system. In the following paragraphs, we outline the key policy goals that each country has set for its energy and electricity system.

Switzerland, in an effort to limit its climate impact, has committed to reducing its greenhouse gas (GHG) emissions by 50% compared to 1990 levels by 2030, and to further reach net-zero emissions by 2050 [26]. Currently, Switzerland has one of the cleanest electricity mixes in Europe due to high shares of hydro and nuclear power (corresponding to 56% and 35% of total electricity production in 2019, respectively [4]). However, the country has also decided to prohibit the building of new nuclear plants and phase out all current ones by 2034. As a result, the primary challenge facing the Swiss electricity system over the coming years is to fill the supply gap due to the nuclear phase-out, while maintaining security of supply and preventing an increase in GHG emissions.

Germany, as part of its energy transition or "Energiewende", has also committed to net-zero GHG emissions by 2045, according to the new climate law [27]. The electricity sector has been at the forefront

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[2] For example, policymakers can use the country-specific implications derived for Italy as trend indicators for Spain, since both countries currently have comparable electricity generation mixes, relying heavy on oil and natural gas [4], and both benefit from a high solar power potential.

Table 2
Electricity generation mix and yearly CO_2 emissions from fuel combustion for Switzerland, Germany, France, and Italy in 2019, taken from the IEA "Data and Statistics" database [4] and the IEA annual CO_2 emissions report [25].

Country	Electricity supply	Electricity demand	CO_2 from fuel combustion[a]	Share of RE[b]	Share of low-carbon sources[c]	Main generation technologies[d]
Switzerland	73.6 TWh	63.1 TWh	0.5 Mt CO_2	60%	96%	Hydro, nuclear, waste
Germany	618.2 TWh	558.9 TWh	284.3 Mt CO_2	40%	52%	Coal, wind, natural gas
France	570.8 TWh	474.4 TWh	35 Mt CO_2	20%	90%	Nuclear, hydro, natural gas
Italy	291.7 TWh	311.9 TWh	37 Mt CO_2	39%	39%	Natural gas, hydro, solar PV

[a] Annual CO_2 emissions from fuel combustion for 2017.

[b] Includes solar PV, wind, geothermal and biomass.

[c] In addition to the renewables, nuclear power and technologies combined with carbon capture and storage (CCS) are added.

[d] Highest contributor is named first.

of the energy system transformation in Germany, which has vowed to phase out nuclear power by the end of 2022 and coal power by 2038 [28]. Additionally, the country plans to further reinforce the role of RE in its electricity mix, and to reach a share of 65% renewable electricity by 2030 [29]. Since Germany has one of the highest electricity demands in Europe (see Table 2), moving away from fossil fuels and introducing large shares of RE is a challenging task.

France's electricity system relies primarily on nuclear power, as the country produces around 70% of its electricity from nuclear fission [4]. France currently aims to reduce this share to 50% in the upcoming years [30] and focuses on increasing the efficiency of its overall energy system to reduce total national carbon emissions until 2030 and beyond in accordance with the Paris Agreement. In addition to the planned reduction of nuclear power, France has also decided to phase out its remaining coal power plants by 2022 [31]. As a result, France will need to introduce renewable technologies to fill the gap in the electricity supply left by the partial nuclear and full coal phase-outs.

Italy, by publishing its National Energy and Climate Plan [32] in 2017, also took the necessary actions to move towards reducing its carbon emissions in the coming decades. As a member of the EU, it translates the EU climate goals into national law and aims for a 55% reduction of GHG emissions by 2030 [33]. The country also aims to produce 28% of its gross final energy consumption through RE in 2030, and has adopted an even more ambitious goal of 55% RE for its electricity sector by 2030. Furthermore, Italy also aims to phase out the use of coal-fired electricity generation as early as 2025. Another key element of the Italian strategy is to increase energy efficiency through the electrification of other sectors (e.g., transport and buildings). As a country relying heavily on natural gas, but with highly favorable solar potential, Italy needs further developments in both areas to enable a stable electricity supply.

2.2. Selection of model-based electricity system scenarios

To compile a list of electricity system scenarios for each studied country, we relied on a four-step process comprising scenario collection, scenario filtering, scenario investigation, and result reflection. The specifics are as follows:

1. Scenario collection: In the first step, we relied on three main sources to create an initial, preliminary list of studies and scenarios. We began by collecting studies that focused on any of our case countries and were carried out using the models discussed in the reviews of Table A.1. We then used keyword-based searches on Scopus and Google Scholar to discover additional studies on the topic that were not included in the review studies from the previous step.[3] Third, we consulted the list of energy models published by the Open Energy Modeling Initiative (openmod) [34] in order to source studies that had used those models but were not included on the list. The initial, extensive literature search yielded approximately 300 to 400 studies per country. In order to obtain a final list of studies, we formulated multiple filtering criteria that pertained to chronological and methodological aspects, as well as to data availability.

2. Scenario filtering: First, we excluded studies published before 2014, to ensure that the policy instruments and policy targets considered in each study were up to date. Second, we selected only those studies that had used bottom-up energy system models to generate electricity transition scenarios, as their technology-rich focus ensured that all technologies and their characteristics were represented in sufficient detail.[4] Finally, given this study's focus on transition scenarios for future electricity systems, we retained only those studies that included detailed information about the country's electricity generation mix (i.e., information about domestic electricity generation and imports/exports). We then took the electricity supply scenarios for 2030 and 2050 from the studies. The year 2040 was not investigated, as only limited data was available for this year. Further information on data processing is given in Appendix B.

The final set comprised a total of 171 scenarios, of which 52 focused on Switzerland, 47 on Germany, 43 on France, and 29 on Italy. More than 75% of the scenarios in the final set presented the evolution and the transition of the studied energy/electricity system by modeling a series of years; the remainder analyzed a single target year in the future. Moreover, most of the scenarios were generated with optimization models, with around 20% stemming from purely simulation-based models or combining simulation with optimization. Additionally, approximately half of the scenarios discussed only the electricity system, while the other half covered multiple sectors such as electricity, heating, and transportation. Finally, out of all scenarios, 36 could be classified as reference scenarios and 70 as climate target-based scenarios (incorporating constraints for CO_2 emissions or shares of RE). The remaining 65 scenarios investigated a variety of aspects, such as the limitations of certain technologies (38), the impact of electricity trade (11), cost parameters (12), or efficiency measures (4). The 171 scenarios were evenly spread between the investigated years 2030 and 2050.

3. Scenario investigation: To analyze the scenarios, we followed a qualitative comparison approach. Applying rigorous quantitative methods on sets of heterogeneous electricity system scenarios resulting from different energy system models can be challenging, and might even lead to erroneous conclusions [22]. Knutti et al. [35] further elaborate that using statistical methods on model outputs can lead to the loss

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[3] The terms used for the search included: "energy model", "energy modeling", "energy system model", "energy system modeling", "electricity system model", "electricity system modeling", "generation expansion planning", "electricity generation", and "energy transition". All these terms were always combined with the name of each considered case-study. Additionally, both British and American English spellings were used for these search terms.

[4] Besides the bottom-up model requirement, no further filtering was performed regarding the model's methodology (simulation vs. optimization models), the sectors covered (electricity system vs whole energy system models), or the model's horizon (modeling only a target year in the future vs. the evolution of the energy/electricity system in annual or multi-annual steps until a target year).

of critical information and can result in unrealistic suggestions. For these reasons, we have decided to not use quantitative methods. For the comparison, we collected the same set of outputs from every model-based scenario and analyzed the main trends and extreme outcomes. Essentially, we treated each scenario as an "expert opinion" on the possible evolution of the electricity system, with the model input parameters and assumptions serving as the personal beliefs of the expert. Through this endeavor, we aimed to understand the range of options the "experts" presented for the electricity system; therefore, we focused primarily on the key metrics of interest in each scenario. In extreme cases, such as scenarios with highly diverging generation mixes, we sought to understand which expert choices might have contributed to this outcome.

The key metrics that the analysis focused on were the annual electricity production by each generation technology for 2030 and 2050, the supply share of each technology, import and export data, electricity demand, and information on storage capacity or size. We could not investigate the annual electricity system costs for 2030 and 2050 due to the lack of data in the individual studies and discrepancies between the system costs defined for energy systems and electricity systems.

4. Result reflection: In the last step of our process, we derived policy implications based on the outcome of the scenario investigation. To this end, we combined policy-related aspects included in the scenarios, such as phase-out strategies or climate targets, with the projected generation mixes and key technologies to derive individual policy recommendations for each case study, which we then aggregated across the four case countries.

Condensed overviews of the studies and scenarios chosen for each country are given in Tables 3–6. In the results of the next section, the scenarios are identified by their new scenario name. Depending on the aim of the scenario in the original study, the scenarios are also categorized into different groups (e.g., climate-focused, least cost etc.). Detailed information on the main details and key assumptions of each scenario is provided in Tables D.1–D.4, and additional details on the energy system models of each study are given in Table E.1.

3. Review results

This section presents the key findings of our scenario analysis. The core results cover the electricity generation mixes as described in different scenarios for 2030 and 2050, and for the four case-study countries (Section 3.1). The key opportunities and challenges for the most prominent technologies, as presented in the analyzed scenarios, are then highlighted in a cross-country comparison (Section 3.2), and prominent electricity demand trends are discussed (Section 3.3).

3.1. Scenarios for electricity generation mixes

For all case study countries, the electricity generation mixes for the years 2030 and 2050 vary widely among the scenarios and are discussed on a country-by-country basis in the following paragraphs. The 2019 electricity mixes for each country, taken from the IEA "Data and Statistics" database [4], are included in the figures of this section to highlight the degrees of change between the present state and the future possibilities reflected in the different scenarios.[5]

To facilitate the discussion of the results, we sort the scenarios according to their share of low-carbon sources[6] in the electricity mix and assign them into one of three categories: "low", "moderate", and "ambitious". Since each country is positioned differently when it comes to low-carbon sources and has unique challenges to overcome, these indicators are not meant to judge the current state of a country's electricity system, nor their potential to become more sustainable in the future, but are introduced as a means to facilitate scenario comparisons. The categorization is explained in detail in Appendix C.

Projections for the electricity generation mix in Switzerland

Fig. 1 shows the range of scenarios for the Swiss electricity generation mix for 2030. Within the **low** category, most scenarios suggest that natural gas will replace most of the nuclear power that is being gradually phased out. There is also a slight increase of solar PV, although only in scenarios that include tighter CO_2 emission targets, such as *PanKan.CO2*, or prohibit the deployment of combined heat and power (CHP) plants, such as *KanTur.L60NoCentGas*. Hydropower is shown to maintain its role as the main provider of electricity, while waste will also remain in the generation mix, albeit as a minor electricity source. The **moderate** scenarios follow generally similar trends to the low ones, with natural gas replacing nuclear and solar PV growing only slightly in importance. One exception is the *Volkart.Climate* scenario, whose large amount of solar PV can be traced back to an imposed RE target, which also leads to a significant increase in bioenergy. The generation mix in the **ambitious** scenarios is characterized either by solar PV replacing nuclear to some extent, or by nuclear remaining in the generation mix (*Pattupara.LeastCost, Bartlett.Reference*). Some scenarios also highlight the role of bioenergy – still minor overall, but more important compared to other scenarios (see *Weiss.Renewable, Abrell.Reference*). Wind is deemed only marginally relevant by most scenarios except for *Limpens.50RE*. Finally, across the three categories, electricity imports also increase, peaking in the *DiazRedondo.Import* and *Abrell.Reference* scenarios, where nuclear power is fully phased out. Nearly all other scenarios assume Switzerland to be self-sufficient, resulting in zero net electricity imports.

The scenarios for Switzerland's electricity mix in 2050, presented in Fig. 2, show similar patterns as for 2030. All of the **low** scenarios see nuclear fully replaced with natural gas-based generation, and at levels that exceed the current nuclear supply in most scenarios. Additional changes include a slight rise in solar PV (*KanTur.LC60*) and an increase in geothermal — however, both technologies play only a minor role. The additional deployment of solar PV found in *KanTur.LC60* is primarily caused by the target to reduce CO_2 emissions by 60%. The **moderate** scenarios replace nuclear with similar shares of natural gas and solar PV, while a slight rise in wind is also present in some scenarios. In contrast to the previous scenario categories, most of the **ambitious** scenarios estimate solar PV to replace nuclear (e.g., *Weiss.Renewable, Maeder.LimitTrans*). Those scenarios that do not compensate for the nuclear phase-out with solar PV have it superseded by either natural gas + CCS (*Pattupara.CO2*) or electricity imports (*DiazRedondo.Import*). This is in contrast to the *Maeder.LimitTrans* scenario, in which Switzerland is a net exporter of electricity.

Projections for the electricity generation mix in Germany

Starting the discussion with the results for 2030, summarized in Fig. 3, most **low** scenarios suggest that coal and natural gas will remain core providers of electricity. The variations in coal-based generation can be attributed to the phase-out assumptions in each scenario, which in some cases (*Keles.Phaseout, Tash.CO2ORG*) even result in gas-based generation reaching higher levels. Nevertheless, a general increase in wind and solar PV generation can also be observed, though scenarios differ slightly in their predicted power generation through biomass (*Keles.Base*) and waste (*Tash.CO2ORG*), with both technologies, however, shown to play only a minor role. Turning to the **moderate** scenarios, the differences in the projected generation mixes are more profound. Some moderate scenarios envision natural gas as a potential replacement for coal and nuclear (e.g., *Muller.Reference, Tash.CO2TAM*); however, most project a reduction of natural gas compared to today's

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[5] It is important to note that the displayed numerical values throughout the results section have been taken from diagrams and tables in the studies rather than from the original model data. Thus, minor errors may have been introduced.

[6] These include renewable technologies, nuclear power, and fossil fuel power plants coupled with CCS technologies.

Table 3
List of model-based electricity system scenarios for Switzerland.

Author(s) and year	Original scenario name	New scenario name	Scenario type	Target year
Abrell et al. 2019 [36]	No-intervention case	Abrell.Reference	Business-as-usual	2030, 2050
	Renewable support case	Abrell.Renewable	Climate	2030, 2050
Bartlett et al. 2018 [37]	Intermediate	Bartlett.Intermediate	Climate	2030[a]
	Current	Bartlett.Reference	Business-as-usual	2030[a]
	Renewable	Bartlett.Renewable	Climate	2050[a]
Diaz Redondo and van Vliet 2015 [38]	Variant E	DiazRedondo.Import	Trade	2030[b], 2050
Kannan and Turton 2016 [39]	LC60	KanTur.LC60	Climate	2030, 2050
	LC60-NoCent	KanTur.LC60NoCentGas	Technology/Climate	2030, 2050
	BAU-NoCent	KanTur.NoCentGas	Technology	2030, 2050
	BAU	KanTur.Reference	Business-as-usual	2030, 2050
Kannan 2018 [40]	LowElcImpPrice	Kannan.ElcImpPrice	Cost	2050
	NoElcImp	Kannan.NoElcImp	Trade	2050
	NoFuelTax	Kannan.NoFuelTax	Cost	2050
	NoGas	Kannan.NoGas	Technology	2050
	NoRCSV	Kannan.NoRCSV	Efficiency	2050
	Ref	Kannan.Reference	Business-as-usual	2050
Limpens et al. 2019 [41]	50% RE target	Limpens.50RE	Climate	2030[b]
Maeder et al. 2021 [42]	Limited transmission expansion	Maeder.LimitTrans	Trade/Climate	2050
Panos and Kannan 2016 [43]	CO2	PanKan.CO2	Climate	2030, 2050
	CO2NoGas	PanKan.CO2NoCentGas	Technology/Climate	2030, 2050
	NoGas	PanKan.NoCentGas	Technoloy	2030, 2050
	Reference	PanKan.Reference	Business-as-usual	2030, 2050
Panos et al. 2019 [44]	Climate	Panos.Climate	Climate	2030, 2050
	Baseline	Panos.Reference	Business-as-usual	2030, 2050
Pattupara and Kannan 2016 [45]	CO2	Pattupara.CO2	Climate	2030, 2050
	Least cost	Pattupara.LeastCost	Business-as-usual	2030, 2050
	NoNUC	Pattupara.NoNUC	Technology	2030, 2050
Volkart et al. 2017 [46]	Clim+CCS	Volkart.CCS	Technology/Climate	2030[b]
	Clim	Volkart.Climate	Climate	2030[b]
	Ref	Volkart.Reference	Business-as-usual	2030[b]
Weiss et al. 2021 [47]	NUC +	Weiss.Nuclear	Technology	2030, 2050
	Reference	Weiss.Reference	Business-as-usual	2030, 2050
	RES+	Weiss.Renewable	Climate	2030, 2050

[a] Indicates that no specific year was given in the study. The results are assumed to reflect a particular outcome for 2030 and 2050 respectively (see Appendix B).

[b] Indicates that the scenario results were originally presented for the year 2035 but are assumed to account for 2030 here (see Appendix B).

Table 4
List of model-based electricity system scenarios for Germany.

Author(s) and year	Original scenario name	New scenario name	Scenario type	Target year
Bartholdsen et al. 2019 [48]	European Island	Bartholdsen.EUIsland	Technology	2030, 2050
	Green Democracy	Bartholdsen.GreenDem	Climate	2030, 2050
	Survival of the Fittest	Bartholdsen.Survival	Trade	2030, 2050
Hansen et al. 2019 [49]	100% RE & Elec. Transp.	Hansen.100REEV	Technology/Climate	2050
	100% RE & H2 transp.	Hansen.100REH2	Technology/Climate	2050
	5% excess & Elec. Transp.	Hansen.5excessEV	Technology/Climate	2050
	5% excess & H2 transp.	Hansen.5excessH2	Technology/Climate	2050
	Reference	Hansen.Reference	Business-as-usual	2050
Keles and Yilmaz 2020 [50]	Base	Keles.Base	Climate	2030, 2050
	Phaseout-DE	Keles.Phaseout	Technology/Climate	2030, 2050
Knaut et al. 2016 [51]	Fuel Cost Low	Knaut.LowFuelCost	Cost	2030, 2050
	Low RES-E cost	Knaut.LowRESCost	Cost	2030, 2050
	Reference	Knaut.Reference	Business-as-usual	2030, 2050
Ludig et al. 2015 [52]	All Opt High	Ludig.AllOptLHigh	Climate	2050
	All Opt Low	Ludig.AllOptLow	Climate	2050
	All Opt Med	Ludig.AllOptMed	Climate	2030, 2050
Maeder et al. 2021 [42]	Limited transmission expansion	Maeder.LimitTrans	Trade/Climate	2050
Müller et al. 2019 [53]	Baseline Scenario	Muller.Reference	Business-as-usual	2030[b], 2050
Palzer and Henning 2014 [54]	Medium	Palzer.Medium	Climate	2050[a]
	REMax	Palzer.REMax	Climate	2050[a]
	RetrofitMax	Palzer.RetrofitMax	Climate	2050[a]
Rogge et al. 2020 [55]	Pathway A	Rogge.PathA	Technology/Efficiency	2030, 2050
	Pathway B	Rogge.PathB	Technology/Efficiency	2030, 2050
Sterchele et al. 2020 [56]	Referenz	Sterchele.Reference	Business-as-usual	2030, 2050
Tash et al. 2019 [57]	CO2_ORG	Tash.CO2ORG	Climate	2030, 2050
	CO2_TAM	Tash.CO2TAM	Climate	2030, 2050
	BAU	Tash.Reference	Business-as-usual	2030, 2050
	RES_ORG	Tash.RESORG	Climate	2030, 2050
	RES_TAM	Tash.RESTAM	Climate	2030

[a] Indicates that no specific year was given in the study. The results are assumed to reflect a particular outcome for 2030 and 2050 respectively (see Appendix B).

[b] Indicates that the scenario results were originally presented for the year 2035 but are assumed to account for 2030 here (see Appendix B).

Table 5
List of model-based electricity system scenarios for France.

Author(s) and year	Original scenario name	New scenario name	Scenario type	Target year
Alimou et al. 2020 [58]	–	Alimou.60RE	Climate	2030
Krakowski et al. 2016 [59]	100RES 2050	Krakowski.100RE	Climate	2030, 2050
	100RES 2050_v5	Krakowski.100REBiomass	Technology/Climate	2030, 2050
	100RES 2050_v3	Krakowski.100REnoImport	Trade	2030, 2050
	60RES 2050	Krakowski.60RE	Climate	2030, 2050
	80RES 2050	Krakowski.80RE	Climate	2030, 2050
	BAU	Krakowski.Reference	Business-as-usual	2030, 2050
Maeder et al. 2021 [42]	Limited transmission expansion	Maeder.LimitTrans	Trade/Climate	2050
Maïzi and Assoumou 2014 [60]	FASTt1	Maizi.Fast	Technology	2030, 2050
	FASTv1	Maizi.FastCO2	Technology/Climate	2030, 2050
	PROGt1	Maizi.Progress	Technology	2030, 2050
	PROGv1	Maizi.ProgressCO2	Technology/Climate	2030, 2050
	BAU	Maizi.Reference	Business-as-usual	2030, 2050
Millot et al. 2020 [61]	FranceNeutrality	Millot.Neutrality	Climate	2030, 2050
Seck et al. 2020 [62]	100 EnR 2050	Seck.100RE	Climate	2030
	40 EnR 2050	Seck.40RE	Climate	2030, 2050
	60 EnR 2050	Seck.60RE	Climate	2030, 2050
	80 EnR 2050	Seck.80RE	Climate	2030, 2050
	100 EnR 2050	Seck.100RE	Climate	2050
	BAU	Seck.Reference	Business-as-usual	2030, 2050
Shirizadeh and Quirion 2020 [63]	0 € /tCO2 SCC	Shirizadeh.0SCC	Cost/Climate	2050
	200 €/tCO2 SCC	Shirizadeh.200SCC	Cost/Climate	2050
	50 €/tCO2 SCC	Shirizadeh.50SCC	Cost/Climate	2050
	50 €/tCO2 SCC, DIV	Shirizadeh.50SCChigh	Cost/Climate	2050
	50 €/tCO2 SCC, SOB	Shirizadeh.50SCClow	Cost/Climate	2050
	100 €/tCO2 SCC	Shirizadeh.100SCC	Cost/Climate	2050
Tlili et al. 2019 [64]	33 GW export case	Tlili.highExport	Trade/Climate	2030[a]

[a] Indicates that the scenario results were originally presented for the year 2035 but are assumed to account for 2030 here (see Appendix B).

Table 6
List of model-based electricity system scenarios for Italy.

Author(s) and year	Original scenario name	New scenario name	Scenario type	Target year
Alloisio et al. 2015 [65]	CCS + Renewables	Alloisio.CCS	Technology	2030, 2050
	Demand Reduction scenario	Alloisio.DemandRed	Climate	2030, 2050
	Energy Efficiency	Alloisio.Efficiency	Climate/Efficiency	2030, 2050
	Reference	Alloisio.Reference	Business-as-usual	2030, 2050
Lanati et al. 2019 [66]	NECP	Lanati.NECP	Climate	2030
	BASE	Lanati.Reference30	Business-as-usual	2030
Lanati and Gaeta 2020 [67]	DEC	Lanati.Decarb	Climate	2050
	REF	Lanati.Reference50	Climate	2050
Maeder et al. 2021[42]	Limited transmission expansion	Maeder.LimitTrans	Trade/Climate	2050
Prina et al. 2018 [68]	Scenario P1, best case	Prina.ScenP1	Business-as-usual	2050
	Scenario P2, best case	Prina.ScenP2	Climate	2050
	Scenario P3, best case	Prina.ScenP3	Climate	2050
	Scenario P4, best case	Prina.ScenP4	Climate	2050
Prina et al. 2019 [69]	Pareto point 1	Prina.ParetoP1	Business-as-usual	2030, 2050
	Pareto point 3	Prina.ParetoP3	Climate	2030, 2050
	Pareto point 5	Prina.ParetoP5	Climate	2030, 2050
Prina et al. 2020 [70]	Advanced	Prina.Advanced	Efficiency	2030
	PNIEC	Prina.PNIEC	Climate	2030
Vellini et al. 2020 [71]	2030 EUCO27	Vellini.EUCO27	Climate	2030
	2030 EUCO40	Vellini.EUCO40	Climate	2030
	2030 NES	Vellini.NES	Climate	2030
	2030-REF	Vellini.Reference	Climate	2030

levels. All moderate scenarios agree, though, that wind power will become more important (e.g., *Muller.Reference, Ludig.AllOptMed*), while the increase in solar PV will be limited (see *Rogge.PathB*). Regarding the generation mixes in the **ambitious** scenarios, solar PV and wind are shown to further increase in importance, covering most of the generation gap due to the phase-out of nuclear and coal power, while the role of natural gas remains small (*Tash.RESORG, Bartholdsen.GreenDem*). Furthermore, compared to the low scenarios, electricity production through bioenergy is shown to be minor (*Bartholdsen.Survival*). Finally, regarding the role of electricity import and export, the scenarios by Knaut et al. [51] show Germany to be a net exporter of electricity, while the scenarios of Keles et al. [72] and Rogge et al. [55] highlight the need for electricity imports. Nevertheless, few scenarios offer any insights into Germany's role in the electricity trade.

For 2050, shown in Fig. 4, the **low** scenarios mostly show an electricity generation mix similar to today, with a shift from coal to wind power as the most major change. Only *Hansen.Reference* diverges from this estimation, showing natural gas and coal to be the core providers of electricity in 2050. In the **moderate** scenarios, wind largely replaces coal and natural gas, becoming the main source of electricity generation. The scenarios further agree that solar PV and, to a lesser extent, bioenergy will cover substantial parts of the electricity demand. Interestingly, a massive increase in wind (e.g., *Stechele.Reference, Bartholdsen.GreenDem, Hansen.100REEV*) compared to the low and moderate scenarios can be observed in the **ambitious** scenarios. This

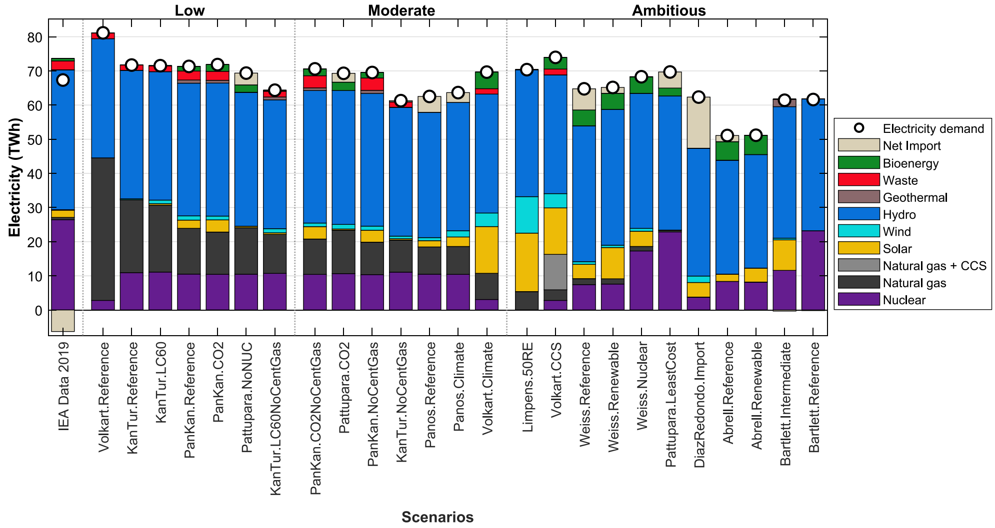

Fig. 1. Model-based scenario results regarding the electricity generation mix for Switzerland in 2030.

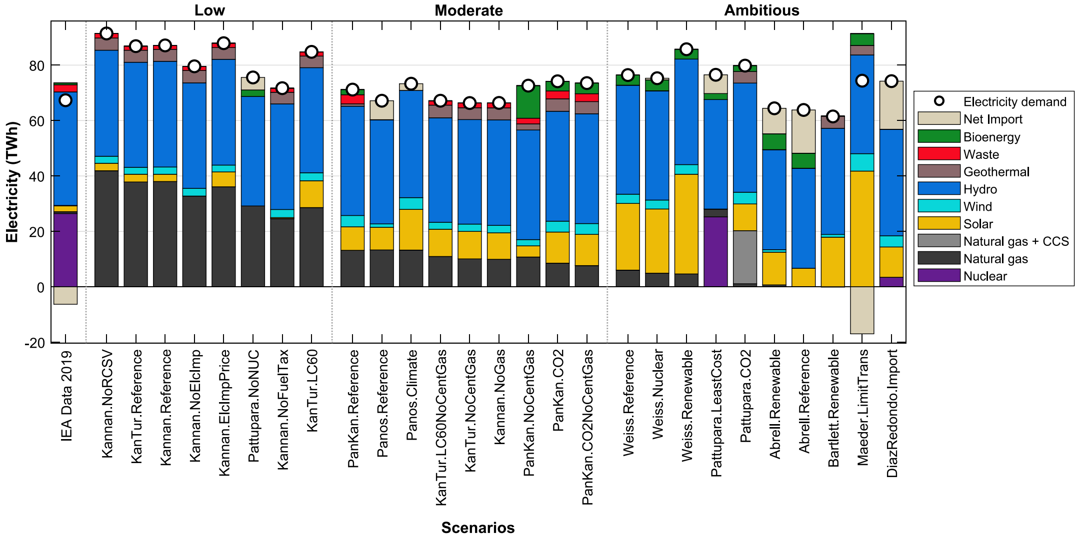

Fig. 2. Model-based scenario results regarding the electricity generation mix for Switzerland in 2050.

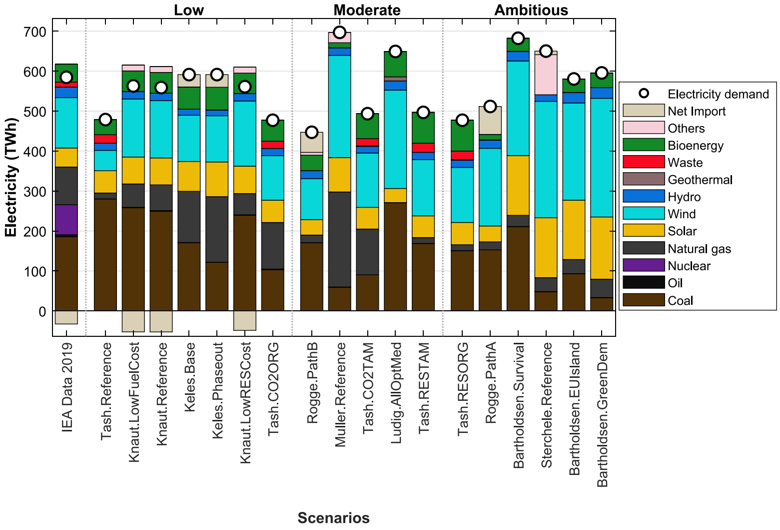

Fig. 3. Model-based scenario results regarding the electricity generation mix for Germany in 2030.

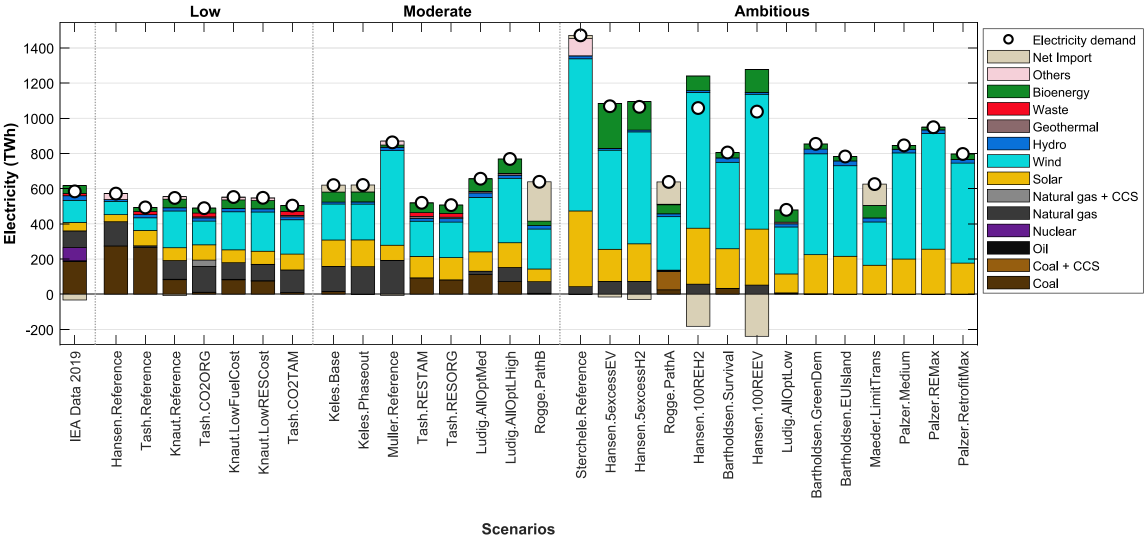

Fig. 4. Model-based scenario results regarding the electricity generation mix for Germany in 2050.

is mostly the result of the imposed CO_2 reduction (*Stechele.Reference*) or RE (*Hansen.100REEV*) targets. Together with wind, solar PV is seen as the main provider of electricity, while bioenergy is seen to increase in importance too (*Hansen.100REEV, Ludig.AllOptLow*), and in the *Hansen.5excessEV* scenario even surpass solar PV. Finally, similar to the findings for 2030, most scenarios offer no insight into the role of electricity trade. Those that do come to diverging conclusions, showing Germany to be a net electricity exporter in some scenarios (*Hansen.100REH2, Hansen.100REEV*) and a net importer in others (*Rogge.PathA, Rogge.PathB* and *Maeder.LimitTrans*).

Projections for the electricity generation mix in France

The main observation regarding France's electricity mix scenarios for 2030, which are shown in Fig. 5, is the reduced prominence of nuclear power, which is substituted in various ways across the scenarios. In the **low** scenarios, coal appears as a prominent replacement, followed by wind. Only *Maizi.FastCO2* replaces parts of the nuclear generation with natural gas, because of a limit on CO_2 emissions imposed in the model. In the **moderate** scenarios, wind is the preferred alternative to nuclear. Small additions of coal can also be observed, but they remain below wind levels. Solar PV and bioenergy see no notable changes compared to today, contributing only little to the annual electricity generation. The trend of wind as a new key technology in the French electricity system is further amplified in the **ambitious** scenarios, with only *Seck.Reference* deviating from it due to coal + CCS replacing the small share of nuclear that is phased out. Just two scenarios show solar PV increasing substantially (*Tlili.highExport, Millot.Neutrality*), while most estimate a growth in bioenergy. Finally, most scenarios agree that France will remain a net export country.

Turning to the 2050 results shown in Fig. 6, in the **low** scenarios, nuclear power loses its role as the core technology in the French electricity system, with coal (*Maizi.Fast, Krakowski.100RE*) and natural gas (*Maizi.FastCO2*) being the two most prominent options to replace it. Moreover, all scenarios include an increase in wind, which is more profound in scenarios that do not replace nuclear power with fossil fuels. In the **moderate** scenarios, wind and solar PV replace much of the nuclear generation and become an integral part of the electricity mix. Some scenarios additionally introduce a small amount of natural gas (with CCS) and coal to the electricity system (see *Maizi.ProgressCO2, Shirizadeh.50SCChigh*), while bioenergy-based electricity generation is also present in some scenarios. The trend of increased wind and solar PV continues in the **ambitious** scenarios, with wind becoming the lead source of electricity in all but two (*Seck.40RE, Seck.Reference*). In these two scenarios, no constraints to phase out nuclear power are imposed and only a low target of 40% RE is set in *Seck.40RE*, disincentivizing the deployment of renewables. After wind, solar PV is the second-placed key generation technology, while bioenergy becomes more relevant in *Krakowski.100REBiomass* due to the increased bioenergy potential in the scenario assumptions. Finally, across the three scenario categories, the role of cross-border electricity trade varies, with France being a major electricity exporter in *Krakowski.Reference, Maeder.LimitTrans,* and *Seck.Reference*, and a significant net importer in *Krakowski.100RE* and *Seck.100RE*.

Projections for the electricity generation mix in Italy

Starting from the results for the year 2030 shown in Fig. 7, in the **low** scenarios, only small changes in the generation mix can be observed compared to 2019. The slight decrease in natural gas in some scenarios is mostly compensated by an increasing deployment of solar PV and wind. Furthermore, coal-fired generation (with and without CCS) also increases in all scenarios, while bioenergy also grows slightly in most of them too, reaching similar levels to wind power. The **moderate** scenarios indicate an even more profound drop in natural gas compared to 2019, which is mostly compensated for by solar PV and wind, with both technologies becoming key players in the generation mix. Similar to the low scenarios, bioenergy also grows in importance, even surpassing wind in *Alloisio.Efficiency*. In contrast to the other two categories, the **ambitious** scenarios feature a complete phase-out of coal power, which can be attributed to the tight emission targets set in *Prina.ParetoP3, Prina.Advanced,* and *Prina.ParetoP5*. All scenarios also project solar PV as a key source of electricity, replacing large portions of natural gas, with wind being in second place in two scenarios. Finally, electricity import plays a small but relevant role across all three categories, with around a quarter of the scenarios highlighting a gap between electricity demand and supply.

The trends analyzed for Italy in 2030 become even more prominent in 2050, as summarized in Fig. 8. The **low** scenarios indicate a sharp increase in wind (*Alloisio.Reference*), solar PV (*Prina.ScenP1*), or both (*Prina.Pareto.P1*). In the latter two scenarios, the growth in RE compensates for the slight drop in natural gas. In the **moderate** scenarios, the reduction in natural gas is more profound, with all of them indicating solar PV as the main generation technology and wind as another key player. Compared to the low and moderate scenarios, major changes in the generation mix can be observed in the **ambitious** scenarios. Natural gas and coal are nearly fully phased out in all scenarios, and solar PV provides most of the electricity required, with wind reaching similar levels as solar PV in some scenarios (e.g., *Alloisio.DemandRed,*

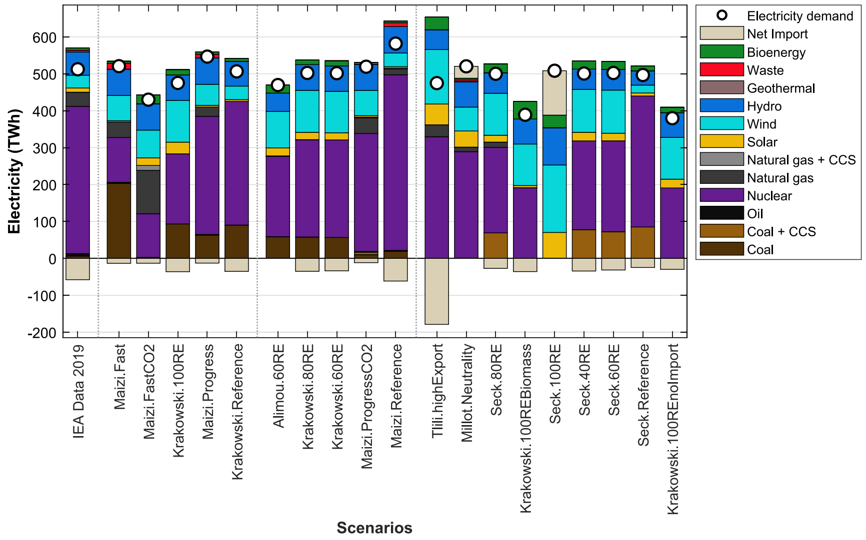

Fig. 5. Model-based scenario results regarding the electricity generation mix for France in 2030.

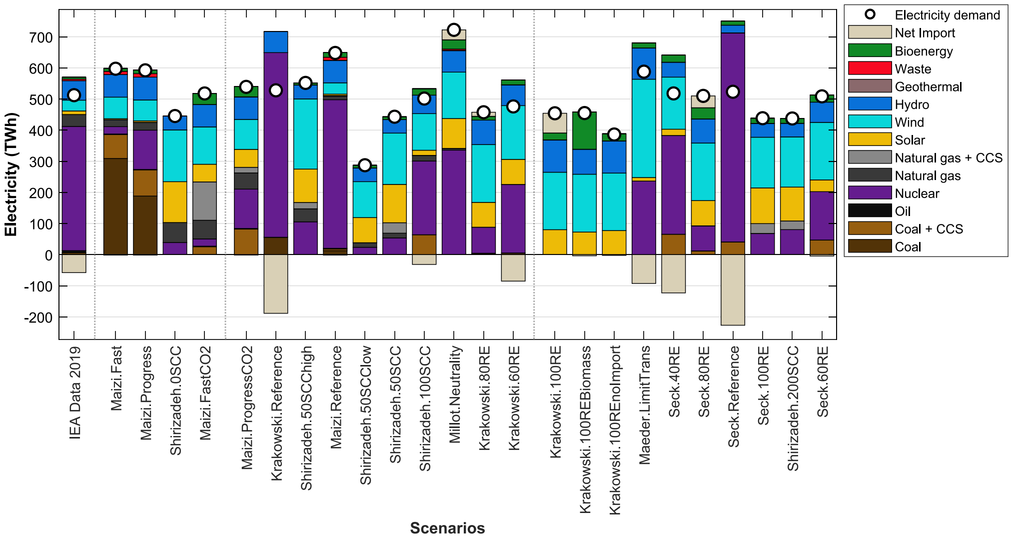

Fig. 6. Model-based scenario results regarding the electricity generation mix for France in 2050.

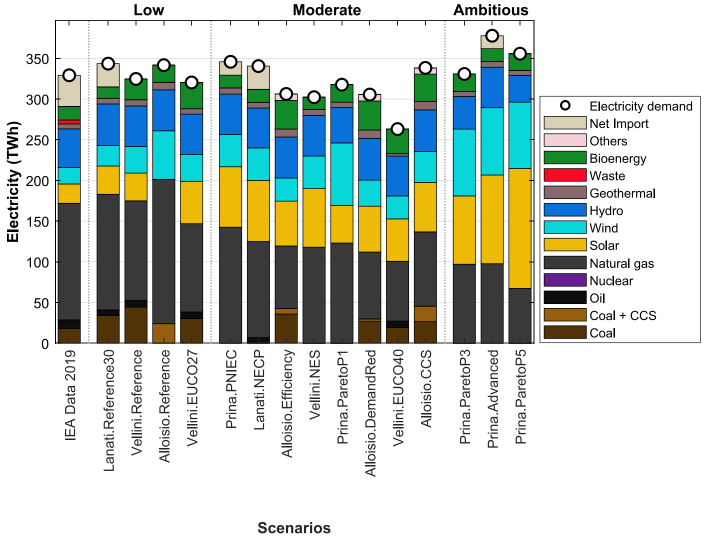

Fig. 7. Model-based scenario results regarding the electricity generation mix for Italy in 2030.

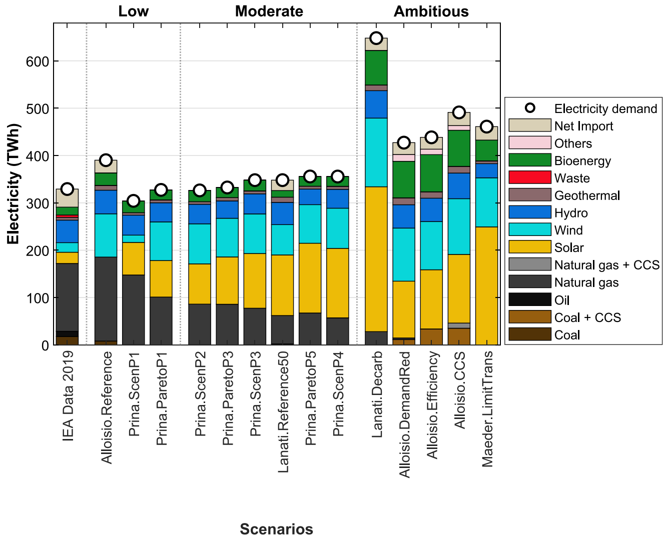

Fig. 8. Model-based scenario results regarding the electricity generation mix for Italy in 2050.

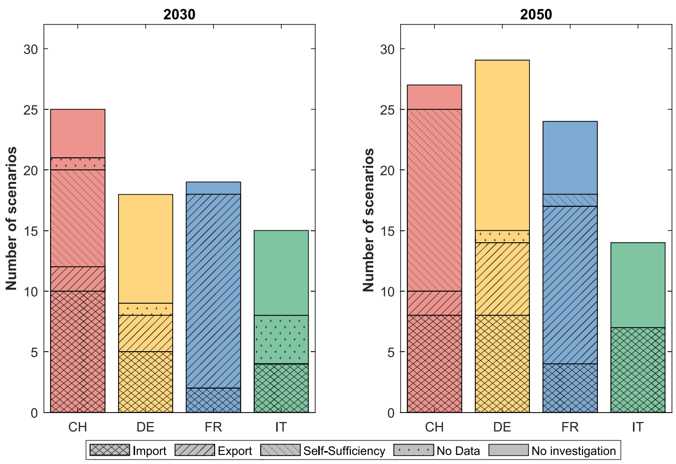

Fig. 9. Number of scenarios indicating a country to be a net importer, net exporter, or self-sufficient. The "No Data" category comprises scenarios that consider cross-border electricity trade, but do not report results. The "No investigation" category comprises scenarios that did not consider electricity trade at all.

Alloisio.Efficiency). Furthermore, bioenergy grows significantly, becoming an important element in the generation mix. Finally, Italy retains its role as a net importer of electricity in most of the scenarios.

Summary of key findings from the country electricity generation mix analysis

The detailed discussion of different electricity mix scenarios in 2030 and 2050 for Switzerland, Germany, France, and Italy shows that each country can follow a multitude of different pathways, depending on the goals they strive to achieve. From a long-term perspective, natural gas or solar PV in addition to the already-present hydropower are prominent technologies for transforming the Swiss electricity system. In Germany, current phase-out policies and climate targets can be addressed by an uptake of natural gas, wind and solar PV. Wind and solar PV are also seen as suitable electricity providers in France, although their deployment is closely related to the presence of nuclear in the electricity system. Finally, in Italy, solar PV and wind are seen as promising additions to the currently natural gas driven electricity production.

The review further highlights the importance of cross-border trade, as Fig. 9 also illustrates. Interestingly, some studies, especially those on Switzerland, assume the countries to be self-sufficient, meaning that net zero import or export is forced in the models. This does not prohibit electricity exchange, but rather forces the annual balance to be zero. Another observation is that Germany, a leading exporter of electricity [73], is projected to rely on electricity imports in some scenarios. Such a development would have severe implications for grid operators and policymakers alike, as it could shift the overall import/export electricity balance of other countries in the region. All responsible stakeholders, but also the neighboring countries, will have to monitor Germany's changing role closely in order to quickly respond to these shifts.

3.2. Opportunities and challenges for different technologies

In this section, we focus on three key electricity generation technologies, namely *natural gas, solar PV,* and *wind*, and visualize their shares in each country's generation mix to identify overarching trends regarding their role in the studied countries. Additionally, we briefly discuss the role that storage technologies play in the various scenarios, as storing electricity becomes increasingly relevant in systems with high shares of fluctuating renewables. The role of bioenergy is not discussed further, since the majority of the scenarios across all countries project bioenergy to play a minor role in the electricity generation mix. Interested readers are referred to Lee et al. [74] and Bhatia et al. [75].

Natural gas is highly policy-dependent

Natural gas is sometimes proclaimed as a reliable "bridge" fuel for the transition from coal- and oil-based electricity generation towards a greener and more sustainable electricity supply [76]. This is especially relevant for Switzerland and Germany, which both plan to phase out their core generation technologies, nuclear and coal power respectively, leaving a significant gap in their current generation mixes. In Fig. 10, we summarize the scenario results on electricity generation from natural gas in absolute numbers (solid bars) and in terms of the countries' electricity production shares (crosshatched bars) and for both 2030 and 2050.

The distribution of scenario results supports several observations. Firstly, across all scenarios, and for both 2030 and 2050, natural gas-based electricity generation is shown to play only a limited role in France, with only a few outlying scenarios suggesting natural gas shares higher than 10% in 2050. Secondly, for 2030, wide variations are shown for the shares of natural gas for Switzerland and Germany, which range from 0% to approximately 30% (median: 10 TWh for Switzerland; 40 TWh for Germany). On the other hand, the role of natural gas in the Italian electricity mix for 2030 contrasts with that of its neighbors, with an estimated share ranging between 20% and 50% (median: 110 TWh), influenced by the path-dependence of natural gas' large share in today's electricity mix (approx. 50%). This discrepancy indicates that future natural gas developments depend largely on the starting conditions for each individual country. Thirdly, the aforementioned variance of scenario results is becoming even more profound for 2050, now covering 0%–50% for both Switzerland (median: 15 TWh) and Italy (median: 60 TWh). The shares in Germany are projected to stay stable, although the median increases slightly between 2030 and 2050. An additional observation can be made from comparing Switzerland and Italy in particular, as the trends for natural gas appear to be polar opposites. Switzerland is projected to see a rise in natural gas, while Italy is more likely to see a drop.

When comparing the absolute values for electricity generation from natural gas, it further becomes clear that the overall role of natural gas at the European level is strongly connected to developments in Germany and Italy, as both countries have high electricity demand and, therefore, supply more electricity from natural gas in absolute terms. The scenarios, thus, indicate that electricity production by natural gas declines between 2030 and 2050, potentially leaving a supply gap that would need to be covered by other technologies.

Overall, based on the diverging outlooks for the four countries, we conclude that the role of natural gas is highly dependent on future

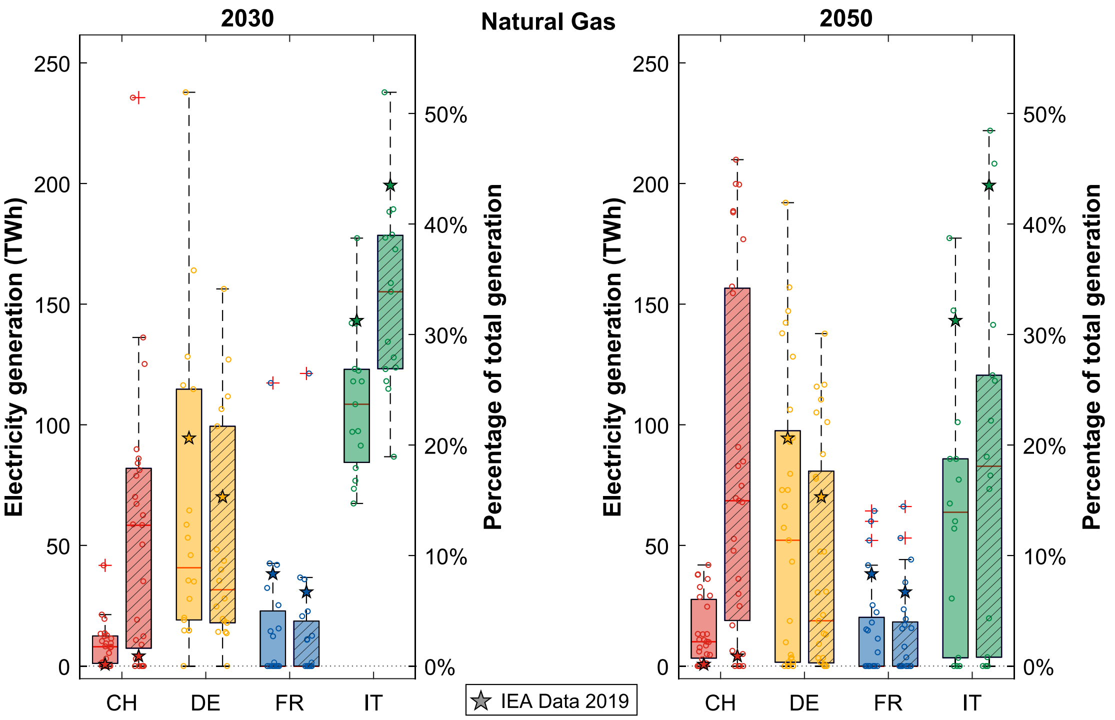

Fig. 10. Distribution of electricity supply through natural gas for each country in absolute (solid bars) and relative (crosshatched bars) terms. The box plots show the median and 25th and 75th percentiles. The stars indicate the 2019 level [4].

policy decisions in each country, as the decision to phase out technologies can drive an increase in natural gas (e.g., *KanTur.Reference* for Switzerland), while imposing CO_2 targets (e.g., *Limpens.50RE* for Switzerland) could significantly reduce the attractiveness of natural gas-based electricity and, hence, its deployment. Thus, it will be important to evaluate the short-term benefits of introducing natural gas as a bridge fuel against potential future natural gas phase-out plans to achieve net-zero carbon emissions for the electricity system.

Renewables will play a key role in all countries

Over the last few years, the deployment of solar PV and wind in Europe has increased rapidly, leading to more than 135 TWh and 403 TWh of electricity generation respectively in 2019 [4]. These upward trends for both RE sources are reflected in the majority of the scenarios. Figs. 11 and 12 summarize the electricity generation from solar PV and wind respectively in absolute (solid bars) and relative (crosshatched bars) terms across all scenarios. The key findings are summarized in the following.

Compared to the 2019 levels, most 2030 scenarios indicate an increase for both solar PV and wind and in terms of both shares and total generation. However, the range of scenario results is noteworthy, with PV shares, for example, for Switzerland ranging from 0 to 25% (median: 2.8 TWh) and for Italy spanning 10 to 41% (median: 58.5 TWh). The scenarios indicate a similarly profound development trend of solar PV for Germany, whereas the changes in France remain more conservative. Wind is predominantly projected as a core electricity provider in Germany, with a share of 23%–39% (median: 150 TWh). In Italy and France, wind is less dominant, but most scenarios still highlight a rise to 12%–22% for France (median: 100 TWh) and 10%–21% for Italy (median: 50 TWh).

The 2030 trends continue in 2050 for both RE sources. Solar PV is seen as a key player in all countries, with particularly widespread uptake in France (3%–20%, median: 75 TWh). Furthermore, a significant variance of the absolute solar PV electricity supply can be observed in Germany, ranging between 80–210 TWh. The central role of wind in 2050 is especially visible in France (20%–40%, median: 190 TWh) and Germany (40%–60%, median: 300 TWh), whereas the deployment of wind in most Italian scenarios converges on a share of approximately 22% (median: 90 TWh), suggesting an upper limit for wind in that country.

Overall, most scenarios highlight both RE sources as integral parts of electricity system transformations, although the ratio between them depends on the country's geographical potential, which in turn affects their economic performance (more detailed discussions on the economics of wind and solar PV can be found in Millborrow [77] and Liu [78]). Taking into account the findings for the individual countries in Section 3.1, the deployment of solar PV and wind will heavily depend on policy changes regarding phase-out of technologies and CO_2 / RE targets, as those encourage a quicker uptake of the technologies, which can in turn lead to the technologies being cost-effective sooner due to learning effects. For instance, the projected rapid deployment of wind in Germany, which is supported by the phase-out of both coal and nuclear, might accelerate its cost-effectiveness significantly and improve its feasibility for the neighboring countries through spillover effects.

The need for short- and long-term storage and the roles of different technologies remain unclear

The role of storage systems in the decarbonization of electricity systems is a widely discussed topic, and multiple studies [21,23,79–83] have analyzed the potential of different electricity storage technologies, such as pumped hydro storage (PHS), battery electric storage systems (BESS), and power-to-gas (PtG), to support a stable integration of RE into the electricity system. Nevertheless, further insights can also be drawn from the studies reviewed here. Of all the scenarios analyzed, only half provide information on storage as part of their examined electricity systems, and most agree that storage becomes more relevant the higher the RE share. For instance, *Seck.Reference* projects 5% RE for 2050 and no storage, while *Seck.100RE*, with 100% RE, estimates 1.6 GW of required storage capacity for France. A similar trend is found for Italy in the study by Lanati and Gaeta [67], where the scenario *Lanati.Reference50* projects 81% RE and 11 GWh of energy storage capacity, while *Lanati.Decarb* estimates 95% RE and 28 GWh.

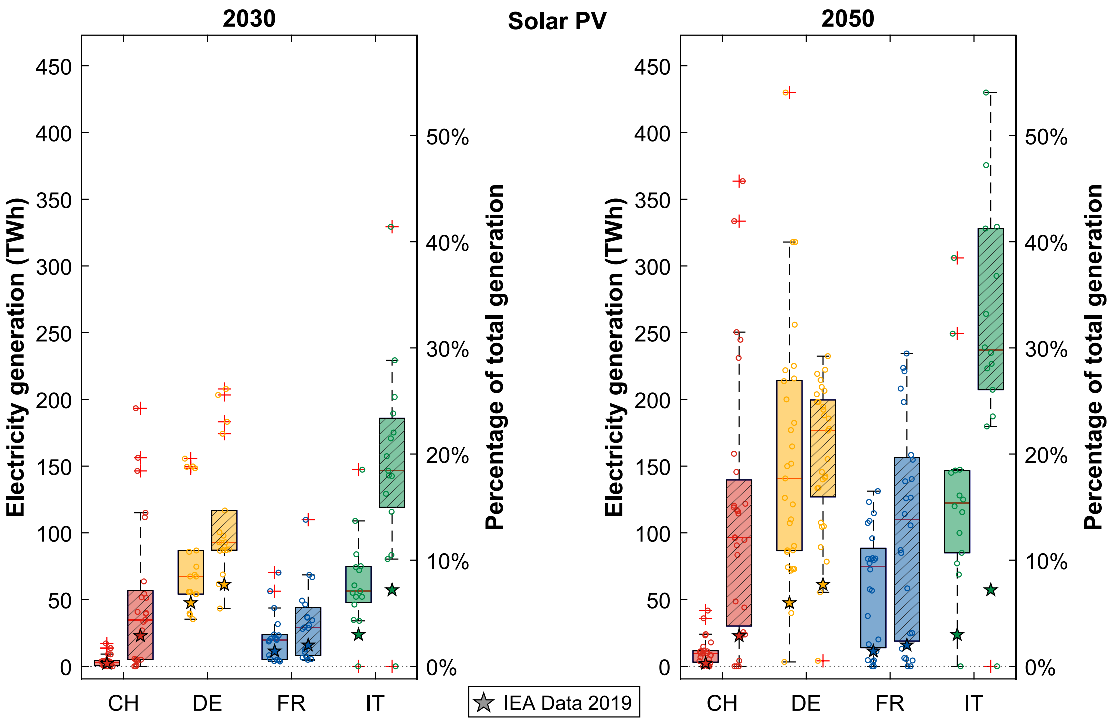

Fig. 11. Distribution of electricity supply through solar PV for each country in absolute (solid bars) and relative (crosshatched bars) terms. The box plots show the median and 25th and 75th percentiles. The stars indicate the 2019 level [4].

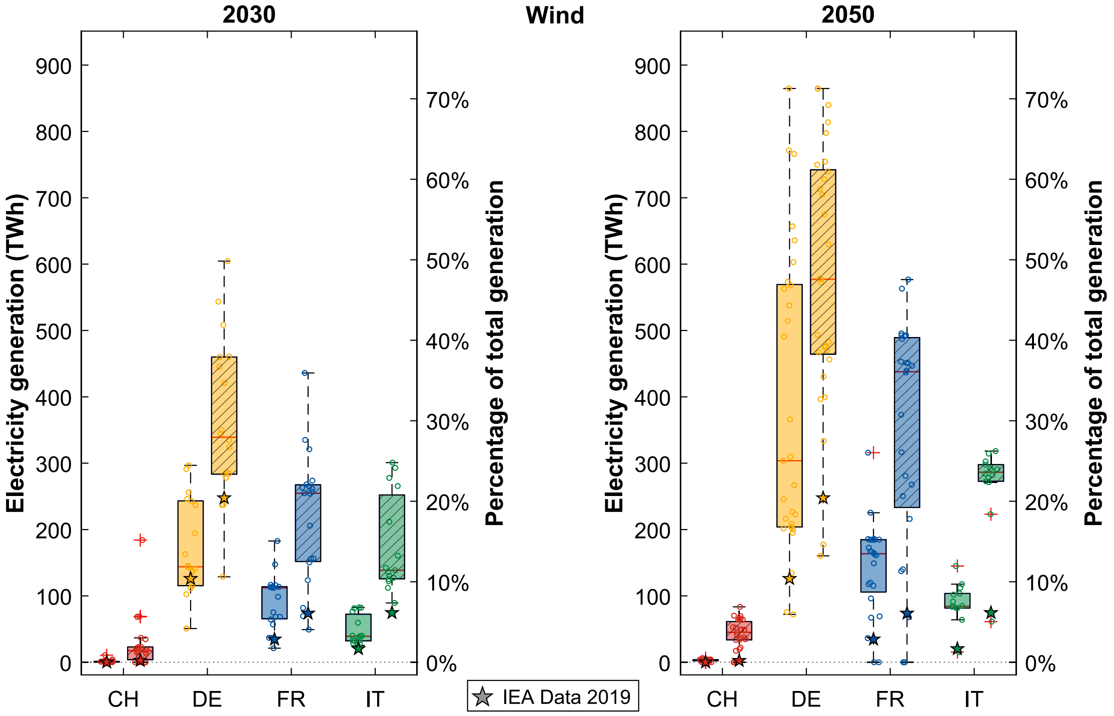

Fig. 12. Distribution of electricity supply through wind for each country in absolute (solid bars) and relative (crosshatched bars) terms. The box plots show the median and 25th and 75th percentiles. The stars indicate the 2019 level [4].

Nonetheless, three issues hamper a conclusive presentation of future storage demands. First, it remains unclear which technologies are most suitable for electricity system applications. When separating the presented information on storage by technology, around 50% of all scenarios report information on PHS, less than 25% on BESS, and only 6% on PtG. Alternative technologies, such as flywheels and compressed air energy storage (CAES), are discussed in one study at most, making it impossible to draw any conclusions. For PtG, this limited information precludes any assessment from being made. For PHS, the majority of scenarios report that, while existing capacities are being fully utilized, no further expansions are likely as the countries' potentials are mostly exhausted. In some scenarios, this leads to an uptake of either PtG or BESS.

Focusing specifically on BESS, a second issue arises, as the scenarios present diverging estimations for the technology, showing that the need for storage depends on more than just the share of RE. For instance, *Maeder.LimitTrans, Bartholdsen.Survival,* and *Palzer.REMax* all reach over 91% RE; however, *Maeder.LimitTrans* and *Bartholdsen.Survival* project BESS storage to provide roughly 20 TWh of electricity annually in 2050 for Germany, while *Palzer.REMax* estimates 10 TWh of annual electricity supply.

Third, comparing storage-related results to each other is further hampered by the fact that some scenarios report storage capacities in GW, while others report the yearly accumulated energy supply in TWh or the storage size in GWh, making direct comparisons difficult.

Overall, our findings on the role of storage lead to no definitive conclusion, which is in line with the findings of Cebulla et al. [21]. One reason for the lack of clarity in this field, which has been pointed out by storage-focused studies [84], is that current legislation might limit the use of storage to the point where it becomes less cost-effective than other options, even if it might be more valuable in the long run. Another reason is grounded in modeling and, more specifically, in mathematical optimization, which was the main method used for the majority of the model-based scenarios. To reduce the computational complexity of optimization models – especially when the long-term, multi-year evolution of electricity systems is investigated – modelers typically resort to using a small number of typical days/periods to represent a full year in the model horizon, often also at a less-than-hourly resolution for each day/period. This practice, however, makes it difficult to represent the full range of operating conditions for the system. Thus, more extreme periods, such as consecutive days with low wind speeds and high electricity demands, during which storage could play a key role, are not included in the model. This, in turn, leads to a potential underestimation of the storage needs in electricity systems.

Nevertheless, the role of storage increases with the RE share, making storage a critical part of ambitious scenarios that aim to reach high climate targets, and one that should be investigated further. Since the EU has just published a new directive on energy storage [85], we encourage policymakers and modelers to engage in a thorough reassessment of storage requirements.

3.3. Electricity demand trends

Projections of future electricity demands[7] are a key input for energy/electricity system models, with a significant influence on model-based electricity system designs and generation mixes. As a result, they are also a key characteristic of electricity system scenarios making it important to examine how demands vary in them and to understand the key drivers behind these differences. Interestingly, information on electricity demand is given explicitly in only a few studies and scenarios. Thus, in order to qualitatively compare the demand developments of the different scenarios of each country, electricity demand was calculated based on the approach used by Xexakis et al. [24], as the sum of total electricity generation and the difference between total electricity imports and exports. In Fig. 13, we summarize the electricity demand information from all scenarios expressed in terms of the percentage deviations from the reference demands of each country in 2019 [4].

For 2030, most scenarios show electricity demands decreasing by up to 30% for Switzerland, Germany, and France. However, this general trend is not observed in the scenarios investigating Italy, which mostly project an increase in electricity demand. For 2050, the disparities between the scenarios for Germany and Italy are even more profound, with a number of scenarios presenting an electricity demand 50% to nearly 150% higher than in 2019. Many scenarios for France continue their projected trend of reduced electricity demand, while most Swiss scenarios see a moderate increase in demand.

Multiple factors can drive these differences, such as the policies that are considered or the fact that electricity demand fluctuated in the past. Having differences in the projected electricity demand due to varying starting points and varying policies is, therefore, understandable. Two other closely correlating factors that impact the future electricity demand are the increasing electrification of other sectors and the increased energy efficiency in the whole energy system.

The majority of scenarios with higher electricity demand assumptions for 2030 and 2050 argue that this increase is driven by the electrification of other sectors. For instance, Hansen et al. [49] analyze the decarbonization of heat, transport, and industry for Germany by electrifying these sectors to a large extent, which leads to a 150% increase in electricity demand compared to 2019. Another example is Lanati and Gaeta [67], who consider more than half of the heat and transport sector to be electrified, leading to a doubling in electricity demand for Italy. These highly electrified scenarios give policymakers valuable insights on what a full decarbonization of the entire energy system might entail.

In contrast, those scenarios with an increase in energy efficiency often show reduced electricity demands. One prominent element here is the introduction of high energy savings in the heating sector through measures such as building retrofitting, which is investigated, for example, in *Alloisio.Efficiency* or *Limpens.50RE*. The improvement of energy efficiency might, thus, mitigate the effects of sector electrification by reducing electricity demands overall. Sterchele et al. [56] investigate a combination of energy efficiency increase and electrification trends (e.g., at least 80% electrification of heat and transport) in their reference scenario for Germany. They conclude that while energy efficiency improvements reduce the total primary energy demand in Germany, electricity demand rises to 1447 TWh compared to 559 TWh in 2019 [4].

A more thorough analysis of demand trends and their origins is complicated by the limited transparency in reporting demand assumptions in the studies. In some cases, studies rely on data sets that allow only limited or paid access, which reduces the traceability of the data used and makes a comparison of the results more challenging.

Although overarching demand trends cannot, therefore, be derived from the scenarios, due to the limited information given, trends within the modeling communities are nevertheless visible. Nearly all Swiss scenarios for 2050 include energy efficiency measures, with a focus on reduced energy demand for heating. Furthermore, nearly half of the Swiss scenarios also consider the electrification of heat and transport. Around half of the 2050 scenarios for Germany directly assume a moderate or high electrification of heating and transport, and one-quarter discuss efficiency improvements to some degree. Nearly all French scenarios for 2050 investigate only the developments of the electricity system and focus on the phase-out of nuclear power or the integration of carbon taxes, without investigating additional demand trends. For Italy, nearly half of the 2050 scenarios consider the electrification of transport, while one-quarter consider an energy efficiency increase in their studies.

In summary, most scenarios include at least one demand trend, but many fail to consider how fulfilling the targets set forth by the Paris Agreement [3] could impact the electricity system explicitly. Moreover, as Fig. 13 shows, the different assumptions used in the scenarios lead to diverging demand projections in all countries. Therefore, when policymakers view the scenario results, they must also consider each scenario's electricity demand levels and demand-related assumptions.

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[7] Some studies and their models require electricity demands to be exogenously defined, while others determine them endogenously by modeling multiple energy system sectors – such as buildings, industry, and transport – and leaving it up to the model to decide whether these demands should be satisfied with electricity, and hence contribute to the total electricity demand, or with alternative sources.

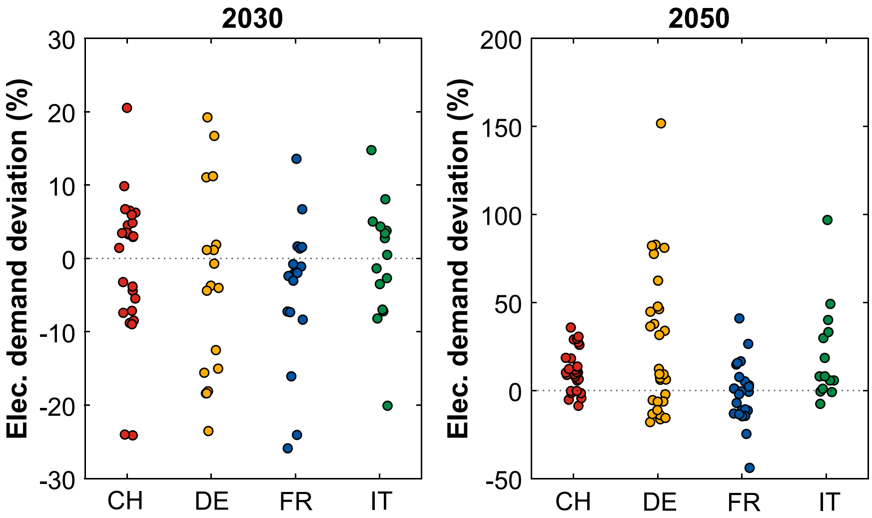

Fig. 13. Relative deviation of the electricity demand of each scenario compared to the baseline of 2019 [4].

4. Discussion of implications for policymakers and modelers

In the following sections, we highlight the impact that policymakers can have on the electricity system with their decisions, present recommendations for modelers that can further improve the transparency and comprehensibility of ESM studies, and finally, we discuss the limitations of this study.

4.1. Policy implications for a sustainable future

Overall, summarizing the findings on Switzerland, Germany, France, and Italy, the transition of each country's current electricity system towards 2050 can follow various pathways. However, not all of these pathways meet or approach each country's established energy and/or climate targets, as discussed in Section 2.1. Some scenarios, for instance, represent business-as-usual trends. This does not diminish the value of these scenarios, though, as they highlight the full range of possibilities and can also be used as benchmarks to evaluate e.g., the "distance" between target-meeting electricity system designs and those that are purely driven by cost minimization. Nevertheless, policymakers must ensure that the electricity system stays on a pathway that meets the established goals. Thus, in the following, we draw from each country's more ambitious scenarios to discuss some key aspects that would be valuable to policymakers.

Regarding the role of natural gas, policymakers on a national but also on a European level need to develop a clear strategy on how much natural gas each country can afford to deploy, and for how long, in order to reach its established climate targets. Many of the analyzed scenarios indicate natural gas as a bridge technology, especially for countries that phase out nuclear and/or coal power. However, to meet the established CO_2 targets discussed in Section 2.1, a reduction of natural gas or a coupling with CCS technologies might become inevitable. For instance, Italy currently relies heavily on natural gas, but has the potential to provide clean electricity through solar PV. Here, policymakers need to find an optimal balance between natural gas, the addition of CCS technologies, or a natural gas phase-out to accommodate solar PV and reach a low-carbon electricity system. In Switzerland, the situation also calls for a clear political stance regarding natural gas in combination with CCS technologies, as gas is seen as a feasible substitute for nuclear power in selected ambitious scenarios. Since CCS technologies are still in the niche phase of their development, a close monitoring of technological trends, for example given by Baena-Moreno et al. [86], and the creation of suitable markets will be a key task for policymakers to provide clean natural gas-based electricity generation.

The phase-out of nuclear power has been decided in all countries except France, which needs clarity on the future of nuclear power in its electricity system. As discussed in Section 3.1, a full phase-out of nuclear power would disrupt the country's entire electricity system and might make France more reliant on electricity import from its neighbors. However, as some of the ambitious scenarios show, retaining a high share of nuclear power in the French electricity system could also lead to a highly decarbonized electricity system. Policymakers should use the presented scenarios to draft a long-term strategy on the future role of nuclear power, and additionally clarify how other technologies might be introduced into the electricity system to ensure sufficient electricity production.

Regarding RE, policymakers need to ensure that deployment rates of renewables, and especially wind and solar PV, further increase in order to meet climate and energy targets. The shares of different technologies depend on each country's potentials, but also other factors, such as public opinion — which, for instance, has been shown to hamper the deployment of onshore wind in France significantly [87]. Addressing such issues through information campaigns and a clear commitment to RE and its deployment by the government could, thus, facilitate its uptake.

Finally, storage systems and their role in highly decarbonized electricity systems require further investigation and, hence, policymakers should promote and support additional research in this field, since storage will be needed to support electricity systems with high RE shares [83,88]. A key area to explore is the need for storage in scenarios that combine extensive electrification with fully renewable electricity production, such as in [49,67], as those electricity systems might benefit most from storage as a flexibility option to stabilize the electricity grid. In addition, we recommend policymakers to support the development of suitable storage applications to allow each country a certain degree of self-sufficiency and reduce dependency on neighboring countries. Furthermore, political clarity on expansion plans for electrical interconnections between European countries is needed, as these links could partly substitute for storage [89].

4.2. Recommendations for the energy system modeling community

In addition to the policy insights presented in the previous section, which were the main aim of our study, we were also able to derive some recommendations for the ESM community. These recommendations aim to help modelers present their findings in a comprehensive and transparent way, which will in turn provide clarity for creating electricity system scenarios.

Transparency in presenting key assumptions

One challenge of ESM is choosing not only the right level of technical model detail, but also the best assumptions to approximate reality. Depending on the focus of each study, these assumptions need to differ in order for studies to offer more nuanced insights into how certain trends or developments could impact the transformation of the energy system. Nevertheless, in compiling our review, we faced many difficulties in deciphering the assumptions from different studies. Therefore, we echo the views of previous scholars (e.g., [19]) in emphasizing the importance of presenting model assumptions in a transparent and comprehensive way. This will help policymakers understand the main drivers behind each study's scenario results and the implications for the studied energy systems.

Towards the standardized presentation of results

In order to allow modelers to compare scenario results and policymakers to compare studies with each other, we argue that it would be beneficial to harmonize practices for reporting model results. Depending on the audience, different levels of detail may be necessary when presenting study findings; however, the wide variation in terms of the results presented in different studies might also impede a cross-study comparison. This variation first and foremost led to the exclusion of prominent ESM studies (e.g. [90–92]) from this review, as they presented future generation capacities (in GW) but no annual electricity generation (in TWh). Moreover, in the studies we analyzed, the results presented relating to battery storage applications ranged from storage size information (in GWh) to accumulated energy supply per year (in TWh) to overall battery capacity (in GW), with most studies reporting just one of these measures. Since none of these units can be directly derived from the other, we could not make extensive comparisons.

Therefore, we propose that the modeling community should also consider introducing guidelines for presenting energy system model results. To this end, the journal *Joule*,[8] for example, has introduced a standard on how battery data must be reported [93], helping its readers find the necessary information about storage systems more easily. We are confident that such a standard would also be beneficial to the understanding and enhanced transparency of ESM-based studies.

Balancing of current and (invented) future policies

All model-based studies that were reviewed for this paper included multiple and diverse scenarios, with some oriented more towards economic objectives and others more towards environmental goals. One characteristic shared by most studies, though, was that the policy landscape reflected in their scenarios corresponded to the policy landscape at the time the study was conducted and published. As a result, some scenarios are no longer relevant, as they included technologies for which phase-out decisions were made after the study was published, indicating a rapid change in the policy landscape.

Indeed, one of the core goals of ESM is to provide insights on current problems that policy- and decision-makers face, and, as others have also argued [15,24,94], modelers should adjust their scenarios to accommodate this. Nevertheless, even though it is impossible to foresee all policy changes, we urge modelers to include more speculative policy developments in their scenarios that go beyond the current policy discourse. Besides offering a wider perspective on a problem to policymakers, this practice could also potentially reveal unconventional but effective policy options that would not have been considered under standard policy assumptions.

4.3. Limitations of the study

As with any study, our review comes with a number of limitations. First, we compare the scenarios on a mostly qualitative basis and, hence, cover only those aspects that we deemed of highest relevance. We refrained from using statistical tests to quantitatively evaluate our findings, as the scenarios rely on several assumptions and modeling choices, which could potentially lead to misleading findings when conducting quantitative tests [22]. Another challenge is the treatment of the model assumptions behind each scenario. We chose to focus only on key assumptions, such as CO_2 targets, that offer the greatest insights into how future policy decisions can impact the electricity system transition, but we have refrained from investigating and comparing the values of input parameters between models, such as for technology costs. Finally, a challenge in our analysis relates to the changes in each country's policy landscape, which rendered some modeling results obsolete (for example, the presence of coal-based generation in some scenarios for Germany in 2050). Although we tried to find a common denominator between the different scenarios, such policy developments complicated the scenario comparisons.

5. Conclusions

ESM is a key tool in our efforts to sustainably transform electricity systems [15,95], as it supports policymakers in their decision processes. However, it can be challenging for policymakers to navigate the results of multiple model-based studies and condense the presented scenarios into policy recommendations they can act upon. With our study, we have added to the field of review papers that synthesize key findings for policymakers by conducting an analysis of model-based electricity system transition scenarios for Switzerland, Germany, France, and Italy. We highlighted the main trends across multiple scenarios pertaining to each country's electricity generation mix for 2030 and 2050 and investigated the overlaps and differences among the scenarios. Furthermore, we discussed the role of different key technologies, such as natural gas, wind, solar PV, and energy storage, and offered insights into the impact of electricity demand trends on the electricity system.

Our results highlight that each country can follow various pathways that correspond to more cost- or emission-oriented transformations, or that achieve specific CO_2 or RE targets. Our analysis showed that scenarios for Switzerland's electricity system place it at a crossroads, with one option being to replace its phased-out nuclear power fleet with natural gas plants and the other to opt for solar PV and other renewables instead. Out of all Swiss scenarios for 2050, those with high shares of solar PV (up to 40 TWh) could reach close to net-zero CO_2 emissions. Germany has to tackle the phase-out of both coal and nuclear, and the scenarios unanimously see wind power as the backbone of its electricity system, with at least 300 TWh of wind-based electricity in 2050. Additionally, natural gas and solar PV can be deployed to support the wind-based electricity generation. The findings for France suggest there are multiple ways to achieve a low-carbon electricity mix, with the deciding factor being the presence of nuclear power, as it in turn defines the amount of new generation capacity required, such as wind and solar PV. Both technologies will play a significant role in achieving low CO_2 emission levels in 2050, with most of the ambitious scenarios projecting over 200 TWh of renewable electricity. For Italy, finally, most scenarios point towards increasing shares of solar PV and wind, with both technologies reaching 100 TWh in the ambitious scenarios of 2050. However, natural gas-based generation could remain a key electricity source until at least 2030 and possibly beyond.

Our study further showed that most scenarios across all countries see natural gas, solar PV, and wind as the key generation technologies. The roles of all three technologies in each country depend, on the one hand, on each country's renewable potentials, and on the other hand, on the implementation of CO_2 or RE targets that reduce the prominence

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[8] https://www.cell.com/joule/home.

of natural gas and facilitate the deployment of renewables. The role of storage technologies remains unclear, as our analysis has uncovered significant differences with regards to the need for storage in all four case-study countries.

Finally, we investigated the overarching role played by policies in the electricity system transition, and showed that phase-out policies and regulatory advancements with regards to storage technologies have a particularly critical impact on transitioning towards decarbonized electricity systems. We also emphasized the need for regulatory clarity over storage systems as a key technology to support high shares of RE. In addition to our key findings and implications for policymakers, we highlighted several implications for modelers, such as more transparent presentation of core assumptions, standardized discussion of study results, and the need for quicker adoption of policies, as well as more creative choice of scenarios.

Moving forward, researchers and policymakers need to redouble their efforts towards defining and investigating the most suitable trajectories for the countries, beyond the range of possibilities that the analyzed scenarios have highlighted. First, policymakers have a significant lever to influence future developments — for example, by penalizing fossil fuels or introducing climate targets, allowing them to directly shape the pathway that their country moves along. Moreover, as the electricity system is expected to play a key role in decarbonizing national energy systems, policymakers should engage in forward-looking discussions on the interdependencies and synergies between the electricity system and other sectors via sector coupling and the connections between national and international electricity systems. Finally, we encourage modelers and policymakers to seek out frequent discussions with each other, to support a continuous and timely exchange on possible future policies and the impacts they might have on the electricity system.

CRediT authorship contribution statement

P.J. Thimet: Conceptualization of this study, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **G. Mavromatidis:** Conceptualization of this study, Methodology, Investigation, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Relevant ESM review studies with a modeling-oriented scope

As briefly discussed in Section 1.2, Table A.1 presents relevant ESM review studies and highlights their limitations. The reviews either collect and compare different ESM modeling tools (Sub-group 1) or discuss specific key dimensions of ESM (Sub-group 2).

Table A.1
Relevant ESM review studies with a modeling-oriented scope.

Publication	Title	Focus
Sub-group 1: General model overview & comparison studies		
Després et al. [17]	Modeling the impacts of variable renewable sources on the power sector: Reconsidering the typology of energy modeling tools	Review of long-term energy modeling and electricity system tools and presentation of methodology to characterize modeling tools based on their general logic (modeled energy sectors, evolution over time, computational logic) and the representation of the electricity system in the model
Foley et al. [11]	A strategic review of electricity systems models	Overview of electricity system modeling techniques and review of proprietary electricity system models
Lopion et al. [6]	A review of current challenges and trends in energy systems modeling	Focus on national energy system models and detailed review in terms of model methodology and analytical approach, time horizon, spatio-temporal resolution, licensing and modeling language, and geographical regions where models are developed
Prina et al. [9]	Classification and challenges of bottom-up energy system models — A review	Detailed review and classification of 22 bottom-up energy models using energy sectors covered, geographical coverage, time resolution, methodology, and programming technique
Ringkjøb et al. [16]	A review of modeling tools for energy and electricity systems with large shares of variable renewables	Review of 75 modeling tools used for ESM (ranging from small-scale electricity system analysis tools to long-term energy models). Comparison of model capabilities and characteristics (spatio-temporal resolution, general logic, technological and economic properties)
Sub-group 2: Studies focusing on specific key dimensions of ESM		
Collins et al. [96]	Integrating short term variations of the power system into integrated energy system models: A methodological review	Review of methodologies to improve the representation of the short term variations of renewables in long-term energy system models
Gacitua et al. [97]	A comprehensive review on expansion planning: Models and tools for energy policy analysis	Review of main policy instruments for RE integration and of existing ESM tools that can support the design and implementation of energy policies
Haas et al. [98]	Challenges and trends of energy storage expansion planning for flexibility provision in low-carbon electricity systems — a review	Detailed review of state-of-the-art approaches and new trends regarding modeling energy storage systems. Aspects covered include the storage technologies modeled, energy sectors and networks, flexibility options, and the treatment of uncertainty.
Koltsaklis et al. [18]	State-of-the-art generation expansion planning: A review	Detailed review of methodologies to address seven key challenges in long-term, strategic ESM: generation and transmission planning, risk assessment, electric vehicle (EV)s, short-term operation and long-term ESM, interactions between electricity and natural gas infrastructures, storage and demand-side management, policy and security of supply
Oree et al. [99]	Generation expansion planning optimization with RE integration: A review	Review of the approaches used by different models to address the needs of decision-makers in terms of environmental considerations, conflicting objectives, uncertainty, and the integration of intermittent REs
Zerrahn & Schill [100]	Long-run power storage requirements for high shares of renewables: review and a new model	Review of model-based studies focusing on the role of energy storage in energy systems with high shares of RE

Appendix B. Data collection

In the process of collecting the scenario results from the different studies, we had to make certain assumptions to ensure a systematic and consistent analysis. These assumptions are presented in the following.

Since our goal was to draw well-supported conclusions from the scenarios analyzed, we aimed at providing at least 10 scenarios per studied year (2030, 2050) and country. Nevertheless, some studies presented scenario results with 2035 as the target year instead of 2030. Although we could apply an interpolation technique to obtain results for 2030, we have instead chosen to directly attribute their 2035 scenario results to 2030 without any modifications, as we did not want to introduce any distortions in the key messages of the studies and the scenarios.

Some other studies presented scenarios without indicating a specific future target year, instead focusing solely on modeling a target future state of the electricity system — e.g., for specific RE shares. To add these valuable scenarios into our overview, we assumed that 100% renewable electricity systems are most likely to be achieved by 2050, allowing us to include these scenarios along with those for 2050. Those studies with around 50% renewables and no year indication were consequently added to the 2030 scenarios.

Moreover, we had to make some choices regarding the treatment of scenario results that pertain to energy storage technologies, considering also the discrepancies discussed in Section 4.2. First, we excluded electricity discharged from storage from our generation-mix presentation in order to avoid double-counting, as this electricity would have to be produced by generation technologies earlier and used to charge the storage technology. In studies where demand was directly given and storage discharge was included in the generation mixes, we further assumed that the demand curve also included the necessary electricity to charge the storage technology; therefore, we deducted it from the demand curve with an assumed round-trip efficiency of 100%.

Finally, to structure the analysis, we grouped the available technologies in the scenarios into the following key technology categories: Coal, Coal + CCS, Oil, Nuclear, Natural Gas, Natural Gas + CCS, Solar, Wind (sum of on- and offshore wind), Hydro (excluding PHS, as this is a storage rather than a generation technology), Geothermal, Waste, Bioenergy, and Others. The last category includes any generation data that was already marked as "other" in the scenarios studied. Due to the nature of the studies we investigated, we sometimes had to combine certain technologies presented in the scenarios into a single technology block. We contacted the responsible authors before adjusting any results to stay as close to their findings as possible.

Appendix C. Categorizing the country scenarios according to the share of low-carbon technologies in their generation mix

To facilitate a clearer result presentation in Section 3, the scenarios are sorted according to their share of low-carbon technologies, which is calculated as the sum of all nuclear, renewable, and fossil fuel + CCS-based electricity generation divided by the total electricity generation. For each scenario, the share of low-carbon sources is then compared to the low-carbon share of the respective country in 2019 (see Table 2). Depending on the difference between the 2019 baseline and the projected generation mix for a scenario, each scenario is categorized as having low, moderate, or ambitious projected shares of low-carbon sources. Table C.1 summarizes the different schemes to classify scenarios for each country according to their low-carbon shares.

Table C.1
Numerical scheme to sort scenarios for each country according to the share of low-carbon technologies in their generation mix.

Country	Share in 2019[a]	Range for 2030			Range for 2050		
		Low	Moderate	Ambitious	Low	Moderate	Ambitious
Switzerland	96%	<80%	80%–90%	>90%	<65%	65%–90%	>90%
Germany	52%	<50%	50%–60%	>60%	<70%	70%–90%	>90%
France	90%	<85%	85%–95%	>95%	<90%	90%–99.5%	>99.5%
Italy	39%	<55%	55%–65%	>65%	<70%	70%–90%	>90%

[a] Based on the IEA database [4].

Appendix D. Scenario information

Tables D.1–D.4 provide detailed information on the scenarios chosen for each country, and investigated year. They highlight key assumptions and the core focus of the scenario, and offer insights on technological restrictions or regulatory aspects such as carbon prices or phase-out requirements.

Table D.1
List of model-based electricity system scenarios for Switzerland and key scenario information.

Ref.	Author & Year	Original scenario name	Scenario name in this review	Scenario description	Target year	Climate targets	Carbon price	Phase-out or limitation of key technologies	Additional assumptions and developments
[36]	Abrell et al. 2019	No-intervention case	Abrell.Reference	Reference scenario	2030, 2050			2035: Nuclear power phase-out	
		Renewable support case	Abrell.Renewable	Impact of an increase in RE	2030, 2050	2030: 9 TWh increase of RE, 2050: 19 TWh increase of RE		2035: Nuclear power phase-out	
[37]	Bartlett et al. 2018	Current	Bartlett.Reference	Reference scenario	2030[a]				
		Intermediate	Bartlett.Intermediate	RE target analysis	2030[a]	50% RE share		50% nuclear power phase-out	
		Renewable	Bartlett.Renewable	RE target analysis	2050[a]	100% RE share		Nuclear power phase-out	
[38]	Diaz Redondo and van Vliet 2015	Variant E	DiazRedondo.Import	Analysis of Swiss Energy Strategy, Variant E	2030[b], 2050			Nuclear power phase-out	Increase in energy efficiency of fossil fuel technologies
[40]	Kannan 2018	LowElcImpPrice	Kannan.ElcImpPrice	Impact of low electricity import price	2050		51 CHF/tCO$_2$	2034: Nuclear power phase-out	Zero net electricity import
		NoElcImp	Kannan.NoElcImp	Impact of prohibited electricity trade	2050		51 CHF/tCO$_2$	2034: Nuclear power phase-out	No electricity import in general
		NoFuelTax	Kannan.NoFuelTax	Impact of tax adjustments for hydrogen and electricity as fuels	2050		51 CHF/tCO$_2$	2034: Nuclear power phase-out	Zero net electricity import
		NoGas	Kannan.NoGas	Impact of excluding centralized combined cycle gas turbines (CCGT)s and CHPs from the generation mix	2050		51 CHF/tCO$_2$	2034: Nuclear power phase-out	Zero net electricity import
		NoRCSV	Kannan.NoRCSV	Impact of missing retrofit possibilities	2050		51 CHF/tCO$_2$	2034: Nuclear power phase-out	Zero net electricity import, no retrofit possible
		Ref	Kannan.Reference	Reference scenario	2050		51 CHF/tCO$_2$	2034: Nuclear power phase-out	Zero net electricity import
[39]	Kannan and Turton 2016	BAU	KanTur.Reference	Least cost scenario	2030, 2050		2050: 51 CHF/tCO$_2$		Reduction of heating demand and availability of retrofit measures
		BAU-NoCent	KanTur.NoCentGas	Impact of excluding centralized CCGT and CHPs on least cost scenario	2030, 2050		2050: 51 CHF/tCO$_2$	No centralized gas power plants available	Reduction of heating demand and availability of retrofit measures
		LC60	KanTur.LC60	Analysis of 60% emission reduction by 2050	2030, 2050	60% CO$_2$ reduction by 2050	2050: 51 CHF/tCO$_2$		Reduction of heating demand and availability of retrofit measures
		LC60-NoCent	KanTur.LC60NoCentGas	Impact of excluding centralized CCGT and CHPs on 60% emission reduction by 2050	2030, 2050	60% CO$_2$ reduction by 2050	2050: 51 CHF/tCO$_2$	No centralized gas power plants available	Reduction of heating demand and availability of retrofit measures
[41]	Limpens et al. 2019	50% RE target	Limpens.50RE	RE target	2030[b]	50% RE share			12.3% reduction of primary energy consumption
[42]	Maeder et al. 2021	Switzerland, limited transmission expansion	Maeder.LimitTrans	Impact of limited transmission expansion and carbon taxes	2050		88 €/tCO$_2$	Nuclear phase-out, seasonal storage is available	
[43]	Panos and Kannan 2016	Reference	PanKan.Reference	Analysis of POM polices from the Swiss Energy Strategy	2030, 2050		2030: 48 CHF/tCO$_2$, 2050: 58 CHF/tCO$_2$	2034: Nuclear power phase-out	Zero net electricity import
		NoGas	PanKan.NoCentGas	Impact of excluding centralized CCGT and CHPs	2030, 2050		2030: 48 CHF/tCO$_2$, 2050: 58 CHF/tCO$_2$	2034: Nuclear power phase-out, no centralized CCGT and CHPs	Zero net electricity import
		CO$_2$	PanKan.CO2	Impact of 70% CO$_2$ emission targets by 2050	2030, 2050	70% CO$_2$ reduction by 2050	2030: 48 CHF/tCO$_2$, 2050: 58 CHF/tCO$_2$	2034: Nuclear power phase-out	Zero net electricity import
		CO$_2$NoGas	PanKan.CO2NoCentGas	Impact of 70% CO$_2$ emission targets by 2050 and excluding centralized CCGT and CHPs	2030, 2050		2030: 48 CHF/tCO$_2$, 2050: 58 CHF/tCO$_2$	2034: Nuclear power phase-out	Zero net electricity import
[44]	Panos et al. 2019	Baseline	Panos.Reference	Analysis of the "WWB" scenario from the Swiss energy strategy	2030, 2050				
		Climate	Panos.Climate	Impact of emission targets for 2030 and 2050	2030, 2050	2030: 28.4 MtCO2, 2050: 20.3 MtCO2	2030: 140 CHF/tCO$_2$, 2050: 300 CHF/tCO$_2$		

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Table D.1 (*continued*).

Ref.	Author & Year	Original scenario name	Scenario name in this review	Scenario description	Target year	Climate targets	Carbon price	Phase-out or limitation of key technologies	Additional assumptions and developments
[45]	Pattupara and Kannan 2016	Least cost	Pattupara.LeastCost	Reference scenario	2030, 2050		2050: 57 CHF/tCO_2	Nuclear power phase-out, lead–acid batteries and CAES as seasonal storage are available	
		NoNUC	Pattupara.NoNUC	Analysis of EU 20-20-20 targets	2030, 2050		2050: 57 CHF/tCO_2	Nuclear power phase-out, lead–acid batteries and CAES as seasonal storage are available	
		CO_2	Pattupara.CO2	Impact of emission targets counting for the five investigated countries together	2030, 2050	2030: 61% CO_2 reduction, 2050: 95 %CO2 reduction	2050: 57 CHF/tCO_2	Nuclear power phase-out, lead–acid batteries and CAES as seasonal storage are available	
[46]	Volkart et al. 2017	Ref	Volkart.Reference	Reference scenario with climate policies	2030[b]				
		Clim	Volkart.Climate	Impact of emission reduction targets	2030[b]	40% CO_2 reduction			
		Clim+CCS	Volkart.CCS	Impact of emission reduction targets and CCS availability	2030[b]	40% CO_2 reduction		2030: CCS is available	
[47]	Weiss et al. 2021	Reference	Weiss.Reference	Analysis of 2016 EU transition pathways, no electricity trade possible	2030, 2050		2050: 60 €/tCO_2	No battery storage available	No electricity trade possible
		NUC +	Weiss.Nuclear	Impact of nuclear power phase-out with prolonged nuclear power lifetime	2030, 2050		2050: 60 €/tCO_2	Nuclear lifetime increase by 10 years, no battery storage available	
		RES+	Weiss.Renewable	Impact of increased financial support for solar PV	2030, 2050		2050: 60 €/tCO_2	No battery storage available	Increased support of solar PV from 0.69c/kWh to 2c/kWh

[a] Indicates that no specific year was given in the study. The results are assumed to reflect a particular outcome for 2030 and 2050 respectively (see Appendix B).

[b] Indicates that the scenario results were originally presented for the year 2035 but are assumed to account for 2030 here (see Appendix B).

Table D.2
List of model-based electricity system scenarios for Germany and key scenario information.

Ref.	Author & Year	Original scenario name	Scenario name in this review	Scenario description	Target year	Climate targets	Carbon price	Phase-out or limitation of key technologies	Additional assumptions and developments
[48]	Bartholdsen et al. 2019	European Island	Bartholdsen.EUIsland	Impact of technology phase-out and high electricity exchange in Europe	2030, 2050	2030: 40% CO_2 reduction, 2050: 80% CO_2 reduction	2030: 35 €/tCO_2, 2050: 85€/tCO2	2035: lignite and hard coal phase-out, 2045: gas and oil phase-out	
		Green Democracy	Bartholdsen.GreenDem	Impact of emission reduction and high carbon taxes	2030, 2050	2030: 55% CO_2 reduction, 2050: 95% CO_2 reduction	2030: 58 €/tCO_2, 2050: 130 €/tCO_2	2025: lignite phase-out, 2030: hard coal phase-out, 2035: gas and oil phase-out	
		Survival of the Fittest	Bartholdsen.Survival	Impact of limited cross-border trade and no technology phase-out	2030, 2050		2030: 15€/tCO2, 2050: 50 €/tCO_2		
[49]	Hansen et al. 2019	Reference	Hansen.Reference	Reference scenario	2050				100% RE in heating, industry, transport and electricity
		100% RE & Elec. Transp.	Hansen.100REEV	Analysis of 100% RE system with electricity as key technology in the transport sector	2050	100% RE share			100% RE in heating, industry, transport and electricity
		100% RE & H2 transp.	Hansen.100REH2	Analysis of 100% RE system with hydrogen as key technology in the transport sector	2050	100% RE share			100% RE in heating, industry, transport and electricity
		5% excess & Elec. Transp.	Hansen.5excessEV	Analysis of 100% RE system with electricity as key technology in the transport sector and limited excess electricity production	2050	100% RE share			100% RE in heating, industry, transport and electricity
		5% excess & H2 transp.	Hansen.5excessH2	Analysis of 100% RE system with hydrogen as key technology in the transport sector and limited excess electricity production	2050	100% RE share			100% RE in heating, industry, transport and electricity
[50]	Keles and Yilmaz 2020	Base	Keles.Base	Impact of 80% RE by 2050	2030, 2050	2050: 80% RE share			
		Phaseout-DE	Keles.Phaseout	Impact of coal phase-out and 80% RE by 2050	2030, 2050	2050: 80% RE share		2040: coal phase-out	

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Table D.2 (*continued*).

Ref.	Author & Year	Original scenario name	Scenario name in this review	Scenario description	Target year	Climate targets	Carbon price	Phase-out or limitation of key technologies	Additional assumptions and developments
[51]	Knaut et al. 2016	Reference	Knaut.Reference	Analysis of German RE policies until 2020	2030, 2050		2030: 40 €/tCO_2, 2050: 76 €/tCO_2		Decrease in electricity demand
		Low RES-E cost	Knaut.LowRESCost	Analysis of a 20% RE cost reduction	2030, 2050		2030: 40 €/tCO_2, 2050: 76 €/tCO_2		Decrease in electricity demand, reduction of RE cost by 20%
		Fuel Cost Low	Knaut.LowFuelCost	Analysis of a fuel cost reduction	2030, 2050		2030: 40 €/tCO_2, 2050: 76 €/tCO_2		Decrease in electricity demand, reduction of fuel cost
[52]	Ludig et al. 2015	All Opt High	Ludig.AllOptLHigh	Analysis of emission and RE target with high electricity demand increase	2050	98% CO_2 reduction, 80% RE share		2022: nuclear phase-out	25% decrease in electricity demand
		All Opt Low	Ludig.AllOptLow	Analysis of emission and RE target with electricity demand decrease	2050	98% CO_2 reduction, 80% RE share		2022: nuclear phase-out	25% savings in electricity demand
		All Opt Med	Ludig.AllOptMed	Analysis of emission and RE target	2030, 2050	2030: 49% CO_2 reduction and 50% RE share, 2050: 98% CO_2 reduction and 80% RE share		2022: nuclear phase-out	0.2% yearly increase in electricity demand
[42]	Maeder et al. 2021	Germany, limited transmission expansion	Maeder.LimitTrans	Impact of limited transmission expansion and carbon taxes	2050		88 €/tCO_2	Nuclear phase-out, seasonal storage is available	
[53]	Müller et al. 2019	Baseline Scenario	Muller.Reference	Analysis of "Big & market" assumptions of E-Highway report	2030[b], 2050			CCS is available	
[54]	Palzer and Henning 2014	Medium	Palzer.Medium	Analysis of 100% RE and 50% energy savings in the building sector	2050[a]	100% RE share			50% energy savings in building sector
		REMax	Palzer.Medium	Analysis of 100% RE	2050[a]	100% RE share			Retrofit options available
		RetrofitMax	Palzer.Medium	Analysis of 100% RE and 60% energy savings in the building sector	2050[a]	100% RE share		Limited offshore wind potential	60% energy savings in building sector
[55]	Rogge et al. 2020	Pathway A	Rogge.PathA	Analysis of CCS potential and efficiency increase in heating and transportation	2030, 2050			Nuclear power phase-out	
		Pathway B	Rogge.PathB	Analysis of new actors in the electricity system and efficiency increase in heating and transportation	2030, 2050			Nuclear power phase-out, no CCS is available	High electrification of heating and transport
[56]	Sterchele et al. 2020	Referenz	Sterchele.Reference	Analysis of emission targets without changes in consumer behavior or tech availability	2030	2050: 95% CO_2 reduction		2022: nuclear phase-out, 2035: coal phase-out	
[57]	Tash et al. 2019	BAU	Tash.Reference	Reference scenario	2030, 2050				
		CO_2_ORG	Tash.CO2ORG	Impact of CO_2 emission tax	2030, 2050		2030: 100 $/tCO2, 2050: 180 $/tCO2		High electrification of heating and transport
		CO_2_TAM	Tash.CO2TAM	Impact of CO_2 emission tax with actor involvement	2030, 2050		2030: 100 $/tCO2, 2050: 180 $/tCO2		High electrification of heating and transport
		RES_ORG	Tash.RESORG	Impact of RE targets	2030, 2050	2030: 65% RE share, 2050: 85% RE share			High electrification of heating and transport
		RES_TAM	Tash.RESTAM	Impact of RE targets with actor involvement	2030, 2050	2030: 65% RE share, 2050: 85% RE share			High electrification of heating and transport

[a] Indicates that no specific year was given in the study. The results are assumed to reflect a particular outcome for 2030 and 2050 respectively (see Appendix B).

[b] Indicates that the scenario results were originally presented for the year 2035 but are assumed to account for 2030 here (see Appendix B).

Table D.3
List of model-based electricity system scenarios for France and key scenario information.

Ref.	Author & Year	Original scenario name	Scenario name in this review	Scenario description	Target year	Climate targets	Carbon price	Phase-out or limitation of key technologies	Additional assumptions and developments
[58]	Alimou et al. 2020	–	Alimou.60RE	Impact of current policies on reliable electricity supply.	2030	39Mt CO_2 reduction		2025: 50% nuclear power limit	Increase in electricity consumption
[59]	Krakowski et al. 2016	BAU	Krakowski.Reference	Reference scenario with no improvements	2030, 2050			No battery storage available	
		60RES 2050	Krakowski.60RE	Impact of 60% RE	2030, 2050	2050: 60% RE share		No battery storage available	
		80RES 2050	Krakowski.80RE	Impact of 80% RE	2030, 2050	2050: 80% RE share		No battery storage available	
		100RES 2050	Krakowski.100RE	Impact of 100% RE	2030, 2050	2050: 100% RE share		No battery storage available	
		100RES 2050	Krakowski.100REnoImport	Impact of 100% RE and no elec. Import	2030, 2050	2050: 100% RE share		No battery storage available	No electricity import
		100RES 2050_v5	Krakowski.100REBiomass	Impact of 100% RE and increase in biomass potential	2030, 2050	2050: 100% RE share		No battery storage available, 5.75 times more biomass	
[42]	Maeder et al. 2021	France, limited transmission expansion	Maeder.LimitTrans	Impact of limited transmission expansion and carbon taxes	2050		88 €/tCO_2	Seasonal storage is available	
[60]	Maïzi and Assoumou 2014	BAU	Maizi.Reference	Reference scenario	2030, 2050		20–50 €/CO_2		
		FASTt1	Maizi.Fast	Impact of fast nuclear power phase-out	2030, 2050		20–50 €/CO_2	Nuclear phase-out after 40 years	
		FASTv1	Maizi.FastCO2	Impact of fast nuclear power phase-out with emission constraints	2030, 2050	2030: 41 $MtCO_2$ reduction, 2050: 32 $MtCO_2$ reduction	20–50 €/CO_2	Nuclear phase-out after 40 years	
		PROGt1	Maizi.Progress	Impact of nuclear power phase-out with prolonged nuclear power lifetime	2030, 2050		20–50 €/CO_2	Nuclear phase-out after 40 years, with partial lifetime increase to 60 years	
		PROGv1	Maizi.ProgressCO2	Impact of nuclear power phase-out with prolonged nuclear power lifetime and emission constraints	2030, 2050	2030: 41 $MtCO_2$ reduction, 2050: 32 $MtCO_2$ reduction	20–50 €/CO_2	Nuclear phase-out after 40 years, with partial lifetime increase to 60 years	
[61]	Millot et al. 2020	FranceNeutrality	Millot.Neutrality	Impact of carbon neutrality through emission targets and carbon taxes	2030	11 Mt CO_2 reduction by 2050	100 €/CO_2	Power-to-gas option and CCS available	
[62]	Seck et al. 2020	BAU	Seck.Reference	Reference scenario	2030, 2050				
		40 EnR 2050	Seck.40RE	Impact of emission constraint and 40% RE on reliable electricity supply	2030, 2050	2030: 39 Mt CO_2 reduction and 40% RE share		2025: 50% nuclear power limit	
		60 EnR 2050	Seck.60RE	Impact of emission constraint and 60% RE on reliable electricity supply	2030, 2050	2030: 39 Mt CO_2 reduction and 40% RE share, 2030: 39 Mt CO_2 reduction and 60% RE share		2025: 50% nuclear power limit	
		80 EnR 2050	Seck.80RE	Impact of emission constraint and 80% RE on reliable electricity supply	2030, 2050	2030: 39 Mt CO_2 reduction and 40% RE share, 2030: 39 Mt CO_2 reduction and 80% RE share		2025: 50% nuclear power limit	
		100 EnR 2050	Seck.100RE	Impact of emission constraint and 100% RE on reliable electricity supply	2030, 2050	2030: 39 Mt CO_2 reduction and 40% RE share, 2030: 39 Mt CO_2 reduction and 100% RE share		2025: 50% nuclear power limit	
[63]	Shirizadeh and Quirion 2020	0€/tCO2 SCC	Shirizadeh.0SCC	Analysis of no social cost of carbon	2050		0 €/CO_2		
		100 €/CO_2 SCC	Shirizadeh.100SCC	Analysis of a social cost of carbon of 100 €/CO_2	2050		100 €/CO_2		
		200 €/CO_2 SCC	Shirizadeh.200SCC	Analysis of a social cost of carbon of 200 €/CO_2	2050		200 €/CO_2		
		50 €/CO_2 SCC	Shirizadeh.50SCC	Analysis of a social cost of carbon of 50 €/CO_2	2050		50 €/CO_2		
		50 €/CO_2 SCC, DIV	Shirizadeh.50SCChigh	Analysis of a social cost of carbon of 50 €/CO_2 with an increase in electricity demand	2050		50 €/CO_2		Increase in electricity demand by 112 TWh
		50 €/CO_2 SCC, SOB	Shirizadeh.50SCClow	Analysis of a social cost of carbon of 50 €/CO_2 with a drop in electricity demand	2050		50 €/CO_2		Decrease in electricity demand by 242 TWh
[64]	Tlili et al. 2019	33 GW export case	Tlili.highExport	Analysis of hydrogen production from surplus electricity	2030[a]			2025: 50% nuclear power limit	

[a] Indicates that the scenario results were originally presented for the year 2035 but are assumed to account for 2030 here (see Appendix B).

Table D.4
List of model-based electricity system scenarios for Italy and key scenario information.

Ref.	Author & Year	Original scenario name	Scenario name in this review	Scenario description	Target year	Climate targets	Carbon price	Phase-out or limitation of key technologies	Additional assumptions and developments
[65]	Alloisio et al. 2015	Reference	Alloisio.Reference	Analysis of EU PRIMES pathway (2013)	2030, 2050			No nuclear power available	High electrification of heating and transport
		Demand Reduction scenario	Alloisio.DemandRed	Impact of high decarbonization cost	2030, 2050	2030: 40% CO_2 reduction, 2050: 80% CO_2 reduction (in the energy system)		No nuclear power available, limited availability of CCS	Reduction of energy demand due to high carbon prices
		Energy Efficiency	Alloisio.Efficiency	Impact of efficiency increases and high decarbonization cost	2030, 2050	2030: 40% CO_2 reduction, 2050: 80% CO_2 reduction (in the energy system)		No nuclear power available	High retrofitting and energy efficiency increase
		CCS + Renewables	Alloisio.CCS	Analysis of CCS potential and efficiency increase in heating and transportation	2030, 2050	2030: 40% CO_2 reduction, 2050: 80% CO_2 reduction (in the energy system)		No nuclear power available, high acceptance of CCS	High electrification of heating and transport
[66]	Lanati et al. 2019	NECP	Lanati.NECP	Impact of 55% RE	2030	55% RE share		2025: coal phase-out	
		BASE	Lanati.Reference30	Reference scenario following the Italian energy strategy	2030			2025: coal phase-out	
[67]	Lanati and Gaeta 2020	DEC	Lanati.Decarb	Impact of 95% RE	2050	95% RE share		Coal phase-out	Increase in electricity consumption for heating (60%) and transportation (50%)
		REF	Lanati.Reference50	Reference scenario following the Italian energy strategy	2050			Coal phase-out	20% natural gas generation
[42]	Maeder et al. 2021	Italy, limited transmission expansion	Maeder.LimitTrans	Impact of limited transmission expansion and carbon taxes	2050		88 €/tCO_2	Nuclear phase-out, seasonal storage is available	
[68]	Prina et al. 2018	Scenario P1, best case	Prina.ScenP1	Least cost and favorable situation for CCGT	2050	12.6% CO_2 reduction		2030: Coal phase-out	
		Scenario P2, best case	Prina.ScenP2	Impact of 24% CO_2 emission reduction by 2050 and favorable situation for CCGT	2050	24.2% CO_2 reduction		2030: Coal phase-out	
		Scenario P3, best case	Prina.ScenP3	Impact of 27% CO_2 emission reduction by 2050 and favorable situation for CCGT	2050	27% CO_2 reduction		2030: Coal phase-out	
		Scenario P4, best case	Prina.ScenP4	Impact of 32% CO_2 emission reduction by 2050 and favorable situation for CCGT	2050	32.3% CO_2 reduction		2030: Coal phase-out	
[69]	Prina et al. 2019	Pareto point 1	Prina.ParetoP1	Least cost scenario	2030, 2050	2050: 15.2% CO_2 reduction		2030: Coal phase-out	
		Pareto point 3	Prina.ParetoP3	Impact of 19.5% CO_2 emission reduction by 2050	2030, 2050	2050: 19.5% CO_2 reduction		2030: Coal phase-out	
		Pareto point 5	Prina.ParetoP5	Impact of 24.7% CO_2 emission reduction by 2050	2030, 2050	2050: 23.7% CO_2 reduction		2030: Coal phase-out	
[70]	Prina et al. 2020	Advanced	Prina.Advanced	Impact of EV increase to 20%	2030	55% RE share			30% energy efficiency of buildings, 20% electrification of transport
		PNIEC	Prina.PNIEC	Analysis of the Italian Energy Action Plan	2030	55% RE share			15% energy efficiency of buildings, 10% electrification of transport
[71]	Vellini et al. 2020	2030 EUCO27	Vellini.EUCO27	Analysis of EUCO policy scenario with a 27% reduction in primary energy consumption	2030	40% GHG reduction			27% reduction in primary energy consumption
		2030 EUCO40	Vellini.EUCO40	Analysis of European Commission policy scenario with a 40% reduction in primary energy consumption	2030	47% GHG reduction			40% reduction in primary energy consumption
		2030 NES	Vellini.NES	Analysis of Italian Energy Strategy	2030	50% CO_2 reduction, 55% RE share		Coal phase-out	42% reduction in primary energy consumption
		2030-REF	Vellini.Reference	Analysis of 2016 European Commission targets	2030	94 MtCO_2			

Appendix E. Model information

In addition to Tables D.1–D.4, Table E.1 offers an overview of the models used in the different studies as well as additional information on the modeling type, the sectors modeled, and whether electricity trade is considered.

Table E.1
Overview of the studies, the models used and relevant modeling parameters.

Ref.	Author & Year	Model	Model horizon[a]	Modeling approach	Sectors	Electricity trade
[36]	Abrell et al. 2019	AFEM	Evolution	Optimization	Electricity	Yes
[58]	Alimou et al. 2020	TIMES-FR, ANTARES	Evolution	Optimization	Electricity	No
[65]	Alloisio et al. 2015	TIMES-Italy	Evolution	Optimization	Electricity, Heating, Transport	Yes
[48]	Bartholdsen et al. 2019	GENeSYS-MOD	Evolution	Optimization	Electricity, Heating, Transport	No
[37]	Bartlett et al. 2018	Own model	Snapshot	Simulation	Electricity	Yes
[38]	Diaz Redondo and van Vliet 2015	Calliope	Snapshot	Optimization	Electricity	Yes
[49]	Hansen et al. 2019	EnergyPlan	Snapshot	Simulation	Electricity, Heating, Transport, Industry	Yes
[40]	Kannan 2018	STEM	Evolution	Optimization	Electricity, Heating, Transport, Industry	Yes
[39]	Kannan and Turton 2016	STEM	Evolution	Optimization	Electricity, Heating, Transport, Industry	Yes
[50]	Keles and Yilmaz 2020	PERSEUS-EU	Evolution	Optimization	Electricity	Yes
[51]	Knaut et al. 2016	Own model	Evolution	Optimization	Electricity	Yes
[59]	Krakowski et al. 2016	TIMES	Evolution	Optimization	Electricity	Yes
[67]	Lanati and Gaeta 2020	TIMES	Evolution	Optimization	Electricity, Heating, Transport, Industry, Agriculture	Yes
[66]	Lanati et al. 2019	TIMES	Evolution	Optimization	Electricity	Yes
[41]	Limpens et al. 2019	EnergyScope TD	Snapshot	Optimization	Electricity, Heating, Transport	No
[52]	Ludig et al. 2015	LIMES-D	Evolution	Optimization	Electricity	No
[42]	Maeder et al. 2021	FLEXIES	Snapshot	Optimization	Electricity	Yes
[60]	Maïzi and Assoumou 2014	TIMES-FR	Evolution	Optimization	Electricity	Yes
[61]	Millot et al. 2020	TIMES-FR	Evolution	Optimization	Electricity, Heating, Transport, Industry, Agriculture	Yes
[53]	Müller et al. 2019	Own model	Evolution	Optimization	Electricity, Heating, Transport	Yes
[54]	Palzer and Henning 2014	REMod-D	Snapshot	Optimization	Electricity, Heating	No
[43]	Panos and Kannan 2016	STEM-HE	Evolution	Optimization	Electricity, Heating	Yes
[44]	Panos et al. 2019	STEM	Evolution	Optimization	Electricity, Heating, Transport, Industry	Yes
[45]	Pattupara and Kannan 2016	CROSSTEM	Evolution	Optimization	Electricity	Yes
[70]	Prina et al. 2020	EPLANopt	Snapshot	Simulation-based optimization	Electricity, Heating, Transport	Yes
[68]	Prina et al. 2018	EPLANopt	Snapshot	Simulation-based optimization	Electricity, Heating, Transport	No
[69]	Prina et al. 2019	EPLANoptTP	Evolution	Simulation-based optimization	Electricity, Heating, Transport	No
[55]	Rogge et al. 2020	Enertile	Snapshot	Optimization	Electricity	Yes
[62]	Seck et al. 2020	TIMES-FR	Evolution	Optimization	Electricity	Yes
[63]	Shirizadeh and Quirion 2020	EOLES_elec	Snapshot	Optimization	Electricity	No
[56]	Sterchele et al. 2020	REMod-D	Evolution	Optimization	Electricity, Heating, Transport, Industry	Yes
[57]	Tash et al. 2019	TAM (TIMES-based)	Evolution	Optimization	Electricity, Heating	No
[64]	Tlili et al. 2019	Europower (PyPSA)	Snapshot	Optimization	Electricity	Yes
[71]	Vellini et al. 2020	Own model	Snapshot	Simulation	Electricity, Heating, Transport, Industry, Agriculture	No
[46]	Volkart et al. 2017	Swiss MARKAL	Evolution	Optimization	Electricity, Heating, Transport, Industry, Agriculture	No
[47]	Weiss et al. 2021	Own model	Evolution	Simulation-based optimization	Electricity	Yes

[a] Snapshot: modeling only a target year in the future, evolution: modeling the evolution of the energy/electricity system in annual or multi-annual steps until a target year.

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