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Research paper

Strategic policy targets and the contribution of hydrogen in a 100% renewable European power system

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ABSTRACT

The goal of the European energy policy is to achieve climate neutrality. The long-term energy strategies of various European countries include additional targets such as the diversification of energy sources, maintenance of security of supply, and reduction of import dependency. When optimizing energy systems, these strategic policy targets are often only considered in a rudimentary manner and thus, the understanding of the corresponding interdependencies is lacking. Moreover, hydrogen is considered as a key component of a fully decarbonized energy system, but its role in the power sector remains unclear due to the low round-trip efficiencies.

This study reveals how fully decarbonized European power systems can benefit from hydrogen in terms of overall system costs and the achievement of strategic policy targets. We analyzed a broad spectrum of scenarios using an energy system optimization model and varied model constraints that reflect strategic policy targets. Our results are threefold. First, compared to power systems without hydrogen, systems using hydrogen realize savings of 14–16% in terms of the total system costs. Second, the implementation of a hydrogen infrastructure reduces the number of infeasible scenarios when structural policy targets are considered within the power system. Third, the role of hydrogen is highly diverse at a national level. Particularly, in countries with low renewable energy potential, hydrogen plays a crucial role. Here, high levels of self-sufficiency and security of supply are achieved by deploying hydrogen-based power generation of up to 46% of their annual electricity demand, realized via imports of green hydrogen.

1. Introduction

1.1. Background

The European Union (EU) is pursuing the goal of achieving climate neutrality by 2050 with the European Green Deal[1]. This goal requires a massive but affordable expansion of renewable energy (RE) and the electrification of the heat and transport sector (Deng et al., 2012). The variability and forecast uncertainty of power generation from RE drives the need for additional flexibility in the energy system (Lund et al., 2015). Despite the increased electricity production from intermittent RE, energy policies often aim for high levels of security of supply for power consumers, such as the capability to meet electrical demand at all times[1]. Accordingly, one central research question in energy systems analysis is how 100% renewable and secure power supply can be ensured. In order to design adequate future power systems, energy system optimization models deploy least-cost flexibility options, such as an extensive expansion of the power grid (Cao et al., 2020). However, such system configurations may deviate strongly from targets set in energy policy for the transition of the energy system. This leads to the question of how political targets can be better considered when modeling future energy systems.

1.2. Strategic energy policy targets

Various aspects of security of supply have been considered in the literature. By spreading the risk of generation outages across a large variety of technologies and thus increasing the adaptability to changing conditions, technological diversity can contribute to long-term resilience (Rammel and van den Bergh, 2003). Therefore, it can be considered as an aspect of security of supply (Stirling, 2010). Furthermore, higher self-sufficiency lowers the risk of energy import uncertainties. Finally, secured generation capacities are considered to ensure an adequate power supply despite the intermittent availability of RE power generation. Considering these aspects, a multitude of transformation

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[1] https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF

https://doi.org/10.1016/j.egyr.2021.07.005
2352-4847/

Nomenclature

Indices and sets

g	Set of technologies
g_{group}	Set of technology groups
i	Set of options
r	Set of regions
t	Set of time steps

Parameters

$D_{t,r}^{conv}$	Conventional electricity demand at time step t in region r [GWh]
$D_{t,r}^{eCars}$	Electricity demand for electric vehicles at time step t in region r [GWh]
$D_{t,r}^{el,total}$	Total electricity demand at time step t in region r [GWh]
$D_{t,r}^{heat}$	Heat demand at time step t in region r [GWh]
$D_{t,r}^{hyCars}$	Hydrogen demand for hydrogen vehicles at time step t in region r [GWh]
f_g^c	Secured capacity factor of technology g
f^{E2H}	Electricity-to-heat conversion factor
f^{E2Hy}	Electricity-to-hydrogen conversion factor
f^i	Independence factor
f^m	Technology mix factor
f^s	Security factor
n	Number of options

Variables

$C_{r,g}$	Installed capacity of technology g in region r [GW]
$e_{r,g,t}$	Generated electricity by technology g in region r in time step t [GWh]

Indicators

H	Shannon–Wiener Index
H^{max}	Maximum value of the Shannon–Wiener Index
I_r^{divers}	Indicator of diversity in region r
I^{even}	Indicator of evenness
$I_r^{secured}$	Indicator of security of supply in region r
I_r^{self}	Indicator of self-sufficiency in region r
p_i	Share of option i
p_r	Share of region r

pathways exist for the European power system. However, they largely depend on the particular weighting of the different aspects of security of supply and thus, on political preferences. In the following, we refer to these preferences as strategic policy targets.

Examples of these preferences can be extracted from the long-term energy strategies of different European countries[2]. In this sense, Austria describes two transformation paths that rely on energy imports and a third path without the import of energy sources, whereby a greater expansion of generation capacities becomes necessary[3]. Portugal plans an increasing utilization of RE sources to decrease its dependency on energy imports from 78% to less than 20%. The cost savings from purchasing less fossil fuels can be redirected to boost the economy[4]. However, cross-border transmission capacities between national energy systems are seen as advantageous according to Denmark's long-term strategy to balance fluctuating electricity generation from renewable sources[5]. France strives for a more diversified power generation compared to its current nuclear-dominated system (Hurst, 2017).

1.3. The role of hydrogen

One element that is also frequently mentioned in national strategies for implementing a fully decarbonized energy supply is a hydrogen economy. Although hydrogen can be produced through different approaches, only hydrogen generated purely from RE ("green hydrogen") serves as a solid basis for this purpose. Several European countries plan to use green hydrogen, but mainly for crucial applications where alternatives are highly limited (e.g., for aviation, waterborne transportation, or high-temperature industrial processes). In addition, the utilization of green hydrogen for long-term storage in the power sector is being considered as an option for load balancing (Evangelopoulou et al., 2019). However, among the variety of available technologies for load balancing, the affordability of power reconversion from green hydrogen is still a subject of discussion due to its rather low round-trip efficiency (Staffell et al., 2019).

In the literature, Sgobbi et al. analyzed the role of hydrogen in decarbonizing different energy sectors in Europe using the energy system optimization model JRC-EU-TIMES. They showed that the industry and transport sector in particular benefit from green hydrogen, while highlighting the importance of a European CO_2 limit for the transition to hydrogen. The authors investigated a broad spectrum of hydrogen production technologies for a greenhouse gas (GHG) mitigation target of 80% across all energy demand sectors. However, they found that hydrogen plays only a negligible role in the power sector because of the high investment costs of fuel-cell power plants (Sgobbi et al., 2016). Cao et al. examined the role of the electricity grid in comparison to other flexibility options in a low-carbon European energy system with different societal preferences for future supply strategies taken into account. For their analysis, they used the energy system optimization model REMix and compared, among other things, European energy scenarios with and without the availability of hydrogen as flexibility option in the power sector. Despite the dual use of green hydrogen in the transport sector and as a long-term storage option, the corresponding scenarios have higher system costs than their counterparts without hydrogen. Nevertheless, scenarios that go beyond decarbonization targets of −85% GHG mitigation in the power sector have not been investigated (Cao et al., 2020). Evangelopou et al. analyzed the role of hydrogen in a carbon-neutral EU energy system using the PRIMES energy system model. They found that hydrogen can play a beneficial role as chemical storage in the power sector. The authors indicated the importance of hydrogen reaching high technology levels in order to achieve an affordable transition to a carbon-neutral energy system (Evangelopoulou et al., 2019).

2 https://ec.europa.eu/info/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-long-term-strategies_en

3 https://ec.europa.eu/clima/sites/lts/lts_at_de.pdf

4 https://ec.europa.eu/clima/sites/lts/lts_pt_en.pdf

5 https://ec.europa.eu/clima/sites/lts/lts_dk_en.pdf

1.4. Modeling European energy futures

Energy system optimization models (ESOMs) are useful tools for identifying potential system transformation pathways. ESOMs calculate the optimal expansion and dispatch of power plants and other system components while minimizing the total system cost. However, ESOMs use their given degrees of freedom to a full extent to minimize system costs[6]. For example, massive regional imbalances in power generation and the multiplication of today's grid transfer capabilities lead to cost-efficient model solutions. However, from today's point of view, these energy system transformations do not seem plausible. Such effects can be avoided by adding constraints on resource availability and grid expansion, or by enforcing national self-sufficiency shares. In other words, implementing strategic policy targets as constraints in ESOMs contributes to increasing the plausibility of the model results.

According to Zappa et al., who compared different studies of optimized energy systems with high RE shares, the aspect of security of supply is only rarely considered in ESOMs. The authors included spinning and standing reserve capacities in their model to achieve a high level of supply security in the short and long term. Using the PLEXOS model, they found that a European power system that consists of 100% renewable energy is feasible; however, large amounts of biomass are necessary as a flexibility option. Other flexibility options such as hydrogen were not considered in this study; however, they are suggested as part of future research (Zappa et al., 2019). Keles et al. examined the impact of a coal phase-out as a decarbonization strategy on the German and European level. For their analysis, they used the ESOM PERSEUS. To provide a sufficient level of secured reserve capacity despite the phase-out of coal power plants, the authors implemented a "generation adequacy restriction" in their model. In addition to the expansion of higher numbers of renewable energy sources, additional gas power plants are installed owing to their high availability factors (Keles and Yilmaz, 2020). Tröndle et al. analyzed the effect of a self-sufficiency constraint with supply scales that range from continental to subnational with an ESOM based on the Calliope framework. They found that self-sufficiency is possible even at a subnational level for a fully renewable European power system. The associated increase in total system cost is approximately 20% (Tröndle et al., 2020). Dominković et al. achieved a 100% renewable energy system for southeast Europe with the energy system model EnergyPLAN, while only allowing the sustainable use of biomass. The distinct geographical features of the analyzed region require the use of a variety of technologies to meet the decarbonization target. The authors identified the 100% renewable energy system for southeast Europe as diverse, since an ex-post analysis showed that no technology produced more than 30% of the annual energy supply. Therefore, the authors declared that the energy system is robust (Dominković et al., 2016).

1.5. Contribution

To construct European energy scenarios, understanding the effects and interactions of various strategic policy targets is important because these targets can compete with or complement each other. Although such targets have already been considered in analyses of European energy scenarios, we conclude from the literature review that, on the one hand, analyses of the interactions of the corresponding model constraints have not been systematically investigated. On the other hand, hydrogen is often not considered as a carbon-neutral option for achieving these strategic policy targets. Other studies that consider hydrogen in the power sector lack ambitious GHG mitigation targets or do not have strategic policy targets included in their analysis of a decarbonized European power system. Therefore, studies analyzing the role of hydrogen are lacking, especially when different strategic policies and high decarbonization targets are considered for the European power system.

Accordingly, the following research questions are examined in this study:

1. What are the impacts of different political targets on the structure, technological preferences, and costs of a 100% renewable European power system?
2. How do a large-scale hydrogen infrastructure and hydrogen imports affect the costs and structure of the power system?
3. What impacts of political targets and hydrogen usage in the power sector can be observed at the national level?

The remainder of this paper is structured as follows: In Section 2, the methods and data used are introduced. The model results of optimized European energy systems with varying political targets are presented in Section 3 and discussed in Section 4. Finally, Section 5 summarizes the findings of this study and presents policy implications.

2. Methods

The following section describes the applied model for the energy system optimization and the general model setup in more detail. Furthermore, the sectors considered and the underlying input data are presented. Finally, the implementation of the strategic policy targets into the model and the considered scenarios are described.

2.1. Energy system optimization model

To investigate the possible future compositions of a fully decarbonized European energy system, the ESOM REMix is used. REMix identifies least-cost energy system configurations while representing the power sector, coupled to energy demands from heat and transport. With consideration given to weather, technology, and scenario data, REMix optimizes the dispatch and expansion of power plants, energy storage, and the transmission grid, while minimizing the total system cost. The total system cost is composed of operating and investment costs. Constraints and limits such as annual biomass budgets, and heat, power, and fuel demands are inputs to the model and are considered as so-called scenario data. Additional political targets can also be added to the scenario data. Further details on the model and its components are described by Gils et al. (2017).

2.2. General model setup

The spatial scope in this paper covers the member states of the European Network of Transmission System Operators for Electricity (ENTSO-E)[7] without Cyprus, Iceland, and Turkey. Additionally, the North African (NA) countries Algeria, Morocco, and Tunisia are considered in the analysis. Due to their high RE potential, they can export additional electricity to Europe. The overall considered area is referred to as the EUNA region. Each country is represented by one node making a total number of 36 model nodes. The analyzed year 2050 has an hourly time resolution of 8760

6 https://www.bmwi.de/Redaktion/DE/Downloads/U/untersuchungsgegenstand-szenarioarchitektur-und-aussagekraft-der-szenarien.pdf?__blob=publicationFile&v=8

7 https://www.entsoe.eu/about/inside-entsoe/members/

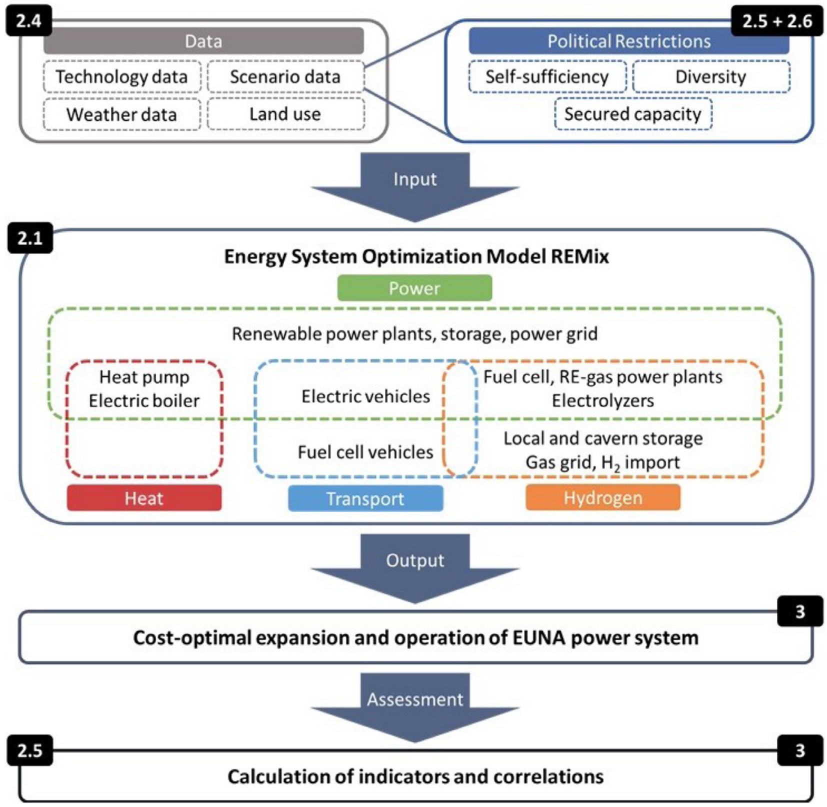

Fig. 1. Model setup overview. The scenario data includes strategic policy targets that are varied throughout the scenarios. The ESOM REMix optimizes the expansion and operation of power plants, storage and the power grid while minimizing the total system costs. REMix represents a coupled energy system consisting of the power, heat and transport sector. Fossil-fueled power plants are not included. Indicators and correlations are calculated ex-post for the assessment of the analyzed scenarios. The numbers in the black boxes refer to the corresponding chapters.

consecutive time steps. The RE potentials are calculated using REMix-EnDAT (Stetter, 2014).

Fig. 1 presents an overview of the model setup. This model is adapted from (Cao et al., 2020). The strategic policy targets are varied in various scenarios and implemented as restrictions in REMix. The impacts of the various political restrictions on the structure of the optimized EUNA power systems are assessed, amongst others, with indicators of the strategic policy targets and their correlations. The calculation of these indicators is described in Section 2.5.

2.3. Basic assumptions

The main focus of this study is the decarbonization of the power sector. Only those parts of the heat and transport sector that are assumed to be electrified and hydrogen-fueled by 2050 according to Cao et al. (2020) are considered and coupled to the power and hydrogen sector. The annual electricity demand of conventional consumers is based on the scenario "Small & Local" from the e-Highway2050 study, where low economic growth and high energy efficiencies are expected in Europe. Therefore, the conventional demand is assumed to decline from approximately 3200 TWh in 2014 to 2700 TWh in 2050 (Bruninx et al., 2014). The assumptions regarding electricity demand for heat pumps and electric heaters are derived from Scholz et al. (2014), resulting in an additional electricity demand of 185 TWh. The annual hydrogen and electricity demand for the transport sector are based on the e-Highway scenario "Small & Local" and scenario A from Pregger et al. (2013). The annual electricity consumption of electric vehicles is assumed to be 263 TWh, and the translated electricity demand for hydrogen vehicles is approximately 570 TWh (Cao et al., 2020).

No CO_2 emissions are allowed for the scope of the model. REMix takes on the role of a central planner with perfect foresight while minimizing the overall system costs of the decarbonized EUNA power system. For optimization, we use a target planning approach. Strategic policy targets are applied at the national level.

In the following sections, the assumptions made for the power and hydrogen sector are described in more detail.

2.3.1. Power sector

Although we assume that no CO_2 emissions are allowed in the power sector in the year 2050, the use of carbon capture and storage (CCS) is not included in our calculations because its commercial availability is highly unclear (Von Hirschhausen et al., 2012). Therefore, the utilization of only a limited number of power plant types, including photovoltaic (PV), wind onshore and offshore, concentrated solar power (CSP), hydro power, biomass, and geothermal power plants is permitted in the ESOM. Nuclear power plants are included and can be expanded in countries that plan further operations according to today's energy policy. Coal-fired power plants are omitted, which is consistent with the goal of several European countries to shut down these power plants (Bixel, 2020).

2.3.2. Hydrogen sector

To meet the exogenous demand for fuel cell vehicles the production, storage, and transport of hydrogen are considered. Electrolyzers use electricity to produce green hydrogen. This hydrogen is stored either in salt caverns or in local storage tanks as indicated in Cao et al. (2020). The hydrogen stored in the salt caverns can either be accessed directly by hydrogen stations to fuel hydrogen vehicles, or transported between countries through the existing gas grid. To transport hydrogen through the gas grid, it is converted to methane with a conversion efficiency of 80%. Carbon, which is used to convert hydrogen to methane, is part of a carbon cycle and can have multiple sources, such as direct air capture or carbon that is generated as a by-product in chemical processes. However, the provision of this carbon exceeds the scope of this study and is therefore not accounted for. One option for the utilization of methane is its application in the fuel cell vehicles. Methane can also be accessed through the gas grid to operate solid oxide fuel cell (SOFC) power plants, and it can replace natural gas in open-cycle gas turbine (OCGT) and combined combustion gas turbine (CCGT) power plants. Hence, their operation can be realized without any carbon emissions. This adds a further flexibility option to the energy system in addition to the electricity grid, battery, and pumped hydro storage. Additionally, in each country, it is possible to import hydrogen from outside the considered regional scope and use it in either the transport or power sector. Hydrogen and methane are summed up under the term "RE-gas" in the following sections. The ESOM optimizes the amount of hydrogen produced by each country and the amount of imported hydrogen.

2.4. Data

Similar to the model setup, the existing power plant, storage and grid capacities, as well as the fuel, heat and electricity demand, and technological data are based on Cao et al. (2020) and are partially updated or added. The investment costs of hydro run-of-river power plants are derived from Lopion et al. (2020). The lifetime and fixed operations and maintenance costs of pump storage are updated based on Cao et al. (2019) and Lopion et al. (2020) respectively. Furthermore, the cost of cavern storage is calculated based on Michalski et al. (2017). The investment costs of local hydrogen storage are based on studies by the Danish Energy Agency[8]. The cost and efficiency parameters of the electrolyzers and hydrogen storage are presented in Table 1. The price of imported hydrogen of 120 €/MWh$_{H2}$ is derived from Lopion et al. (2020). Solid oxide fuel cells are added as further power plant technology, and their techno-economic data are also based on Lopion et al. (2020). Moreover, the list of countries in which nuclear power plants can be expanded is updated[9,10,11,12].

The techno-economic data (investment costs, fixed and variable operations and maintenance costs) for each technology, as well as the installed capacities and expansion limits for each technology and country are listed in the Supplementary Material.

2.5. Implementation and indicators of strategic policy targets

This section describes how the strategic policy targets are implemented as constraints in the ESOM REMix. Furthermore, indicators for analyzing the resulting European energy systems are declared.

Table 1
Efficiency and cost parameters for electrolyzers and hydrogen storage. The efficiency of the electrolyzers represents the ratio of the chemical energy of the hydrogen produced to the electrical energy needed for producing it. For the hydrogen storage the roundtrip efficiency is presented. The value of the fixed operations and maintenance costs (O&M fix) is represented as a percentage of the investment costs.

	Efficiency [%]	Invest. costs [€/kW$_{el}$]	O&M fix [%]	O&M var [€/kWh$_{el}$]
Cavern electrolyzer	84	305	2	0.001
Local electrolyzer	69	853	1.5	0.001
	Roundtrip efficiency [%]	Invest. costs [€/kWh$_{ch}$]	O&M fix [%]	O&M var [€/kWh$_{ch}$]
Cavern storage	95.6	62	3	0
Local storage tank	95.6	1227	2	0

Table 2
Technology groups considered within the technology mix constraint and their corresponding power plant technologies.

Power plant technology	Technology group
CCGT	RE-gas
OCGT	RE-gas
SOFC	RE-gas
Hydro reservoir	Hydro
Hydro run-of-river	Hydro
Nuclear	Nuclear
CSP	CSP
Biomass	Biomass
Geothermal	Geothermal
Wind offshore	Wind offshore
Wind onshore	Wind onshore
PV	PV

2.5.1. Technology mix

The diversity of the energy system is implemented as a technology mix constraint to diversify the installed capacities.

The technology mix constraint

$$\sum_{g \in g_{\mathrm{group}}} C_{\mathrm{r,g}} \leq \sum_{g} C_{\mathrm{r,g}} f^{\mathrm{m}}, \quad \forall\, r, g_{\mathrm{group}}. \tag{1}$$

ensures that the share of the installed capacities C of all technologies g within a technology group g_{group} per region r is not higher than indicated by the technology mix factor f^{m}. In a scenario with a technology mix factor $f^{\mathrm{m}} = 20\%$, at least five technology groups must be available in each region.

Table 2 lists the technology groups considered within the technology mix constraint. Similar power plant technologies are combined into technology groups. For example, the technology group "RE-gas" includes OCGT, CCGT and SOFC power plants because they all rely on the availability of hydrogen. A total of nine technology groups can be exploited by the model to diversify the energy system.

Multiple diversity indicators are available to evaluate the diversity of the energy systems. The Shannon–Wiener Index and the Herfindahl–Hirschman Index take two main diversity aspects into account: variety and balance (Stirling, 2010). Variety refers to the number of available options, and balance refers to how even the quantity in question is distributed among these options (Stirling, 1998). Cooke et al. indicate that in comparison to other indices, the Shannon–Wiener Index

$$H = -\sum_{i=1}^{n} (p_{\mathrm{i}} \ln p_{\mathrm{i}}) \tag{2}$$

8 https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_energy_storage.pdf
9 https://www.world-nuclear.org/information-library/country-profiles/countries-o-s/poland.aspx
10 https://world-nuclear.org/information-library/country-profiles/countries-a-f/bulgaria.aspx
11 https://www.world-nuclear.org/information-library/country-profiles/others/emerging-nuclear-energy-countries.aspx
12 https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/belgium.aspx

acknowledges the existence of small contributors with higher weights (Cooke et al., 2013). We therefore use the Shannon–Wiener Index to quantify the diversity within the analyzed energy systems. In Eq. (2), n refers to the number of options, and p_i is the share of option i within the whole quantity. The diversity indicator I_r^{divers} of region r can be calculated as e^H (Wu and Rai, 2017).

2.5.2. Self-sufficiency

There are different dimensions of self-sufficiency. The supply scale indicates the spatial scope across which the system is net self-sufficient throughout the year. The balancing scale describes the geographical area throughout which the fluctuating RE electricity generation can be balanced (Tröndle et al., 2020).

In this study, we assume an energy system with national supply and transcontinental balancing. This means that electricity can be imported and exported to compensate for intermittent RE electricity generation, but in total, each country produces a predefined share of its annual energy demand throughout the year.

The annual energy demand includes the electricity demand for the power sector $D_{t,r}^{conv}$, demand for the heat sector $D_{t,r}^{heat}$, and for the transport sector. In addition to the electricity demand for electric vehicles $D_{t,r}^{eCars}$, the fixed annual hydrogen demand for fuel cell vehicles $D_{t,r}^{hyCars}$ is considered in the transport sector. The heat and hydrogen demand are translated into the corresponding electricity demand by an electricity-to-heat conversion factor f^{E2H} and an electricity-to-hydrogen conversion factor f^{E2Hy}. The conversion factors are derived from the efficiencies of the electrolyzers, electric boilers, and the coefficient of performance of the heat pumps. The total electricity demand per region r and time step t is then defined as

$$D_{t,r}^{el,total} = D_{t,r}^{conv} + D_{t,r}^{heat} f^{E2H} + D_{t,r}^{eCars} + D_{t,r}^{hyCars} f^{E2Hy}, \quad \forall\, t, r. \tag{3}$$

Most long-term strategies by member states of the EU published to this date do not indicate a target degree of independence. Therefore, a partial self-sufficiency of European nations is also possible. In this context, we introduce the independence factor f^i which indicates the minimum degree of self-sufficiency per country. Its value ranges from 0 to 1. Therefore, the minimally annually produced amount of electricity e per region r by all power plant technologies g can be described as

$$\sum_t D_{t,r}^{el,total} f^i \le \sum_{g,t} e_{r,g,t}, \quad \forall\, r. \tag{4}$$

The self-sufficiency indicator of a region r therefore amounts to

$$I_r^{self} = \sum_{g,t} e_{r,g,t} / \sum_t D_{t,r}^{el,total}, \quad \forall\, r. \tag{5}$$

A higher self-sufficiency of each nation leads to more evenly distributed capacities. Therefore, to measure the level of self-sufficiency of the entire EUNA region, an indicator of evenness is applied. Pielou defines evenness

$$I^{even} = H/H^{max} \tag{6}$$

as the ratio between the Shannon–Wiener Index H from Eq. (2) and its maximum value (Pielou, 1966)

$$H^{max} = \ln n. \tag{7}$$

To determine the EUNA self-sufficiency evenness the number of options n equals the number of countries implemented in the model. The share

$$p_r = I_r^{self} / \sum_{i=1}^{n} I_i^{self} \tag{8}$$

of country r for the calculation of the Shannon–Wiener Index H is defined as its self-sufficiency indicator from Eq. (5) divided by the sum of the self-sufficiency indicators of all countries.

Table 3
Secured capacity factors f_g^c of power plant technologies. The secured capacity factor for dispatchable technologies equals their availability. RE technologies have a significantly lower secured capacity factor.

Power plant technology	Secured capacity factor f_g^c
CCGT	96%
OCGT	94.8%
Nuclear	94%
CSP	90%
SOFC	90%
Biomass	90%
Geothermal	90%
Hydro reservoir	60%
Hydro run-of-river	40%
Wind offshore	8%
Wind onshore	5%
Photovoltaic	0%

2.5.3. Secured capacity

Every power plant technology provides different availabilities, and therefore, different secured capacities (Keles and Yilmaz, 2020). Hence, different technologies can contribute to different extents to the security of supply. This is indicated by a secured capacity factor f_g^c for each power plant technology g.

Table 3 shows the secured capacity factors f_g^c for the power plant technologies in our model. The secured capacity factors f_g^c of dispatchable power plant technologies are comparably high because they depend only on the availabilities of the power plants, which are represented by constant values in the model. RE technologies have a relatively low secured capacity factor f_g^c, owing to their fluctuating electricity generation. Their secured capacity factors are derived from a study on capacity development conducted by Borggrefe et al. (2014). The more dependence the RE technology has on the changing weather conditions, the lower the secured capacity factor f_g^c. Since PV power plants are never available during the night in cases of unexpected shortages, they cannot provide any secured capacity. CSP power plants in comparison run with an attached heat storage and can therefore provide a base load, also during the night.

In the equation for the secured capacity constraint

$$\max_t (D_{t,r}^{el,total}) f^s \le \sum_g C_{r,g} f_g^c, \quad \forall\, r \tag{9}$$

the security factor f^s indicates the minimum share of the peak electricity demand that must be available as a secured capacity. The secured capacity is calculated by multiplying the capacities $C_{r,g}$ of each power plant technology g for each region r with its respective secured capacity factor f_g^c from Table 3. Therefore, the security of supply indicator of region r can be calculated as

$$I_r^{secured} = \sum_g C_{r,g} f_g^c / \max_t (D_{t,r}^{el,total}), \quad \forall\, r. \tag{10}$$

2.6. Main scenarios

To analyze the influence of different strategic policy objectives on a climate neutral European power system, the political restrictions listed in Section 2.5 are implemented in the ESOM REMix. They can be switched on and off separately and the degree of the restrictions can be varied.

Table 4 presents the variations in political restrictions in the 27 main hydrogen scenarios. The "H2:base" scenario does not

Table 4
Main scenarios. The political restrictions are varied in 27 main hydrogen scenarios. The "H2:base" scenario does not include any additional political restriction. The price for imported hydrogen and the investment costs for electrolyzers and hydrogen storage are as indicated in Table 1.

Scenario	Min. self-sufficiency [%]	Min. secured capacity [%]	Max. share per tech. [%]	H_2	H_2 import cost doubling	H_2 domestic cost doubling
H2:base				✓		
H2:self80	80			✓		
H2:self100	100			✓		
H2:secured100		100		✓		
H2:secured120		120		✓		
H2:divers40			40	✓		
H2:divers20			20	✓		
H2:self80:secured100	80	100		✓		
H2:self80:secured120	80	120		✓		
H2:self100:secured100	100	100		✓		
H2:self100:secured120	100	120		✓		
H2:self80:divers40	80		40	✓		
H2:self80:divers20	80		20	✓		
H2:self100:divers40	100		40	✓		
H2:self100:divers20	100		20	✓		
H2:secured100:divers40		100	40	✓		
H2:secured100:divers20		100	20	✓		
H2:secured120:divers40		120	40	✓		
H2:secured120:divers20		120	20	✓		
H2:self80:secured100:divers40	80	100	40	✓		
H2:self80:secured100:divers20	80	100	20	✓		
H2:self80:secured120:divers40	80	120	40	✓		
H2:self80:secured120:divers20	80	120	20	✓		
H2:self100:secured100:divers40	100	100	40	✓		
H2:self100:secured100:divers20	100	100	20	✓		
H2:self100:secured120:divers40	100	120	40	✓		
H2:self100:secured120:divers20	100	120	20	✓		

include any additional political restrictions. In scenarios that consider the independence of the electricity supply, partial self-sufficiency ($f^{\mathrm{i}} = 80\%$), and full self-sufficiency ($f^{\mathrm{i}} = 100\%$) are implemented. Furthermore, scenarios for considering the secured capacity are implemented, which ensure that at least the peak demand is available as secured capacity in each region ($f^{\mathrm{s}} = 100\%$ and $f^{\mathrm{s}} = 120\%$). To diversify the energy system, the technology mix factors $f^{\mathrm{m}} = 40\%$ and $f^{\mathrm{m}} = 20\%$ are included.

Finally, a combination of the introduced restrictions and their values is implemented. For example, the ambitious scenario "H2:self100:secured120:divers40" combines 100% self-sufficiency and 120% secured capacity with a technology mix factor of 40%. The last two columns indicate that in all main scenarios, the cost of imported hydrogen and the investment costs for hydrogen storage and electrolyzers (H_2 domestic cost) match the values in Table 1. All restrictions are implemented at the national level.

2.7. Sensitivity analysis of hydrogen

To examine how possible variations in the estimated costs of hydrogen production, storage, and import influence the energy system, three further sensitivity cases are included. Lopion analyzes the import costs of various renewable fuels, such as hydrogen and synthetic methane, and finds costs ranging from 101 €/MWh to 205 €/MWh (Lopion et al., 2020). In their study on carbon-neutral hydrogen, Evangelopoulou et al. indicate that the cost of hydrogen production presents the main uncertainty (Evangelopoulou et al., 2019). Therefore, in our sensitivity cases either the price of imported hydrogen (see Section 2.4), the investment costs of electrolyzers and hydrogen storage from Table 1, or both are doubled in order to account for the cost uncertainties of hydrogen. As indicated in Table 5, these cost variations are applied to the "H2:base" scenario and to the ambitious "H2:self100:secured120:divers40" scenario.

Furthermore, to analyze the role of hydrogen in the implementation of the different political restrictions, a sensitivity case without the use of hydrogen is considered. The sensitivity case without hydrogen is applied to the 27 political restriction variations from the main scenarios. For this sensitivity case, we assume that the availability of green hydrogen is limited to crucial applications such as industrial processes, and so it is not considered in the power sector. Therefore, the production, transport, storage, and reconversion of hydrogen is not taken into account. Because hydrogen is not available for reconversion, RE-gas power plants cannot be used. In addition, the exogenous hydrogen demand for fuel cell vehicles is omitted. In previous studies, hydrogen is often not considered when 100% renewable power systems are analyzed (Zappa et al., 2019; Dominković et al., 2016). In comparing the sensitivity case without hydrogen to the scenarios with hydrogen, we can assess how pivotal the role of hydrogen is within ESOMs, especially with regard to the considered political targets.

3. Results

To analyze the influence of strategic policy targets on the overall European power system, the total system costs and capacity variations for the various scenarios are compared and interdependencies are identified. The findings are further examined for power systems at a national level to determine the role of hydrogen in individual European countries.

3.1. Impact on the total system costs

Fig. 2 shows the increase in system costs when different restrictions are added. For instance, the indicator "Self 100%" distinguishes the system cost of scenarios with and without the 100% self-sufficiency constraint and with the same configurations otherwise (e.g. the system cost increase of the "H2:self100:divers40" scenario compared to the "H2:divers40" scenario). The system cost increases are given relative to the system cost in the "H2:base" scenario.

Table 5
Scenarios for sensitivity analysis of hydrogen. Either the cost of imported hydrogen, self-produced hydrogen or both are doubled. Additionally, a sensitivity case without hydrogen demand and without hydrogen availability in the power sector is applied to the 27 political restriction variations from the main scenarios.

Scenario	Min. self-sufficiency [%]	Min. secured capacity [%]	Max. share per tech. [%]	H_2	H_2 import cost doubling	H_2 domestic cost doubling
H2:base:import2				✓	✓	
H2:base:domestic2				✓		✓
H2:base:import2:domestic2				✓	✓	✓
H2:ambitious:import2	100	120	40	✓	✓	
H2:ambitious:domestic2	100	120	40	✓		✓
H2:ambitious:import2:domestic2	100	120	40	✓	✓	✓
NoH2:base						
...						
NoH2:self100:secured120:divers20	100	120	20			

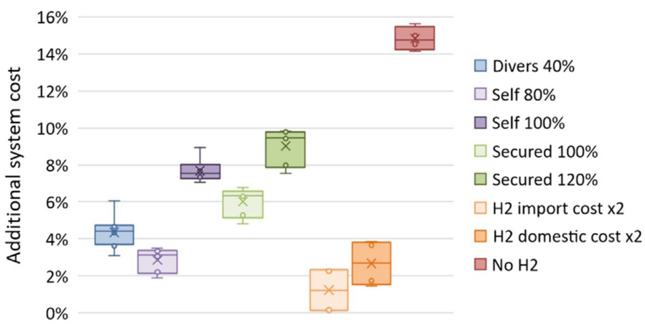

Fig. 2. Additional system costs due to political restrictions, increased hydrogen import and technology costs or the omission of hydrogen. A self-sufficiency of at least 80% per country is achievable with a 2–3% cost increase. Full net self-sufficiency is significantly more expensive. The political restriction of secured capacity shows a less steep cost increase between energy systems with 100% and 120% secured capacity per country. With import prices and investment costs for domestic hydrogen generation twice as high as initially assumed, the system costs are still considerably lower compared to energy systems without hydrogen. Hydrogen plays a central role in achieving the considered political goals.

Table 6
Installed capacities in the "H2:base" scenario. In this scenario no strategic policy targets are applied.

Technology	Capacity C [GW]
Nuclear	2.8
Hydro	219.2
Geothermal	<0.1
Biomass	<0.1
RE-gas	172.0
CSP	96.2
PV	686.0
Wind onshore	625.4
Wind offshore	47.4
Electr. grid	581.9
Li-ion battery	136.7
Pumped storage	52.3
Electrolyzer	130.6

A maximum share of 20% per technology group is not feasible in any of the scenarios considered. Scenarios with a maximum share of 40% per technology group, represented by the "Divers 40%" box, can be implemented with additional costs of about 4% on average, as indicated by the cross. A political restriction of 80% self-sufficiency per country can be implemented with similar cost increases. However, the additional 20% of electricity generation per country in order to become fully net self-sufficient is linked to significantly higher additional system costs of about 7–9% compared to scenarios without a self-sufficiency constraint.

In comparison, the increase in the system costs of energy systems with at least 100% secured capacity per country to energy systems with 120% secured capacity is less steep, with an average of 3%.

The influence of higher hydrogen costs is analyzed with a doubling of cost estimates for both imported hydrogen ("H2 import x2") and for electrolyzers and hydrogen storage ("H2 domestic x2"). In addition, a combination of cost increases in both quantities is examined. The system costs increase by up to 4% due to each increase in the hydrogen costs. In comparison, in energy systems where a hydrogen infrastructure is not implemented at all, system costs increase by up to 16%. Although the exogenous hydrogen demand for fuel cell vehicles ceases, at the same time hydrogen is no longer available for long-term energy storage and flexible application in RE-gas power plants. Therefore, a majority of the political restrictions are not applicable in scenarios without

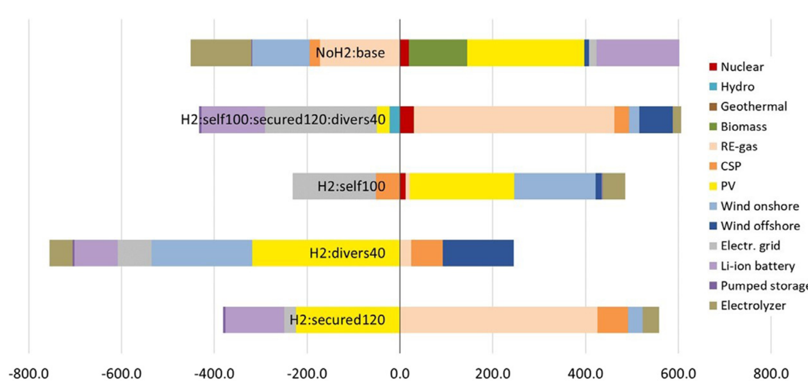

Fig. 3. Capacity differences compared to the "H2:base" scenario. Scenarios with a secured capacity constraint need a higher amount of flexible RE-gas power plants and less lithium-ion batteries. In diverse energy systems, CSP and offshore wind power are partially substituting PV and onshore wind power. Self-sufficiency leads to a reduced electricity grid expansion. Scenarios without hydrogen are more dependent on biomass and battery storage.

hydrogen. A secured capacity of at least 100% per country is not feasible in any of the scenarios, and a more diverse energy system per country is only possible when no additional self-sufficiency constraint is applied. This indicates that hydrogen plays a central role in the energy system, especially when additional political goals are required to be met.

A variety of strategic policy targets can be implemented in a decarbonized European power system, each at an additional cost increase of 2–10%. Above all, the availability of hydrogen in the power sector plays a crucial role. First, power systems without hydrogen are significantly more expensive, even compared to power systems where the hydrogen costs are doubled. Apart from the costs, power systems without hydrogen cannot be realized in most cases; only four out of the 27 political target variations are feasible. Power systems without hydrogen especially struggle with providing the required levels of secured capacity.

3.2. Impact on the overall European energy system

Fig. 3 shows the deviation in capacity expansion for different scenarios compared with the "H2:base" scenario. As a reference, the installed capacities in the "H2:base" scenario are listed in Table 6.

A secured capacity constraint of 120% adds a significant amount of RE-gas power plant capacity to the energy system in the "H2:secured120" scenario. PV capacities are partly replaced by more CSP power plants, which provide a higher secured capacity. The energy system becomes more diverse as wind offshore and CSP partially replace wind onshore and PV capacities in the "H2:divers40" scenario. Due to their higher secured capacity factors, the total installed capacity decreases compared to the "H2:base" scenario. Simultaneously, with decreasing lithium-ion battery and grid capacities, less flexibility is implemented in the system. Furthermore, the electrolyzer capacities decrease as the amount of fluctuating RE power plants decrease. To gain more self-sufficiency, the capacities of PV and wind onshore increase, while CSP capacities decrease in the "H2:self100" scenario. Since every country has to fulfill its self-sufficiency constraint, poorer locations for RE have to be used, whereby higher RE capacities need to be installed. The electricity grid becomes less relevant, and its capacity decreases considerably. In the scenario "H2:self100:secured120:divers40" with all three constraints applied, the amount of RE-gas power plant capacity increases significantly, fulfilling the secured capacity constraint. More wind offshore and CSP capacities compared to the "H2:base" scenario result in a more diverse energy system. The power plant expansions in this scenario lead to less dependency on the electricity grid and lithium-ion batteries as flexibility options. In comparison to the "H2:base" scenario, the unconstrained scenario without hydrogen "NoH2:base" lacks the RE-gas power plant and electrolyzer capacities. As no long-term storage is available, the model chooses to invest in more lithium-ion batteries to provide short-term balancing. This is accompanied by high PV capacities, whose power generation profiles better fit with typical battery cycles. As a result, less wind onshore is used. Furthermore, to gain more flexibility and reliability, biomass and nuclear power plants are installed to a greater extent. Nuclear power plants are almost non-existent at the European and North African level in the "H2:base" scenario. Only if hydrogen is unavailable in the "NoH2:base" scenario or a self-sufficiency constraint is added in the "H2:self100" scenario, do nuclear power plants become an attractive option.

The strategic policy targets lead to fundamentally different European energy systems. Depending on the applied political targets, the structure of the European power system varies in size and the deployment of different flexibility options. Moreover, different power plant technologies are best suited to achieve each strategic policy target in the most cost-optimal way. To further study the dependency of the energy system infrastructure on these targets, various indicators are analyzed in their correlation. The correlation is applied to the main hydrogen scenarios.

The correlation matrix in Fig. 4 shows the interdependencies of the strategic policy targets in the main scenarios and the infrastructure of the EUNA energy system. The correlation matrix is derived using the Pearson correlation coefficient, which is an indicator of linear positive and negative correlations. The self-sufficiency for the whole region indicates how evenly the power generation is split between the countries in comparison to their individual electricity demands (see Section 2.5.2). The secured capacity indicator indicates how much secured capacity is available in the entire EUNA region. The indicators "diversity of caps" and "diversity of supply" are derived by the Shannon–Wiener Index and indicate the diversity of the installed power plant capacities and electricity generation in the EUNA region.

A higher level of self-sufficiency in Europe requires less grid capacity expansion, since spatial load compensation becomes less necessary. Import dependency on North African countries decreases. At the same time, more self-sufficiency leads to a higher exploitation of nuclear power plants. More regionally produced electricity is accompanied by a more diverse electricity generation in the EUNA region. The constraint of higher secured capacities is fulfilled by additional CSP and RE-gas power plants. However, the power generation of RE-gas power plants increases to a much lower extent, which leads to a reduction in annual full load hours (FLH). Nevertheless, with a higher share of dispatchable power plants and less PV in the energy system the necessity for temporal balancing by lithium-ion batteries decreases. With the availability of more wind onshore power plants and more total installed capacity the amount of electrolyzer capacity increases. A higher number of fluctuating RE power plants leads to longer time periods with excess electricity available. This excess electricity can be exploited to produce more hydrogen within the EUNA region. Hence, less additional hydrogen is imported from outside the region. To obtain an energy system with higher power plant diversity, PV and onshore wind power plants are partially replaced by CSP and wind offshore power plants. Since these technologies have higher secured capacity factors, a decreasing necessity for lithium-ion batteries is noticeable, and lower power plant capacities are installed throughout the EUNA region. Furthermore, as technologies with higher secured capacity factors are used, the frequency and extent of generation peaks are reduced. This lowers the production of hydrogen in the EUNA region at the expense of higher imports.

Various strategic policy objectives alter the European energy system to different extents. The exploitation of different power plant technologies is identifiable. In addition, the necessity for flexibility options, such as lithium-ion batteries and electricity grids, decreases if these political targets are implemented. On the other hand, RE-gas power plants are installed in higher numbers since they promote achieving the strategic policy targets, especially with regard to secured capacities. However, these modifications of the structure of the European energy system are associated with higher system costs.

3.3. Impact on national level

In the main scenarios, where hydrogen is available in the power sector, each European country can achieve the formulated independence, diversity, and security objectives, and combinations of them. However, in each country, different power plant technologies are available, their expansion potentials differ, and the power generation of RE power plants in each region varies depending on the local weather conditions. Therefore, we examine

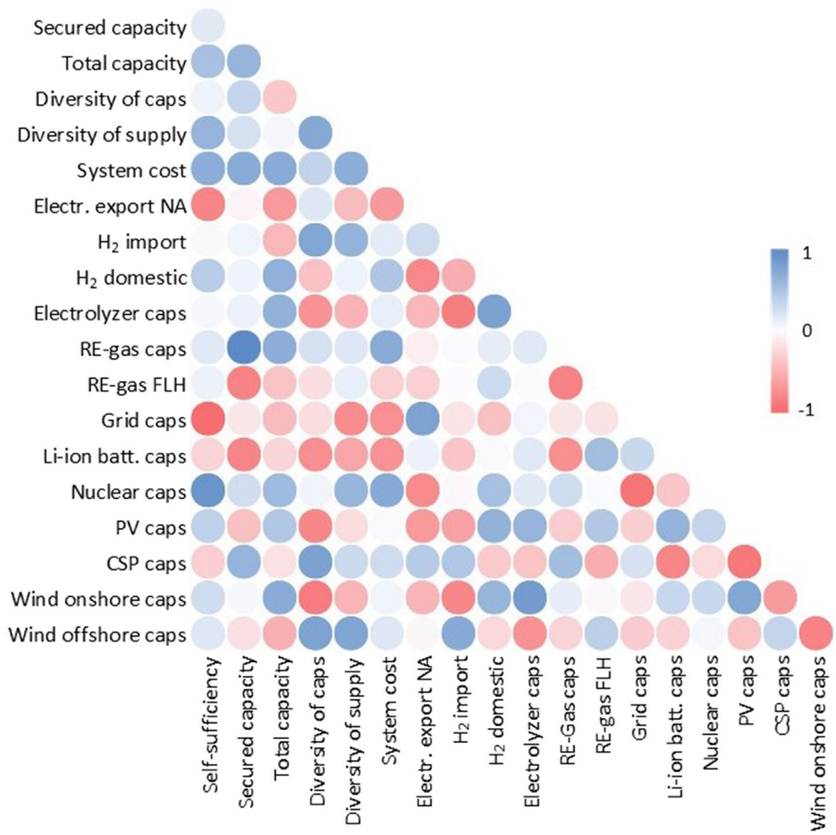

Fig. 4. Interdependencies of strategic policy targets and the structure of the EUNA energy system. Positive values of the Pearson correlation coefficient indicate a positive linear correlation and negative values represent a negative linear correlation. The political constraints lead to different impacts on power plant expansions and varied needs in flexibilities.

the energy systems of four countries with different geographical locations.

Fig. 5 shows the impact of various strategic policy targets on the energy systems of Denmark, Germany, Spain, and Bosnia–Herzegovina. For each country, the diagrams illustrate the installed capacities, electricity exchange, and hydrogen production and exchange. The value of the hydrogen exchange is obtained by subtracting the annual hydrogen export from the total amount of imported hydrogen. Hydrogen can be imported from neighboring countries through the gas grid and from outside the scope of the model.

Denmark has a highly oversized energy system in the "H2:secured120" and "H2:base" scenario. Due to the high but one-sided wind onshore dominated RE potentials, a higher domestic share and diversification result in a significant decrease in power plant capacities, which are otherwise used for the production of high amounts of electricity and hydrogen for export. In the "H2:divers40" scenario, Denmark still exports a large amount of electricity. To meet this export demand, Denmark has to import hydrogen to fuel its RE-gas power plants.

In comparison to Denmark, the energy system in Germany is highly dependent on electricity imports in the "H2:base" scenario. Hydrogen imports are necessary to meet the exogenous hydrogen demand and for further power reconversion. For a more independent energy system, the installed capacities in Germany are considerably increased compared to the "H2:base" scenario. Due to the higher installed power plant capacities, electricity imports decrease significantly, and more hydrogen is produced in Germany. Although the RE-gas power plant capacities in the "H2:self100:secured120:divers40" scenario further increase compared to the "H2:self100" scenario, the amount of electricity generated in them decreases slightly. The higher amount of PV and wind offshore power plants decreases the necessity for power reconversion to meet the self-sufficiency constraint. The additional RE-gas power plant capacities are expanded to provide secured capacity.

To gain more security and diversity, the energy system in Spain replaces PV power plants with CSP power plants. Hydrogen plays a minor role in the Spanish energy system in achieving the different political goals. All hydrogen produced that exceeds the annual hydrogen demand is exported. This is also the case in the "H2:secured120" and "H2:self100:secured120:divers40" scenario, where the installed RE-gas power plants are only added to meet the secured capacity constraint.

Compared to Spain, the energy system in Bosnia–Herzegovina is highly dependent on hydrogen, especially in scenarios with a self-sufficiency constraint. To produce a sufficient amount of electricity to cover the annual electricity demand, RE-gas power plants are used, which also add diversity and security to the energy system. The amount of hydrogen needed to run the RE-gas power plants is seven to nine times the exogenous annual hydrogen demand of Bosnia–Herzegovina. An exchange of hydrogen with neighboring countries is not possible because they lack a gas grid. A small share of the hydrogen is imported from outside the scope of this study. The larger part of the hydrogen used is produced in Bosnia–Herzegovina. However, because insufficient excess electricity is provided by the energy system to produce this high amount of hydrogen a similarly high electricity import as in the other scenarios is necessary in the scenarios with net self-sufficiency. Hydrogen is therefore essential for Bosnia–Herzegovina to meet the analyzed strategic policy objectives.

Overall, different changes to the energy system are necessary for different countries to achieve the strategic policy targets in the

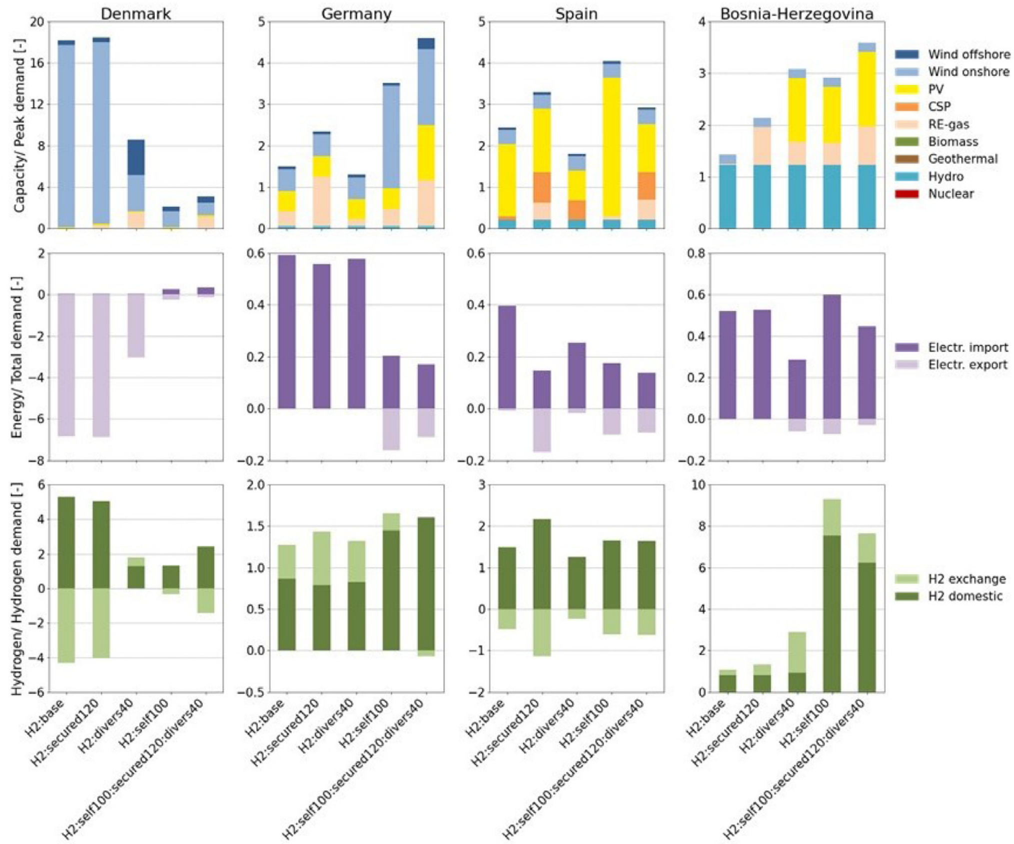

Fig. 5. Influence of strategic policy targets on Denmark, Germany, Spain and Bosnia–Herzegovina. The installed capacities are depicted relative to the peak demand for each country. The electricity imports and exports are shown in relation to the total annual electricity demand. Exports are represented by negative values. The production and import or export of hydrogen is displayed in relation to the exogenous annual hydrogen demand for fuel cell vehicles. Due to Denmark's high wind potentials the country is an exporter of either electricity or hydrogen depending on the applied strategic policy targets. The installed capacities in Germany increase significantly in order to achieve the self-sufficiency objective. Hydrogen does not play a crucial role in Spain's energy system. Hydrogen that is produced on top of its exogenous demand is exported. The energy system in Bosnia–Herzegovina is strongly dependent on electricity imports, even in scenarios with 100% self-sufficiency.

most cost-optimal manner. In particular, the role of hydrogen for reconversion is highly diverse. Therefore, we examine the electricity generation by RE-gas power plants in each EUNA country with varying political objectives applied.

Fig. 6 shows the electricity generation of RE-gas power plants for all considered European and North African countries relative to their total annual electricity demand. Each of the four maps represents varying strategic policy targets.

In the "H2:base" scenario, countries with lower RE potentials use hydrogen to produce additional electricity. As indicated in Fig. 5, the amount of electricity produced differs to a large extent between different countries in order to exploit the best RE sites throughout Europe and North Africa, resulting in countries importing or exporting electricity. The import of hydrogen presents a more cost-optimal alternative to electricity imports for some European countries with poor RE potentials.

The map on the lower left shows the "H2:secured120" scenario. The same countries generate electricity in RE-gas power plants as in the base scenario, but to a greater extent. When a 120% secured capacity constraint is applied, the capacities of RE-gas power plants are expanded to a greater extent in many cases. These additional capacities are used to generate more electricity by reconverting hydrogen, shifting their import dependency from electricity further in the direction of hydrogen.

In the "H2:self100" scenario, each country has to achieve net self-sufficiency. Italy, for example, can achieve this goal by expanding its PV capacities significantly, making power reconversion in RE-gas power plants less crucial. On the other hand, countries such as France and the Czech Republic, which are highly dependent on electricity imports in the base scenario and have rather low RE potentials, can achieve the goal of self-sufficiency by operating RE-gas power plants to a greater extent. Countries such as Bulgaria and Slovakia switch to electricity generation from nuclear power plants to achieve self-sufficiency.

With a 40% diversity constraint, additional countries such as Ireland and Morocco turn slightly red, which are almost independent of RE-gas power plant electricity generation in the other scenarios. Although these countries are characterized by rather high RE potentials, they often lack diversity in their energy systems. Diversity can be provided by additional RE-gas power plants. These power plants are also used to a greater extent to meet the overall energy demand. Because balancing options such as the electricity grid and batteries decrease in the "H2:divers40" scenario, as indicated in Fig. 3, the operation of RE-gas power plants provides further flexibility.

In summary, we can observe a shift in the extent and the regions where hydrogen is used for power reconversion, depending on the applied strategic policy targets. Hydrogen can be used as an alternative to electricity imports while providing a secure and flexible source of energy. Especially for countries with low RE potentials, hydrogen and RE-gas power plants can play a crucial role in achieving the strategic policy objectives. In addition to RE potentials, other factors such as the availability of alternative energy sources like nuclear power plants, are essential to determine the extent to which hydrogen is exploited in each individual country.

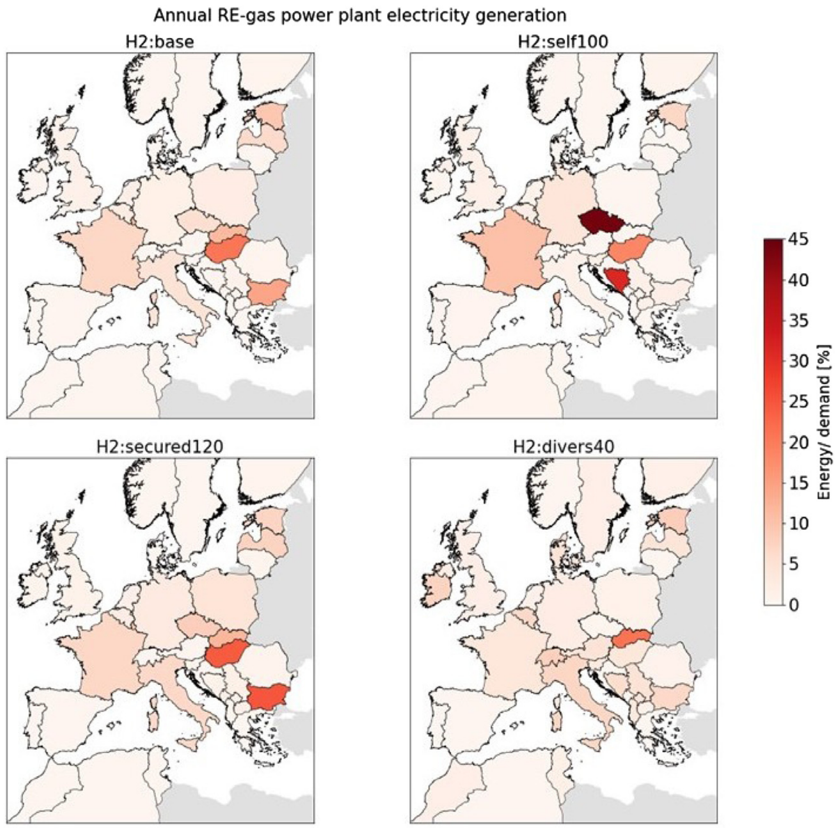

Fig. 6. Electricity generation of RE-gas power plants of European and North African countries for different strategic policy targets. The electricity generation is given relative to each countries total electricity demand. Countries with lower RE potentials are dependent on hydrogen for power generation to a greater extent. In the "H2:secured120" scenario, the additional RE-gas power plant capacities are used to produce more electricity by reconverting hydrogen. The "H2:self100" scenario shows changed regions relying on RE-gas power plants for electricity generation. In the "H2:divers40" scenario, countries with rather high RE potentials use hydrogen in their power plants to diversify their energy system.

4. Discussion

The integration of hydrogen as a flexibility option in fully decarbonized power systems is advantageous from the perspective of cost optimization and for achieving various strategic policy targets. Even when assuming significantly higher hydrogen technology and import costs, the total system costs remain below those for power systems without hydrogen. This relates to the fact that power generation overcapacities and battery storage can be substantially reduced if hydrogen is available for long-term storage.

At first glance, this is in contrast with the findings of Cao et al., who report higher system costs for systems with hydrogen in the power and transport sectors (Cao et al., 2020). However, the results are based on different model assumptions. Cao et al. examine energy systems with an 85% carbon reduction. Thus, natural gas is still available for flexible utilization in gas power plants. The same applies to the findings of Sgobbi et al., which indicate that fuel cell power plants are too expensive at a GHG mitigation target of 80% (Sgobbi et al., 2016). In contrast, no carbon emissions are allowed within our power sector; thus, the flexible use of natural gas is omitted. The system benefits of hydrogen outweigh the low roundtrip efficiency of using hydrogen in the power sector. Evangelopou et al. also emphasize the importance of hydrogen as long-term storage in decarbonized energy systems (Evangelopoulou et al., 2019).

Moreover, with hydrogen, a further technology group is available that contributes to the diversity of the power supply. In addition, hydrogen-fueled power plants add further secured capacity to the system. Power systems without hydrogen lack long-term energy storage. This is compensated for by more generation capacity, and the share of biomass power generation increases significantly. Further flexibility is provided by the expansion of the battery and grid capacities. On the one hand, this makes power systems without hydrogen considerably more expensive than systems with hydrogen. On the other hand, it becomes highly challenging to reach the targets of diversification and secured capacity at a national level, as the corresponding scenarios become infeasible.

The findings concerning the integration of self-sufficiency at a national level are in line with the reported system cost increases, decreasing cross-border transmission capacities and increasing supply capacities in the results from Tröndle et al. (2020). Because the self-sufficiency constraint is only applied to the exogenous energy demand, hydrogen can also be imported for reconversion in RE-gas power plants to achieve self-sufficiency. In the case of Bosnia–Herzegovina, the least-cost option is to produce hydrogen with imported electricity instead of importing hydrogen. Depending on the definition of self-sufficiency by European countries, hydrogen imports and electricity imports for hydrogen production could additionally be accounted for in the self-sufficiency constraint to achieve even higher independence.

The model setup is subject to limitations: while the power sector is fully decarbonized, carbon emissions in the heat and transport sector are possible. GHG mitigation in all sectors is necessary to meet the goal of climate neutrality. Therefore, compared to our assumptions, power and hydrogen demands would increase, and a sufficient amount of RE potential becomes even more important for achieving strategic policy targets. This effect would be further amplified by also considering the hydrogen demands for energy-intensive applications, such as industry and aviation. Moreover, the methanation and gas grid are modeled in a simplistic manner. Improvements may involve the modeling of the chemical conversion process, the provision of carbon, and the transport of hydrogen-based fuels. In this study, the latter is modeled as free of charge and has unlimited transport capacity. This implies two aspects: On the one hand, the transmission capabilities of the gas grid may be overestimated. However, this needs to be assessed against the background of less grid utilization due to the absence of natural gas. On the other hand, our study assumes that the required fuel transmission infrastructure is available in time (e.g., fostered by efforts to transform the existing gas grid for hydrogen consumers in the industry and transport sector). Finally, the directional transmission restrictions of the current gas grid are neglected in this study.

5. Conclusion

This study examines the impact of various strategic energy policy targets and the role of hydrogen in a fully decarbonized European power system. To investigate their interrelationships, a hydrogen infrastructure and hydrogen imports are modeled in the energy system optimization model REMix to complement the technology options of a fully decarbonized power sector. The strategic energy policy goals are implemented as constraints in the model, and their impact intensities are varied in more than 50 scenarios. In particular, these constraints represent the technological diversity, self-sufficiency, and secured power generation capacities of a country.

In our analysis, we benchmark these differently restricted scenarios against scenarios without political constraints in terms of total system costs. We find that the corresponding cost increases for each additional political constraint range between 2% and 10%. The evaluation of the impact on the resulting structure of the European power system shows that (i) technological diversity calls for building more expensive technologies, such as wind offshore and CSP, however with the co-benefit of greater security of supply; (ii) self-sufficiency constraints lead to higher power plant capacities, reducing transmission needs by up to 30%; and iii) RE-gas power plants are a key technology to meet the secured capacity targets.

The crucial role of hydrogen becomes even more apparent when scenarios with and without hydrogen are compared. The analyzed systems benefit from using green hydrogen since the total system costs are 14% to 16% lower than those of power systems without hydrogen. Moreover, hydrogen is mandatory for realizing a wide range of energy policies. Power systems without hydrogen rely to greater extents on biomass power plants and lithium-ion battery storage as flexibility options.

A more detailed investigation at the national level shows that countries with low RE potentials benefit greatly from hydrogen to achieve strategic policy targets. For countries with high RE potentials, the export of hydrogen could become a further asset that boosts their economies. Furthermore, hydrogen can assist in the diversification of their power systems.

Although hydrogen is mentioned in the long-term strategies of several European countries, it is mainly considered for crucial applications. However, this study shows that the integration of hydrogen in the power sector plays a central role in the implementation of a variety of strategic policy targets.

CRediT authorship contribution statement

Shima Sasanpour: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Visualization. **Karl-Kiên Cao:** Conceptualization, Methodology, Software, Investigation, Writing – review & editing, Supervision. **Hans Christian Gils:** Conceptualization, Software, Writing – review & editing, Supervision. **Patrick Jochem:** Conceptualization, 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.

Data availability

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

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Appendix A. Supplementary data

The cost and capacity data used in REMix and the impact of strategic policy targets on the energy system of each county are shown in the supplementary material.

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.egyr.2021.07.005.

References

Bixel, E., 2020. Overview of national phase-out announcements October 2020. [cited 26.11.2020]. URL https://beyond-coal.eu/2020/10/15/overview-of-national-phase-out-announcements-july-2020/.

Borggrefe, F., Pregger, T., Gils, H., Cao, K., Deissenroth, M., Bothor, S., Blesl, M., Fahl, U., Steurer, M., Wiesmeth, M., 2014. Kurzstudie zur Kapazitätsentwicklung in Süddeutschland bis 2025 unter Berücksichtigung der Situation in Deutschland und den europäischen Nachbarstaaten. Kurzstudie des Deutsches Zentrum für Luft und Raumfahrt (DLR) und Institut für Energiewirtschaft und Rationelle Energieanwendung (IER) der Universität Stuttgart im Auftrag des Landesministeriums für Umwelt und Energiewirtschaft Baden-Württemberg (UMBW), Stuttgart.

Bruninx, K., Orlic, D., Couckuyt, D., Grisey, N., Betraoui, B., Franck, N.T., Keane, G., Hickman, B., Huertas-Hernando, D., Anderski, T., et al., 2014. E-highway2050: D2. 1 data sets of scenarios for 2050.

Cao, K.-K., Pregger, T., Haas, J., Lens, H., 2020. To prevent or promote grid expansion? Analyzing the future role of power transmission in the European energy system. Front. Energy Res..

Cao, K.-K., Pregger, T., Scholz, Y., Gils, H.C., Nienhaus, K., Deissenroth, M., Schimeczek, C., Krämer, N., Schober, B., Lens, H., et al., 2019. Analyse von Strukturoptionen zur Integration erneuerbarer Energien in Deutschland und Europa unter Berücksichtigung der Versorgungssicherheit (INTEEVER).

Cooke, H., Keppo, I., Wolf, S., 2013. Diversity in theory and practice: A review with application to the evolution of renewable energy generation in the UK. Energy Policy 61, 88–95.

Deng, Y.Y., Blok, K., van der Leun, K., 2012. Transition to a fully sustainable global energy system. Energy Strategy Rev. 1 (2), 109–121.

Dominković, D.F., Bačeković, I., Ćosić, B., Krajačić, G., Pukšec, T., Duić, N., Markovska, N., 2016. Zero carbon energy system of South East Europe in 2050. Appl. Energy 184, 1517–1528.

Evangelopoulou, S., De Vita, A., Zazias, G., Capros, P., 2019. Energy system modelling of carbon-neutral hydrogen as an enabler of sectoral integration within a decarbonization pathway. Energies 12 (13), 2551.

Gils, H.C., Scholz, Y., Pregger, T., de Tena, D.L., Heide, D., 2017. Integrated modelling of variable renewable energy-based power supply in Europe. Energy 123, 173–188.

Hurst, A., 2017. France could close 'up to 17' nuclear reactors by 2025. France24 [cited 26.11.2020]. URL https://www.france24.com/en/20170710-france-hulot-could-close-nuclear-plants.

Keles, D., Yilmaz, H.Ü., 2020. Decarbonisation through coal phase-out in Germany and Europe—Impact on emissions, electricity prices and power production. Energy Policy 141, 111472.

Lopion, P.M., Stolten, D., Pitz-Paal, R., 2020. Modellgestützte Analyse Kosteneffizienter CO_2-Reduktionsstrategien. Tech. rep., Lehrstuhl für Brennstoffzellen (FZ Jülich).

Lund, P.D., Lindgren, J., Mikkola, J., Salpakari, J., 2015. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew. Sustain. Energy Rev. 45, 785–807.

Michalski, J., Bünger, U., Crotogino, F., Donadei, S., Schneider, G.-S., Pregger, T., Cao, K.-K., Heide, D., 2017. Hydrogen generation by electrolysis and storage in salt caverns: Potentials, economics and systems aspects with regard to the German energy transition. Int. J. Hydrogen Energy 42 (19), 13427–13443.

Pielou, E.C., 1966. The measurement of diversity in different types of biological collections. J. Theoret. Biol. 13, 131–144.

Pregger, T., Nitsch, J., Naegler, T., 2013. Long-term scenarios and strategies for the deployment of renewable energies in Germany. Energy Policy 59, 350–360.

Rammel, C., van den Bergh, J.C., 2003. Evolutionary policies for sustainable development: adaptive flexibility and risk minimising. Ecol. Econom. 47 (2–3), 121–133.

Scholz, Y., Gils, H.C., Pregger, T., Heide, D., Cebulla, F., Cao, K.-K., Hess, D., Borggrefe, F., 2014. Möglichkeiten und Grenzen des Lastausgleichs durch Energiespeicher, verschiebbare Lasten und stromgeführte KWK bei hohem Anteil fluktuierender erneuerbarer Stromerzeugung.

Sgobbi, A., Nijs, W., Miglio, R.D., Chiodi, A., Gargiulo, M., Thiel, C., 2016. How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system. Int. J. Hydrogen Energy 41 (1), 19–35. http://dx.doi.org/10.1016/j.ijhydene.2015.09.004, URL //www.sciencedirect.com/science/article/pii/S0360319915301889.

Staffell, I., Scamman, D., Abad, A.V., Balcombe, P., Dodds, P.E., Ekins, P., Shah, N., Ward, K.R., 2019. The role of hydrogen and fuel cells in the global energy system. Energy Environ. Sci. 12 (2), 463–491.

Stetter, D., 2014. Enhancement of the REMix energy system model: Global renewable energy potentials, optimized power plant siting and scenario validation.

Stirling, A., 1998. On the economics and analysis of diversity. In: Science Policy Research Unit (SPRU), Electronic Working Papers Series, Paper 28. Citeseer, pp. 1–156.

Stirling, A., 2010. Multicriteria diversity analysis: a novel heuristic framework for appraising energy portfolios. Energy Policy 38 (4), 1622–1634.

Tröndle, T., Lilliestam, J., Marelli, S., Pfenninger, S., 2020. Trade-offs between geographic scale, cost, and infrastructure requirements for fully renewable electricity in Europe. Joule 4 (9), 1929–1948.

Von Hirschhausen, C., Herold, J., Oei, P.-Y., 2012. How a "low carbon" innovation can fail—tales from a "lost decade" for carbon capture, transport, and sequestration (CCTS). Econ. Energy Environ. Policy 1 (2), 115–124.

Wu, T.Y.-w., Rai, V., 2017. Quantifying diversity of electricity generation in the US. Electr. J. 30 (7), 55–66.

Zappa, W., Junginger, M., van den Broek, M., 2019. Is a 100% renewable European power system feasible by 2050?. Appl. Energy 233, 1027–1050.