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Comparison of different drivers on energy systems investment dynamics to achieve the energy transition goals

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ABSTRACT

The signing of the Paris Agreement represents a consensus on limiting the increase of the average global temperature compared to the preindustrial period. The European Union has set an ambitious goal of achieving climate neutrality by 2050. By 2030, the European Commission's REPowerEU plan aims to accelerate the processes of increasing the share of renewable energy sources, improving energy efficiency, reducing energy use, and, at the same time, diversifying energy sources and increasing electricity connectivity between member states.

In order to achieve the stated goals, future energy systems will be based on renewable energy sources, which are characterized by production variability. Such systems require flexibilization technologies that ensure security and stability of supply. In this study, an analysis of how different fuel and technology costs, as well as policy targets, influence the pace of the energy transition dynamic was made on the case study of Croatia, as there was no such previous investigation. Therefore, the goal of the research is to identify the most prominent driver to achieve energy transition targets in Croatia, with an emphasis on the required flexibilization technologies. The investigation has been implemented in the energy planning tool H2RES, a detailed open-source long-term optimization model in a five-year step model based on scenario analysis of different RES and CO_2 targets, technology costs, and fuel prices. The results reveal a need for an ambitious energy policy if the goal is to achieve full energy system decarbonization. Currently, high carbon prices and lower technology costs won't be enough to lead the energy transition, without legislative support.

1. Introduction

The focus on climate change is rapidly increasing at the global, European, and local levels. The adoption of the Paris Agreement represents the beginning of the multilateral process against climate change, with the aim of keeping the average global temperature increase at a level significantly lower than 2 °C compared to pre-industrial levels and with an additional effort to limit it to 1.5 °C [1]. It represents a pivotal framework for global climate action, pushing climate targets toward more ambitious efforts to combat climate change. With the adopted mechanism, countries are required to submit nationally determined contributions (NDCs) every five years to set, track, and revise climate targets and report on their emissions and progress. In alignment with the Paris Agreement, the European Union (EU) has set ambitious targets to become climate neutral until 2050. With enforced legislative and policy measures, the EU has taken on the role of global leader to ensure the success of the Paris Agreement and, at the same time, initiate economic, social, and environmental European transformation led by innovation in green industries. Moreover, to reduce the dependence on Russian fossil fuels and accelerate the clean transition, in 2022, EU proposed REPowerEU plan aimed at further increase of previous 2030 renewable energy target to 45 %, while strongly supporting the development of solar and wind energy. To successfully transform EU's energy system, the increase of renewable energy on the supply side also needs to be accompanied by actions on the demand side, i.e., increasing energy efficiency targets, accelerating building renovation, and transitioning to renewable-based heating and cooling systems [2].

Clean transition is not only encouraged by policy measures. Renewable energy sources (RES), [3] especially variable renewable energy sources (VRES), were the most cost-effective form of electricity production in 2021, with expected further cost reduction [3]. In the same year, a total of 3064 GW of new RES capacity was installed, justifying high expectations for an increase in the share of renewable energy in the energy mix, not only in already high renewable markets but in emerging market countries as well [4]. Moreover, the energy transition towards renewable energy sources can positively affect the

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stability and future expansion of global economies and potentially increase global direct jobs associated with the power sector from about 21 million in 2015 to nearly 35 million in 2050 [5]. Therefore, due to their favorable climate footprint [6] and low costs, it is both technically and economically viable to decarbonize the EU economy until 2050, and with the appropriate policy measures it can also be socially acceptable [7]. However, to ensure a smooth reconstruction of energy system, there is a need to accelerate development and deployment of not yet mature technologies and infrastructure. For that again, policy and regulatory frameworks need to be established [8], to attract investments and secure a stable economic environment [9]. Only a multi-dimensional approach combining technology, policy, and society will lead to the realization of European decarbonization goals [10].

To comprehensively encompass multiple segments, an energy planning approach is employed to investigate different scenarios and evaluate the impact of regulations and policies on the mitigation of CO_2 emissions, where financial and technological incentives can direct or accelerate the energy transition [11]. Energy policies have been one of the key drivers of the energy transition, constantly changing and evolving to meet market needs, but there is no comprehensive instrument that would guarantee a successful transition [12]. Only a combination of different incentives and methods will have a sustainable impact on achieving transition goals [13]. Therefore, not only policy measures but the cost of the technology [14], demand structure [15], renewable source variability [16], and broad social-technical concepts [17] influence sustainable energy system development.

For this reason, policymakers rely on researchers to study integration of RES and its effects on different energy transition scenarios. Their aim is to provide a better understanding of cost-effective strategies to policymakers in countries already invested in the energy transition [18], but also to encourage transition in developing countries [19]. In [20], an overview of the challenges and solutions of RES integration is given, concluding that further research is needed in order to obtain a better understanding of the specific problems and characteristics of individual systems. However, global energy transition scenarios still fail to sufficiently discuss the vital responsibilities that flexibility would play in future energy systems that heavily rely on renewable energy [21]. In long-term energy planning optimization, each step is influenced by the prior one, making it sensitive to input data and beforehand decided final targets. Moreover, as prices are affected by unpredictable factors and it is essentially impossible to make an exact prediction [22], uncertainties present another challenge for complete accuracy in long term energy planning, leading to a need for broad analysis of possible scenarios in the most comprehensive model.

Consequently, numerous studies have been conducted dealing with energy system modeling and smart energy systems, including sector coupling and the introduction of power-to-X technologies [23], for which many different energy systems modeling tools can be utilized [24]. In [25], the EnergyPLAN model was used for the analysis of VRES and electric vehicles in the island energy system, while EPLANopt was used to assess the optimal energy mix needed to reach European energy targets [26]. Dispa-SET, an unit commitment and power dispatch model, was used in the case of the Western Balkans power system to analyze dispatch decisions under different related formulations [27]. Moreover, Pymedeas is developed as an open-sourced model for the design and planning of strategies and policies for the decarbonization of the energy sector regarding biophysical limits, availability of raw materials, and climate change impacts [28]. However, there was still a gap in existing energy modeling tools with a lack of open-sourced long-term optimization models at hourly resolution, where Power-to-X and demand response technologies are considered together with market coupling. To address this gap, a new tool, H2RES, was developed by Feijoo et al. to provide an optimal energy system decarbonization pathway [29].

Such model is necessary to present possible development pathways for future energy systems, including investments in different flexibilization technologies that ensure stability and security of energy systems by balancing demand and supply based on variable renewable energy sources [30]. As potential climate change impacts can lead to variability in renewable source production, such investigation is even more needed [31]. The interaction with the renewable mix can be achieved with energy storage [32], demand response [33], and sector coupling [34], providing greater efficiency and cost reduction thus simultaneously providing flexibility [35] and decarbonizing different energy sectors [36]. Such linkage was shown through the analysis of seven European electricity system scenarios, where it was shown that a 100 % renewable European energy system is possible by 2050, but it would require a 90 % increase in production capacity, 140 GW of additional cross-border transmission capacity, and the integration of heat pumps and electric vehicles into the power system to provide flexibility [37].

As shown, future renewable energy systems will be characterized by sector coupling and different flexibilization technologies to ensure grid stability and sector linkage. While the goal is to reduce CO_2 emissions, at the same time, energy transition should also be achieved in the most economical and efficient way possible, but limitations regarding the potential and use of resources, costs, technical restrictions, and imposed policy measures can all lead to distinct pathways and pace of energy transition. Therefore, in this research, the goal is to identify the most prominent driver to achieve energy transition targets in Croatia, with an emphasis on the required flexibilization technologies. Integration of RES generation in Croatia was already examined with high penetration of wind [38], solar [39] and with the focus on electrical energy storage [40] in the EnergyPLAN simulation tool. However, to determine optimal decarbonization pathway for Croatia, there was a need for a long-term optimization approach with the integration of all energy sectors and flexibilization technologies. For that reason, as mentioned before, Felipe et al. [29] investigated how Power-to-X technology is used to achieve renewable electricity targets and its impacts on imposed CO_2 limits in the case study of Croatia, in a newly developed optimization model, H2RES. Additionally, previous research has examined the application of the H2RES model in decarbonization analyses of island systems [41], district heating and cooling [42], with the use of electric vehicles [43], as well as demand response and primary and secondary reserves for island energy systems [44] in Italy.

Nevertheless, in those analyses, there was no investigation of how different fuel and technology costs, as well as policy targets, influence the pace of the energy transition dynamic and the use of different flexibilization technologies. As optimization in long-term energy planning depends on input data, it is necessary to investigate different scenarios to evaluate their influence on the optimal configuration of the energy system in the future. Therefore, with this research, the aim is to bridge the gap between long-term optimization modeling in Croatia and technology deployment under the influence of different cost and policy targets. As previous studies didn't take into account possible scenarios, they insufficiently addressed the complex setting of the renewable transition of a large national energy system. Thus, the purpose of this study is to demonstrate the viability of developing a fully renewable energy system in Croatia and to identify drivers that can accelerate energy transition. These finding can serve as inputs for policymakers, providing reliable and scientific-based insight, when discussing future ambitions for decarbonized Croatia.

2. Modeling framework

To investigate investment dynamics regarding different technology cost, scenario analysis was carried out in the open-sourced linear optimization model H2RES [45], which was already compared and proved competent with existing commercially available tools such as PLEXOS Energy Exemplar [46]. It was chosen for its wide technology consideration, high temporal resolution and sector coupling approach of power, heat, transport and industry sectors. The model considers three main sets of decision variables, namely: 1) capacity investments on a yearly basis for all modeled technologies; 2) hourly dispatch modeling for all modeled technologies; and 3) optimization of energy storage levels and technologies with storage ability. In this research simulations are carried out for a coupled power, heat and road transport sector in a timeline of a five-year intervals from 2020 to 2050. The objective function of H2RES is to minimize yearly system costs, both capital and variable, which are brought to net present value with a chosen discount rate. The optimization is carried out in line with satisfying imposed constraints while fulfilling all forms of energy demand from various sectors (power sector, heating and cooling, industry, and transport) at the lowest cost. The main H2RES constraints regarding policy measures for energy transition pathways are renewable portfolio standard in the power sector (RPS), CO_2 emissions reduction targets, and the limitation of Critical Excess of Electricity Production (CEEP).

The specific of H2RES energy system model is the distinction between non-dispatchable and dispatchable units with an unlimited number of power plants that can be newly defined. For non-dispatchable units, it is possible to define several production zones since their characteristics, particularly meteorological conditions, can vary significantly depending on the geographical area and thus lead to different production potentials. Every zone requires separate inputs (potential, availability profile, investment costs), and the investments into each one as well as the dispatch are optimized. Dispatchable units consider coal, oil, diesel, natural gas, biomass, nuclear, and hydroelectric plants, while non-dispatchable are wind, solar, and run-of-river power plants. Heating is also divided into centralized and decentralized production and considers both renewable and conventional heating solutions, in which centralized production can be linked with cogeneration power units. Furthermore, hydrogen serves as an energy vector connecting different sectors. Its hourly demand is allocated for industry, transport, heating, and power through optimized size and dispatch of electrolysers, storage, and fuel cells. Additionally, users can define various constraints on technology installed capacity, dispatch and demand levels and fuel shares in particular sectors. Most importantly, H2RES allows definition of net present values of capacity, operation, and fuel cost for each year through the horizon of the modeling period. For this reason, it is possible to investigate how fuel and technology cost influence cost-optimal development of energy systems in a long-term planning horizon.

The main structure of H2RES is shown in Fig. 1, and a more detailed description of the model can be accessed in [29].

Scenario analysis in H2RES is performed to investigate investment dynamics in flexibilization technologies for different cost and policy targets. The analysis sequence is presented in Table 1, where differences between scenarios are shown regarding the input data. In total, five

Table 1
Different input data by scenario.

	RPS	CO_2 emissions	Fuel prices	Technology cost
S1	energy development strategy	energy development strategy	as expected	as expected
S2	energy development strategy	energy development strategy	as expected	lower than expected
S3	energy development strategy	energy development strategy	lower than expected	as expected
S4	100% renewable energy system	zero CO_2 emissions	as expected	as expected
S5	100% renewable energy system	zero CO_2 emissions	lower than expected	lower than expected

scenarios are examined. The first scenario, S1, represents the base-case scenario with the expected development of the energy system in line with the current national energy development strategy and expected system costs until 2050. Following S1, subsequent scenarios implement different cost scenarios to investigate the effect on technology mix. Furthermore, in addition to cost analysis, in last the two scenarios, a target of achieving full energy system decarbonization was set. The purpose of this is to determine importance of policy measures in achieving energy transition goals, even with the economic incentive of lower investment technology costs. The last scenario, S5, contains all previous initial premises from the cost scenarios. A further explanation of each scenario is presented below.

2.1. S1 - Base case scenario

The base-case scenario stands for the development of an energy system with the application of existing measures that represent the continuity of the current policy and climate settings, expected system costs, and fuel prices in the energy sector, according to the available literature.

2.2. S2 – Base case scenario with lower technology cost

Second scenario builds on the base-case scenario with the adoption of lower Power-to-X (P2X) and flexibilization technology costs. The cost of P2X is still relatively high compared to fossil-based alternatives, but

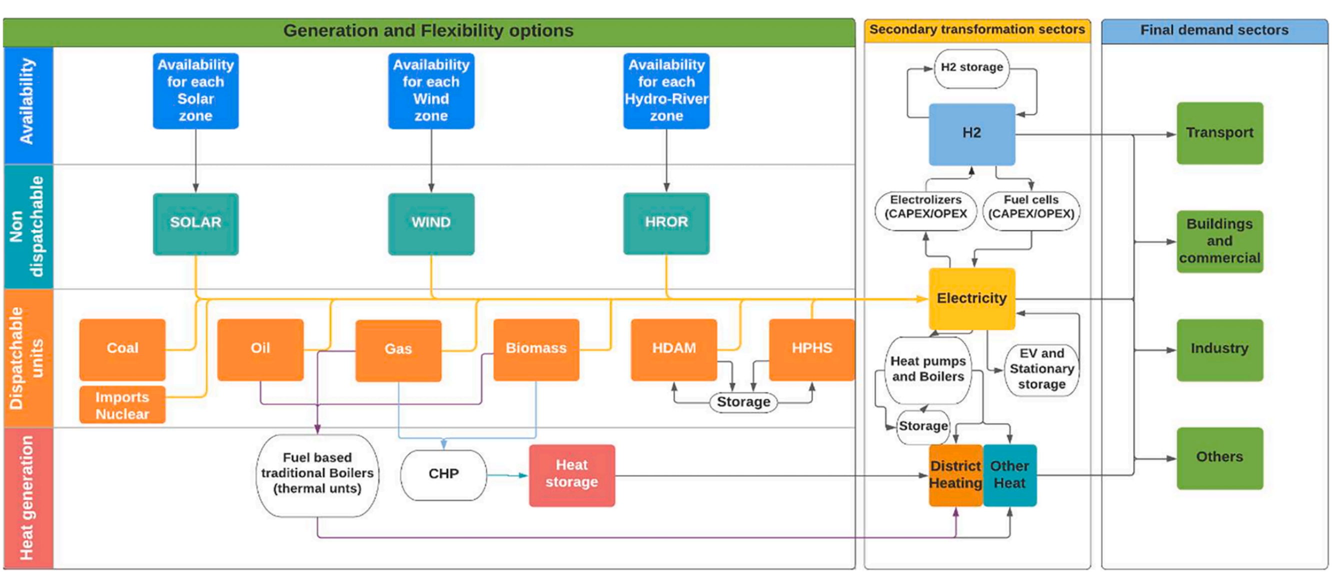


Fig. 1. Main H2RES structure [29].

the major role for their implementation could be found in the cost reduction of renewable power through technological improvements, policy measures, and economies of scale. Therefore, with this scenario, an analysis is made to evaluate how cost reduction can influence the dynamic of energy system development based on literature socioeconomic forecast

2.3. S3 - Base case scenario with lower fuel prices

Scenario S3 builds on base-case scenario, but with the implementation of projected fuel prices in accordance with the objectives of achieving zero emission strategies until 2050, as well a higher carbon price from the literature. As investments in clean technology displace fossil fuel demand, an overturn can be achieved, leading to significantly lower and less volatile fossil fuel prices [47]. Therefore, it is important to take into the account possible fossil fuel price reductions that can lead to overturns in renewable energy investments.

2.4. S4 - 100% RES scenario

The 100 % RES scenario includes the expected technology costs and fuel prices as in scenarios with a continuation of current state energy policies. However, to investigate investment dynamics, this scenario has the requirement of achieving 100 % renewable capacities in electricity generation and zero CO_2 emissions until 2050, in alignment with the European decarbonization target.

2.5. S5 - 100% RES scenario with lower P2X technology cost and lower fuel cost

The last scenario encompasses achieving a 100 % RES system with zero CO_2 emissions with both lower P2X technology cost, and lower fuel with higher carbon prices until 2050. The relevance of the concluding scenario is in the investigation of how reduced costs influence the pace of achieving renewable targets.

3. Case study

The scenario analysis was made on the Croatian energy system case study. The base year for the simulations is 2020 and the end year is 2050 with the five-year time step. As part of the EU, Croatia is aiming to achieve climate neutrality by 2050. Therefore, it is important to investigate how a reduction of CO2 emissions and complete renewable generation can be achieved in the required timeframe. According to the current national energy development strategy, complete decarbonization will not be reached until 2050 [48]. For this reason, it is necessary to provide accurate and reliable indicators to policymakers and encourage more ambitious targets. Recent political conflicts and global events showed how sensitive energy and climate policy is to outside stimulus [49]. Hence, it is beyond doubt that scenario analysis is required for responsible and comprehensive long-term energy planning.

As a result, this study aims to show the possibility of achieving a complete renewable Croatian energy system and highlight the drivers that are responsible for the most cost-effective and fastest system transformation regarding different possible external conditions. Those findings can serve as a reference for public discourse and be used to shape public opinion, potentially putting pressure on more ambitious energy transition targets. For this purpose, the Croatian energy system, i.e., power, heating, industry, and road transport sectors, were modeled, and a scenario analysis was made. The following sections describe energy system modeling inputs.

3.1. Model inputs

3.1.1. Generation capacities

Data on current generating capacities and their technical characteristics were collected from the Dispa-SET [50] data package and adjusted according to [51] for the 2020 base year, resulting in production capacities as shown in Table 2. For each production type, every production unit was defined along with its specifications required for the model.

For power generating capacities whose load factors depend on geographic area, several different production zones were formed depending on their characteristics to simulate possible development areas. In total, four availability curves were modeled for wind power plants (continental, mountainous, coastal, and north-west) according to Fig. 2 [52], and two for solar power plants (continental and Adriatic), representing different photovoltaic power potentials, as can be seen in Fig. 3 [53]. For defined production zones, availability curves were extracted based on [54] and [55].

3.1.2. Electricity demand

The distribution for the basic electricity demand load is taken from ENTSO-e [56] for 2020, and it is assumed that the annual electricity consumption is growing by 1 % every year until 2050, considering the general increase in electricity demand.

3.1.3. Heating demand

The heating demand is divided into three distributions for district heating systems and one representing individual heating demand. Each district heating plant has its own input data about generating capacities, efficiencies, and heat demand distributions. The total heating demand for individual heating was calculated from Eurostat data [57] and amounts to 19 TWh in 2020. District heating demand was taken from the annual energy report of Energy in Croatia [58], and amounts to a total of 1.8 TWh, while the distribution loads were calculated by the hour-degree method. The projected change in heat demand until 2050 was determined according to the potential study of efficiency in the heating and cooling sector as described in [59].

3.1.4. Industry demand

Total industrial energy demand in 2020 was also taken from [57], representing industry energy demand, and it is supplied by different fuels, with natural gas at 49.8 %, oil at 26 %, coal at 15.1 %, and biomass at 6.1 %. Industry demand change by 2050 was modeled according to the same study as individual and district heating demand [59]. It has to be noted that this demand does not include base-year electricity demand in industry, which is already included in the electricity demand. Only the additional electricity demand in industry sector as compared to the base-year electricity demand is observable in the results.

3.1.5. Transport demand

Here, the transport sector is exogenously defined in relation to the rest of the system. In 2020, Croatia had 2312280 registered road vehicles [60], and it is assumed to remain the same through the years. The normalized hourly transportation load curve for electric vehicles is considered the same throughout the years, and actual electricity consumption for transport was modeled by electrification share, total kilometers travelled per vehicle, and energy efficiency of different fuels.

Table 2
Production capacities in 2020 for Croatia [50,51].

Production Type	Capacities (MW)
Natural gas	848.8
Coal	215
Biomass	84
Storage hydro	1485.7
Run-of-river hydro	438.6
Pump hydro	275.4
Wind	801.3
Solar	108.5
TOTAL	4257.3

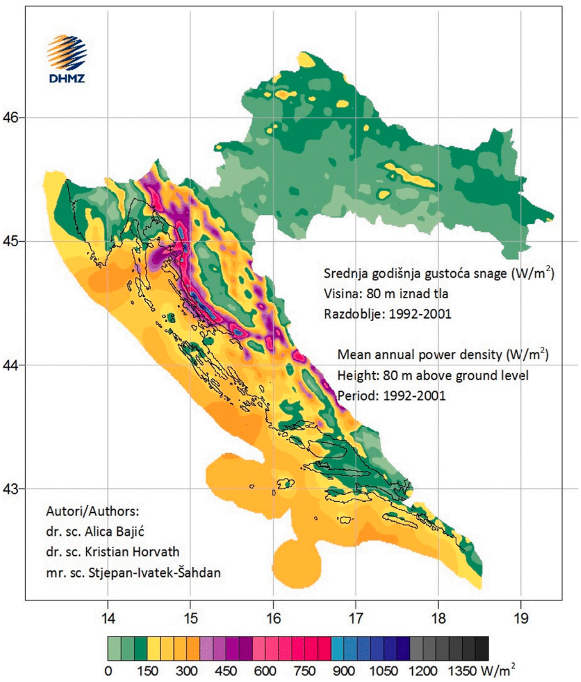


Fig. 2. Mean annual power density for Croatia [52].

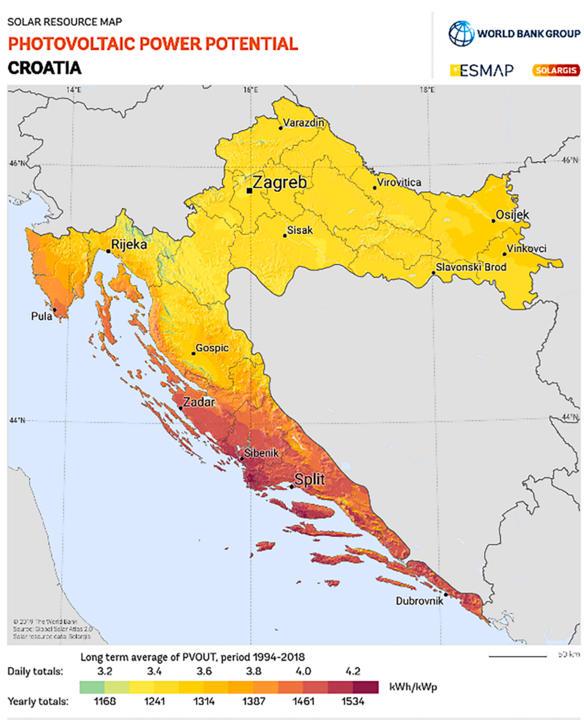


Fig. 3. Photovoltaic power potential for Croatia [53].

The electrification share was 0.001 % in 2020, and it changes throughout the years according to different policies from the Croatian energy strategy [48]. In scenarios based on national strategy, it goes to 20 % in 2050, and in scenarios with 100 % renewable energy systems and zero CO_2 emissions, electrification share is assumed to reach 85 %, while the rest is fuelled by hydrogen.

3.2. Scenario inputs

3.2.1. RES share in electricity generation

Targets of RES share in electricity generation were modeled according to the Energy development strategy for the Republic of Croatia until 2030 with a view to 2050 [48] for the base case scenario regarding development with the application of existing measures, reaching 82 % in 2050 For the rest of scenarios, a full renewable generation was assumed, linearly increasing the share from 50 % in 2020 to 100 % in 2050 as can be seen in Fig. 4.

3.2.2. CO_2 limits

Likewise, CO_2 emissions were modeled according to Energy development strategy for the base case, while for the rest of the scenarios, the goal of achieving zero emissions was set. From 8,1 Mt of CO_2 in 2020, emission will be limited to 4,1 and 0 Mt in 2050, for scenarios with existing measures and complete decarbonization respectively. Fig. 5 presents CO_2 emission limits for both cases in Mt of CO_2.

3.2.3. Technology cost

Future expected technology costs were modeled based on [61]. For the scenarios with lower technology costs, values with lower assumptions for future projections were considered. Table 3 presents an overview of the differences between expected and lower future costs for P2X technologies in 2050. As can be seen, the biggest reduction from the initial cost is expected for solid oxide (SO) electrolyzers and fuel cells, while the cost of a hydrogen tank is expected to reach 22,000 €/MW in both cases.

3.2.4. Fuel prices

Oil, natural gas, and coal prices for 2020 were taken from World Energy Outlook 2021 [62] and were 25, 13 and 5.6 €/MWh, respectively. Biomass and biogas prices were set at 15 and 35 €/MWh [63], and the average nuclear price is taken as 3 €/MWh in 2020 [64]. Projections for expected and lower prices until 2050 were made based on [65] for fossil fuel prices, [66] for bioenergy, and [67] for nuclear generation, for which reduction pattern remained the same for both cases. The change in prices can be seen in Fig. 6. Spikes in 2025 are the result of high prices in 2022 caused by the energy crisis.

3.2.5. Carbon price

Carbon prices are modelled according to [65] resulting in 135 €/tCO_2 and 250 €/tCO_2 in 2050 for the case with expected fuel prices and lower fuel prices, respectively, as can be seen from Fig. 7.

4. Results and discussion

All scenarios fulfilled the required constraints of RES share in power generation and kept CO_2 emissions within the limits. On Fig. 8, the trend of RES share in electricity generation for each scenario is shown. In scenarios S1, S2, and S3, with current measures according to national energy strategy emission goals, the RES share is reaching even higher values until 2030 than what is currently proposed. However, after 2030, the share is kept at the minimum required level and does not exceed expectations without additional artificially imposed incentives. For the zero-emission scenarios, S3 and S4, investments in RES capacities are made from the beginning, leading to a high RES share throughout the whole period and reaching the final 100 % in 2050. The reason for early investments lay in long-term optimization approach, called perfect foresight. As the information on 2050 targets are known in advance, optimization problem is solved at the same time for all simulation steps, resulting in high early investments. In this way, the model faces a single optimization problem considering the whole system evolution over time, and optimizing all simulation steps together, achieving gradual 100 % share by 2050.

Additionally, between, those two scenarios, these is no big

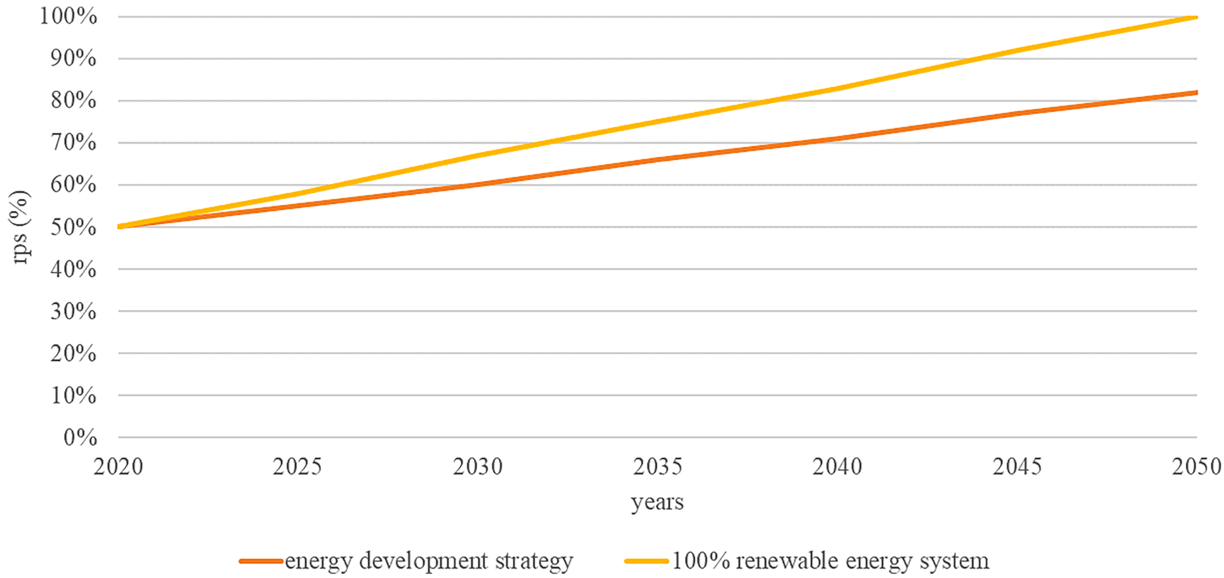


Fig. 4. Share of RES in power system generation for different scenario inputs.

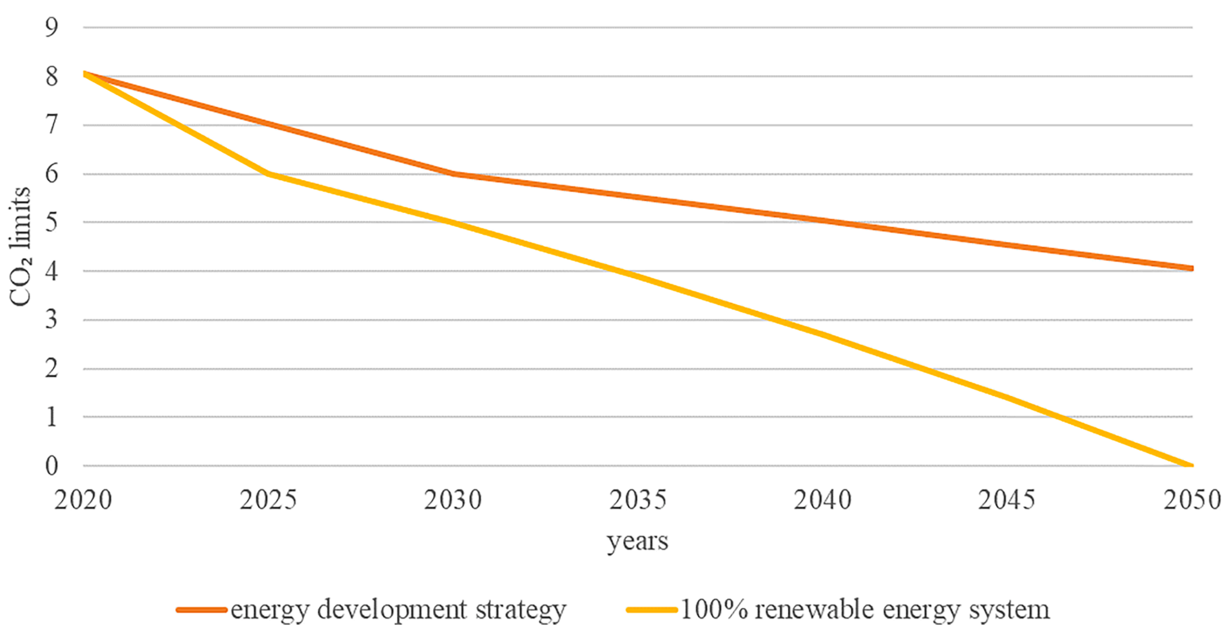


Fig. 5. CO_2 limits in power system for different scenario inputs in Mt of CO_2.

Table 3
Technology costs comparison until 2050 [61].

	2020	2050	
		expected cost	lower cost
Air sourced heat pumps (k€/MW)	1214	956	764
Geothermal heat pumps (k€/MW)	2220	1970	1210
PEM fuel cell (k€/MW)	1380	850	530
SO fuel cell (k€/MW)	3510	850	430
Electric boiler (k€/MW)	160	140	110
PEM electrolyzers (k€/MW)	925	400	300
SOEC electrolyzers (k€/MW)	4491	783	525
Alkaline electrolyzers (k€/MW)	750	350	200
Gas boilers (k€/MW)	279	240	146
Biomass boilers (k€/MW)	214	184	157
Oil boilers (k€/MW)	350	300	255
H2 storage tank (k€/MWh)	61	22	22
Li-ion batteries (k€/MWh)	1110	270	180

differences, as the CO_2 emission targets are not intense enough to require a higher share in the first three scenarios. However, the condition of zero emissions in the last two scenarios imposes a big investment in RES from the beginning to satisfy the required CO_2 reduction in line with constraints in the yearly allowed capacity installation. Critical excess electricity production was also contained under 5 % in all scenarios.

Fig. 9 shows reached CO_2 emissions for each scenario until 2050. Scenario S1 and S2 are achieving the same trend throughout the years, meaning lower P2X costs in scenario S2 don't lead to a quicker reduction in CO_2 emissions compared to the base case S1 scenario. However, in both scenarios, emissions are kept within the imposed limits. On the other hand, scenario S3 with lower fossil fuel and higher carbon price, is reaching maximum allowed CO_2 emissions throughout the modeled period. The reason it keeps a higher share of fossil fuels in the systems is due to their lower prices than in scenarios S1 and S2, while at the same time, an increase of carbon prices to 250 €/t CO_2 is not sufficient enough

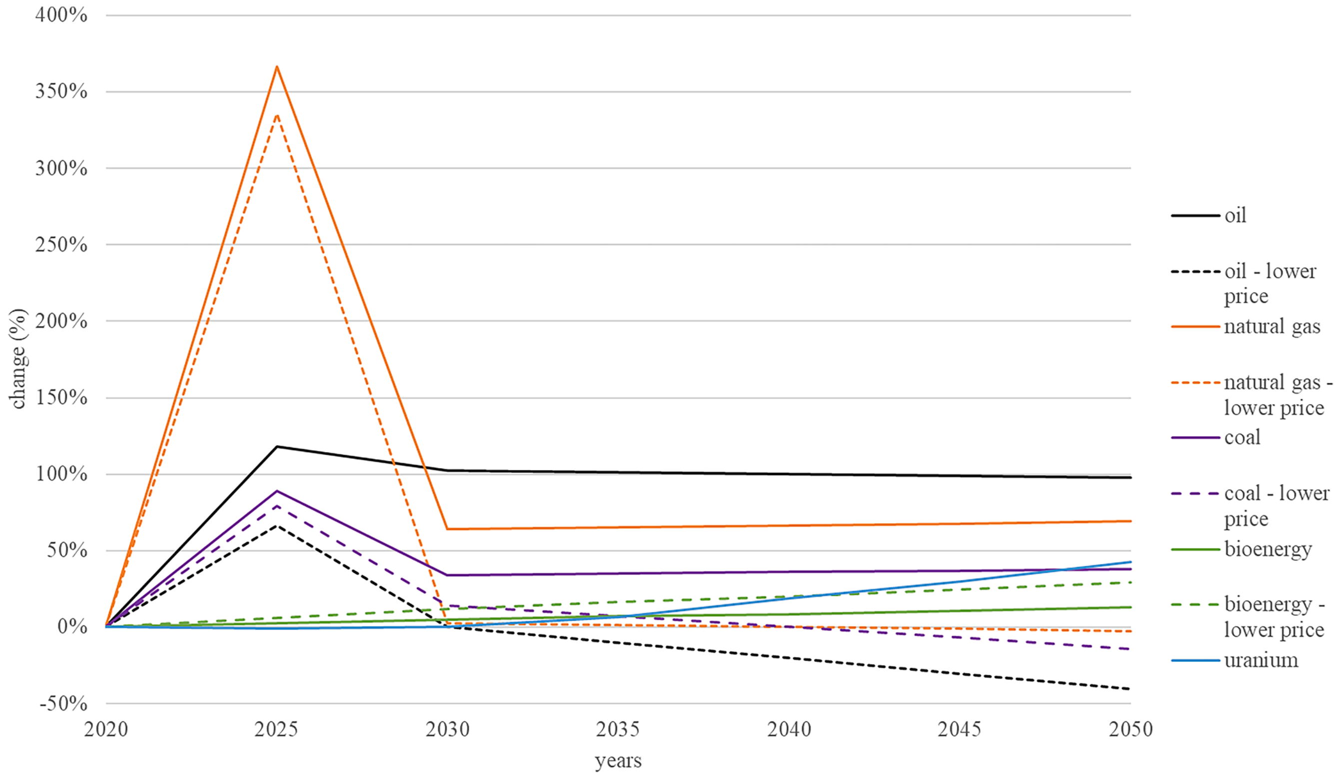


Fig. 6. Change of fuel prices until 2050 in relation to 2020 prices.

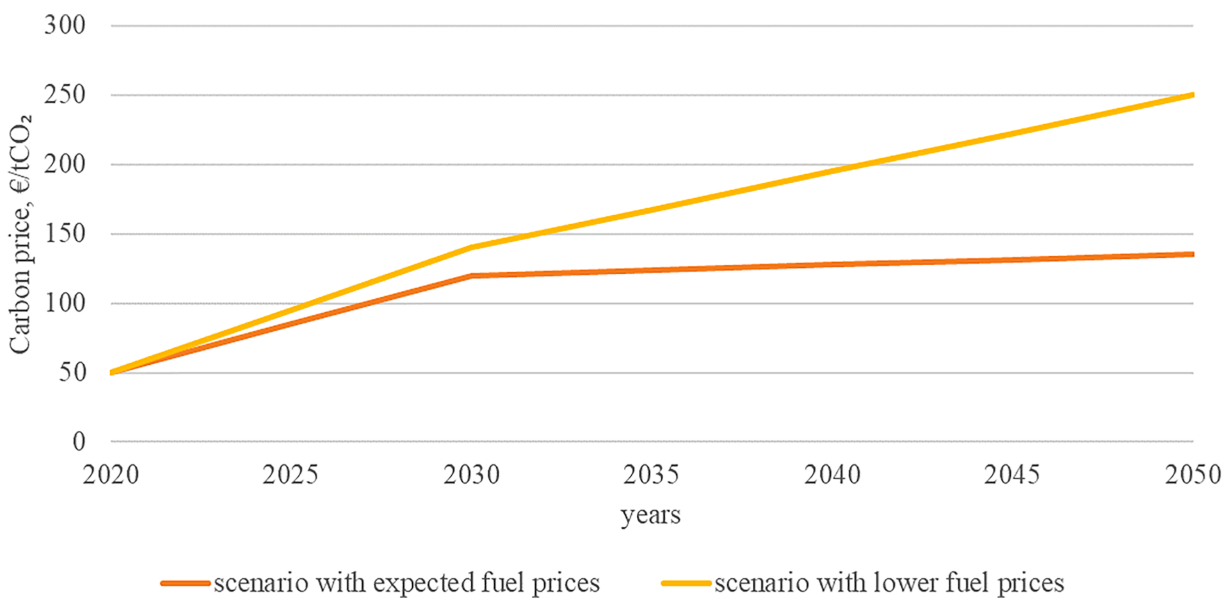


Fig. 7. Carbon price projection until 2050 [65].

to compensate for the difference. Scenario S4 achieves the most rapid and highest CO_2 reduction among all scenarios, much more than it is imposed. Lastly, scenario S5 with all combined measures, is roughly tracking the zero-emission target trajectory. The increase after 2025 happens with the decrease of fossil fuel prices after previous high ones, and as 2030 marks the year after which the decommission of nuclear power plant is set, leading to a rise in power generation from available fossil fuel sources.

A High RES share was achieved with investments in renewable energy sources, as displayed in Fig. 10. The scenarios S4 and S5, with the goal of full system decarbonization, invest almost the same capacities in each modeled period. Those results are explained by one of the optimization constraints: limiting the value of possible investment in RES for each period with the intent to avoid unrealistic investment in just one period. In this case, allowed installations are 450 MW for solar and 600 MW for wind in each zone and for each five-year step period. Hence, S4 and S5 scenarios invest the full potential of allowed renewables in each period for both wind and solar production zones. The rest of the scenarios don't start RES capacity investments until 2030. Between them, the slowest investments are in scenario S2, as it invests more in P2X

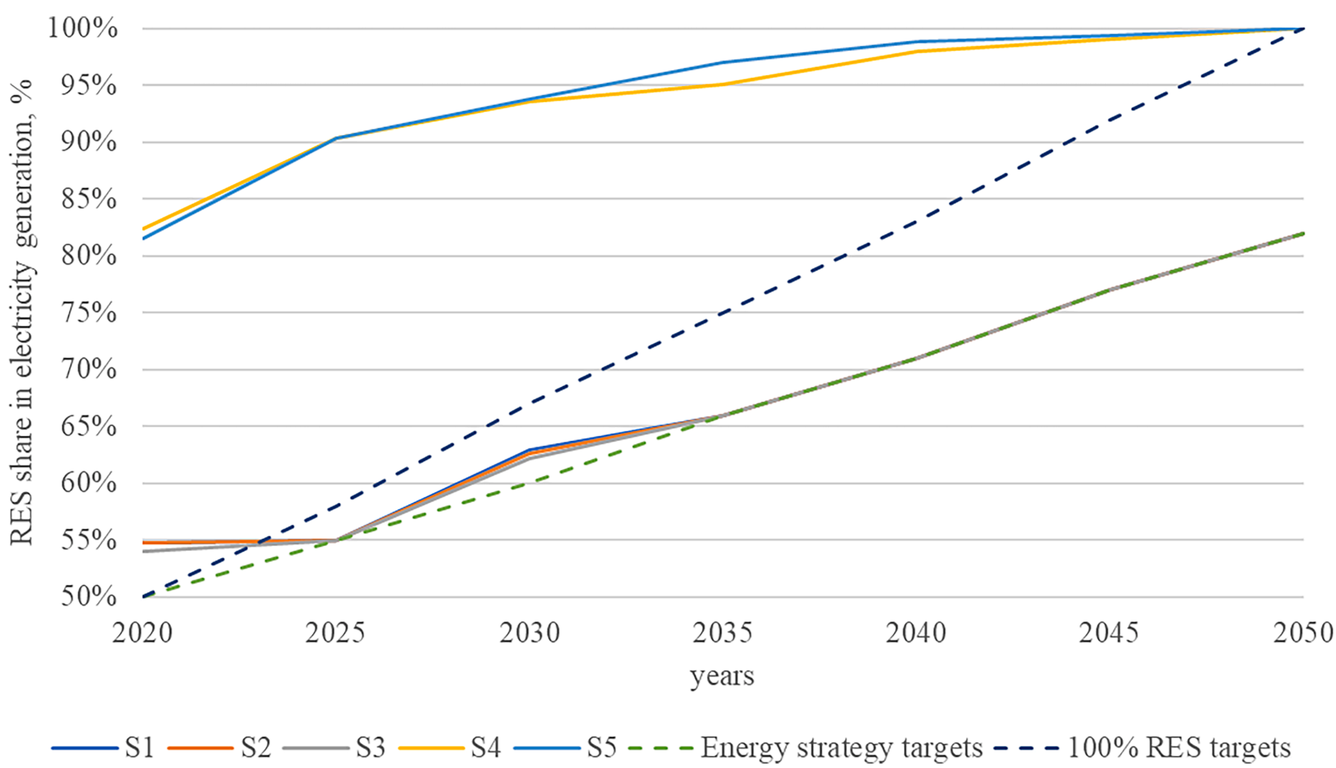


Fig. 8. Achieved RES share for each scenario.

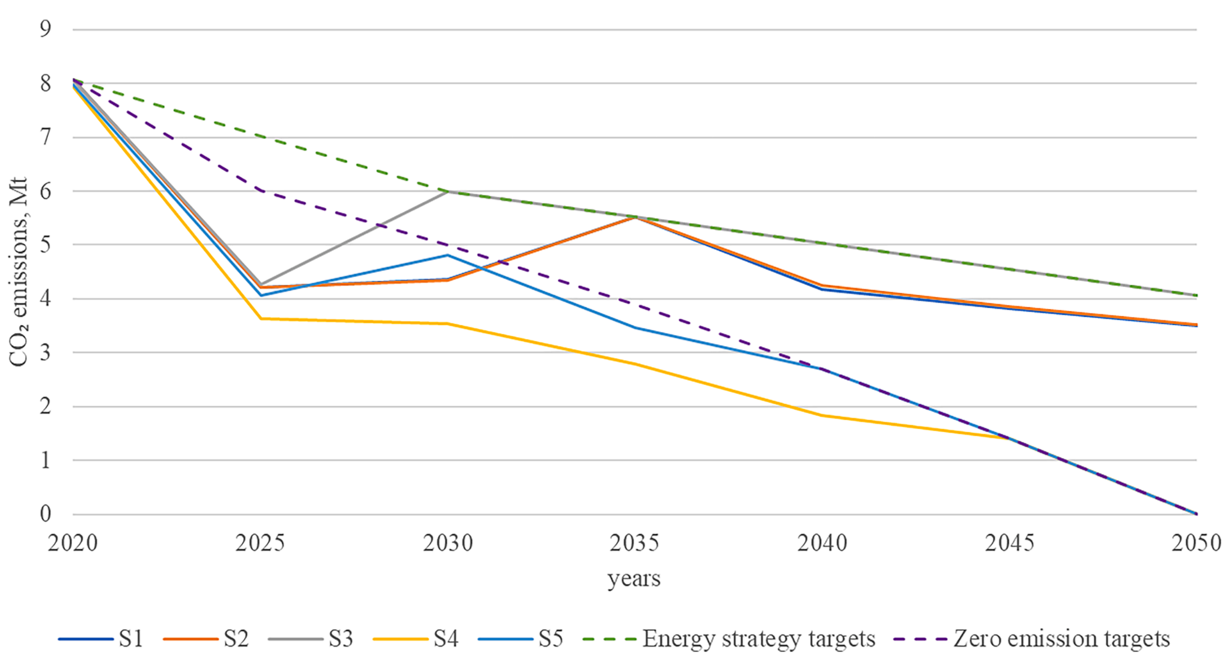


Fig. 9. CO_2 emissions for each scenario.

technology due to lower costs but compensates later in 2045 and 2050, resulting in overall only around 20 MW lower installed RES capacity in comparison with the S1 and S3 scenarios. The investments are mostly made in Adriatic solar, coastal, and north-west wind production zones, while there is no investment in continental and mountain production zones in base case scenarios. This is the result of different capacity factors for each zone based on their geographical position, leading to different production potential. Therefore, the investments are mostly prioritized in the zones with higher capacity factors to utilize the largest potential. Exceptions in the investment into zones with lower capacity factors are made in the case that the capacity factor curve of that zone is better matching the load requirements.

Fig. 11 shows total investments in boilers for all scenarios. The total newly installed capacities are under 2000 MW for gas boilers as a result of a set constraint to limit excessive new installations. Furthermore, a constraint is also made for biomass boilers to prevent unsustainable use of biomass. The reduction of CO_2 emissions is initially achieved with the decarbonization of individual heating sector with the replacement of gas

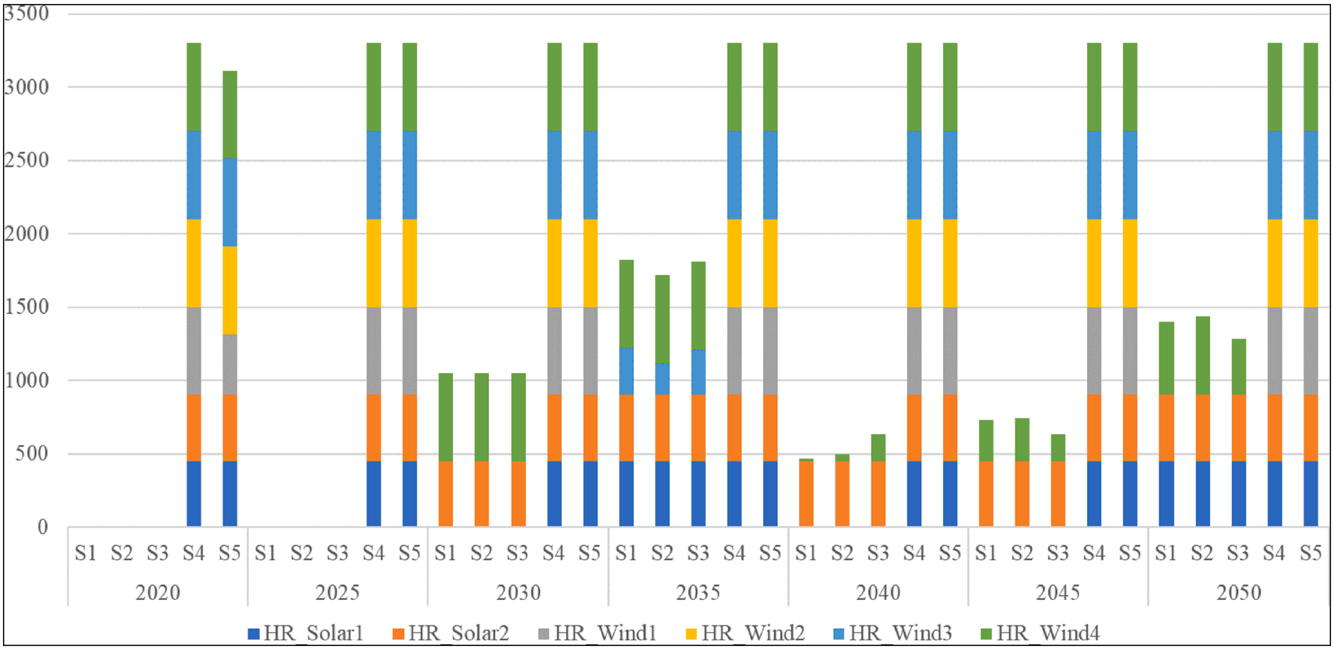


Fig. 10. Newly installed RES capacities for each scenario.

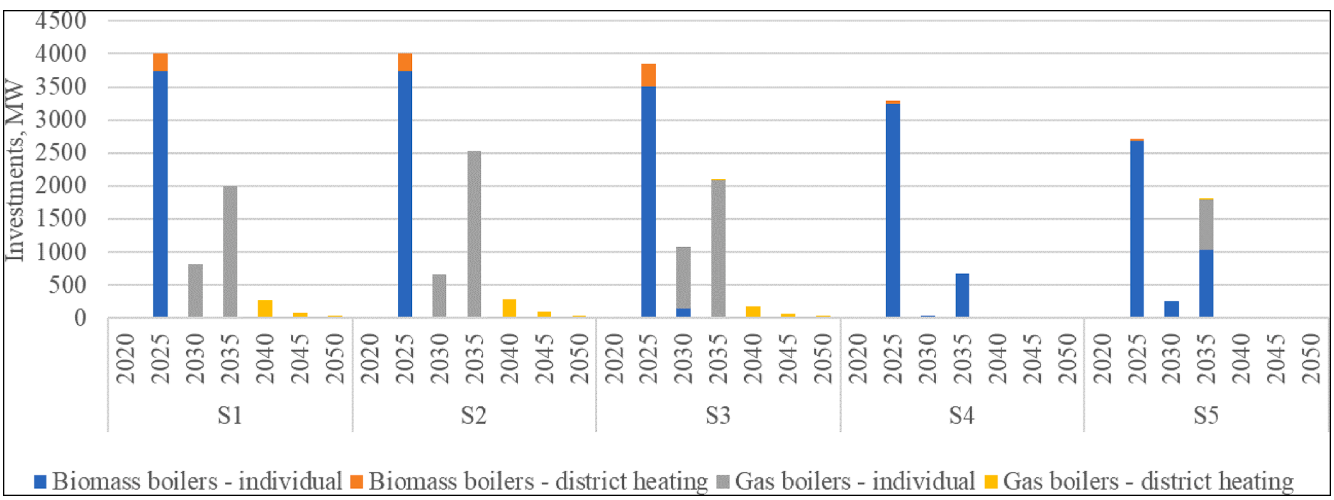


Fig. 11. New capacities in boilers for each scenario.

boilers with biomass boilers in 2025, as it is a more affordable solution. The most capacities before 2035 are installed for individual heating, with biomass boilers in 2025 and gas boilers in 2030. Investments from 2035 onward are gas boilers in scenarios without full decarbonization. In the last two scenarios, there are no big investments in boilers as previously installed technology has its own lifespan, and bigger investments will be made in heat pumps in that period, as can be seen in Fig. 12.

At the beginning, the development of energy system is concentrated on the decarbonizing heating sector with new heating solutions, which at the same time have the possibility of providing system flexibility as they have a certain amount of energy storage. Furthermore, the leading investments in electrically driven heating solutions are electrical boilers due to their low price. Significant investments are starting in 2030, as can be seen in Fig. 12, following the initial investments in biomass boilers, as shown in Fig. 11. There is a distinct difference between scenarios based on energy development strategy and RES scenarios, as there is no incentive to fully decarbonize the heating sector in the first three scenarios. Investments are also made in air-sourced and geothermal heat pumps, but in lower quantities in comparison with electric boilers. Significant investments in heat pumps are made only in 2050 for RES scenarios, with the requirements of the fully decarbonized sector. The lowest total installed capacities in the observed period are in scenario S2, while the most are in scenario S4. In comparison, scenario S5 invests almost 750 MW less than scenario S4 because of lower technology costs and lower fuel prices, including biomass.

Fig. 13 shows investments into the electrolyzers for scenarios S4 and S5 for each 5-year step investment period. In scenarios S1, S2, and S3, there are no requirements for complete decarbonization of the electricity, heating, industry, and transport sectors, and there is a lower penetration of variable renewable energy sources, leading to a lower need for balancing the excess production. As a result, in those scenarios, there are no investments in the electrolyzers for hydrogen production that are used for decarbonization and flexibilization of the energy system in the last two renewable scenarios. Consequently, there are also no investments in hydrogen tank storage in those three scenarios, while in

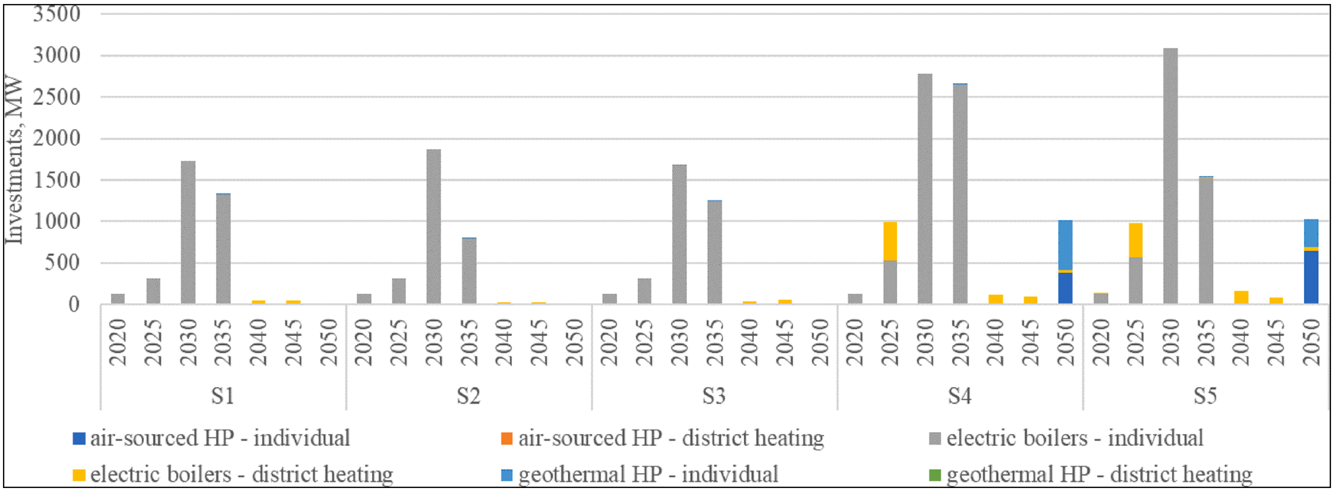


Fig. 12. New capacities in electrical driven heating solutions for each scenario.

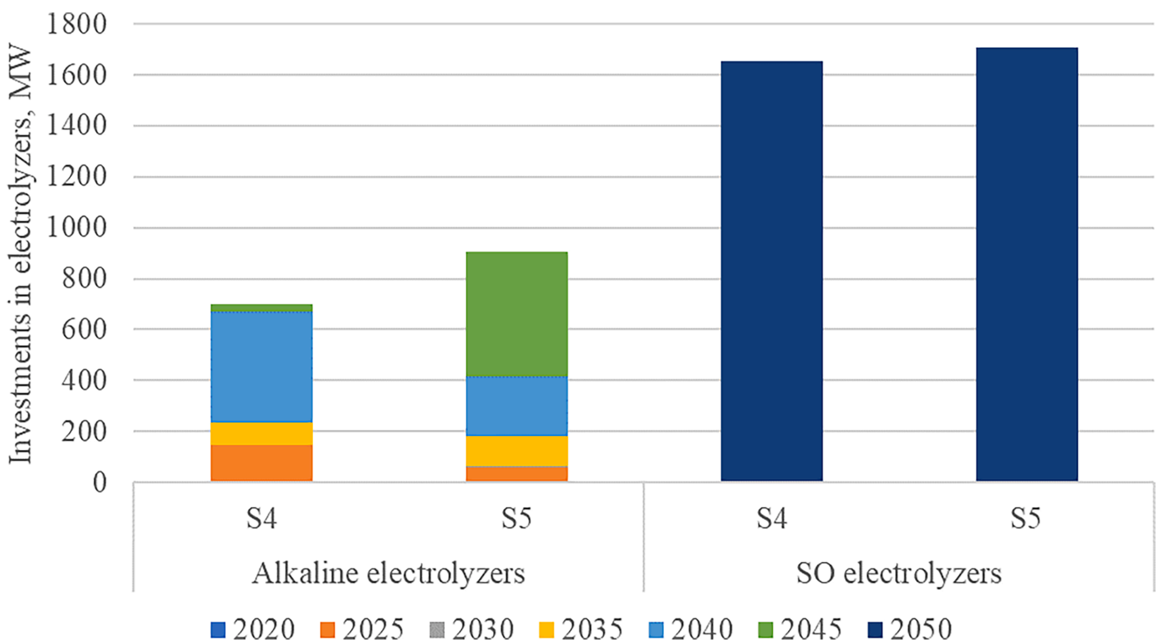


Fig. 13. New capacities in electrolyzers for each scenario.

the renewable S4 and S5 scenarios, there are new capacities in total of 50000 MWh by 2050, limited by a set constraint in the model. Because of a need for system decarbonization, hydrogen is produced in times of high-RES production, stored, and then used for industry and transport demand. Moreover, due to the lower technology cost in scenario S5, investment into hydrogen technology starts earlier with more installed capacity than in S4 scenario. On the other hand, that leads to lower investments in new wind turbines, as shown in Fig. 10 and summarized in Table 4. Until 2050, all electrolyzers were alkaline due to their initial low cost, but in 2050, with the requirement of full decarbonization, all investments will be in SO electrolyzers as their price significantly drops and they have higher efficiency.

Lastly, Fig. 14 presents the investments in Li-ion batteries used as energy storage. As can be seen, there are no investments in scenarios S1, S2, and S3. Because there is no goal of full system decarbonization, there are much lower investments in new RES capacities, leading to much lower excess production and, therefore, a requirement for electricity storage. On the other hand, there are investments in scenarios S4 and S5., but considerably lower compared to the investments in hydrogen

Table 4
Total installed capacities for each scenario.

	S1	S2	S3	S4	S5
Solar capacity (MW)	3150	3150	3150	6300	6300
Wind capacity (MW)	2321.92	2301.01	2323.78	16800	16613.23
Biomass boilers (MW)	4000	4000	4000	4000	999.9
Gas boilers (MW)	3192.2	3608.8	3920.5	0	1000
Air-sourced HP (MW)	7.24	218.93	0.88	389.57	656.12
Electric boilers (MW)	3609.81	3184.06	3483.69	6794.21	6035.18
Geothermal heat pumps (MW)	0.66	33.11	0.66	602.26	335.69
Hydrogen storage tank (MWh)	0	0	0	50000	50000
Alkaline electrolyzers (MW)	0	0	0	698.01	906.98
SO electrolyzers (MW)	0	0	0	1653.05	1706.14
Fuel cell (MW)	0	0	0	0	0.01
Li-ion batteries (MWh)	0	0	0	4917.23	18119.89

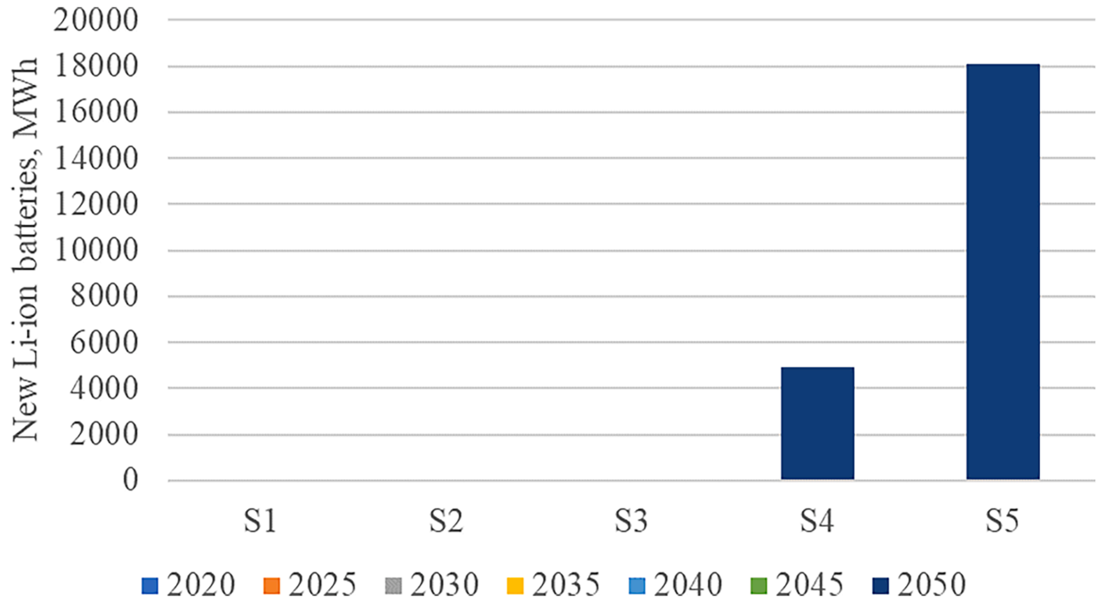


Fig. 14. New capacities in Li-ion batteries for each scenario.

technologies, due to the use of hydrogen in the decarbonization of other sectors, namely industry and transport, and not just as energy storage as the case is for Li-ion batteries. Comparing scenarios S4 and S5, it can be seen that scenario S4 is investing more in RES power and cheaper and less efficient technological solutions like electric boilers. Additionally, it opts for more investments in wind at the expense of a lower use of P2X solutions. With lower technology costs, scenario S5 focuses on system flexibility with the use of hydrogen and energy storage.

Finally, Table 4 shows the summarized total investments for each scenario and each technology of conducted scenario analysis. Energy system optimization was carried out regarding imposed constraints and set goals. The main result that can be seen from the table is that without set decarbonization targets by 2050, there will be no high investments in solar and wind power capacities. Consequently, there is no need for technologies that can provide system flexibility and decarbonize hard-to-electrify sectors, as can be observed for scenarios S1, S2, and S3. Furthermore, the use of biomass is restricted to sustainable limits, and the CO_2 emission price is still not sufficient enough to push out the use of fossil fuels, so there are investments in new gas boilers.

5. Conclusion

This research assessed the influence of fuel and technology costs, as well as policy targets, on the energy transition dynamic and the use of different flexibilization technologies. The needed investments and the development of energy system were examined in the energy planning optimization tool H2RES, with integration of the power, heating, and road transport sector and the use of flexibility technologies.

From the results, it can be concluded that the policy measures of increasing share of renewable power generation and limits on CO_2 emissions are the biggest drivers of energy transition, leading to high investments in renewable energy sources and flexibility options. With the decrease in technology costs, there is a possibility of achieving a slightly lower investment in renewable energy sources for the same demand and more investments in power-to-x technologies. For scenario S3, with lower fuel prices and high carbon prices, there is an increase in fossil fuel utilization in the heating sector, as carbon price isn't enough enticement to switch to electric heating solutions without restrictions on CO_2 emissions. System flexibility in the first three scenarios is achieved through heat storage, and in later years with introduced electric vehicles. There is also no investment in hydrogen production and stationary storage in scenarios without the requirement of full decarbonization.

The last two scenarios achieve full decarbonization due to imposed constraints. They hugely invest in the available potential of renewable energy sources. In both scenarios, system flexibility is achieved through heat storage, utilization of available electric vehicles, stationary storage, and hydrogen production, which is also used for industry decarbonization and transportation demand. In comparison with scenario S4, scenario S5 invests in gas boilers because of lower fossil prices but reduces investments in biomass boilers. Due to lower technology costs, it also invests more in hydrogen production and stationary storage for system flexibility and less in electrically driven heating solutions. Hence, as full decarbonization is achieved only with imposed policy measures and legislative obligations, there are no sufficient cost benefits only in lower technology costs and higher carbon prices to achieve zero CO_2 emissions in future energy systems. Nonetheless, it contributes to the diversification of installed P2X technologies. Expanding on the research in [29], it is demonstrated that CO_2 emission targets have a crucial role in the energy transition of future energy systems in comparison with fuel and technology cost decrease. Only in scenarios with the request of zero CO_2 emissions is achieved full decarbonization. Electrification and the use of hydrogen in hard-to-electrify sectors are the most prominent P2X technologies to achieve set goals.

However, it is important to address uncertainties in the study. Fuel prices are market-oriented and widely depend on a variety of social-economic factors for each country, geopolitical circumstances, and events of unpredictable significance. Technology costs are also highly variable, conditioned on industry development and established value chains in certain areas. Moreover, the accuracy of future costs and technological development can't be guaranteed, especially for the technologies in their early stages. Policy measures are also under constant revision and are periodically updated. However, precisely for that reason, studies that take into account cost variations are even more important to address possible scenarios of energy system decarbonization. Findings can provide an outlook on the sensitivity of energy system transition pathways even under unpredictable cost scenarios, leading to a stable investment environment for industry stakeholders. Policymakers can use the results in the discussion of the need for ambitious decarbonization targets in national energy strategies that will, in the long term, have benefits for society as a whole.

To further improve conducted analysis, in future research, there should be the inclusion of additional sectors and flexibility technologies in energy system studies that would influence the installation dynamics of P2X solutions. Hard-to-electrify sectors are in need of alternative renewable fuel options, leading to additional challenges in balancing hourly demand and renewable generation. Additionally, changes in projected cost scenario pathways can lead to different energy transition investment dynamics and stricter requirements on flexibilization technologies, which leads to higher energy system costs. Hence, with the room for further sensitivity analysis, additional research is still needed to provide the best overview to policymakers and technology developers on the most likely transition scenario and dismiss the restraint on fully considering the provided results.

To summarize, the conclusion of the study indicates the need for agreed-upon policy obligations from decision-makers to achieve decarbonization of energy systems. Without the ambitious targets, it is not expected to reach full energy system transition, as technology and fuel prices do not offer enough incentive to be pivotal in achieving stated goals. Therefore, findings can serve as valuable insight for policymakers to recognize the importance of high targets to lead the development of renewable energy systems and provide support for the use of P2X solutions in different energy sectors in the future.

CRediT authorship contribution statement

Doris Beljan: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Luka Herc:** Writing – review & editing, Methodology, Conceptualization. **Antun Pfeifer:** Writing – review & editing, Supervision. **Neven Duić:** 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

Data will be made available on request.

References

[1] "Paris Agreement to the United Nations Framework Convention on Climate Change, Dec. 12, 2015, T.I.A.S. No. 16-1104.".
[2] European Commission, REPowerEU Plan, 2022. Accessed: Jun. 18, 2024[Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483.
[3] International Renewable Energy Agency (IRENA), Renewable power generation costs in 2021, 2022. Accessed: Feb. 13, 2023[Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Power_Generation_Costs_2021.pdf?rev=34c22a4b244d434da0accde7de7c73d8.
[4] V. Khare, A. Jain, M.A. Bhuiyan, Perspective of renewable energy in the BRICS country, e-Prime - Adv. Electr. Eng., Electr. Energy 5 (2023) 100250, https://doi.org/10.1016/j.prime.2023.100250.
[5] M. Ram, A. Aghahosseini, C. Breyer, Job creation during the global energy transition towards 100% renewable power system by 2050, Technol. Forecast. Soc. Change 151 (2020) 119682, https://doi.org/10.1016/J.TECHFORE.2019.06.008.
[6] T.A. Hamed, A. Alshare, Environmental Impact of Solar and Wind energy- A Review, J. Sustain. Dev. Energy Water Environ. Syst. 10 (2) (2022) 1–23, https://doi.org/10.13044/j.sdewes.d9.0387.
[7] S. Tagliapietra, G. Zachmann, O. Edenhofer, J.-M. Glachant, P. Linares, A. Loeschel, The European union energy transition: key priorities for the next five years, Energy Policy 132 (2019) 950–954, https://doi.org/10.1016/j.enpol.2019.06.060.
[8] K. Neumann, M. Hirschnitz-Garbers, Material efficiency and global pathways towards 100% renewable energy systems – system dynamics findings on potentials and constraints, J. Sustain. Dev. Energy Water Environ. Syst. 10 (4) (2022) 1–20, https://doi.org/10.13044/j.sdewes.d10.0427.
[9] P. Capros, et al., Energy-system modelling of the EU strategy towards climate-neutrality, Energy Policy 134 (2019) 110960, https://doi.org/10.1016/j.enpol.2019.110960.
[10] K. Hainsch, et al., Energy transition scenarios: what policies, societal attitudes, and technology developments will realize the EU Green Deal? Energy 239 (2022) 122067 https://doi.org/10.1016/j.energy.2021.122067.
[11] V. Terjanika, J. Pubule, D. Blumberga, E. Zarins, Policy instruments for CO2 valorisation support, e-Prime - Adv. Electr. Eng., Electr. Energy 4 (2023) 100181, https://doi.org/10.1016/j.prime.2023.100181.
[12] K. Daszkiewicz, "Policy and regulation of energy transition," 2020, pp. 203–226. doi: 10.1007/978-3-030-39066-2_9.
[13] D. Borozan, Detecting a structure in the European energy transition policy instrument mix: what mix successfully drives the energy transition? Renew. Sustain. Energy Rev. 165 (2022) 112621 https://doi.org/10.1016/j.rser.2022.112621.
[14] F. Egli, B. Steffen, T.S. Schmidt, Bias in energy system models with uniform cost of capital assumption, Nat. Commun. 10 (1) (2019) 4588, https://doi.org/10.1038/s41467-019-12468-z.
[15] A. Grubler, et al., A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies, Nat. Energy 3 (6) (2018) 515–527, https://doi.org/10.1038/s41560-018-0172-6.
[16] F. Flores, F. Feijoo, P. DeStephano, L. Herc, A. Pfeifer, N. Duić, Assessment of the impacts of renewable energy variability in long-term decarbonization strategies, Appl. Energy 368 (2024) 123464, https://doi.org/10.1016/j.apenergy.2024.123464.
[17] S. Bolwig, et al., Review of modelling energy transitions pathways with application to energy system flexibility, Renew. Sustain. Energy Rev. 101 (2019) 440–452, https://doi.org/10.1016/j.rser.2018.11.019.
[18] K. Hansen, B.V. Mathiesen, I.R. Skov, Full energy system transition towards 100% renewable energy in Germany in 2050, Renew. Sustain. Energy Rev. 102 (2019) 1–13, https://doi.org/10.1016/j.rser.2018.11.038.
[19] F.A. Plazas-Niño, R. Yeganyan, C. Cannone, M. Howells, J. Quirós-Tortós, Informing sustainable energy policy in developing countries: An assessment of decarbonization pathways in Colombia using open energy system optimization modelling, Energy Strategy Rev. 50 (2023) 101226, https://doi.org/10.1016/j.esr.2023.101226.
[20] S.R. Sinsel, R.L. Riemke, V.H. Hoffmann, Challenges and solution technologies for the integration of variable renewable energy sources—a review, Renew. Energy 145 (2020) 2271–2285, https://doi.org/10.1016/J.RENENE.2019.06.147.
[21] M. Child, O. Koskinen, L. Linnanen, C. Breyer, Sustainability guardrails for energy scenarios of the global energy transition, Renew. Sustain. Energy Rev. 91 (2018) 321–334, https://doi.org/10.1016/j.rser.2018.03.079.
[22] H. Lu, X. Ma, M. Ma, S. Zhu, Energy price prediction using data-driven models: a decade review, Comput. Sci. Rev. 39 (2021) 100356, https://doi.org/10.1016/j.cosrev.2020.100356.
[23] M.G. Prina, F. Feijoo, M. Mimica, N. Duić, Advances in energy system modeling, sector coupling, and emission reduction strategies, e-Prime - Adv. Electr. Eng., Electr. Energy 6 (2023) 100316, https://doi.org/10.1016/j.prime.2023.100316.
[24] S. Ferrari, F. Zagarella, P. Caputo, M. Bonomolo, Assessment of tools for urban energy planning, Energy 176 (2019) 544–551, https://doi.org/10.1016/j.energy.2019.04.054.
[25] A. Pfeifer, V. Dobravec, L. Pavlinek, G. Krajačić, N. Duić, Integration of renewable energy and demand response technologies in interconnected energy systems, Energy 161 (2018) 447–455, https://doi.org/10.1016/j.energy.2018.07.134.
[26] M.G. Prina, G. Barchi, S. Osti, D. Moser, Optimal future energy mix assessment considering the risk of supply for seven European countries in 2030 and 2050, e-Prime - Adv. Electr. Eng., Electr. Energy 5 (2023) 100179, https://doi.org/10.1016/j.prime.2023.100179.
[27] M. Pavičević, K. Kavvadias, T. Pukšec, S. Quoilin, Comparison of different model formulations for modelling future power systems with high shares of renewables – the Dispa-SET Balkans model, Appl. Energy 252 (2019) 113425, https://doi.org/10.1016/j.apenergy.2019.113425.
[28] J. Solé, et al., Modelling the renewable transition: scenarios and pathways for a decarbonized future using pymedeas, a new open-source energy systems model, Renew. Sustain. Energy Rev. 132 (2020) 110105, https://doi.org/10.1016/J.RSER.2020.110105.
[29] F. Feijoo, A. Pfeifer, L. Herc, D. Groppi, N. Duić, A long-term capacity investment and operational energy planning model with power-to-X and flexibility technologies, Renew. Sustain. Energy Rev. 167 (2022) 112781, https://doi.org/10.1016/J.RSER.2022.112781.
[30] B. Hrnčić, A. Pfeifer, F. Jurić, N. Duić, V. Ivanović, I. Vušanović, Different investment dynamics in energy transition towards a 100% renewable energy system, Energy 237 (2021) 121526, https://doi.org/10.1016/J.ENERGY.2021.121526.
[31] E. Rusu, An evaluation of the expected wind dynamics in the black sea in the context of the climate change, e-Prime - Adv. Electr. Eng., Electr. Energy 4 (2023) 100154, https://doi.org/10.1016/j.prime.2023.100154.
[32] C. Li, et al., Exploring the interaction between renewables and energy storage for zero-carbon electricity systems, Energy 261 (2022) 125247, https://doi.org/10.1016/J.ENERGY.2022.125247.
[33] J.G. Kirkerud, N.O. Nagel, T.F. Bolkesjø, The role of demand response in the future renewable northern European energy system, Energy 235 (2021) 121336, https://doi.org/10.1016/J.ENERGY.2021.121336.
[34] D. Bogdanov, A. Gulagi, M. Fasihi, C. Breyer, Full energy sector transition towards 100% renewable energy supply: integrating power, heat, transport and industry sectors including desalination, Appl. Energy 283 (2021) 116273, https://doi.org/10.1016/J.APENERGY.2020.116273.
[35] H. Dorotić, B. Doračić, V. Dobravec, T. Pukšec, G. Krajačić, N. Duić, Integration of transport and energy sectors in island communities with 100% intermittent

renewable energy sources, Renew. Sustain. Energy Rev. 99 (2019) 109–124, https://doi.org/10.1016/J.RSER.2018.09.033.

[36] E.N. de Carvalho, A.C. Pinho Brasil Junior, A.C. de Mendonça Brasil, Energy impact assessment of electric vehicle insertion in the Brazilian scenario, 2020 –2050: a machine learning approach to fleet projection, e-Prime - Adv. Electr. Eng., Electr. Energy 4 (2023) 100184, https://doi.org/10.1016/j.prime.2023.100184.

[37] W. Zappa, M. Junginger, M. van den Broek, Is a 100% renewable European power system feasible by 2050? Appl. Energy 233–234 (2019) 1027–1050, https://doi.org/10.1016/J.APENERGY.2018.08.109.

[38] T. Cerovac, B. Ćosić, T. Pukšec, N. Duić, Wind energy integration into future energy systems based on conventional plants – the case study of Croatia, Appl. Energy 135 (2014) 643–655, https://doi.org/10.1016/j.apenergy.2014.06.055.

[39] I. Komušanac, B. Ćosić, N. Duić, Impact of high penetration of wind and solar PV generation on the country power system load: the case study of Croatia, Appl. Energy 184 (2016) 1470–1482, https://doi.org/10.1016/j.apenergy.2016.06.099.

[40] Z. Tomsic, I. Rajsl, P. Illak, M. Filipovic, Optimizing integration of the new RES generation and electrical energy storage in a power system: Case study of Croatia, in: 2017 52nd International Universities Power Engineering Conference (UPEC), IEEE, 2017, pp. 1–6, https://doi.org/10.1109/UPEC.2017.8232025.

[41] G. Krajačić, N. Duić, M.D.G. Carvalho, H2RES, Energy planning tool for island energy systems – the case of the Island of Mljet☆, Int. J. Hydrogen. Energy 34 (16) (2009) 7015–7026, https://doi.org/10.1016/j.ijhydene.2008.12.054.

[42] T. Novosel, F. Feijoo, N. Duić, J. Domac, Impact of district heating and cooling on the potential for the integration of variable renewable energy sources in mild and Mediterranean climates, Energy Convers. Manag. 272 (2022) 116374, https://doi.org/10.1016/j.enconman.2022.116374.

[43] P. Prebeg, G. Gasparovic, G. Krajacic, N. Duic, Long-term energy planning of Croatian power system using multi-objective optimization with focus on renewable energy and integration of electric vehicles, Appl. Energy 184 (2016) 1493–1507, https://doi.org/10.1016/j.apenergy.2016.03.086.

[44] D. Groppi, F. Feijoo, A. Pfeifer, D.A. Garcia, N. Duic, Analyzing the impact of demand response and reserves in islands energy planning, Energy 278 (2023) 127716, https://doi.org/10.1016/j.energy.2023.127716.

[45] "H2RES." Accessed: Dec. 28, 2023. [Online]. Available: https://h2res.org/.

[46] L. Herc, A. Pfeifer, F. Feijoo, N. Duić, Energy system transitions pathways with the new H2RES model: a comparison with existing planning tool, in: e-Prime - Adv. Electr. Eng., Electr. Energy, 1, 2021 100024, https://doi.org/10.1016/j.prime.2021.100024.

[47] A. Americo, J. Johal, and C. Upper, "The energy transition and its macroeconomic effects," Basel, Switzerland, 2023. [Online]. Available: https://www.bis.org/.

[48] Ministry of Environmental Protection and Energy, "Energy development strategy for Republic of Croatia until 2030 with a view to 2050," 2020, Accessed: Apr. 03, 2023. [Online]. Available: https://mingor.gov.hr/UserDocsImages/UPRAVA%20ZA%20ENERGETIKU/Strategije,%20planovi%20i%20programi/Strategija%20energetskog%20razvoja%20RH%202030%20s%20pogledom%20na%202050.pdf.

[49] M. Mišík, A. Nosko, Post-pandemic lessons for EU energy and climate policy after the Russian invasion of Ukraine: introduction to a special issue on EU green recovery in the post-Covid-19 period, Energy Policy 177 (2023) 113546, https://doi.org/10.1016/j.enpol.2023.113546.

[50] "Dispa-SET model." Accessed: Apr. 03, 2023. [Online]. Available: http://www.dispaset.eu/en/latest/.

[51] Ministry of Economy and Sustainable Development, "Energy in Croatia," 2020. Accessed: Apr. 03, 2023. [Online]. Available: https://mingor.gov.hr/UserDocsImages/UPRAVA%20ZA%20ENERGETIKU/Ostali%20dokumenti/Energija_u_Hrvatskoj_2020-1.pdf.

[52] DHMZ, "Mean annual power density." Zagreb, Croatia, 2009. Accessed: Jan. 10, 2024. [Online]. Available: https://meteo.hr/klima.php?section=klima_hrvatska&param=k1_8.

[53] The World Bank, Solar Resource Maps of Croatia, Global Solar Atlas 2.0, Solar resource data: Solargis, 2020. Accessed: Jan. 10, 2024[Online]. Available: https://solargis.com/maps-and-gis-data/download/croatia.

[54] I. Staffell, S. Pfenninger, Using bias-corrected reanalysis to simulate current and future wind power output, Energy 114 (2016) 1224–1239, https://doi.org/10.1016/j.energy.2016.08.068.

[55] S. Pfenninger, I. Staffell, Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data, Energy 114 (2016) 1251–1265, https://doi.org/10.1016/j.energy.2016.08.060.

[56] "ENTSO-e." Accessed: Apr. 03, 2023. [Online]. Available: https://www.entsoe.eu/.

[57] "Eurostat." Accessed: Apr. 03, 2023. [Online]. Available: https://ec.europa.eu/eurostat/web/energy/data/energy-balances.

[58] Energetski institut Hrvoje Požar, "ENERGIJA U HRVATSKOJ 2020," 2020. Accessed: Nov. 29, 2022. [Online]. Available: https://www.eihp.hr/wp-content/uploads/2022/01/Velika_EIHP_Energija_2020.pdf.

[59] Energy Institute Hrvoje Požar, "Comprehensive assessment of the potential for efficiency in heating and cooling in Croatia under Annex VIII to Directive 2012/27/EU," 2021, Accessed: Apr. 03, 2023. [Online]. Available: https://energy.ec.europa.eu/system/files/2022-01/HR%20CA%202020%20en.pdf.

[60] "Centar za vozila Hrvatske." Accessed: Apr. 03, 2023. [Online]. Available: https://www.cvh.hr/naslovnica/.

[61] The Danish Energy Agency, "Technology data catalogue." Accessed: Apr. 03, 2023. [Online]. Available: http://www.ens.dk/node/2252.

[62] International Energy Agency (IEA), World Energy Outlook 2021, 2021 [Online]. Available: www.iea.org/weo.

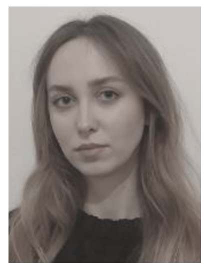
[63] C. Kost, S. Shammugam, V. Fluri, D. Peper, A. Davoodi Memar, T. Schlegl, Levelized Cost Of Electricity Renewable Energy Technologies, 2021 [Online]. Available: https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/EN2021_Fraunhofer-ISE_LCOE_Renewable_Energy_Technologies.pdf.

[64] International Energy Agency (IEA) and Nuclear Energy Agency, Projected Costs of Generating Electricity, 2020 [Online]. Available: https://www.oecd-nea.org/upload/docs/application/pdf/2020-12/egc-2020_2020-12-09_18-26-46_781.pdf.

[65] International Energy Agency (IEA), World Energy Outlook 2023, 2023 [Online] Available: https://www.iea.org/reports/world-energy-outlook-2023.

[66] Ea Energy Analyses, Analysis of biomass prices, 2013. Accessed: Apr. 03, 2023. [Online]. Available: https://www.ea-energianalyse.dk/wp-content/uploads/2020/02/1280_analysis_of_biomass_prices.pdf.

[67] D. Kryzia, L. Gawlik, Forecasting the price of uranium based on the costs of uranium deposits exploitation, Gospodarka Surowcami Mineralnymi 32 (3) (2016) 93–110, https://doi.org/10.1515/gospo-2016-0026.



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