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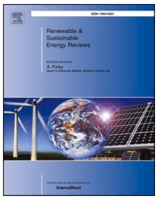

A long-term capacity investment and operational energy planning model with power-to-X and flexibility technologies

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ABSTRACT

In this research, we present a new long-term energy planning model that considers endogenous capacity investment, energy dispatch, Power-to-X, and demand response technologies. A thorough literature review of existing energy planning models is also presented, allowing to present the distinctive characteristics of the proposed model. The proposed model considers an energy system with the objective of minimizing the total capacity investment cost, throughout all technologies, and the operational cost faced by the system in satisfying energy demand. The model also considers the links among different demand sectors, including the links between the electricity, industry, heat, transport, and electro-fuels (e.g., Hydrogen) sectors. The proposed model is used to study the decarbonization of the Croatian energy system under distinct policies associated to RES levels and CO2 emissions goals. We demonstrate that Power-to-X technologies can certainly provide the flexibility that is required by new capacity investments in variable renewable energy sources, obtaining systems with lesser levels of critical excess of energy production. Higher usage of battery storage and Power-to-heat technologies are adopted primarily for variable renewable shares and CO2 reductions of close to 80%, while below such levels, the adoption of such technologies is limited. Additionally, Power-to-heat flexibility options become the major technologies when limits on CO2 emissions from the heating sector are imposed and, particularly, when the variable renewable energy shares in the electricity sector gets close to levels of 60%.

1. Introduction

Global warming and other effects of climate change are amongst the core challenges that humanity encounters nowadays [1]. It is well known that carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions have a significant part in this context [2]. In order to reduce the increased surface temperature levels, countries worldwide agreed on emissions and climate targets (e.g., National Determined Contributions, NDC) that seek to limit their emissions levels, particularly from the main emitting sectors, the energy, industry, and transport sectors [3,4], and are implementing other economic measures, such as carbon taxes [5] and other supporting policies [6], in order to reach such targets. From the technical point of view, to attain those goals, the energy and other systems are currently facing important transformations, significantly increasing the shares of variable renewable energy, such as solar and wind, which could in fact result in large curtailment or excess of energy [7]. However, a significant deployment of variable renewable sources also introduces operational and balancing challenges [8]. To adequately balance supply and demand in energy systems and avoid large curtailments, new approaches and technologies must be introduced [9]. Among these technologies, Power-to-X and demand response can provide the required flexibility, becoming a feasible solution [10].

In previous research, several Power-to-X and demand response technologies were pick-pointed as the most relevant to use the synergies between sectors of electricity production and various sectors of demand to decarbonize them using locally available renewable energy [11–13]. Such synergies are obtained by providing balancing services, allowing a flexible system operation as well as storage ability. Therefore, technologies that can help to balance power supply with demand from different sectors, such as heating, ventilation, and cooling (HVAC) demand, are of increasingly importance, particularly in modern cities where these loads can account up to 40% of the power consumption [14]. The role of balancing technologies capable of providing flexibility to the system also becomes more important with the increasing deployment of Distributed

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Energy Resources (DER), particularly in small communities (isolated or non-connected microgrids) as well as in Local Energy Markets (LEM) [14,15]. For instance, using all available heat pumps in smart grids would achieve a significant flexibility of the grid [11]. Heat pumps are an alternative option to transfer electrical energy to heating or cooling energy, which can then be stored using thermal storage tanks. In this context, the study presented in Ref. [16] demonstrated that air conditioning (cooling) heat-pump operated by PV panels and the electricity grid could reduce non-primal energy consumption to a 26%. Authors in Ref. [17] investigated the integration of solar and storage units by different balancing groups. They also concluded that Power-to-Heat (PtH) technologies provide are an alternative for handling balancing concerns. In the same context, the role and flexibility provided by district heating (DH) was studied in conjunction to energy efficiency by Pavičević et al. [18], and along waste management and heat markets by Tomić et al. [19]. Another opportunity for flexibility is considers the coupling of the power and transport sectors. Atia et al. [20] demonstrates that Vehicle-to-grid (V2G) can considerably influence renewable energy sources (RES) capacity plans, mainly for micro-grids design, showing that V2G is likely to play an important role in the integration of RES. Dorotić et al. [21] analyzed the economically optimal mix of solar and wind sources maintained by V2G while considering minimal electricity trade (import and exports). Also, Dominković et al. [22] showed via simulation that for integrated planning in small islands, EV smart-charging obtains similar effect as V2G.

Most of the research presented above have been done in short-to-medium time horizon, where the behavior or dispatch of technologies was studied, rather than the optimal size of such. However, it is needed to understand the role and required sizes of Power-to-X technologies in evolving environments towards low carbon economies [23]. In this context, Dominković et al. [13] studied, through scenario analysis with EnergyPLAN model [24], the possibility to reach 100% renewable energy systems in 2050 for the European South East region. They showed that this goal can be achieved with different types of storage and demand response technologies, including light-road transport electrification with 85% on smart-charging, and with the use of solar-thermal with additional storage for space heating, among other actions. Although simulation is a feasible approach to study different configurations of energy systems, it does not guarantee that the best solution, given a criterion, is achieved. Therefore, a different set of models, based on optimization algorithms, have also been proposed for planning and analysis of energy systems. For instance, the Dispa-SET tool [25], an hourly level unit commitment model, has been used to study the European Union power sector under high shares of renewable sources. The model obtains the hourly dispatch for each technology, given pre-defined capacities for such technologies, that result in the minimum yearly operational cost. However, the current version of the model does not optimize the size of the existing or new technologies and hence does not allow to endogenously optimize (long-term) energy systems.

Models that address long-term capacity planning and (or) operation-dispatch include, among others, PLEXOS [26,27], OSeMOSYS [28,29], GenX [30], PyPSA-Eur-Sec-30 (PyPSA) model [31], and the LUT Energy System Transition model [32,33]. PLEXOS is developed as a commercial software that models unit commitment and capacity planning of energy systems. PLEXOS has been used to study capacity expansion in the power sector [34] and electricity and natural gas sectoral system integration [35], among others. The GenX is a power system constrained optimization model that determines the share of generation (sources), storage, and demand-side resource investments to comply with the electricity demand while minimizing total cost subject to a variety of power system constraints (e.g., unit commitment constraints) and carbon policy constraints. The Open-Source Energy Modeling System (OSeMOSYS) model is developed as an open-source and free modeling software. OSeMOSYS solves for the minimum energy system cost, while satisfying a set of given demands. The cost considers both operating and investment cost, emissions cost, and a salvage value. Unlike PLEXOS, OSeMOSYS does not model the unit commitment problem, but rather the dispatch of different technologies considering constraints for supply-demand balance, minimum-maximum per year-total investment of technologies, minimum stable operation levels, and emissions considerations (penalties and limits) [29,36]. To guarantee computational flexibility, OSeMOSYS, as many other energy planning models, applies time slices for each year or period that is considered. For instance, the study presented in Ref. [29] considers one representative day for each season within a year period (hence, 4 time slices per year), while the study in Ref. [28] considered twelve time slices per year. A detailed comparison of the abovementioned models (PLEXOS and OSeMOSYS, and other models) can be found in Refs. [28,37]. The LUT Energy System Model (LUTESM) was used to study energy system transitions in regional contexts, such as in Bolivia [33] and Kazakhstan [38], and for global analysis [32]. The model is formulated as a long-term capacity optimization model with hourly energy dispatch while minimizing the total annual cost of an integrated (power, heat, industry, and transport sectors) system. The LUTESM also can consider different regions and the underling transmission grid connecting such regions. Given the detail of the model, units have been mainly grouped in terms of technology or fuel usage. The PyPSA-Eur-Sec-30 (PyPSA) model [31] is a capacity investment and operational energy system model which, as the LUTESM model, is capable of considering cross-border trade of electricity. PyPSA also has the ability to analyze cross-sectoral integration, including, power, heat, and transport sectors. The model is particularly designed to optimize the operation and investments of technologies for a single year (due to large size of the model in terms of decision variables). Although the great detail and cross-border ability, the decarbonization of the industry sector and transport (number of electric vehicles) is not yet fully modelled (exogenous parameters to the model).

There are several other energy planning models (short to long term) that have been presented in the literature. A summary of the main features of some of those models is presented in Table 1. Existing models can be initially differentiated by the sectoral coverage they consider. For instance, the Open Energy Modeling Framework (oemof) was developed as a general and flexible modeling toolbox to construct and for analysis of complex energy systems [55,56]. Models such as ReEDS, PLEXOS, SWITCH, DIETER, and HOMER were initially developed for analysis of the power sector only. Other models, such as Dispa-SET, consider a subset of the energy systems (power and heat sectors). Following, there are several models that attempt to account for the complete (or more details in the) energy sector, such as EnergyPlan, OSeMOSYS, LUTESM, PRIMES, REMix and NEMS. These models mainly differ on modeling assumptions, technologies that are considered and the type of modeling approach that is used (system optimization via LP or MIP models, simulation models, or equilibrium models). Integrated Assessment Models (IAM), such as GCAM, TIMES, and ReMIND are models that consider interactions between sectors beyond the energy sectors. For instance, IAMs normally account for relations among the human, climate, economic, energy, and land use systems. These models, due to their complexities, are normally used long term policy and climate analysis, considering 5-year (or 10) time steps, with no consideration of hourly variations and availability of renewable sources. Therefore, different models (sector specific, energy sector or IAM) should be used considering their own advantages and limitations and results should be analyzed based on their assumptions. In this context, several authors have attempted to quantify the difference among energy system models. For instance, authors in Ref. [57] quantified the outcome differences in power system models with sector coupling. They find that most of the outcome differences are due to the model scope rather than to the modeling approach. Note that this study focused on a yearly operation (not capacity investment) of a power system during a single year. In a similar effort, authors in Ref. [58] used four models with different scope (one economy-wide model, two partial equilibrium models with a full energy sector, and an electricity sector-only model) to evaluate the energy sector impacts of technology innovation, fuel price, and electric

Table 1
Energy system models.

Model	Coverage	Methodological approach	Resolution
Dispa-SET [25]	Power and heat sectors	optimization (MIP)	Hourly
LUT Energy System Transition model [33]	Energy sector	Optimization (LP)	Hourly
EnergyPlan [24]	Energy sector	Simulation	Hourly
ETSAP-TIAM [39]	energy sector and links	IAM optimization (LP)/partial equilibrium	Yearly (seasonal time slices)
GCAM [40]	energy sector and links	IAM/partial equilibrium	Yearly (5 years)
HOMER [41]	power sector	Simulation	Minutes
LEAP [42]	Energy sector	Simulation	Yearly
MARKAL [43]	Energy sector	IAM/optimization (LP)	Yearly (seasonal time slices)
MESSAGE [44]	Energy sector	IAM/optimization (LP)	Yearly (5 years)
NEMS [45]	Energy sector	optimization (LP)/ partial equilibrium	Yearly
OSeMOSYS [46]	Energy sector	optimization (LP)	Hourly (time slices)
PLEXOS [26]	power sector	optimization (MIP)	Minutes to Hourly
DIETER [47]	Power sector (integration with P2Heat and EV)	Optimization (LP)	Hourly
GenX [30]	Power sector (alternatively heat sector)	Optimization (MIP)	Flexible degree of resolution
REMix [48]	Power sector (alternatively heat, H2, others)	Optimization (LP)	Hourly
PyPSA-Eur-Sec-30 [31]	Energy sector	Optimization (MIP)	Hourly (single year)
PRIMES [49]	Energy sector	optimization (LP - EPEC)/partial equilibrium	Yearly
ReEDS [50]	power sector	Optimization	Hourly (time slices)
ReMIND [51]	energy sector and links	IAM	Yearly (5–10 years)
TIMES [52]	energy sector and links	IAM	Yearly (time slices)
WITCH [53]	energy sector and links	IAM	Yearly (5 years)
SWITCH [54]	power sector	optimization (MIP)	Hourly Dispatch/ Decadal Investment

sector CO2 policy. Authors conclude that general trends can be obtained, however, results vary based on how models determine capacity retirements, how models value variable renewable energy, and capability to include a price responsive demand. Additionally, authors in Ref. [47] present a thorough review of model-based analyses on the role of power storage in electricity systems with high penetration of variable renewable energy. They identify relevant modeling features to properly assess the role of storage, including a fine temporal resolution, a large set of contiguous time periods to capture short and long-term variability, the inclusion of competing flexibility option, among others.

Based on the literature, there is no detailed open-source model alternatives particularly built for the assessment of the whole energy system with hourly resolution and long-term planning of capacities of all generating units, as well as different types of Power-to-X (PtX) and demand response (DR) technologies. Similar models, such as PyPSA and OSeMOSYS, are built in similar spirit than H2RES, however, they are not always long-term, multi-year investment operational models with hourly resolution (without time slices), or, on the other hand, they do not consider decarbonization of other sectors, such as the industry or transport sectors. Therefore, this paper seeks to present a model for the study, assessment, and optimization of different PtX and DR technologies in a market coupling environment, to provide comprehensive knowledge about these technologies and their opportunities on emerging markets. The role of these technologies is assessed in a newly developed version of the H2RES model [59–62]. This new version of H2RES is built such that it provides a high degree of flexibility in terms of the technological and sectoral scope to consider. Hence, users can easily assess the role of a large set of technologies under different policy designs (e.g., CO2 or CEEP limits). The H2RES model was originally planned for water, electricity, heat, and hydrogen demand balancing using hourly time series and appropriate storages, and supply (wind, solar, hydro, geothermal, biomass, fossil fuels) profiles, focusing on islands and isolated regions. The new H2RES model considers the planning of an energy system in short-to-long horizons, with capacity (size) additions optimized for each of the technologies, including variable renewable and Power-to-X technologies. Additionally, the model considers hourly scale resolutions for energy dispatch (unlike models that use simpler time slices within a time period). The specific details of the model are presented later in the methods section. The new version of the H2RES model is used in this manuscript to evaluate the role that PTX technologies have in the transition towards a low carbon Croatian energy system.

The rest of the manuscript is organized as follows. We proceed with the methodology section, where details of the H2RES model are presented. Thereafter, we describe the Croatian energy system and the main data used for the analysis. The paper continues with the results section and concludes with final remarks.

2. Methods

This section presents the most important aspects of the enhanced H2RES model. The main sectors and the links among them are depicted in Fig. 1. H2RES considers the interactions among sectors, including heat sector, industry sector, power sector, and the transport sector. The modeling approach for each sector is presented next.

2.1. Power sector

H2RES first considers two set of units in the power sector: dispatchable units (DU) and non-dispatchable units (NDU). The NDU mainly consider solar, wind, and hydro-river (HROR) technologies. The flexible structure of the model allows to model different solar/wind/HROR zones, each of them characterized by different hourly-level availability profiles, capital cost, and installed and maximum capacity levels (technology potential by zone). Given the information regarding these technologies and zones, H2RES optimizes the capacity investments in each zone and in each period (long-term planning) while guaranteeing that the yearly Critical Excess of Energy Production (CEEP) does not surpasses a defined level (e.g., 5% of total yearly demand). The second set of units are the DU. Fig. 1 shows units aggregated based on primary fuel consumption, however, each power plant (PP) can be individually modelled and optimized. The set of DU consider coal, oil/diesel, natural gas, biomass, nuclear, and hydro units. Hydro based units are furtherer differentiated by hydro-dam (HDAM) and hydro-pump (HPHS) systems. As for the set of fossil-fuel PP, H2RES is able to optimize dispatch and seasonal storage for each of the HDAM and HPHS unit in a region, independently.

2.1.1. Heat sector

The heating sector demand is primarily served by either conventional boilers or through the link with the power sector (see Fig. 2). The power and heat sectors are linked through different technologies, depending on the heat demand to be satisfied. H2RES considers two main different heat demand types: District Heating (DH) and general

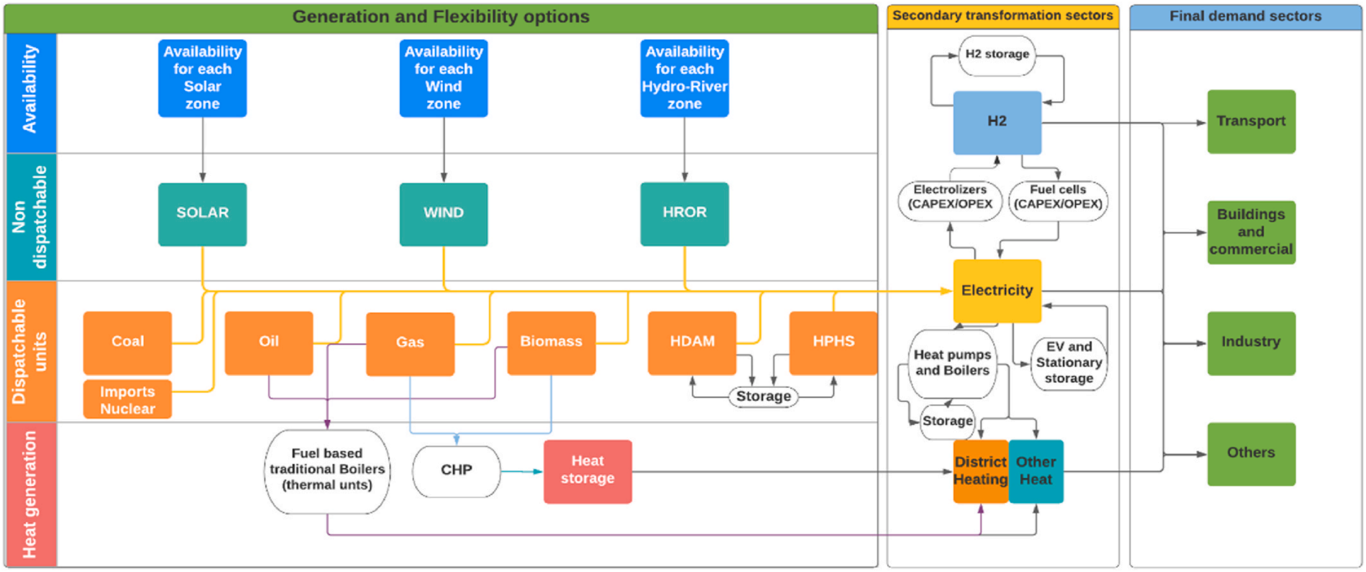

Fig. 1. Representation of the H2RES model.

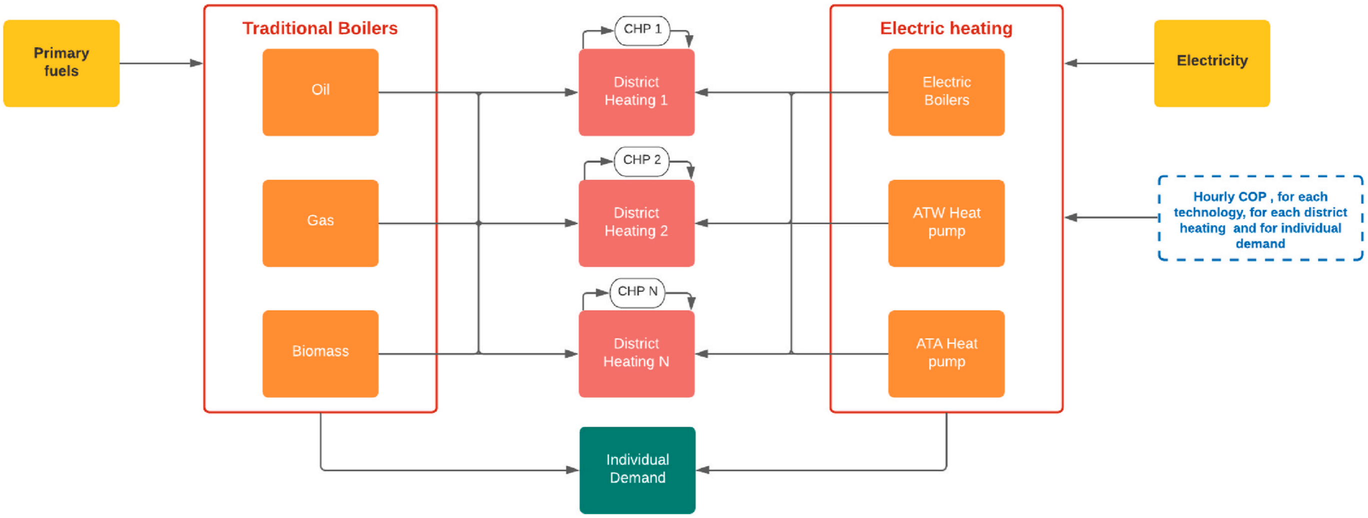

Fig. 2. Representation of the Heating sector in H2RES.

(individual space and hot water) heat-demand (GHD). The current version of H2RES allows to model different DH demand markets. Each of these DH demand markets could be met by an attached combine heat-and-power (CHP), traditional fuel-based boilers, and/or different technologies of boilers and heat-pumps (e.g., air-to-air heat-pumps). The GHD markets can only be supplied by a mix of electric boilers, traditional boilers, and different types of electric heat-pumps. Hence, the power and heat sectors are linked either by CHP units or electric heating systems. It is important to note that both, CHP and electric heating systems, serve as Power-to-X technologies as they provide high degree of flexibility with their storage capacities. Additionally, H2RES can model different technologies within the CHP, traditional fuel boilers, and electric heat systems. This allows to consider Power-to-X technologies that provide the same service, but with different technical characteristics capacity potential, and cost structure (e.g., air, water, or ground heat pump technologies).

3. Industry sector

H2RES follows a logit approach rather than a purely cost based approach to model the share of different fuels in the industry sector. The logit approach uses a choice function which uses as input prices and preferences for the different choices. The logit approach then returns a vector of market shares for the corresponding choice alternatives. Choice functions reflect that the single best choice (e.g., based on price or cost only) does not necessarily capture the entire market. This allows to account for other factors, such as user preferences, in the determination of the market share of different alternatives (see Refs. [63,64] for further details). Given this approach, H2RES considers hourly profiles of different fuels that can supply the hourly demand profile of the industry sector. The price of each fuel is further adjusted based on the CO2 price and emissions factor of a fuel considered on a scenario run. Additional to traditional fuels (coal, gas, oil, biomass, among others), electricity and hydrogen can be used as alternatives to decarbonize the industry sector. Penetration of hydrogen and electricity is defined by H2RES based on the environmental constraints that can be considered (limit of CO2 emissions or market share of RES in the power sector) and cost of generation against the cost of traditional fuels. H2RES can also consider limits (defined by the user) on the level of hydrogen and electricity penetration on a yearly basis. The graphical representation of the industry sector is depicted in Fig. 3.

4. Transport sector and stationary storage

Another flexibility option in H2RES is provided by electric storage, either through electric vehicles (EVs) or stationary storage. For the case of EVs, H2RES considers that EVs can act as variable storage (depends on driving profiles given to H2RES) and provide vehicle-to-grid (V2G) services. The level of V2G is subject to required exogenous EV demand profiles and minimum battery level requirement, similar to the assumptions in the EnergyPLAN model [65,66]. Additionally, H2RES considers two other modes of transportation, Fuel Cell Electric vehicles (FCEV) and Internal Combustion Engine (ICE) vehicles. H2RES has an installed "legacy" number of different types of vehicles that are eventually decommissioned. Furthermore, as decommission happens, along with RES and CO2 level constraints, H2RES optimizes the investment of EV and FCEV (number of vehicles needed) in order to satisfy a predefined transport demand. The investments into EV and FCEV are constrained by the limitations on the sale of new vehicles, their investment price, and restrictions on emissions.

5. Hydrogen generation/demand and hydrogen to power

Similar to the heat demand, H2RES considers based hourly profiles of hydrogen (H_2) demand. Based profiles of demands for H_2 are distributed across the transport, building, industry, and other final demand sectors. Additionally, H2RES allows to increase the penetration of H_2use in both transport and industry sectors in order to decarbonize those or to comply with other constraints, such as limits of excess of energy produced, balancing, or simply store H2 for utilization in future periods (H_2 storage). In order to satisfy demand levels, electrolyzers and H_2 storages are optimized. H2RES provides the optimal generation and storage levels at hourly levels, and investments in capacity for each year in the planning horizon. Similarly, H2RES optimizes (dispatch and sizes) for fuel-cell technologies. Like the case of the heat (DH and GHD) sector, H2RES allows to model different electrolyzers and fuel-cell technologies, with distinct technical and cost characteristics.

5.1. Mathematical structure: objective and main constraints of the enhanced H2RES

The proposed new H2RES model is a large-scale linear optimization program. H2RES is written in Python (programming language) and solved using the GUROBI optimization solver (library gurobipy) for linear programming problems. For problems that are computationally expensive or intractable, users can set the Barrier algorithms and configurations of H2RES-GUROBI to increase computational speed. However, quality of the solution might be compromised, obtaining near-optimal solutions or non-corner points. Regarding the optimization, H2RES considers three main sets of decisions variables. First, we consider yearly investment capacities choices for each of the technologies (dispatch and storage size). H2RES assumes that if a capacity addition is made for a given technology, then this addition becomes available at the beginning of the year. Secondly, we consider dispatch variables for all technologies. Dispatch of the technologies considers hourly resolution for every year of the modeling time horizon. The choice of hourly resolution, instead of the standard time-slice approach, significantly increases computational time. However, this allows to better represent the relation between variable renewable sources and Power-to-X technologies. Third set of variables corresponds to storage levels (hydro, heat, H_2, electricity-EV-Stationary). Storage levels for each of unit or technology, when available, are also represented with an hourly resolution for every year considered in the planning horizon. The main objective (optimization) and the most important constraints of H2RES model are described next.

Objective. H2RES minimizes yearly operation and capacity cost. Since H2RES allows to model long-term planning horizon, the net present value of future operation and capacity costs are considered. The model also considers ramp up/down and CO_2 costs. A general mathematical representation of the model's objective is shown in equation (1).

$$\sum_{y}\sum_{p}\sum_{t} df_y \left[C_{t,p,y}D_{t,p,y} + TC_{t,y}K_tInv_{t,y} + R_{t,p,y}Ramp_{t,p,y} + I_{p,y}Imp_{p,y} + CO_2Price_yCO_2Levels_{t,p,y}\right] \quad (1)$$

The first component in the objective function (1) corresponds to the variable cost (fuel and non-fuel cost) associated to dispatching a given technology (*t*), in each period or hour (*p*), and for every year (*y*). The parameter for the variable cost, $C_{t,p,y}$, is a function of fuel cost and non-fuel cost, allowing to model cost structures for different categories of technologies.

$$C_{t,p,y} = \left[\frac{FuelCost_{t,p,y}}{eff_{t,p,y}} + NonFuelCost_{t,p,y}\right] \quad (2)$$

The second component in objective function (1) considers the annualised capital investment cost (K_t) of technology *t*. This represents the cost incurred per-unit of additional capacity of a given technology (e.g., per EUR/MW). The term $TC_{t,y}$ models the technology change cost (learning curve) of a technology that might have reduced capital cost in the future. The third and fourth terms of the objective function (1)

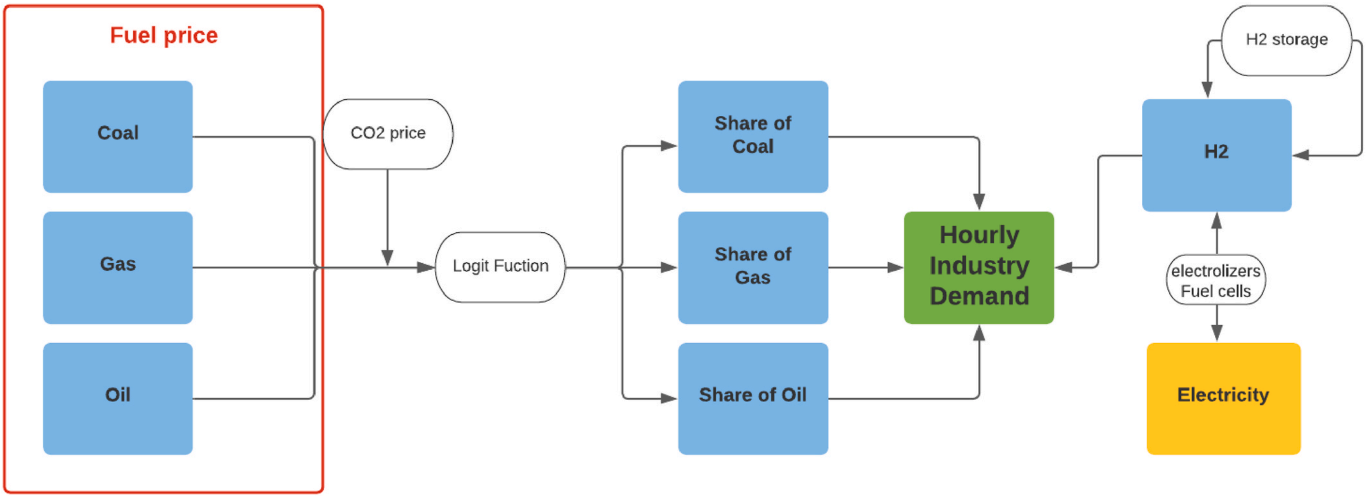

Fig. 3. Representation of the Industry sector in H2RES.

represent the ramp up/down and import cost, respectively. Note that the current version of H2RES allows for electricity imports only. Finally, the model also considers the CO_2 emissions cost for each of the emitting technologies.

Constraints. H2RES provides the size of technologies and the dispatch levels that provide the minimum cost as defined by the objective function (1), under a set of defined constraint that model technical, operational, and logical aspects of energy systems. The main set of constraints are briefly described next.

a) Dispatch and technical constraints: Each technology's output level has a defined upper bound corresponding to the installed capacity at the start of the simulation period. When capacity investment is permitted, maximum investment levels can be set for different technologies (potential of each technology). If required, a lower bound on investment can be defined for a subset of technologies. Note that H2RES considers dispatchable and non-dispatchable units, such as wind and solar. We also consider technical constraints for power plants, such as ramp up and down limits.
b) Storage constraints: For the set of technologies that have storage capacity, H2RES models the hourly level state of charge for every year in the planning horizon. Some of these storage technologies (hydro-dam units) have natural inputs (inflows), while inputs for other technologies must be optimized, such as heat stored in district heating, H_2 in H_2-storage, or electricity in stationary batteries. Each of the considered storage technologies has a minimum-maximum state of charge that must be met in every hour of the planning horizon.
c) Demand constraints: H2RES disaggregates demand levels of electricity, heat, and H_2 in different demand sectors, including transport, industry, agriculture, and others. The main constraint of the H2RES model is to guarantee that each of the demand for different energy carriers in each demand sector is supplied in all hours and years of the planning horizon. The demand constraint for the electricity sector is further described in Equation (3). The constraints indicates that dispatch from all units, outputs of storage services and imports (if available) must equal (satisfy) the demand from all sectors, input into storage services, energy transform into a different carrier (e.g., Power-to-Heat or Power-to-H_2) and the CEEP level to account for any excess of electricity production.

$$\sum_{t\,\in\,Units} D_{t,p,y} + \sum_{t\in Sto} Out_{t,p,y} + Imp_{p,y} = \sum_{d\,\in\,DS} Dem_{d,p,y} + \sum_{t\in Sto} In_{t,p,y} + \sum_{t\,\in\,PtX} PtX_{t,p,y} + CEEP_{p,y}\ \forall y,p\ (3)$$

d) Policy constraints: The H2RES model allows to consider three (individually or simultaneously) policy dimensions. Firstly, H2RES considers different limits of Critical Excess of Energy Production (CEEP) during a time horizon. When the model is run for long-term planning scenarios, a maximum CEEP level can be defined for every year in the planning horizon. Secondly, H2RES allows to set targets for renewable energy (%-RES) in the power sector. Like the case of the CEEP target, H2RES models different %-RES targets for each year in the planning horizon. Therefore, H2RES is designed to evaluate different systems configurations aligned with low carbon future economies. Finally, H2RES considers sectoral bounds for CO_2 (or CO_2eq) emissions.
e) Penetration level constraints: H2RES allows to model the level (maximum and minimum) penetration of electricity and hydrogen in the heat, transport, and industry sectors. Such penetration levels can be subject to upper and lower bounds to avoid, for instance, fully electrified industry sector, as some processes might require higher degree temperature. H2RES can also use these bounds to assess different pathways of decarbonization via means of electrification or usage of alternative fuels, such as Hydrogen.

6. Description of the case study: Croatian energy system

6.1. Croatian power and heat sectors

This research focuses on the decarbonization of the Croatian energy (power, heat, industry, and transport) system. Regarding the power sector, Croatia had, as of 2019, a total capacity of 5211 MW. Additionally, Croatia owns 50% (348 MW) of the Krško Nuclear Power Plant, currently situated in Slovenia. Also, data based on data from the Croatian Independent Transmission System Operator (HOPS) as of 2019, Croatia had 10 thermal (mainly coal and gas) power plants with a total capacity of 2019 MW, 19 hydro (dam and pump systems) power plants (2127 MW), and 18 wind farms with a total installed capacity of 671 MW [67].

The Croatian Annual energy report, Croatian Energy Regulatory Agency, and HOPS [67,68] estimate that the total electricity consumed in Croatia in 2019 was 18,169 GWh. Most part of the demand (12,006 GWh, 66.1%) was delivered by local power plants, whereas imports (6.163 GWh, 33.9) supplied the remaining demand (this trend is similar in years 2018 and 2019). In recent past, the peak load happened during the summertime, mainly driven by somewhat mild winters and increasing demand due to cooling demand (air-conditioning) during summer months. The peak load in 2019 happened on 25 July, reaching 3038 MW. Of the total electricity consumed in 2019, the households share was 37.6%, whereas the portion of energy (electricity) delivered to other end-consumers was 62.4%, also following similar trends from 2018. The daily production (mix of technologies) and consumption levels in the Croatian power sector during 2019 is shown in Fig. 4 [69].

Regarding Croatia's future energy system, different reports considered that the predominant new sources of RES will come from wind and solar power plants. Also, a constant growth of hydropower and gas power plants is expected. In the case of hydropower plants, most of the Croatian dammed potential has been already exhausted. Therefore, most of the new hydropower energy is expected to come from run-of-river (ROR) and minor hydropower power plants. Biomass and geothermal power plants are also expected to have steady but small growth in the future. However, opposite to the current context, electricity generation in Croatia from thermal plants is projected to have significant drop. Oil based plants are to be closed by 2030, while coal fired plants are to be shut down by 2040. The Krško nuclear power plant is intended to be out of operation by the year 2043. The technical potential and limitations of RES in Croatia are shown in Table 2. Note that the largest potential corresponds to wind and solar power sources, while biomass has the potential to be used in the heating and industrial sectors.

Regarding the heating sector in Croatia, DH systems supply around 10% of the domestic heat (space heating) demand. The biggest system is located in Zagreb. The systems in Zagreb, Osijek and Sisak are being supplied by the heat from cogeneration plants (gas CHP units), while the remaining systems use traditional boilers. The total heat delivered (district heating) in 2020 to end users accounted to approximately 1.45 TWh, where Zagreb alone delivered 1.16 TWh (80% of the district heating demand). Total heat demand in Croatia, driven by its declining population and energy efficiencies measures, is expected to decline approximately 58% from 2020 to 2050, reducing 26.84 TWh in 2020 to 11.29 TWh in 2050 [67,68].

6.2. Case Study

The H2RES model is applied to the Croatian energy system to comprehend the role of flexibility options in the decarbonization of the power, industry, heat and transport sectors. We particularly consider Power-to-Heat flexibility options (different technologies of heat pumps and boilers), Power-to-H_2 (via different electrolyzer technologies), Power-to-Storage (EV and stationary storage) and H_2-to-Power with fuel cell technologies. Demand levels for electricity, heat and hydrogen are exogenous. Hence, the model optimizes the mix of technologies (size and

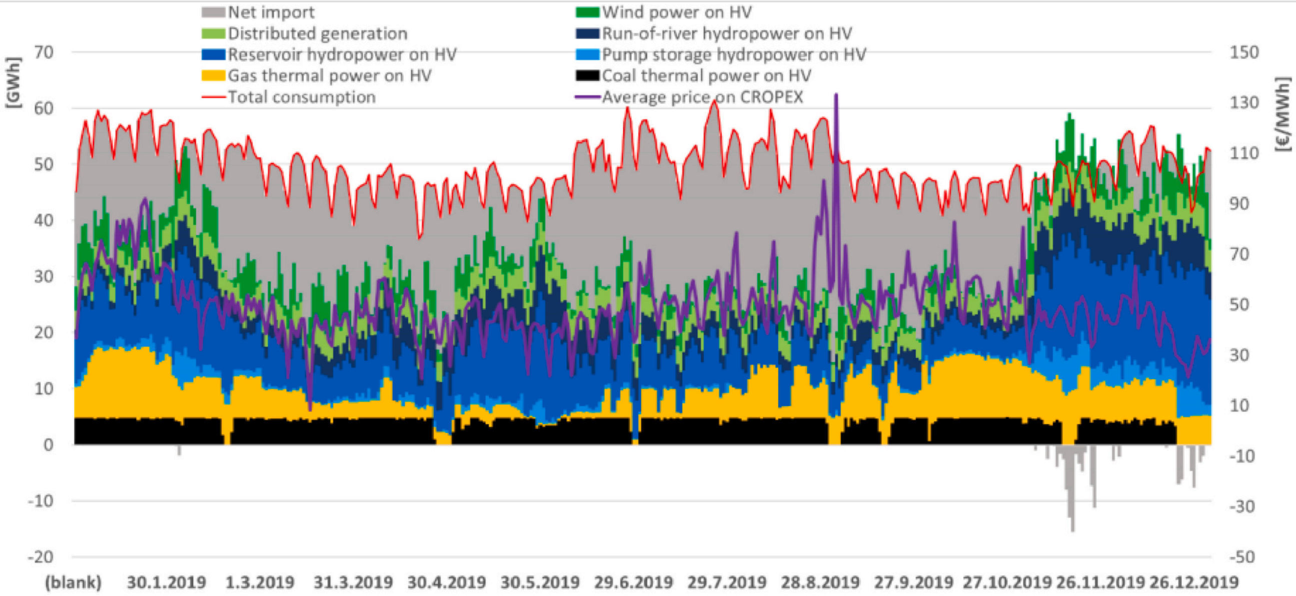

Fig. 4. Daily production and consumption electricity profile for the Croatian electricity system in 2019. Figure obtained from the Croatian Energy Regulatory Agency [69].

Table 2
Comparison of technical potentials in Croatian energy system. Data from Croatian energy development strategy [70].

RES	Technical potential	Unit
Hydropower	3700–4250	MW
Wind power	7000–9000	MW
Solar power	8000	MW
Biomass (forests)	36,2–72,21	PJ
Agricultural leftover biomass	18,44–57,93	PJ
Biogas and biomethane	5,83–11,5	PJ
Waste	13,54–17,27	PJ
Biomass from crops	5,99–6,08	PJ
Energy crops	60–109,43	PJ
Geothermal energy	56,5–67,6 up to 100	MW

dispatch) to account for all demand at the least cost. We consider that power demand grows at a rate of 1% per year, considering the 2020 demand levels as baseline. Heat demand is modelled considering a low efficiency case, where heat demand is reduced 25% between 2020 and 2050. Based on the study presented by uel Cells and Hydrogen Joint Undertaking (FCH JU) and the European Commission [71], hydrogen demand is assumed to reach approximately 0.45 TWh in 2030. We assume a yearly increase of 1% for hydrogen demand from 2030 towards 2050.

We consider two different policy scenarios. The first set of scenarios considers penetration level of RES technologies of 90% towards 2050, limiting the CEEP levels to 5% and 10%. The second set of scenarios adds CO_2 emissions limits to the RES penetration scenarios. We impose a CO_2 reduction of 90% (power and heat sector) in 2050 based on 2020 levels. The RES and CO_2 limit scenario is also considered under CEEP levels of 5% and 10%. We also consider a decommission of heat technologies of 10% per year after the lifetime is reached (10 years of lifetime). The technology data used for flexibility options in the heat sector (and other) is described in Table 3. We also assume that all fuel prices (coal, gas, oil, biomass, uranium) increase with a rate of 1% per year in relation to historical 2020 levels. Inflows for hydro units and availability factors of wind and solar are considered to remain similar to 2020 levels for each future year. Finally, for stationary storage, we consider a maximum potential of 4000 MW.

Table 3
Technology data for H2RES.

Technology	Units	INV 2020 (M€/unit)	INV 2030 (M€/unit)	INV 2040 (M€/unit)	INV 2050 (M€/unit)	Efficiency	Source
Large scale PV	MW	0.53	0.38	0.33	0.3	–	[72]
		0.83	0.69	–	0.56	–	[24]
Residential PV	MW	1.13	0.87	–	0.59	–	[72]
		1.25	1	–	0.85	–	[24]
Wind	MW	1.12	1.04	0.98	0.96	–	[72]
PEMFC CHP	MW	1.3	1.1	–	0.8	50%	[72]
SOFC CHP	MW	3.3	2	–	0.8	60%	[72]
Alkaline Electrolyzer	MW	0.65	0.45	0.3	0.25	66.5–78	[73]
SOEC Electrolyzer	MW	4.5	1.9	1.3	0.78	77–83.5%	[73]
PEM Electrolyzer	MW	0.92	0.65	0.45	0.4	58–70.5%	[73]
H2 storage (tanks)	MWh	0.057	0.045	0.027	0.021	–	[74]
Li-ion Battery	MWh	1.042	0.622	0.394	0.255	92% (charge/discharge)	[74]
biomass boiler	MWth	0.47	0.447	0.425	0.404	79–85%	[75]
gas boiler	MWth	0.278	0.265	0.252	0.24	99%	[75]
air-to-water HPs	MWth	1.2	1.076	1.016	0.956	3.282 (SCOP evaluated)	[75]
geothermal HP	MWth	1.932	1.836	1.74	1.566	4.621 (SCOP evaluated)	[75]
Electric boilers	MWth	0.89	0.85	0.81	0.77	100%	[75]

7. Results and discussion

This section presents the results of the study. The results will be exposed depending on the constraints; thus, at first, the scenarios with RPS limit will be shown and the difference caused by the different CEEP limit will be identified and discussed; then, the scenarios with RPS and CO_2 limits will be analyzed and compared. In the end, a comparison between the two approaches (with and without CO_2 limit) will be developed.

7.1. Renewable Portfolio Standard constraint only

In the simulations that assumed only Renewable Portfolio Standard (RPS), no restrictions on emissions were implemented. Still, the system in these cases achieved decarbonization since the existing capacities are decommissioned or replaced with more economically viable renewable energy solutions. Also, there was no possibility offered in the model to invest into fossil technologies such as natural gas boilers. The results of CO2 emissions (power, heating, industry, and transport sectors) and CEEP are displayed in Table 4. For most of the cases, CEEP values are between 1% and 2%, while maximum of 5% and 10% respectively is reached in 2050. It is interesting to observe that the sectors of industry and transport are decarbonized even though they are not captured under the RPS restrictions (power sector only). Achieved values of emissions for 5% and 10% CEEP are similar and there is no significant difference.

The results for capacity buildup of VRES are shown in Table 5. It is interesting to observe different investment strategies resulting from the differences in capacity factors and capacity investment costs, such as the case of the small installed capacities of HR_WindPP (low capacity factors compared to other RES-wind areas).

When capacity investments are compared, the differences between the cases with 10% and 5% CEEP restriction are small. Total installed wind capacity in the scenario with 5% CEEP is 9960 MW while for the case with 10% CEEP is 9961 MW. As for PV, the total installed capacity in the cases with 5% CEEP is 16,791 MW, while for 10% CEEP it is 16,796 MW.

As previously stated, the energy system chose to produce more energy from renewables even in the early stages of transition. This is mainly due to the fact that it provides a more economical option than continuation of using fossil fuels. Also, to continue using fossil fuels in power system, new capacities would have to be built since majority of the existing thermal capacities is planned to be decommissioned around 2030. The results for generation in each year are shown in Fig. 5, with the figure displaying only the case with 5% CEEP.

The results for heating sector are displayed in Fig. 6. Fossil fuel boilers are replaced with biomass at first and then by heat pumps and electric heaters. The replacement is due to decommissioning of boilers and because the biomass and electrical heating system are more economical.

Table 4
CO2 emissions by sector and year for different CEEP limits.

Year	CEEP limit (%)	CO_2 power	CO_2 heating	CO_2 industry	CO_2 transport	CEEP (%)
2020	5	382	2810	4177	7365	1.43
	10	382	2810	4177	7365	1.43
2025	5	111	1690	2474	7201	2.15
	10	112	1689	2474	7201	2.16
2030	5	68	847	1918	6095	1.35
	10	67	849	1919	6095	1.36
2035	5	44	0	1337	4989	1.74
	10	43	0	1336	4989	1.75
2040	5	30	0	861	3883	1.65
	10	30	0	861	3883	1.71
2045	5	23	0	490	3883	2.65
	10	23	0	489	3883	2.69
2050	5	73	0	0	3883	5
	10	64	0	0	3883	10

The list of installed capacities in the heating sector is shown in Table 6. Most notable differences are in the installations of heat pumps, where more capacity is installed in the cases with CEEP limit of 5% due to heat pumps being able to provide energy system flexibility. It should be noted that the thermal storage size for individual heating is not optimized; nevertheless, an initial capacity of 1000 MWh has been assigned to every HPs (and electric boiler) technology, hence, it is possible to think that the thermal storage size is not limiting the installed HPs capacities.

The results for the two CEEP cases in the realm of Hydrogen and energy storage are displayed in Table 7. Most notable differences are in alkaline and SOEC electrolyzer where the case with 5% CEEP has more installed capacity. Also, the hydrogen storage is notably higher in the case with 5% CEEP. Larger amounts of Hydrogen storage are required to provide options to reduce excess of electricity by transforming it into Hydrogen and storing it for future heat, power, transport or industrial demand.

The results for system cost are displayed in Fig. 7. It is visible that the system cost increases when installing new technologies due to large investments. Also, it decreases after majority of the investments it complete.

7.2. Renewable Portfolio Standard and carbon emission constraints

In these scenarios, as previously explained, both constraints, RPS and the limit on the level of emissions, are adopted. In Table 8, the CO_2 emissions across sectors are shown for the two CEEP scenarios. It is interesting to observe that the observed CEEP limit as well as the CO2 emissions behave similarly in both CEEP limit scenarios. Also, CO2 emissions are minimized by 2050 while CEEP peaks, reaching the maximum allowed. As for emissions, the system opts to decarbonize power and heating sector as quickly as possible. Power sector is initially decarbonized only by balancing the power supply and therefore using only available zero carbon energy in combination with the imports.

The results for total capacity investment in renewable systems are shown in Table 9. For the case with CEEP limit of 5%. The comparison with the case of 10% CEEP limit is shown in Table 9. As expected, the differences in obtained values of VRES capacities are small. The total solar and wind capacities installed by 2050 are 9960 MW and 11,802 MW, respectively in the scenario with 5% CEEP allowed; while in the scenario with 10% CEEP they are 2050 are 11,802 MW and 11,808 MW, respectively.

The results for the power generation by fuel source in each year are shown in Fig. 8. Since there is no significant difference between the installed capacities, only the case with 5% CEEP constraint is shown. As mentioned before, the system already in 2020 invests into renewable sources and minimizes the use of thermal power plants. Only the biomass power plants continue working, but are not actively invested into. Nuclear power plant is decommissioned after 2030. Generation from variable renewable power plants, most notably wind power, is drastically increased by 2050. Also, it is interesting to observe that in 2050, the system chose to reduce the usage of hydropower to reduce the levels of excess electricity.

The results for the heating sector in individual households are displayed in Fig. 9, while all the results for heating sector are displayed in Table 10. It can be observed that the system first invests into biomass boilers to discontinue to use of fossil fuels, but after 2030 starts to rapidly shift towards electrically powered heating solutions. These include heat pumps and electric heaters. CHP's are also replaced with the combination of biomass boilers and heat pumps as a side effect of RPS and CO2 mandates as well as because of the increasing prices of natural gas and emission tax.

The new installed capacities of each thermal technology in each year are shown in Table 10. It should be noted here that, although the system does have existing capacities in a form of gas and oil boilers capable of

Table 5
Installed capacities of VRES in the cases with only RPS restriction.

Year	CEEP limit	HR_SolarHigh	HR_SolarPP	HR_WindPP	HR_WindPP1	HR_WindPP2	HR_WindPP3
	%	MW	MW	MW	MW	MW	MW
2020	5	1999	0	0	79	358	0
	10	2000	0	0	94	348	0
2025	5	807	0	0	349	520	0
	10	810	0	0	334	523	0
2030	5	1479	0	0	2	464	0
	10	1480	0	0	1	466	0
2035	5	675	1	290	1175	959	0
	10	670	0	238	1152	1028	0
2040	5	0	1000	369	327	1	0
	10	0	986	399	330	1	2
2045	5	0	1993	351	190	0	78
	10	0	1990	305	207	1	79
2050	5	10	1997	236	676	0	2005
	10	10	2010	364	793	0	2005
Total	5	4971	4989	2222	3724	2284	3572
	10	4971	4988	2201	3712	2328	3567

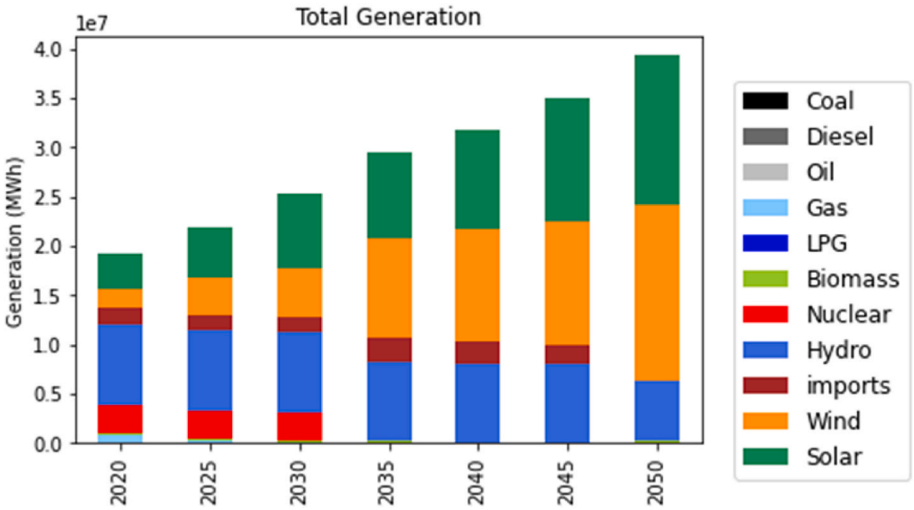

Fig. 5. Power generation by the fuel for the case with 5% CEEP limit.

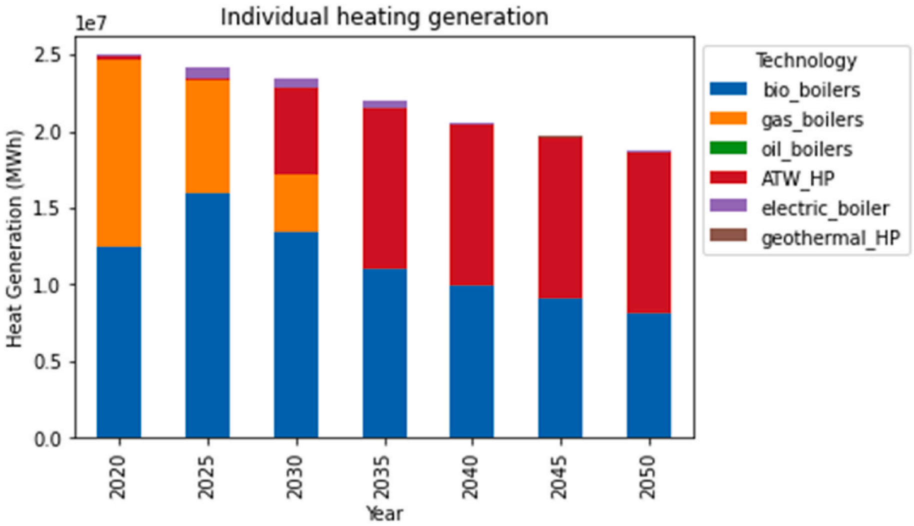

Fig. 6. Generation by fuel per year with a 5% CEEP constraint.

Table 6
Installed capacity for thermal technology per year expressed in MWth.

Year	CEEP limit (%)	Biomass boilers	Gas + Oil boilers	ATW HPs	Electric boilers	Geothermal HPs
2020	5	2201.49	0	0.05	0	0.01
	10	2199.9	0	0.14	0.07	0.01
2025	5	3814.01	0	107.79	19.34	20.38
	10	3816.38	0	113.06	19.4	19.67
2030	5	0.77	0	3015.08	0.41	15.88
	10	0.4	0	3006.37	0.78	17
2035	5	0.1	0	2618.98	208.67	8.65
	10	0.1	0	2630.91	200.82	10.2
2040	5	0.04	0	0.7	30.11	0.66
	10	0.03	0	0.82	24.94	1.64
2045	5	0.1	0	1.16	50.97	0.88
	10	0.01	0	0.54	51.71	0.49
2050	5	0.23	0	0.86	23.49	0.49
	10	0.15	0	1.56	22.44	1.65

covering heat demand, it chooses to invest into carbon neutral solutions rather than to use existing equipment.

The results for the implementation of energy storage technologies are displayed in Table 11. In this case, the differences between the scenario with 5% CEEP limit and the one with the limit of 10% are shown. The scenario with the limit of 5% CEEP invested more into energy storage technologies, especially in alkaline electrolyzer and hydrogen storage systems. It is interesting to observe that the system with greater capacity of Li-ion battery storage is the one with 10% CEEP limit. The reasoning behind this is due to lower cost of battery storage which was required to be used far less than the hydrogen storage as in the case that achieved 5% CEEP.

8. Discussion on H2RES results and comparison among scenarios

In this section, the two policy scenarios (RPS and RPS with CO2 limits) are compared and contextualized with existing literature. Only the results for 5% CEEP are displayed since they are similar to the ones with 10% CEEP.

The comparison of results between the case with carbon limits and the one without is displayed in Table 12. The results on installations of PV and Wind power are displayed. As can be seen the case with carbon restriction provides higher installed capacity of VRES. Therefore, with the same CEEP limitation, this means that more of the renewable energy is used indicating faster transition. This is largely due to the greater electricity demand generated by the flexibility options, as for example heating and transport (see Supplementary material for results on Transport and Industry).

The production of heat from heat pumps and electric boilers is displayed in Table 13. As expected, the case with carbon limit required more energy from electrically driven heating systems.

The limitation on CO2 emissions also influences the strategies of investments into energy storage technologies. The results for the case

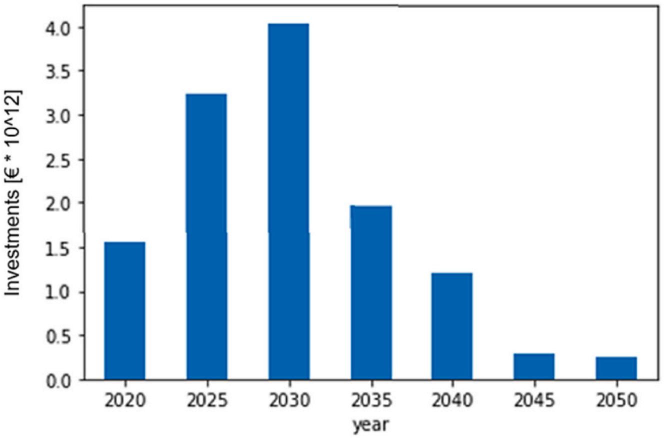

Fig. 7. System cost.

Table 8
Results for CO2 emissions and CEEP values.

Year	CEEP limit (%)	CO_2 power sector	CO_2 heating sector	CO_2 industry sector	CO_2 transport sector	CEEP (%)
2020	5	366	1453	4177	7365	1.48
	10	367	1456	4177	7365	1.48
2025	5	54	1341	2458	7200	2.58
	10	54	1330	2470	7201	2.57
2030	5	62	841	1919	5838	1.39
	10	61	841	1916	5843	1.37
2035	5	48	0	1337	4366	1.6
	10	47	0	1337	4372	1.6
2040	5	32	0	861	2895	1.5
	10	31	0	861	2901	1.49
2045	5	14	0	417	1790	2.4
	10	13	0	417	1796	2.49
2050	5	0	0	0	0	5
	10	0	0	0	0	10

Table 7
Installed capacity for hydrogen related technologies and Li-ion batteries per year.

Year	CEEP limit (%)	Alkaline (MW)	PEM (MW)	SOEC (MW)	PEMFC (MW)	SOFC (MW)	H2 storage (MWh)	Li-ion (MWh)
2020	5	0	0.01	0	1.47	0.42	0.02	0.01
	10	0.01	0.01	0	1.49	0.41	0.02	0.01
2025	5	59.48	0.01	0.19	0.13	0.53	45.55	0.01
	10	59.85	0	0	0.15	0.54	44.59	0.01
2030	5	138.99	0.01	0.08	1.07	1.09	485.89	1.31
	10	137.6	0.01	0	1.11	1.08	483.81	1.47
2035	5	362.28	0	0.02	1.32	1	1871.8	2.37
	10	363.62	0.06	0.12	1.23	1.02	1884.11	2.77
2040	5	461.62	0.43	0	1.41	1.29	2107.68	4.08
	10	427.9	1.49	0.04	1.31	1.15	1824.21	4.28
2045	5	152.95	0.66	0.19	0.74	1.07	181.78	5.83
	10	148.09	0.06	0.07	0.87	1.27	0.11	6.58
2050	5	0	0	206.43	0.3	0.97	1.46	0.04
	10	0.69	1.01	149.2	0.25	0.87	0.3	1.58
TOT	5	1175.32	1.12	206.91	6.44	6.37	4694.18	13.65
	10	1137.76	2.64	149.43	6.41	6.34	4237.15	16.7

Table 9
Results for VRES investments for the cases with 5% and 10% CEEP limit.

Year	CEEP limit	HR_SolarHigh	HR_SolarPP	HR_WindPP	HR_WindPP1	HR_WindPP2	HR_WindPP3
	%	MW	MW	MW	MW	MW	MW
2020	5	2000	0	0	84	364	0
	10	2000	0	0	82	364	0
2025	5	856	0	0	494	755	0
	10	856	0	0	490	747	0
2030	5	1550	1	0	0	222	0
	10	1555	0	0	1	234	0
2035	5	555	0	545	1213	942	0
	10	550	0	507	1199	982	0
2040	5	0	1241	355	287	1	249
	10	0	1229	368	295	0	221
2045	5	0	1737	2	2	0	1319
	10	0	1798	1	1	0	1341
2050	5	10	2009	1320	1643	0	2004
	10	10	1960	1324	1644	1	2005
Total	5	4971	4989	2222	3724	2284	3572
	10	4971	4988	2201	3712	2328	3567

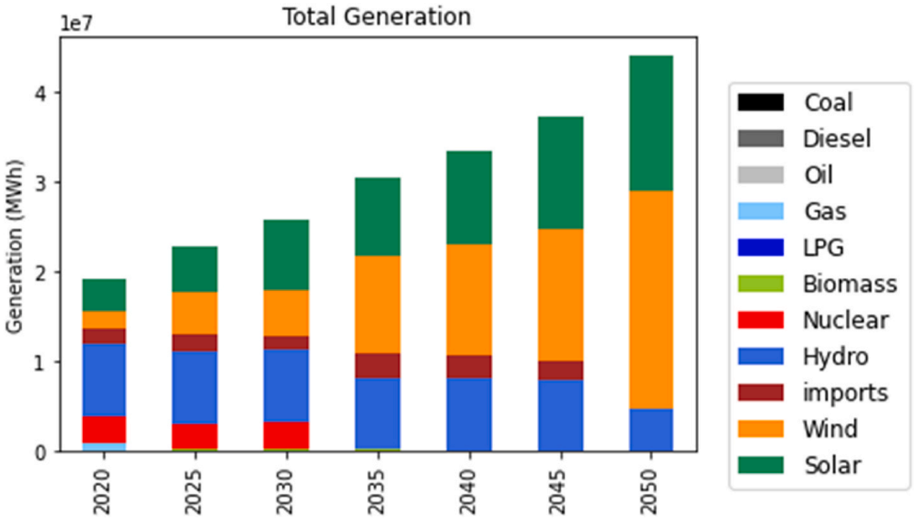

Fig. 8. Power generation by the fuel for the case with 5% CEEP limit.

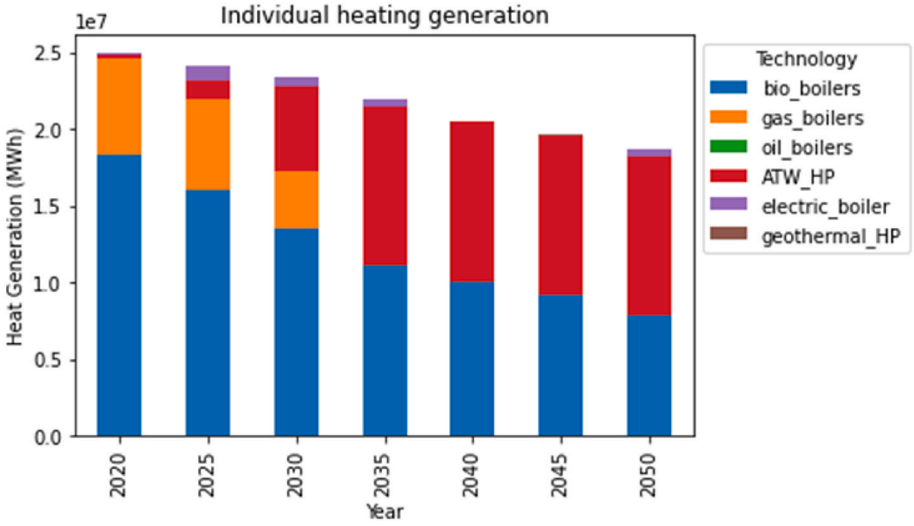

Fig. 9. Generation by fuel per year with a 5% CEEP constraint.

Table 10
Installed capacity for thermal technology per year expressed in MWth.

Year	CEEP limit (%)	Biomass boilers	Gas + Oil boilers	ATW HPs	Electric boilers	Geothermal HPs
2020	5	5327.21	0	0.34	0.54	0
	10	5319.24	0	0.28	0	0.01
2025	5	688.31	0	809.22	19.82	34.63
	10	696.74	0	835.65	18.74	33.94
2030	5	0.86	0	2333.58	0.28	1.39
	10	0.33	0	2305.3	0.74	1.16
2035	5	0.1	0	2597.85	195.78	7.37
	10	0.19	0	2601.01	192.93	9.66
2040	5	0.09	0	0.23	36.21	0.38
	10	0.22	0	0.19	35.78	0.43
2045	5	0.07	0	0.45	66.42	0.35
	10	0.04	0	0.2	70.82	0.22
2050	5	0.3	0	0.62	19.46	0.61
	10	0	0	0.82	17.46	0.64

with the CO2 limit and the one without the limit are shown in Table 14. In both cases, alkaline electrolyzer dominates in installed capacities, followed by SOEC type. There are notable differences in installed capacities of fuel cells. The reason for the differences is the differences in hydrogen demand in these two cases. For example, the case with CO2 restriction invested into FCEVs while the one without the restriction did not invest (see supplementary material). The scenario with CO2 restriction has slightly higher installed capacity of fuel cells. This is due to the necessity to adhere to the same limitation on CEEP, while at the same time having higher energy production to supply the conversion of all sectors. Generally, the electrolyzer are used only in minor fashion, due to cost and the existence of better solutions for flexibility management such as the batteries of electric vehicles. From the side of energy storage systems, generally, hydrogen storage is used in both cases, while battery storage is used only in smaller amounts. Still, the case with CO2 constraint invested into higher capacities of both due to higher energy demand overall.

The results displayed in Table 14 indicate that the consideration of different technologies, such as electrolyzers, fuel cells, and fuel cell electric vehicles, indeed provide different degrees of flexibility and decarbonization options. For instance, when stringent allowed limits on CEEP are imposed, H2RES finds that the least cost alternative that complies with demand levels, CO2 emissions limits, RPS requirements and CEEP limits include a larger set of technologies (FCEV) than the case when no CO2 limits are imposed. Therefore, without consideration of FCEV or limits on fuel cells, a higher cost solution would be found if this exists (a feasible solution might not exist). This provides justifications for models that are flexible in terms of the technologies that can be considered for decarbonization but might compromise computational time.

The ideas presented above have also been discussed in the literature. For instance, authors in Ref. [57] compare several energy systems models. They discuss that the model scope in terms of technology available options is among the key drivers that describe the differences that can be found across the models results. Such conclusion is obtained

Table 11
Installed capacities for hydrogen related and storage technologies.

Year	CEEP limit (%)	Alkaline ELY (MW)	PEM ELY (MW)	SOEC (MW)	PEMFC (MW)	SOFC (MW)	H2 storage (MWh)	Li-ion batteries (MWh)
2020	5	0.02	0.01	0	1.79	0.41	0.03	0.01
	10	0.01	0.01	0	1.48	0.36	0.03	0.01
2025	5	62.43	0	0.03	0.18	0.61	70.7	0.01
	10	61.82	0.02	0	0.12	0.55	70.74	0.01
2030	5	217.18	0.02	0.02	1.16	1.3	722.44	1.87
	10	217.75	0.05	0.04	1.12	1.1	721.34	2
2035	5	440.96	0.01	0.03	1.31	1.05	2029.55	2.34
	10	438.3	0.01	0.02	1.2	1	2024.04	2.98
2040	5	569.74	2.65	0.01	1.49	1.39	2155.23	4.67
	10	565.06	0.74	0	1.24	1.17	2112.59	4.42
2045	5	145.7	0.93	1.77	0.71	1.31	0.6	6.03
	10	106.93	1.68	0.06	1.12	1.28	4.41	6.86
2050	5	3.68	0.7	533.67	0.14	0.53	0.42	0.01
	10	1.12	0.01	531.18	0.53	1.68	0.01	1.15
TOT	5	1439.71	4.32	535.53	6.78	6.6	4978.97	14.94
	10	1390.99	2.52	531.3	6.81	7.14	4933.16	17.43

Table 12
Installed capacity for VRES capacities, expressed in MW.

Scenario	Technology	2020	2025	2030	2035	2040	2045	2050	TOT
Without CO_2 constraint	PV	1999.75	806.74	1479.01	676	1000.65	1992.99	2006.91	9962.05
	Wind	437.4	868.67	465.96	2424.16	696.88	618.98	2916.61	8428.66
With CO_2 constraint	PV	2000.04	855.64	1551.21	555.27	1241.41	1736.7	2019.24	9959.51
	Wind	448.35	1248.86	222.37	2699.98	891.35	1323.12	4967.39	11801.42
Without	**TOTAL**	**2437.15**	**1675.41**	**1944.97**	**3100.16**	**1697.53**	**2611.97**	**4923.52**	**18390.71**
With	**TOTAL**	**2448.39**	**2104.5**	**1773.58**	**3255.25**	**2132.76**	**3059.82**	**6986.63**	**21760.93**

Table 13
Heat generation from electrically driven heating technologies (P2H).

Scenario	Unit	2020	2025	2030	2035	2040	2045	2050
Without CO_2 constraint	GWh	324.3	1595.6	7279	12084.6	11698.9	11718.3	11884.6
With CO_2 constraint	GWh	330.6	3594	7467.8	12159.8	11776.6	11813.4	12304.6

Table 14
Installed capacities of electrolyzer, fuel cells, hydrogen storage system and battery storage, expressed.

Scenario	Technology	Unit	2020	2025	2030	2035	2040	2045	2050	TOT
Without CO_2 constraint	Alkaline_EC	MW	0	59.48	138.99	362.28	461.62	152.95	0	1175.32
	PEM_elec	MW	0.01	0.01	0.01	0	0.43	0.66	0	1.12
	SOEC_elec	MW	0	0.19	0.08	0.02	0	0.19	206.43	206.91
	Battery storage	MWh	0.01	0.01	1.31	2.37	4.08	5.83	0.04	13.65
	Hydrogen storage	MWh	0.02	45.55	485.89	1871.8	2107.68	181.78	1.46	4694.18
	PEMFC	MW	1.47	0.13	1.07	1.32	1.41	0.74	0.3	6.44
	SOFC	MW	0.42	0.53	1.09	1	1.29	1.07	0.97	6.37
With CO_2 constraint	Alkaline_EC	MW	0.02	62.43	217.18	440.96	569.74	145.7	3.68	1439.71
	PEM_elec	MW	0.01	0	0.02	0.01	2.65	0.93	0.7	4.32
	SOEC_elec	MW	0	0.03	0.02	0.03	0.01	1.77	533.67	535.53
	Battery storage	MWh	0.01	0.01	1.87	2.34	4.67	6.03	0.01	14.94
	Hydrogen storage	MWh	0.03	70.7	722.44	2029.55	2155.23	0.6	0.42	4978.97
	PEMFC	MW	1.79	0.18	1.16	1.31	1.49	0.71	0.14	6.78
	SOFC	MW	0.41	0.61	1.3	1.05	1.39	1.31	0.53	6.6

based on the differences in technology scope (and sectoral scope) among the models that were compared, as well as the experimental designed that authors developed. Similarly, authors in Refs. [58,76] also provide model comparison studies to assess the role of technology in decarbonization strategies in the North America (USA). Authors used energy system models and Integrated Assessment Models (model that indeed different in the sectoral and technological scope they are capable of considering). They do find differences among models that are derived from the differences in their scope. In this context, H2RES has been built as a modular model that allows inclusion of several different technologies. Even more, for a given technologies, H2RES allows to consider variations of such technology, such as different types of electrolyzers, fuel cells, or heat-pumps (e.g., ATW heat pumps, ATA heat pumps or geo – heat pumps). This feature, along with the different policy options that H2RES allows to model (CO2 limits, RPS, CEEP limits, individually or combined), present an important contribution to the set of open-source energy system models available in the literature.

9. Conclusions

This research describes and uses a new version of the H2RES model, formulated as a long-term energy planning and operational model. H2RES considers endogenous capacity investment decisions for all technologies that provide flexibility in energy systems, particularly Power-to-Heat, Power-to-Storage, Power-to-H_2, and H_2-to-power. Additionally, we consider investment in different technologies in the power sector. The H2RES model simultaneously and endogenously optimizes such capacities and the dispatch, at an hourly level, for the time horizon of the analysis. In particular, this paper explores the role of Power-to-X technologies to decarbonize the Croatian Energy sector. We develop two sets of policy scenarios. First, we analyze the role of Power-to-X in response to targets of renewable electricity generation (RPS). Secondly, we study the role of these technologies when CO2 limits are further imposed (along with RPS technologies). The analysis is carried out in a time horizon of 30 years, considering hourly dispatch of technologies from 2020 towards 2050, with five-year time intervals. The result indicates that the RPS alone scenarios can decarbonize the power sector, reaching renewable shares of 90% by the year 2050. However, the transport sector remains partly supplied by fossil-fuels. In addition, it was also observed that introduction of carbon limit affected the use of energy storage technologies and prompted the additional investments into renewable generating technologies. In all of the cases, emissions from considered sectors are significantly reduced. Reduction is in part because of the implemented restrictions in the form of RPS and carbon limits, but also due to economical side of the energy system. Also, the decommissioning of some of the technologies is mandated by the end of their working life and restrictions on the installations of the new capacities.

Further work encompasses the expansion of the functionalities of the model. These include integration of multi-system model and integration of the submodule dedicated to the electrofuels. Also, bottom-up households model is being worked on.

Author Contribution

Felipe Feijoo: Conceptualization, Methodology, Software, Visualization, Investigation, Writing- Original draft preparation Antun Pfeifer: Data curation, Software, Writing- Original draft preparation, Investigation. Luka Herc: Data curation, Software, Writing- Original draft preparation, Investigation. Daniele Groppi: Writing- Original draft preparation, Software, Investigation: Neven Duic: Writing- Reviewing and Editing, Software, Supervision, Conceptualization, Methodology, 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.

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Appendix A. Supplementary data

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