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Energy system transitions pathways with the new H2RES model: A comparison with existing planning tool

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A R T I C L E I N F O

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A B S T R A C T

Anthropogenically caused climate change is amongst the main problems that society faces today. To limit the increase in average global surface temperature, several countries have developed targets (e.g., goals of the Paris agreement) that seek to reduce their greenhouse gas emissions levels, particularly from the energy and transport sectors. The installation of large renewable generating capacities creates new challenges. Particularly, their high variability creates uncertainties to the energy system regulators and operators to guarantee the security of supply at affordable prices. Therefore, new approaches must be considered to help reduce the uncetainty associated with variable renewable energy. Power-to-X and demand response technologies, which provide a high degree of flexibility to energy systems, could be in fact a viable solution.

This research compares two methods of planning the development of energy system. The developed software H2RES is being compared to the existing commercial energy system's configuration optimization program PLEXOS. The research compares these models in terms of endogenous capacity expansion of renewable sources and flexibility options Additionally, H2RES is extended to account for endogenous capacity investment decisions in power and energy storage technologies. The two models are compared on the case of the Croatian Energy system. Results show that Power-to-X technologies provide the required flexibility in order to successfully integrate new generating capacities of variable renewable sources, reaching economically optimal and low carbon energy systems. Newly developed software H2RES is shown to be capable in providing energy system simulations, optimization and investment planning. Displayed functionalities in some aspects have shown to be even more capable than in established software PLEXOS to which it is compared. There is as well high amount of room for improvements due to its open-source nature.

Introduction

The world faces an emerging new crisis in a form of climate change and consequent effects on all aspects of human activity. Intergovernmental Panel on climate change (IPCC) has published a summary of recent advances in understanding the effects and feedback loops that come into effect, as a consequence of rising greenhouse gas (GHG) concentrations in Earth's atmosphere [1, 2]. Findings of the IPCC indicate the necessity to implement more strict goals and limitations on GHG emissions. IPCC has examined carbon emissions in different scenarios representing a wide range of activity levels to address the crisis. The report states that to avoid the worst of the consequences, it is mandatory for the global temperatures not to increase by more than 2 °C or 1.5 °C which is the preferred target. To achieve this goal, total global emissions must reach net-zero between 2055 and 2080. If net zero is not reached in this window, extensive atmospheric carbon removal and sequestration techniques may be required to stay below 2 °C of warming. To provide the means to facilitate the implementation of required actions, the Paris Climate Agreement [3] has been signed in 2015 by 196 parties that promised to implement measures to help tackle the crisis.

The energy sector is one of the biggest contributors to rising GHG levels so there is a big emphasis on energy transition and the use of clean energy sources to reduce emissions [4,5]. Clean energy generation, most notably variable renewable energy sources (VRES) cannot efficiently solve this problem on its own. Their operation is variable and thus not all of the available energy generation can be utilized. The ability of a system to integrate VRES is dictated by the available installed capacities of power plants. Typically, a system is only able to integrate a small percentage of VRES without encountering the problems with grid stability or necessity for VRES curtailment. The exception to this rule is present in systems with high installed capacities in hydropower generation such as the Norwegian energy system [6]. To

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avoid curtailments, and achieve high penetration of renewable energy, energy system balancing, and flexibility options must be implemented. On the other hand, in systems without already implemented balancing technologies such as hydropower, it is necessary to implement demand response and flexibility options [7]. Balancing becomes even more of a problem if an unbalanced mix of VRES is being used such as if large capacities of wind with no or little photo-voltaic (PV) capacity is used.

Electrification of the energy demand sectors allows for a complete transition towards renewable energy. The key point in this concept is the introduction of sector coupling measures. Sector coupling is shown to being able to facilitate the high shares of VRES as in the example from the Nordic and Baltic regions of Europe [8]. Examination of technologies such as power to heat (P2H) and vehicle to grid (V2G) has been performed in [9] with a conclusion on measurable benefits of including these technologies into the electricity grid. Benefits reflect through the increased ability of VRES integration, lower emissions, and lower total system costs. Similar conclusions have been obtained with the use of software used as well in this research, PLEXOS which has demonstrated the effectiveness of integration of electrified transport on enabling the integration of VRES [10]. Additional benefit of considering P2H is relatively easy technical complexity since most of the heating system already are or can easily be adapted for flexible operation [11]. Transition of heating in the realm of district heating systems towards sustainable operation is challenging when considering environmental aspects of overreliance on biomass. Therefore, one of the solutions may lay with higher degree of utilization of renewable energy potential. Most notably, with electricity itself of synthetic fuels when they are more applicable [12]. Although wind and solar energy sources are amongst the cheapest energy sources available [13], there is a negative side effect of the installation of large generating capacities of wind and solar energy as demonstrated by Meha et al. [14]. One of the possible problems is the curtailment of VRES. This problem would occur as a side-effect of the actions taken by the grid operator to preserve electricity grid stability under the influence of variable generation from VRES. The ability of an energy system to integrate VRES depends on the composition of different subsectors of the energy system. For example, if large capacities of generation units consist of inflexible thermal power plants, there may not be adequate reserve available to balance out the variations from VRES generation. An additional problem occurs when an inflexible generating unit is expected to cover the load when generation from VRES is reduced, for example, solar power plants in the late afternoon. If a power plant is unable to perform a fast start-up procedure, the operator may opt to keep it powered on even if it is not required in the system during most of the day. This type of energy system operation implies that VRES will be curtailed [15]. The solution of VRES curtailment is in the application of flexibility options as well as the power-to-X technologies. These technologies also support sector coupling. Sector coupling is defined as “a strategy to provide greater flexibility to the energy system so that decarbonisation can be achieved in a more cost-effective way” [16]. Therefore, the goal is to integrate big polluters and energy use sectors into one interconnected energy sector. These include heating, transport, and industry sectors [17]. Installation of flexibility options in line with VRES generation has been demonstrated to be able to provide required flexibility [18]. Examined flexibility options include interconnections with the heating and transport sector. The flexibility of a system is even more important when dealing with small systems with limited or no possibility to balance out the variations from VRES through interconnections. Examples of such systems are island-based isolated systems [19]. Similar problem can be mitigated with the use of hydrogen energy storage [20]. The significant effort required to reach a 100% renewable energy system is reflected through the necessity of synthetic fuels [21]. When considering socio-economic aspect, the systems with high shares of renewable energy are more tailorable as well which is additional reasoning for implementation of higher shares of renewable energy [22].

Modelling tools

The development of an energy system can best be managed by conducting a series of simulations to project and test possible development pathways. These pathways must be followed up as closely as possible to ensure a transition to renewable energy and to guarantee that the reduction of emissions is achieved economically and efficiently.

Simulation of energy systems can be carried out in two possible pathways. The first one allows for basic modelling to take place and it is focused on the optimization of power plant scheduling. Some models also offer which regulations strategy to apply. For example, to optimize for CO_2 emissions or total system costs. EnergyPLAN [23] is one of the most recognized software in this category. It deals with simulating an energy system on an hourly level for one year. The capacities of power plants and energy demand of various sectors do not change during a simulation. This means that the system in EnergyPLAN is simulated in a configuration set up by the modeller. The program is in that case configured with simulation goals which may dictate when and if some of the technologies are used. An additional step forward in comparison to programs like EnergyPLAN is the inclusion of a longer planning horizon and the possibility of capacity investment or decommissioning. Such options are implemented in the models that are compared in this research. With the inclusion of these options, it is possible to model the development of an energy system during a set of years. Models offering this functionality are generally more complex and thus are developed for commercial purposes. Some of the modelling schematics are taken from EnergyPLAN and implemented in H2RES such as modelling of electric vehicles in transport sector.

Other energy system simulation tools are displayed in Table 1. These models are recognized in the field of energy system modelling and development. As it can be seen, some of them are only defined as simulation tools, while others serve to optimize the energy system operations as well as the capacity investments.

Abbreviations used in the table: Purpose: IDS –Investment Decision Support, ODS –Operation Decision Support, S – Scenario, PSAT – Power System Analysis Tool, A –Analysis; Approach: BU –Bottom-up, TD –Top-down, H –Hybrid; Methodology: S –Simulation, LP –Linear Programming, MIP –Mixed Integer Programming, PE –Partial Equilibrium, A- Accounting, ABS –Agent-based Simulation, MIQCP –Mixed Integer Quadratically Constrained Programming, CGE –Computable General Equilibrium, E –Equilibrium, CMA-ES –Covariance Matrix Adaptation Evolution Strategy, HO –Heuristic Optimisation, ECE –Economic Computable Equilibrium, SDDP –Stochastic Dual Dynamic Programming; Temporal Resolution/Modelling Horizon/Geographical Coverage: UD –user-defined, NL –No limitations. The explanations of the abbreviations are shown in Table 13.

Contribution and novelty

The new developed H2RES model [25] is comparable to the OSeMOSYS model [26]. OSeMOSYS has been developed to provide open access energy modelling software and replicates the functionalities of software such as MARKAL [27]. It also allows for capacity expansion and energy system optimization. OSeMOSYS uses an approach in modelling an energy system only by modelling time slices (subset of days in a year) which it deems to be characteristic days. Another open-source software is EnergyScope [28]. It optimises both the capacity investment and operation. Energy, heating, and transport systems are included in its scope. Only the industry sector is not modelled. EnergyScope model also uses time slices. It models the typical days in hourly resolution and considers the optimization of a whole energy system on performance in a couple of characteristic days spread out through the year. The use of time-sets allows the program to handle complex tasks but sacrifices accuracy. PLEXOS, as well as H2RES do posses the ability of modelling the system without the use of time-slices. Therefore, it was chosen for comparison. The model is also available for download at GitHub [29].

Table 1
List of other recognized energy system simulation and optimization tools [24].

Model	Purpose	Approach	Method	Resolution	Timespan	Geographical coverage
Dispa-SET	ODS, S, PSAT	BU	MILP	15 min	UD (50+ years)	Single project → Global
EnergyPlan	S, IDS	BU	S	Hourly	1 year	Local → Continental
energyPro	I & ODS	BU	AO[c]	Minutes	Max 40 years	Local → Regional
HOMER	I & ODS	BU	S & O	Minutes	Multi-Year	Local
LEAP	S	H	S & LP	Yearly	Usually 20–50 years	Local → Global
MARKAL	S	BU	LP/MIP, PE	Multiple years (UD time-slices within a year)	Long-term (UD)	Local → Regional
OSeMOSYS	IDS	BU	LP	UD (intra-annual)	UD (10–100 y)	Community → Continental
PLEXOS	I & ODS, S,PSAT	BU	f	UD up to 1 min (Usually hourly)	UD (1 day to 50 + years)	Single project→ Global
RETScreen	IDS, S	H	S	Monthly/Yearly/Daily	Max 100 years	Single-system → Global
TIMES	I & ODS	H/BU	LP/MIP, PE	Multiple years - with UD time-slices within a year	Long-term (UD)	Local - Global
TRNSYS18	PSAT	BU	S & L/NLP	0.01 s to 1 h	Multiple years	Single Project → Local

Table 13
Legend of notation in Table 1 [24].

Category	Abbreviation	Meaning
Purpose	IDS	Investment Decision Support
	ODS	Operation Decision Support
	S	Scenario
	PSAT	Power System Analysis Tool
	A	Analysis
Approach	BU	Bottom-up
	TD	Top-down
	H	Hybrid
Methodology	S	Simulation
	LP	Linear Programming
	MIP	Mixed Integer Programming
	PE	Partial Equilibrium
	A	Accounting
	ABS	Agent-based Simulation
	MIQCP	Mixed Integer Quadratically Constrained Programming
	CGE	Computable General Equilibrium
	E	Equilibrium
	GERDS	General equilibrium recursive-dynamic simulation
	CMA-ES	Covariance Matrix Adaptation Evolution Strategy
	HO	Heuristic Optimisation
	ITO	Inter temporal optimization
	ECE	Economic Computable Equilibrium
	RDS	Recursive dynamic solution method
	SDDP	Stochastic Dual Dynamic Programming
Temporal Resolution, Modelling Horizon	UD	User-defined
	NL	No limitations
Geographical Coverage	UD	User-defined
	NL	No limitations

The motivation for performing a comparison between PLEXOS and H2RES is to validate the performance of H2RES as a new energy system modelling software. PLEXOS is an established and well-known energy modelling, optimization, and system development software. Therefore, it can be used as a benchmark when establishing the capabilities of new software. Another key point for carrying out the comparison with PLEXOS is the ability of PLEXOS and H2RES to develop analyses using full hourly resolution scale for a complete year or a time horizon of interest, hence, without using time slices. The differences in the abilities of both models are displayed in Table 2. The table depicts some important differences. For example, PLEXOS does not offer a way to model CHP technologies, while it is indeed integrated into the H2RES model. There is also the problem of the necessity to acquire both the “electricity” and “gas” modules of PLEXOS. Both modules are required to model systems such as the power to gas options. H2RES is open source which means that anyone can develop it for their purposes. Open-source software spur development communities. When the community spurs around open-source software, new developments can happen quickly. The quick development of modelling software is a highly wanted characteristic when dealing with a significant task as is the development of energy systems. An additional benefit in using open-source software is that the model is not considered a “black box”. All equations used in the model are available to all parties and they can be verified and modified.

The novelty gained by the creation of H2RES can be summarized in the following points:

- H2RES offers much of the same functionalities as PLEXOS but is an open-source software. Therefore, modellers can modify the base software to better suit their needs.
- When compared with other models, such as OSeMOSYS, H2RES offers greater flexibility in modelling. The key aspect comes from the ability to model the virtually unlimited complexity of an energy system. Another keynote is the ability to use actual chronology in comparison to time-slices used in OSeMOSYS. Using actual chronology is beneficial especially when examining energy storage options. For example, dammed hydropower plants may optimize for storage levels over longer periods of time, especially when variations in precipitation are considered.
- Another novelty in using H2RES is the flexibility of a time scale itself. Models are defined by the inserted data. Therefore, one can model an energy system with consideration of only a few hours to a couple of decades if required. All of the calculations are performed on an hourly basis.

Comparison of abilities of PLEXOS and H2RES

The main differences between PLEXOS and H2RES are displayed in Table 2. They both have the same basic abilities regarding power plant

Table 2
Differences between PLEXOS and H2RES.

Category	Name	PLEXOS	H2RES
District	CHP	Not available	Available
heating	Modelling of each individual system	Available	Available
Industry	Total demand	Modelled as a heating node	Modelled with logit approach
	Application of P2G	Available only if “gas” module is included	Available
Transport	Electric vehicles	Available – predefined demand	Available – predefined demand
	Hydrogen fuel cell vehicles	Not available	Available – predefined demand
	Internal combustion vehicles	Not available	Not implemented
	Transport demand [1]	Not implemented	Not implemented
	V2G	Implemented	Implemented
	Capacity expansion	Not implemented	Not implemented
Heating sector	Capacity expansion	Implemented	Implemented
Electricity generation	Capacity expansion	Implemented	Implemented
Network congestion		Implemented	Not implemented

[1] Transport sector is modelled only with required distance travelled and the ability of a software to sub divide travel distance into multiple available fuel sources. Fuel source can range from fossil fuels, hydrogen, electricity, biofuels and synthetic fuels.

despatch optimization, capacity investment, and adherence to limitations (for example carbon emissions).

Method

The same energy system is modelled using the commercial energy modelling and optimization software PLEXOS as well as in the open-source software H2RES developed at the University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture. This section presents a general overview of modelling each part of the energy system with respect to modelling software. Differences in approach towards modelling the same problem is presented.

PLEXOS [30] is a commercial software intended for scheduling optimization and investment planning for an energy system. It deals with the electricity and natural gas sector. For the purposes of this research, the distribution with electricity package is used. The software optimizes the energy system with the use of Mixed-Integer, Linear and Non-Linear Programming, or Partial Equilibrium method [24]. There is no limit on the geographical aspect of the model meaning it can model anything ranging from a small local energy system all the way to a global energy system. Interconnection between the systems and congestion can also be considered by modelling all the transmission lines. Timescale is defined from the side of the user, but it can go down to a one-minute scale. The simulation planning horizon is also set by the user and it can range from minutes to multiple decades. It is also possible to use time slices as well as full year to model energy system. Example of the use of PLEXOS include capacity expansion in the power sector [31], which is the same module considered in this paper, and its integration with natural gas systems [32], amongst other areas. The objective function of PLEXOS considers the optimization (minimize) total discounted cost, including both capital and variable (operational) costs of the different technologies.

The new H2RES model is a linear optimization program presented for the first time in this study. The model uses Gurobi solver [33]. The solver GUROBI is an optimization software of free use for academic research. GUROBI provides a set of different algorithms that are used to solve large scale optimization problems efficiently, including Barrier, SIMPLEX and DUAL-SIMPLEX algorithms. H2RES is written in python and uses GUROBI as the main optimization solver.

H2RES consists of three main sets of decisions variables. First, capacity expansion on yearly basis is considered for each of the technologies. The next set of decision variables consists of hourly scale modelling, and in this level, additions or retirements made in the previous step are considered. The third set of variables includes technologies such as energy storage technologies. These include pumped hydro storage, heat, H_2, electricity storage in stationary batteries and EV batteries. Storage levels for each of the mentioned technologies are also modelled in hourly resolution for each year on the horizon. Storage capacities in the individual heating systems, and hydrogen storage and stationary electricity storage are optimized. In comparison, storage capacities of heat storage in district heating, and storage in electric vehicles are fixed during a certain predefined period. Given these main decisions, the main objective, and constraints of H2RES are described below.

The objective of H2RES is to minimize the (discounted) yearly operation and system costs. Since the model is intended for the development of future energy systems, all the future costs are brought to net present value. H2RES considers operation, investment, fuel, generator ramping, energy import and CO_2 emissions cost. Eq. (1) displays a general representation of the objective function with all of the parameters included.

$$\sum_y \sum_p \sum_t df_y \left[C_{t,p,y} D_{t,p,y} + TC_{t,y} K_t Inv_{t,y} + R_{t,p,y} Ramp_{t,p,y} + I_{p,y} Imp_{p,y} + CO_2 Price_y CO_2 Levels_{t,p,y} \right] \tag{1}$$

Where:

- $C_{t,p,y} D_{t,p,y}$ – variable cost for dispatching a technology t, in period p, in year y
- $TC_{t,y} K_t Inv_{t,y}$ – annualized capital cost (K_t) of technology t
- $R_{t,p,y} Ramp_{t,p,y}$ – ramp up/down cost
- $I_{p,y} Imp_{p,y}$ – import cost
- $CO_2 Price_y CO_2 Levels_{t,p,y}$ – cost per unit of CO_2 emissions for each of the technologies

In order to model a realistic energy system, constraints (restrictions on decision variables) must be included. H2RES uses constraints that can be divided into 4 categories:

- despatch and technical constraints: generators, as well as energy storage systems, are constrained by their maximum operating capacity, minimum operating capacity, ramping up/down rate and availability factors. Availability factors are very important since they set the differences between dispatchable and non-dispatchable power plants such as VRES. Also, maximum installed capacities for each of the technology are considered here. Total available capacities are also modified from year to year since total capacity is subject to investment into new capacity as well as decommissioning.
- Storage constraints: the level of storage is modelled on an hourly basis for each year in the model horizon. Technologies with storage constraints include hydro-dam units, which have a natural input level, while the others are filled and discharged in accordance with the model. Therefore, they must be completely optimized by the model. Each storage unit has a minimum and a maximum state of charge that must be guaranteed for each hour in the time horizon. H2RES also considers technologies with given capacities (stationary electric batteries and EV batteries) and others with variable (optimized) storage capacity, such as H_2 storage and heat (heat pump and electric boilers)

- Demand constraints: this set of constraints ensures that the demand for electricity, heat, transport, hydrogen in industry and other sectors are satisfied at every hour and year in the time horizon.
- Policy constraints: H2RES considers three main different policy dimensions, which can be used independently or together. These are the level of critical excess of energy production (CEEP) allowed during a given year. The second possible requirement is the targeted share of renewable energy. The final possible requirement tackles the level of yearly CO_2 emissions which can also be set upon for each of the years.

The current version of H2RES can model power generators located at different geographical locations. This is accomplished with the use of different availability factor curves representing generation from VRES at different locations. In comparison to PLEXOS, it does not provide network congestion ability.

Constraints

The model uses constraints in order to obtain results with certain parameters. Most notably, constraints are used in order to limit emissions as well as to set up a goal on the share of RES in each of the years. The model can work with the constraints turned off as well. Also, other constraints such as minimum share of hydrogen in industry are used in order not to end up with the unrealistic results displaying complete electrification of industrial processes. Since H2RES does have the ability to implement constrains on share of RES, the expression “[0.4, 0.5, 0.60, 0.7, 0.8, 0.9, 1]” has been implemented where each sequential number presents the minimum share of RES in the year starting from 2020. Also, CEEP is limited to the maximum of 5% in relation to the total electricity demand which besides the basic demand, includes the additional demand for electrified transport, hydrogen generation, electricity in industry and electrically driven heating solutions.

Electricity demand

Electricity demand encompasses the basic (baseload) electricity demand excluding additional demand generated by the addition of electric heating, H_2 generation via electrolysis, and transport electrification. H2RES model uses time slices with a duration of one year every five years to simulate the energy system in this case. On the other hand, PLEXOS model uses full chronology from 2018 till 2050. Thought, H2RES can use full chronology as well if required. The reason for using time slices in H2RES is a reduction of computational time.

Heating demand

Heat demand is divided in both models into the part supplied by individual heating systems and district heating systems. PLEXOS focuses on electricity generation and system optimization but does not offer extensive support for the heating sector. It has an option of heat demand and generation systems including different kinds of heat sources described by the used fuel, efficiencies and flexibility characteristics. This allows modellers the option to model different types of boilers or heat pumps that can have efficiencies dependant upon the ambient temperatures in order to reflect real-life scenarios. The disadvantage of the heat module in PLEXOS is the lack of support towards the district heating systems supplied from cogeneration power plants – CHP. Due to this restriction, CHP is represented with the boilers in PLEXOS. It should be noted that it is possible to model cogeneration in PLEXOS, but the option is not available in native configuration [34].

H2RES on the other hand supports the heating sector on the individual and district level. Cogeneration plants are modelled and can supply both electricity and heat. District heating systems and individual heating are modelled separately. Each of the district heating systems has its demand curve, assigned generators and CHP units. Also, a list of available units for expansion is available. Each of the units has defined characteristics such as capacity, efficiency, fuel type, investment cost, lifetime and maximum capacity investment levels. As well as in PLEXOS, multiple regions and heat demand nodes can be used in H2RES. Initially installed generating capacities as well as other characteristics such as heat storage capacity are defined before starting the simulations, and then optimized for future periods. Optimization includes both despatch and capacity investment.

Industry sector

The industry sector is also modelled differently in PLEXOS and H2RES. PLEXOS model uses the methodology of modelling adopted from EnergyPLAN [23] where final energy demand is defined to an industry sector as a whole. Existing capacities of heat-generating systems such as boilers are defined as well as available capacities for expansion of heat-generating capacity. The model, therefore, decides which of the available energy sources to use or invest into additional generating capacities. This approach is displayed in Fig. 1.

A different approach is used in H2RES. Demand is supplied from sources such as coal, natural gas, oil, biomass, electricity and hydrogen as depicted in Fig. 2. Additionally, a logit function is used to determine the shares of fuels in the model.

The Logit function is displayed in Eq. (2)

$$S_i = \frac{\alpha_i \exp\left(\beta p_i\right)}{\sum_{j=1}^{N} \alpha_j \exp\left(\beta p_j\right)} \tag{2}$$

Where:

- s_i – factor determining the maximum share of choice alternative
- α_i – share weight - used to calibrate the model to observed historical values as well as
- also used for new technologies to be phased in/out gradually.
- p_i – price of choice alternative
- β- logit coefficient - It determines how large a cost difference is needed to produce a given difference in market share.

Transport sector

The transport sector can be divided with respect to the energy sources or fuel used. It can be divided into 5 groups: electric vehicles, fuel cell hydrogen vehicles, vehicles that use fossil fuel, biofuel or synthetic fuels. This sector is not fully modelled in both models.

PLEXOS allows modelling of electric vehicles as well as their interaction with the electricity grid through charging and discharging services or “smart charge” and “vehicle to grid – V2G”. Both models use the same methodology of modelling electric vehicles. The distribution for the demand and maximum available charging, discharging and storage capacities are defined. Also, limitations on the battery state of charge are implemented. Electric vehicles in PLEXOS are modelled based on travel demand distribution expressed in kilometres travelled each hour. The model then determines the availability of electric vehicles for charging/discharging based on the travel demand. This procedure allows for simulation of a load of EV’s on the electricity grid and examination of charging/discharging techniques. The problem with this methodology is that it does not offer an insight into the process of transition towards the low emission transport sector since the total influence of emission reduction and sector coupling is not considered.

H2RES also models electric vehicles and uses them as energy storage. Smart charge and V2G are utilized. Modelling of these two systems reflects the methodology used in EnergyPLAN. Therefore, the availability of vehicles to participate in charging or discharging is determined by the energy demand for travelling itself. Available charging/discharging capacity and storage capacity are calculated by H2RES based on the number of vehicles, average charging/discharging capacity per vehicle, average storage capacity and share of electrification in each of the years.

The part of the transport sector with influence on energy system management is encompassed using electric vehicles and hydrogen fuel cell vehicles. Both systems can provide balancing and flexibility to the energy system with a high share of VRES. Electric vehicles provide this

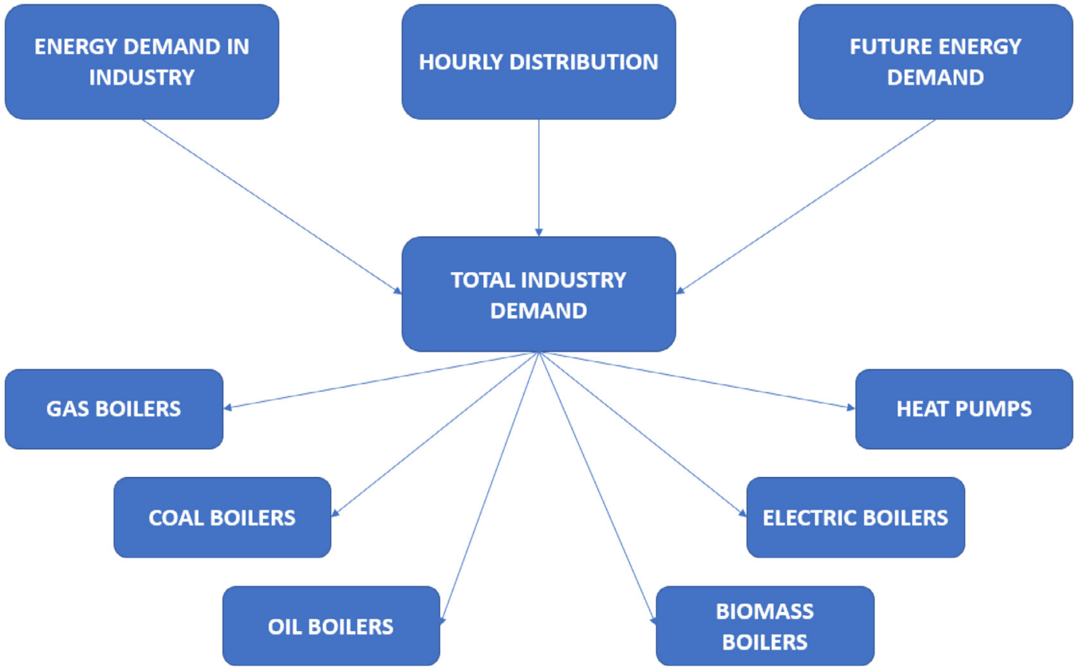

Fig. 1. Industry energy demand in the PLEXOS model.

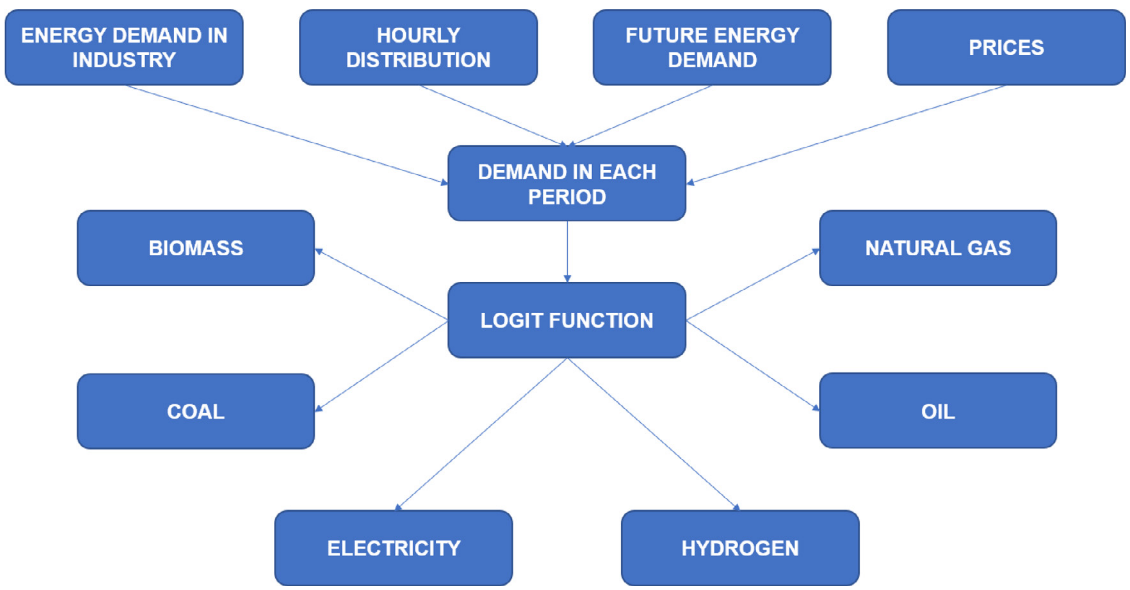

Fig. 2. Industry energy demand in the H2RES model.

service with the use of V2G and Smart charge. On the other hand, hydrogen fuel cell vehicles accomplish a similar task of providing flexibility to the grid with the use of electrolyzers and hydrogen storage.

Generating capacities

The addition of generating capacities and scheduling is implemented in both models. Both models use investment, operation, and maintenance costs to optimize for the least cost path while at the same time satisfying the limitations set upon the required share of renewables or maximum amount of CO_2 emissions. One major difference in this aspect is how CEEP is tackled. In H2RES, the user can explicitly define a maximum acceptable level of CEEP, while in PLEXOS there is no option to limit CEEP but the system just tries to reach the lowest cost configuration which may sometimes require curtailment of VRES and slightly higher emissions if the pathway with curtailment is cheaper than the implementation of flexibility options. Both models allow the use of multiple generator zones. Multiple generator zones for example allow for the implementation of differing capacity factors of wind power or solar power plants. Also, decommissioning of power plants is assumed.

Emissions

Not all sectors are considered in both models. This affects the CO_2 limit which changes not only in accordance with the European Union's climate goals but with relation to the sectors and the share included in the given year as well. For example, if 50% of the transport sector is electrified in the given year, only 50% of the original emissions amount is considered. Therefore, the allowed emissions are determined in accordance with the predetermined rate of decrease and the amount corresponding to the system in the given year. Agriculture is not part of the energy sector, so it is not considered in further analysis.

Table 3
Hydropower plant capacities.

Dammed hydro power plants	Capacity[MW]	Pumped hydro power plants	Capacity[MW]	Run of the river hydro power plants	Capacity[MW]
HE Zakucac	538	RHE Velebit	276	HE Varazdin	94.6
HE Senj	216	RHE Orlovac	237	HE Dubrava	79.78
HE Dubrovnik_HR	117	RHE Vinodol	5.4	HE Cakovec	77.44
HEVinodol	90			HE Gojak	55.5
HE Peruca	60			HE Kraljevac	46.4
HE Sklope	22.5			HE Lesce	41.2
				HE Dale	40.8
				HE Rijeka	36.8
				mHE Hrvatska	27.393
				HE Miljacka	20

Table 4
Thermal power plant capacities in [MW].

Fuel source	Power plant	Capacity [MW]
Biomass	Bovis	1
	mTEO Jakusevac	2.036
	PZOsatina	1
	TE BiomassHR	24.6
	Bovis	1
Coal	TE Plomin1	110
	TE Plomin2	192
Natural gas	TE-TO Osijek	90
	TE-TO Zagreb	440
	EL-TO Zagreb	90
	KTE Jertovec	78
Nuclear	NPP Krško	348

Table 5
VRES capacities.

Variable renewable	Capacity	Unit
Solar	85	MW
Wind onshore	646	MW

Modelling of power-to-X and energy storage options

Both models differ in the modelling approach and availability of power-to-X and energy storage options. The version of PLEXOS used in this study is the basic version of the model. That version was unable to model power to gas systems because the “Gas” module of PLEXOS is not implemented in that version. Therefore, hydrogen-based energy storage and power-to-X options are modelled as a battery storage system. Electrolyzers are combined with hydrogen storage and fuel cells as a single unit with defined charging, discharging and storage capacities.

Case study

This section applies both models to the Croatian case study. The goal of both simulations is to reach a carbon neutral energy system by 2050.

Modelling assumptions

Existing generators

Both models consider the additions of generating capacities to already existing capacities which are in turn being replaced by renewable energy producing capacities. Table 3., Table 4. and Table 5. display already existing capacities. The data is sourced from Dispa-SET model database [35] and IRENA [36].

Thermal power plants are divided based on which fuel is used.

Electricity demand

Both models use the same assumptions in the electricity sector. Electric devices are assumed to become more energy efficient, while the use of more electrical devices is expected at the same time. Increase of demand is assumed to be driven mostly by the increase of cooling demand. Basic demand is therefore assumed to increase by 1% per year from 18 TWh in 2020 to 24 TWh in 2050. Upon basic electricity demand, additional demand consisting out of demand for electric vehicles, electric heating, energy storage and hydrogen generation is added. These types of demand are partially flexible, and they are used to displace fossil fuels and to help integrate VRES. The distribution for electricity demand is sourced from Entso-e [37].

Heating sector

The heating sector is divided the same in both models. It is divided into 4 parts, 3 of which belong to district heating systems and one belongs to individual heating systems. District heating systems cover approximately 10% of heat demand. Each district heating plant has its own input data which consists out of generating capacities, efficiencies, and heat demand distributions. Demand decreases each year by 1% resulting in 26% decrease by 2050.

Industry sector

Energy demand in the industry is projected to increase 1% on annual basis totalling a 34% increase till 2050. Total industrial energy demand in 2020 accounts for 9 TWh and it is supplied by the share of natural gas of 41%, oil at 46%, coal at 6% and biomass at 7%. Demand curve is an aggregated demand curve generated based on the shares and typical distributions of various industry branches. The resulting demand curve is displayed in Figure 11.

Transport sector

In both models the transport is assumed to reach an electrification share of 80% by 2050. Therefore, the use of V2G and smart charge technologies is assumed. The number of vehicles is assumed to remain the same through the years. Croatia currently has 2,312,280 registered vehicles [38]. The final electrification share in transport of 80% is assumed with an average charging/discharging capacity of 7 kW and an average battery capacity of 50 kWh. Using these numbers, we get a maximum charging/discharging capacity of 12,949 MW and a storage capacity of 92,5 GWh in 2050. Charging/discharging capacity and storage capacities are modelled accordingly with the share of electrification.

Allowed CO_2 emissions

Both models have an ability to limit CO_2 emissions in a given year or period. Allowable emissions of CO_2 through the years are the result of adherence to the European Union’s climate goals. Croatia is a member state of European Union which means that the goals on emission reduction are valid as well for Croatia. Since both of the models model in full extent the electricity generation, heating demand, industry demand and the electrified transport, the CO_2 limit is the same in both of the models. Therefore, these 3 sectors are included fully in the calculation of allowable emissions while transport sector is only included partially. The limit is set to 8,1 Mt in 2020 and it gradually decreases towards 2050 reaching 0 t [39]. It should be noted that although the goal is net zero emissions, the limit in these cases is set at 0 since most of the residual emissions are presumed to be in agriculture sector which is not a part of this research.

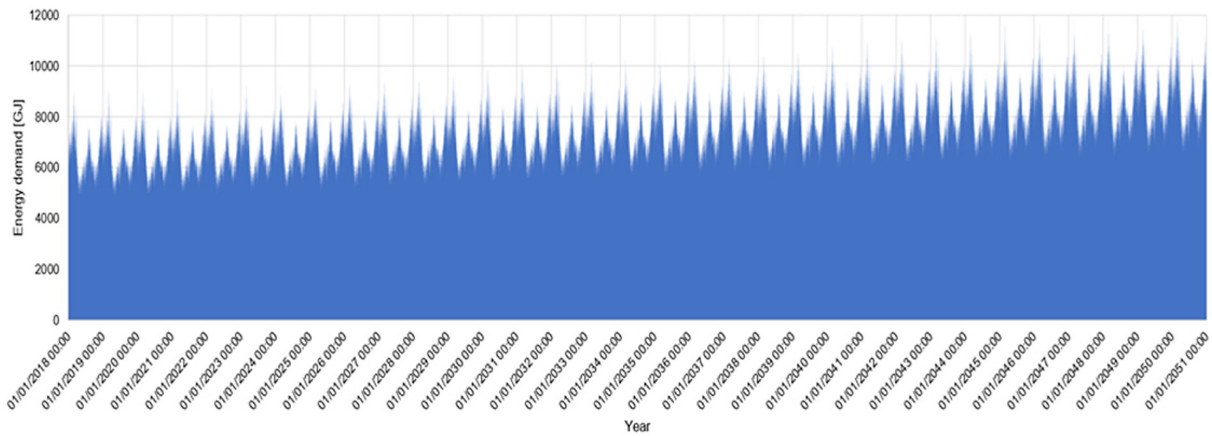

Fig. 11. Energy demand in industry.

Table 6
Data on VRES generators.

Type of a generator	Maximum capacity	Maximum installed in a period	Total installed	Unit
Onshore wind power	9000	500	3328	MW
Photovoltaic panels	8000	200	4980	MW

Table 7
Installed capacities.

Generator	Capacity factor [%]	Installed capacity [MW]
W1	23,62	1248
W2	26,28	2080
W3	20,2	0
WPP	20,9	0
PV	14,25	980
PV_High	20,17	4000
m_HE	37,86	575

Results

This section displays the results for both cases. Installation of new electricity generating capacities, development of the heating sector, flexibility options and development of transport sector are displayed.

PLEXOS

The installation of VRES generating capacities in PLEXOS is shown in Table 6. PLEXOS offers a limit on total installation and installation in the given period represented by the year. Numbers limiting total installation are sourced from Croatian energy development strategy [40]. As can be seen in Table 7, PLEXOS prefers the installation of power plants with greater capacity factor. Also, aggressive installation of new capacities can be observed which is done as a response to the optimization goal of system cost reduction since VRES requires no operation cost. A possible way of limiting the excessive build-up of new generating capacities is the introduction of stricter limitations on possible investment in the given period.

PLEXOS model performs big investment into heat generating capacities as well in the first year, most notably into boilers. The only exception is industry sector which experiences a more gradual transition conditioned by the CO_2 emission limitations. It also may be noticed that initial investments are primarily in biomass powered heating solutions, while the industry sector in later years opts for electric boilers.

Also, the individual heating sector has an investment into biomass boilers in the first year only. This investment, in combination with declining heat demand under the influence of demographics and energy efficiency measures, means that only this is enough to completely decarbonize the heating sector by 2050. One flaw which may be required to be addressed and accounted for is the perceived interconnectivity of all parts of an individual heating sector. This is not reflected in reality. This way, PLEXOS perceives existing biomass and electric boiler heat generating capacities as being able to supply the heat to all the parts of a sector. This problem is even more exaggerated when considering decreasing heat demand. One way of addressing this problem in a future analysis is the introduction of sector subdivisions, each with its assigned capacities and heat demand. This way, the problem of capacity aggregation may be limited or completely solved, depending on the level of sector demand aggregation. Additionally, the model invests into biomass since it is considered carbon neutral energy source. Ewen thought it is carbon neutral, there are some undesirable consequences. Firs of all is the danger of excessive deforestation as well as high level of local emissions in a form of particulate matter.

Energy storage technologies are being used, but PLEXOS chose not to implement expansion of the capacities. Expansion is not carried out because most of the necessary balancing is being provided by the electric vehicle batteries through V2G and “Smart charge” technologies.

The results for demand and generation of electricity in PLEXOS are shown in Fig. 3. An increase of electricity demand is a subject of fixed demand increase as in electric vehicles but is also a subject to the decisions made by PLEXOS to use electricity in the industry for example. An increase in industry electrification can be observed in a rapid increase in electricity demand after 2044. Generation closely follows the demand and does not generate excessive amounts of CEEP.

H2RES

H2RES can include policy constraints in a form of a minimum required share of renewable energy sources in electricity demand as well as in the maximum amount of CO_2 emissions. For the purposes of this research, both constraints are used in H2RES since PLEXOS does not offer a share of renewable energy constraints. CO_2 limit in the H2RES model is closely followed and respected.

The results in terms of total capacity investment in renewable systems are shown in Table 8. Total installation of solar and wind capacities by 2050 are 9940 MW of solar and 8883 MW of wind power respectively. This makes the total installed renewable capacity of 18,823 MW with the constraint of 5% CEEP.

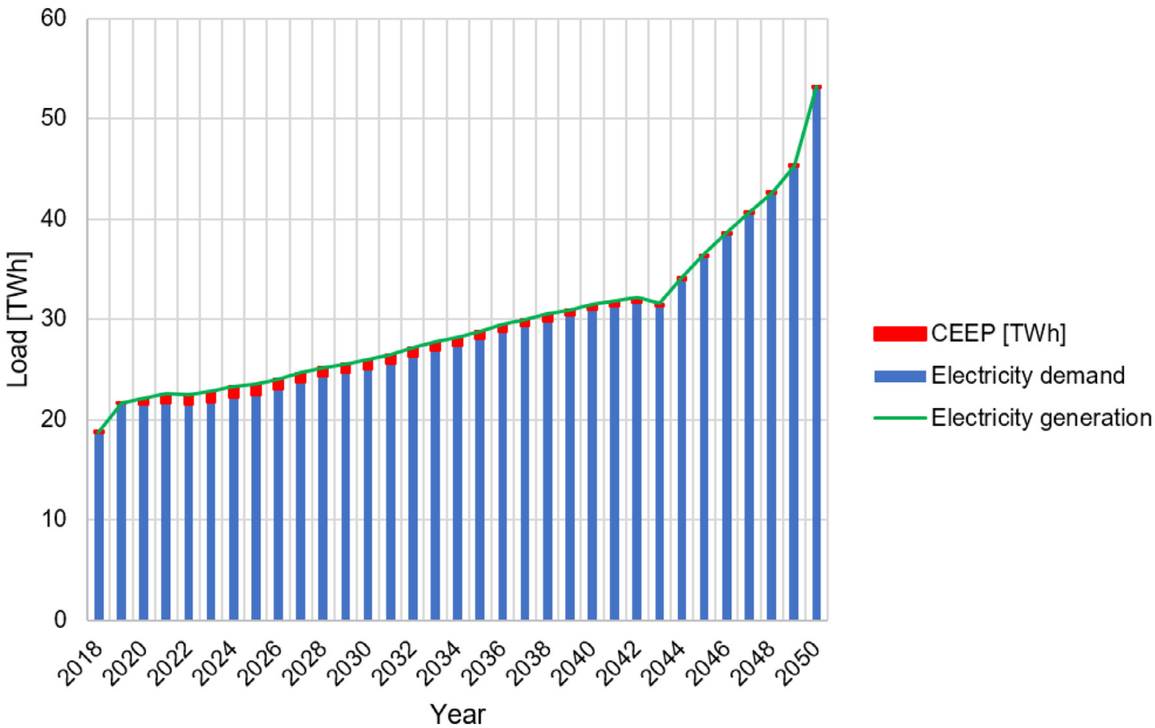

Fig. 3. Resulting demand, generation and CEEP.

Table 8
Investment into VRES generating capacities displays in MW.

Year	HR_Solar High	HR_SolarPP	HR_WindPP	HR_WindPP1	HR_WindPP2	HR_WindPP3
2020	106	0	0	0	0	0
2025	2000	0	0	0	0	0
2030	1080	0	0	0	0	0
2035	1774	0	0	0	651	0
2040	0	1179	0	89	1251	0
2045	0	1801	0	1245	0	499
2050	0	2000	1148	2000	0	2000
Total	4960	4980	1148	3334	1902	2499

The results for energy generation per fuel in each of the examined years is displayed in Fig. 4. Gradual increase of renewables through the years is shown while generation from hydropower and biomass remains the same. Decrease of use of fossil fuels is shown as well as retirement of nuclear power plant.

The hourly distribution of electricity generation through the development of an energy system is shown in Fig. 5. Similarly, as in Fig. 4., there is an evident increase in VRES generation which displaces fossil fuel generation and replaces nuclear power plant after decommissioning. The energy system after 2045 is supplied exclusively by hydropower, wind, and solar power.

Heating demand decreases through the years. Approximately 10% of heating demand is in a form of district heating which is supplied by the combination of cogeneration plants, boilers and heat pumps. By 2050, the share of electrically driven heating solutions in district heating increases to approximately 60% while the rest is supplied by biomass. Fossil fuelled boilers are the most used technology for individual heating with a small percentage of it covered by HPs in the beginning of the modelling horizon (2020). The situation starts changing after 2035, when the system starts adding heat pumps into individual heating systems. The addition of electrically driven and biomass powered heating solutions in mandated by the requirements to reach certain carbon limit and share of renewable energy. In 2050, the system reaches the share of electrically driven heating solutions of 70% in individual heating system while also the remainder is supplied by biomass.

The installed capacity of each of the heat generators is shown in Table 9. It should be noted here that the requirement for the share of renewables only considers the share in electricity demand. Therefore, a transition of heating towards renewable energy is conditioned by the introduction of carbon emissions limits. Therefore, only after 2035, it can be seen a significant contribution towards installed capacities of renewable heating solutions and displacement of fossil fuel powered boilers The inclusion of electrically driven heating solutions is not only conditioned by the mandated carbon emissions, but also by the requirements for energy system flexibility. Since all heating solutions have a certain amount of energy storage allocated to them, there is a possibility of delivering the required heat demand and decoupling the heating session itself from the electricity demand profile. When compared between themselves, air-to-water heat pumps are more widely used than geothermal HPs.

The addition of generating capacities into the district heating systems is shown in Table 10. In this case, the most extensive additions happen in 2050 with significant additions of air to water heat pumps.

The capacities of energy storage technologies such as various electrolyzers, hydrogen storage system and electricity storage in a form of Li-ion batteries are displayed in Table 11. Results show the necessity only for the installation of alkaline electrolyzers and a hydrogen storage system. The reason for the lack of necessity of stationary electricity storage is the use of other flexibility options such as electricity-based

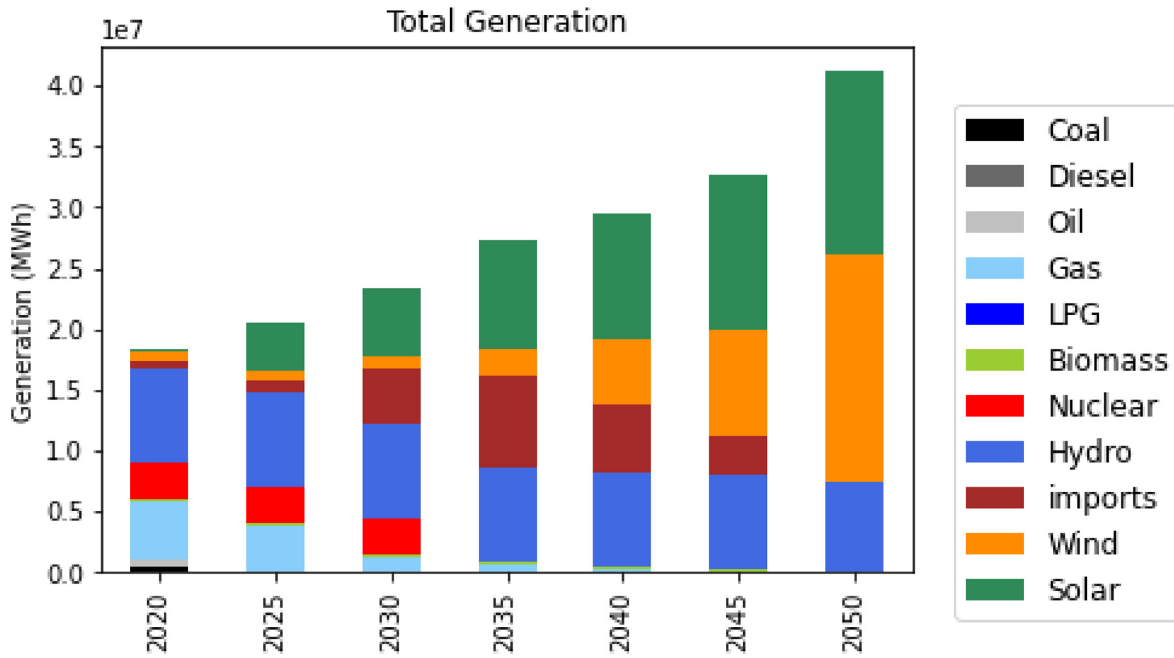

Fig. 4. Generation by fuel per year.

Table 9
New installed capacity for thermal technology per year in individual heating systems expressed in MW_{th}.

Year	Biomass boilers	Gas boilers	Oil boilers	ATW HPs	Electric Boilers	Geothermal HPs
2020	0	0	0	0	0	0
2025	3972	0	0	0	385	0
2030	0	0	0	11	3748	0
2035	0	0	0	3402	0	0,3
2040	0	0	0	0	0	0
2045	0	0	0	0	0	0
2050	0	0	0	0	0	0
Total	3972	0	0	3414	4134	0,3

Table 10
New installed capacity for thermal technology per year in district heating systems expressed in MW_{th}.

Year	Biomass boilers	Gas boilers	Oil boilers	ATW HPs	Electric boilers	Geothermal HPs
2020	28	0	0	0	0	0
2025	0	0	0	0	0	0
2030	0	0	0	0	0	0
2035	0	0	0	0	0	0
2040	0	0	0	156	44	0
2045	0	0	0	25	92	0
2050	0	0	0	0	12	0
Total	28	0	0	181	148	0

heating solutions as well as the large implementation of V2G technology.

The use of excess electricity can be observed in Fig. 6. The figure displays power-to-X options. As discussed before, electric vehicles, hydrogen generation and heating represent the bulk of power-to-X options in this case.

Comparison of the models

The comparison of PLEXOS and H2RES is displayed in Table 12. It may be noted that both models installed significant capacities of VRES. Both models use cost-based optimization, and the transition is mandated by introduction of CO_2 emission limits. H2RES model in comparison to the PLEXOS did install smaller capacities in biomass power plants. Also, different schemes of heating sector transition are evident. PLEXOS avoids much of the decommissioning by using existing boilers for a longer time period. It differs economical and technical lifetime. It does not decommission capacities if not explicitly stated that certain installed capacities would need to be decommissioned by a certain year. Here the problem of aggregation of capacities in the “individual” section of the heating sector is emphasised. By aggregation of generating capacities as well as decreasing demand, PLEXOS opts to use existing capacities. This may not physically be possible since a portion of generating capacities is not able to deliver the required heat to the location where it is required. This notion is not considered when aggregating the demand and generating capacities of interconnected heating systems, which are geographically distant. The next notable difference in the results is present in the results of installed capacities for industrial heat demand. PLEXOS model considers the whole industry sector. Therefore, in the final years of the modelling horizon, the industry is covered with the combination of existing biomass boilers, electric boilers, and newly installed electric boilers. H2RES model uses logit approach to determine the shares of

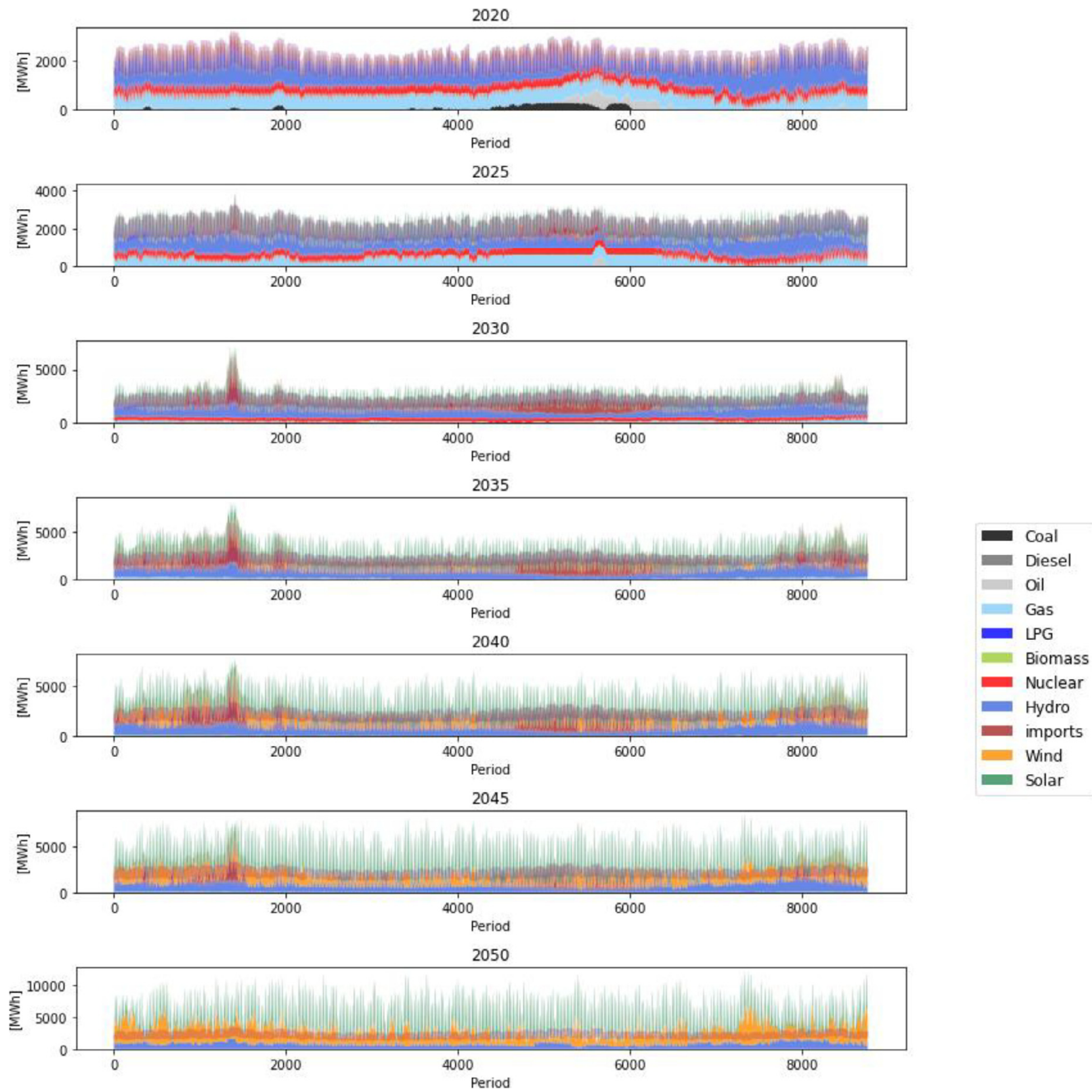

Fig. 5. Electricity generation.

Table 11
Installed capacity for hydrogen related technologies and Li-ion batteries per year.

Year	AlkalineELY(MW)	PEMELY(MW)	SOEC(MW)	PEMFC(MW)	SOFC(MW)	H2 storage(MWh)	Li-ionbatteries(MWh)
2020	0	0	0	0	0	45	0
2025	67	0	0	0	0	157	0
2030	88	0	0	0	0	325	0
2035	14	0	0	0	0	0	0
2040	135	0	0	0	0	763	0
2045	140	0	0	0	0	849	0
2050	259	0	0	0	0	9184	0
Total	703	0	0	0	0	11,322	0

various energy sources including coal, oil, natural gas, biomass, electricity and hydrogen. Differences in the application of energy storage and power-to-X options are also present. Both models had the same flexibility options available. The approach in modelling is different due to limitations in PLEXOS. Due to the inability to fully model the power to gas system, H2RES managed to achieve optimization with the use of the said system. On the other hand, due to the inflexibility of the approach in PLEXOS, the model opted to rather use electric boilers as a flexibility source on the demand side whereas H2RES decided to use storage in electric vehicles, hydrogen storage and heat storage. On the generation side, PLEXOS chose to invest into big dispatchable biomass capacity as a means of delivering zero emission electricity, and balancing out the variable generation from VRES. Also, there is notable difference in power plant and heat generating unit decommission. PLEXOS did not consider decommission while it is considered in H2RES. Also, H2RES uses a curve for determining the residual capacities of the units. The curve is determined by the factors such as the year when decommission starts, equipment lifetime and residual value at the end of lifetime.

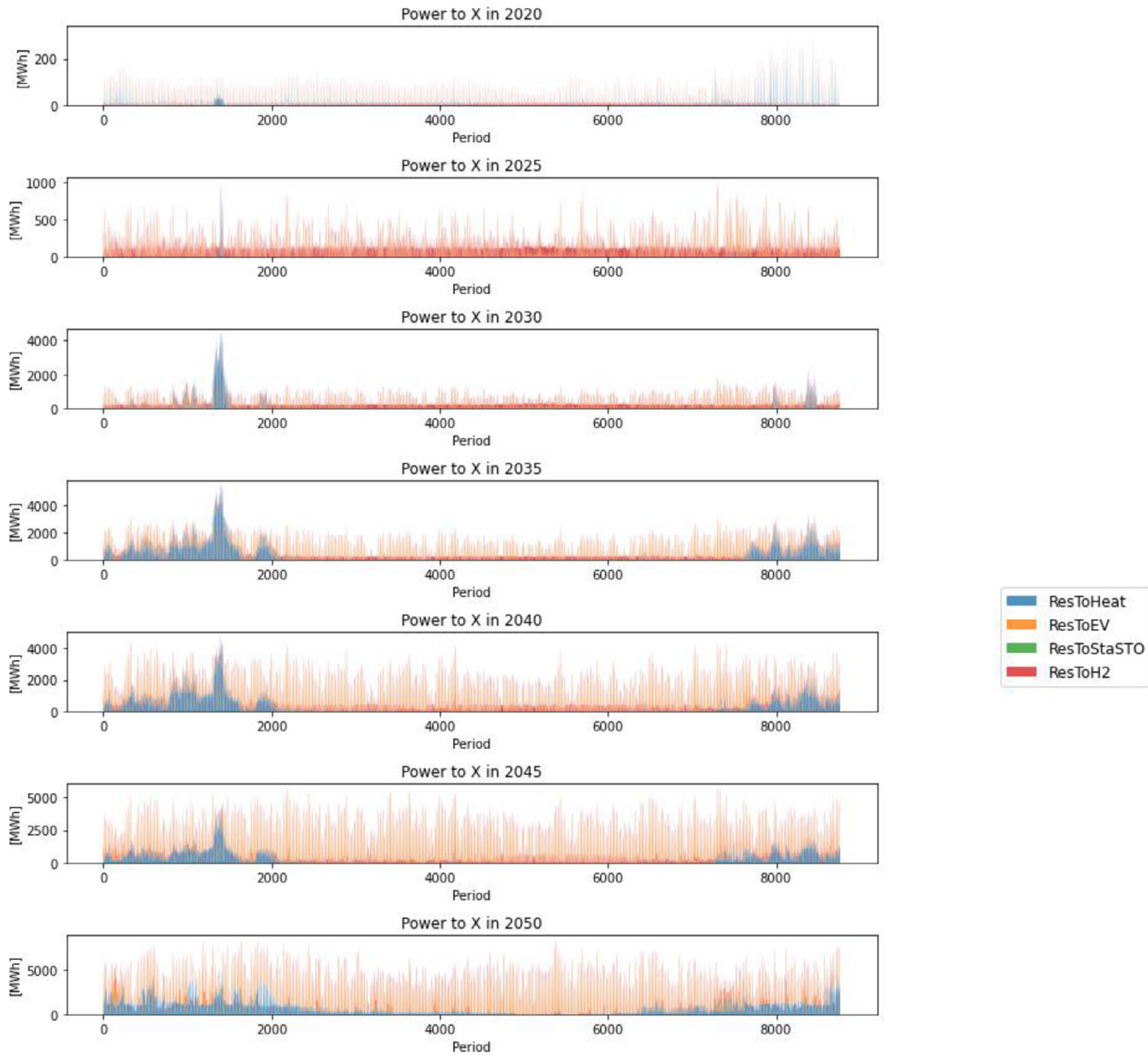

Fig. 6. Power-to-X options.

Capacity investment in both models is displayed in Fig. 7. One key difference to observe here is different capacity investment schemes performed by the models. PLEXOS chose to invest in VRES right at the start of the planning horizon. These investments are not mandated by CO_2 limits, but by the low capital and operating cost of VRES. On the other hand, H2RES starts investing later and it even increases the average investment capacities throughout the years. This is opposite to PLEXOS which does not have new capacity investments after 2037. Due to the different decommission techniques, installations in the H2RES model are higher.

The main drawback of PLEXOS are limitations in modelling the whole energy system. For example, there is no clear cut-way of modelling cogeneration power plants in district heating systems although there are methods to avoid these limitations of the software and implement it anyway as shown in [34]. This method would require “gas” module which was not used for the purposes of this paper. It may be noted that full version of PLEXOS does poses this ability, but that version was not used for the purposes of this research. Another drawback is an inability to model industrial energy demand which can consist out of various used fuels and processes. Some of the processes can be electrified, but not all. An additional problem is the inability to use power to gas options in the “power system” PLEXOS module. Therefore, the industry sector is modelled as a heat demand node with various types of boilers supplying the required heat demand. Power to gas options have been simulated as an energy storage system with defined efficiencies, capacities, storage size, flexibility, and financial data. Also, in the industry sector as well as in district heating grids, no CHP is available to supply heat or steam to industrial consumers. The transport sector is also modelled in a limited aspect in the model. PLEXOS offers a high level of detail in modelling electric vehicle-based transport by the inputs such as distribution of travelling distances, charging capacities and storage capacities. It offers V2G and smart charge functionality to balance the energy grid. The drawback of modelling the transport sector is that only electric vehicles are modelled. The rest of the vehicles are not modelled and there is no way to leave it up to the software to adjust the ratios of different types of vehicles. An additional drawback of PLEXOS which may become of greater significance in the realm of high VRES energy systems is the lack of CEEP limits which H2RES does possess.

Comparison of results for CEEP generation is displayed in Fig. 8. The figure displays both generation of CEEP expressed as an energy [TWh] as well as a percentage of total electricity demand. The results for H2RES display verry low CEEP generation until 2045 where it starts to rise to maximum value of 4% for the year 2050. Because of different investment strategy, PLEXOS model displays high CEEP at the beginning which reduces as the demand increases and makes it possible to use excess electricity. In PLEXOS model CEEP stays under 5% for all the years in the

Table 12
Comparison between PLEXOS and H2RES newly installed capacities.

Variable	PLEXOS	H2RES	Units
Onshore wind installed capacity	3328	8883	MW
PV installed capacity	4980	9940	MW
Run of the river installed capacity	575	0	MW
Biomass power plant installed capacity	2400	0	MW
Transport electrification	80	80	%
Hydrogen fuel cell vehicles	0	0,2	%
Electric boilers installed capacity in individual heating systems	0	4134	MW
Air to water heat pumps installed capacity in individual heating systems	0	3414	MW
Geothermal heat pumps installed capacity in individual heating systems	0	0,3	MW
Biomass boilers installed capacity in individual heating systems	3068	3972	MW
Natural gas boilers installed capacity in individual heating systems	0	0	MW
Oil boilers installed capacity in individual heating systems	0	0	MW
Electric boilers installed capacity in district heating systems	0	148	MW
Air to water heat pumps installed capacity in district heating systems	0	181	MW
Geothermal heat pumps installed capacity in district heating systems	0	0	MW
Biomass boilers installed capacity in district heating systems	450	28	MW
Natural gas boilers installed capacity in district heating systems	0	0	MW
Oil boilers installed capacity in district heating systems	0	0	MW
Electric boilers installed capacity in industry	2833 MW	Share – 43%	
Air to water heat pumps installed capacity in industry	0 MW	Share – 0%	
Geothermal heat pumps installed capacity in industry	0 MW	Share – 0%	
Biomass boilers installed capacity in industry	0 MW	Share – 27%	
Natural gas boilers installed capacity in industry	0 MW	Share – 0%	
Hydrogen in industry	0 MW	Share – 30%	
Oil boilers installed capacity in industry	0 MW	Share – 0%	
Installed PEM electrolyser capacity	0	0	MW
Installed Alkaline electrolyser capacity	0	703	MW
Installed SOEC electrolyser capacity	0	0	MW
Installed hydrogen storage capacity	0	11,322	MWh

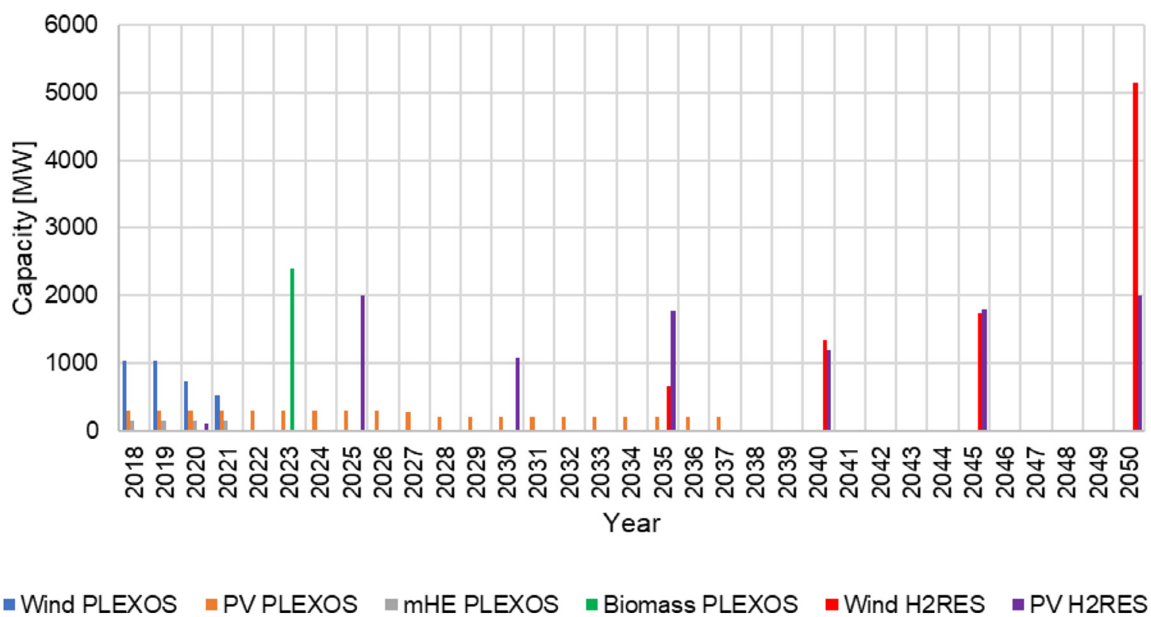

Fig. 7. Comparison of capacity investment.

planning horizon except for 2023 where it reaches 5,17%. Generation of CEEP is not limited in PLEXOS. PLEXOS can achieve lower generation of CEEP due to large investments into dispatchable biomass power plants, whereas H2RES uses hydrogen generation and storage systems, especially in industry sector to balance out the variations in energy generation. Both models use as well electric vehicles with technologies such as smart charge and V2G for balancing purposes.

Investments into heating systems in both models are displayed in Fig. 9. Here as well is visible different investment strategy. In the figure, investments in PLEXOS model are aggregated into 5-year steps for graphing purposes. PLEXOS makes most of the investments at the beginning, except for the investments into boilers in industry. Contrary, H2RES rather opts to use existing boilers until they are decommissioned and then it invests into carbon neutral technologies such as biomass boilers, electric boilers, and heat pumps.

H2RES does not as well as PLEXOS offer full functionality in modelling transport sector. It is possible to model modes of transport that use energy derived from electricity. This can be battery electric vehicles themselves or fuel cell hydrogen-electric vehicles. Both are modelled based on preconfigured travel demand hourly distributions. Same as in PLEXOS, there is no option to have users shift from internal combustion engine (ICE) towards EV's for example. Electric vehicle module also allows for energy system balancing with the use of V2G and "Smart charge".

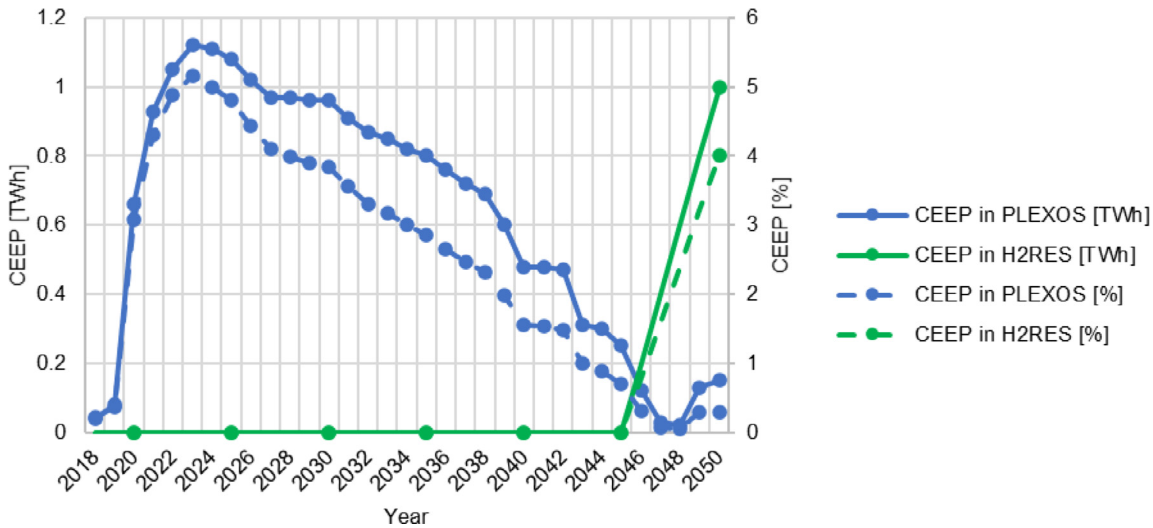

Fig. 8. CEEP in H2RES and PLEXOS.

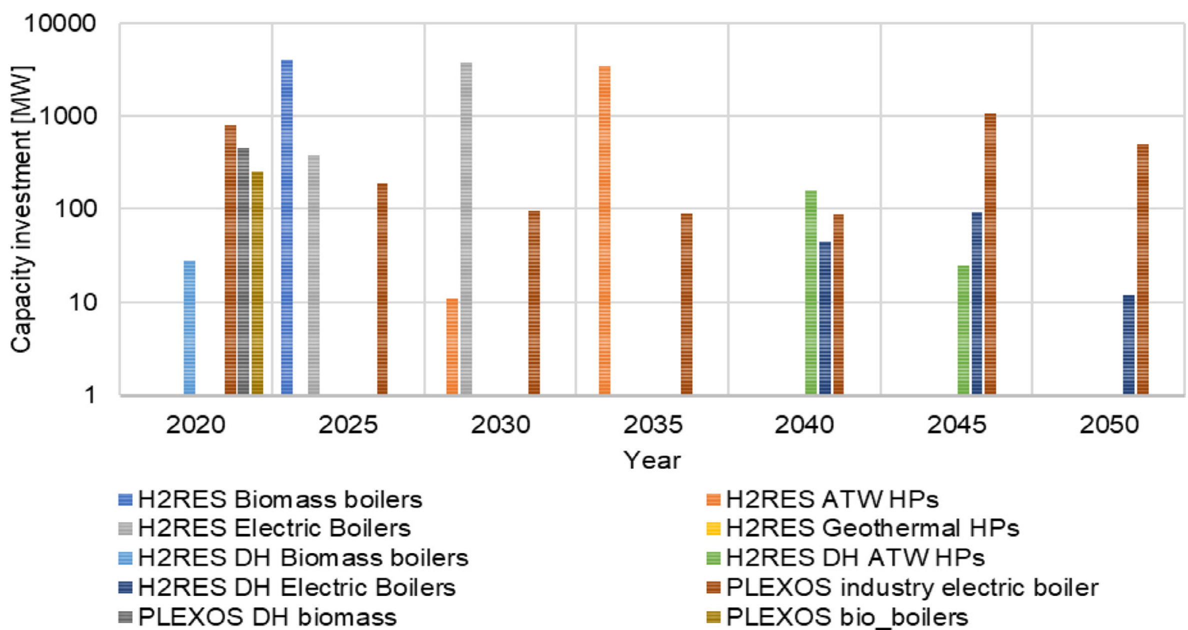

Fig. 9. Investment in boilers and heating systems.

Both models managed to adhere to CO_2 emission limits. PLEXOS restricted the use of fossil fuel even more than mandated by the CO_2 limit. Only after 2044., actual emissions and the CO_2 limit come close together as displayed in Fig. 10. The case with H2RES as well generates lower emissions than stated in the model. Emissions match only in the beginning and the end year.

Conclusion

This research compared two energy modelling software, PLEXOS and H2RES. Both examined models offer significant insight into energy system development and operation. They differ in capabilities and available options, but it is possible to model and simulate the development of a complex energy system in both models.

PLEXOS is commercial software with long development history and a number of ever more capable releases. The focus is on the electricity grid and the system itself. Consideration of other sectors such as heating systems is possible but with some of the limitations as it was not intended to be used to model the whole energy system.

H2RES is open source, therefore a lot of the problems noted here can be accounted for in the later development of the software. On the case of Croatia, the output of generating capacities is different in the examined models. One major difference which has conditioned differing numbers of RES generation capacities is the inclusion of the possibility of constructing new run of the river hydropower plants and biomass powered thermal plants in the PLEXOS case. Both are absent in H2RES results as a side effect of more adept use of flexibility options, for example, with power-to-X options.

In conclusion, a significant advantage of PLEXOS is the sheer number of available options to include and detailly model the workings of each individual generator. On the other hand, H2RES allows for the implementation of virtually all mentioned options available only in PLEXOS and that is its greatest advantage. Modelling an energy system with H2RES may take a longer time since the modellers may encounter a range of problems when presenting the model with a new configuration. With that said, H2RES offers practically unlimited potential for functionality expansion since it is an open-source program. The only

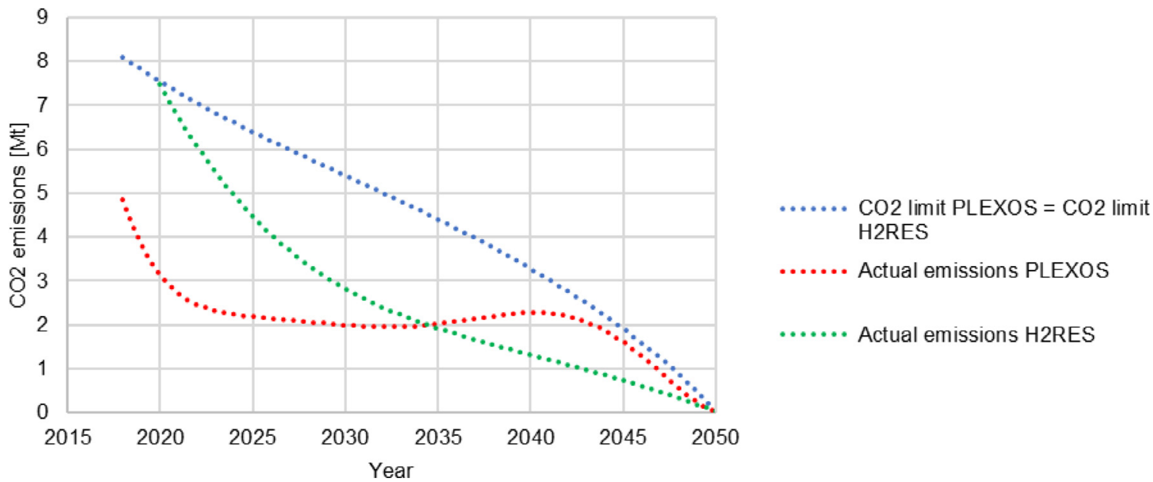

Fig. 10. CO_2 emissions.

limitation is the necessity to adhere to linear programming structure guidelines in order for the problem to have feasible solutions by using the Gurobi solver [33]. The new long-term planning model H2RES is shown to be capable of following a majority of PLEXOS functionalities. Its functionalities will be refined in future work and will be expanded on other energy demand sectors.

Further research and development of the H2RES model will take into account improvements of transport module in order to be able to include other types of vehicles except EVs as well as other modalities of transport. This would enable the modellers to model multiple modes of transport separately. Therefore, specific restrictions such as difficulties in electrification of trucking and aviation can be considered. Additionally, portion of the demand would be able to be shifted between different transport modalities such as shift of goods transported by trucks on the railways with associated efficiency gains. Also, at this stage of the development, salvage costs have not been considered, but they plan to be implemented in further model development.

Acknowledgment

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Appendix

Heating

The distribution of heat demand is modelled with an hour-degree method. The method requires hourly distribution of the temperatures on the location of modelled heating system, required indoor temperature, ambient temperature bellow which the heating system starts working. Also, the time schedule at which hours during the day system is considered to not work. The only difference between district heating systems and individual heating is that individual heating system can provide heating even outside normally considered heating season if the ambient temperatures are sufficiently low. On the other side, the district heating system only works in a predetermined time span of the heating season.

Assumptions:

- Heating season starts 15th of September and lasts till 15th of May [41] [42],.
- Heating does not work if ambient temperature is higher than 15°C
- Heating system works only between 6:00 and 23:00
- Specially, if ambient temperatures drop below −15°C during the time when system normally does not work, an exception is made and the system works during these hours

$$Q_t = \frac{HD \cdot Q_{year}}{\sum_1^{8760} HD} \tag{2a}$$

Where is:

- Q_t – hourly heat demand [MWh]
- Q_{year} – total heat demand [MWh]
- HD – hour-degree [°C] is defined as a difference of targeted and ambient temperature. Targeted temperature is 21°C.

$$HD = T_{target} - T_{ambient} \tag{3}$$

Demand for domestic hot water is determined on the basis of typical daily domestic hot water demand distribution [43].

$$Q_{DHW} = \frac{Q_{DHW\,year} \cdot \mu}{365 \cdot 100} \tag{4}$$

Where is:

- Q_{DHW} – hourly domestic hot water demand [MWh]
- μ – load factor
- $Q_{DHW\,year}$ – total domestic hot water demand [MWh]

Industry

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