Optimization of the Possible Pathways for Gradual Energy System Decarbonization

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ABSTRACT

The European Union and other signatories to the Paris Climate Accord have agreed to limit global warming to 2 degrees Celsius above pre-industrial levels. There have been a number of studies performed which demonstrate the possible end goals of an energy system that align with climate neutrality goals. This paper focuses on addressing the intermediate steps towards decarbonization. The steps are quantified as the percentage share of renewable energy sources. The objective of the optimization is to reach a predetermined level of renewable energy and emissions, minimize curtailment of renewable energy sources, minimize system cost, and limit the use of natural resources such as biomass in the energy sector. Considered technologies in the optimization process are energy-generating capacities, demand response technologies, and energy storage. The results of such a method reflect the use of considered technologies and are displayed as a function of renewable energy share and carbon dioxide emissions level, which also represent the decarbonization timeline from 2020 to 2050. The method is carried out with the use of energy planning software EnergyPLAN and highly modified Python-based optimization software EPLANopt. The results presented in the research display the necessity for continuous implementation of variable generating capacities as well as demand response technologies, mainly vehicle to grid.

KEYWORDS

EnergyPLAN, Decarbonization, optimization, renewable energy

1. INTRODUCTION

Decarbonization is one of the main challenges today. One of the biggest contributors to climate change caused by anthropogenic activity is the energy system. The energy system encompasses everything from the generation of electricity in power plants all the way to industrial processes and the transport sector. Changes are required in all of the sectors. Some of the changes may only consider energy efficiency improvements, while others call for the rebuilding of various sectors from the ground up.

This research proposes a method of tackling the problems policymakers may face on the matter of energy system development. One would just propose installing vast amounts of renewable generating capacity. The problem with this pathway is that it does not tackle the problems caused by variations in the generation of electricity from such sources, as stated by Spiegel et al. [1]. The installation of vast capacities would provide high penetration of renewable energy sources (RES) at times but otherwise would also create the necessity of curtailing said generating capacities [2]. Additional problems may arise in systems with a high reliance on thermal power plants. The problem lies with baseload thermal power plants, which may not be able to start or seize the operation as fast as required. Thermal power plants present the limits of the minimum power they have to run at before shutting down and in terms of ramping rates [3]. Part of the solution is in the flexibilization of the existing thermal power plants, which allows for faster start-up times, but this may not be enough, especially at higher shares of RES. O'Shaughnessy et al. [4] state that integration of flexibility options is mandatory if the goal is to achieve an energy system with high RES penetration. The same notion is further examined by Taseska-Gjorgievska et al. [5] with a focus on transmission capacities between various regions and the problems with transporting large amounts of energy. This emphasizes that the flexibility options are required, and also, their geographical placement and connection to the rest of the system is of great significance. Flexibility options include several different types of technologies. These are energy storage, demand-side flexibility, power to X flexibility and supply-side flexibility [6].

The effects of integration of flexibility options on critical excess electricity generation (CEEP) have been examined by Pfeifer et al. [7]. The examination was performed based on solar PV generation and power to heat to provide flexibility. Simulations have been performed with the use of EnergyPLAN that showed the applicability of the technology in the integration of renewable energy. The benefits of replacing the boilers, with heat pumps, including heat storage are also demonstrated by Østergaard et al. [8][9]. The benefits are reflected through better energy system management due to the provided energy storage and flexibility. Unfortunately, the economic outlook is not currently satisfactory, and incentives are required. Electrification of the transport sector and application of vehicle to grid (V2G) is also shown to be able to provide flexibility to the energy system with a high share of variable generation, as shown by Nadolny et al. [10]. The benefits of smart charging and V2G reflect thought the paper by Ren et al. [11] with the results indicating the reduction of electricity prices and economic benefits for those utilizing the V2G technology. The use of V2G technology is beneficial due to the ability to profit from the changes in electricity prices by choosing when to charge and discharge the battery. The complex interaction and the benefits of such interaction between electric vehicles and the energy grid are examined by Novosel et al. [12]. Backe et al. [13] investigate this relationship as well, presenting the benefits of sector coupling with the use of electric vehicles and electric boilers. The benefits are reflected in the reduction of curtailment. Reduction of curtailment as a final goal also has a positive effect on the development of an energy system. The danger that curtailment poses to the energy system's development is a possible lack of investments into new capacities if the expected generation is low. One way of solving the issues with variability and securing energy supply, especially in isolated regions, is with the introduction of power to gas options. Nastasi et al. [14] examined the performance of the island energy system with hydrogen energy storage. The paper concludes that hydrogen storage is applicable for seasonal energy storage, especially in systems such as the one examined, which heavily relies on solar energy. Also, hydrogen and power to gas technology can be used to directly decarbonize natural gas systems. This can be done directly by injecting hydrogen into pipelines or by the generation of synthetic gas [15]. Hydrogen and synthetic fuel storage are alternatives to battery storage. An additional benefit of such energy storage systems is the capability of decreasing the use of peaking units that may be required in the intermediate stages of reaching a carbon-neutral energy system [16]. Hydrogen and hydrogen-based energy carriers may be of great interest for the industry sector as a large energy demand sector with the necessity for combustible fuels, especially in the processes that require high temperatures and are hard to electrify [17]. The downside of using hydrogen instead of electricity is the increased electricity demand required for hydrogen generation due to energy losses. On the other hand, hydrogen is more easily storable than electricity. Battery energy storage may even become more applicable in grid storage when technical difficulties such as the problems with battery degradation are resolved. The main factor contributing to battery cell degradation is the formation of dendrites. Resolving that problem will increase the number of charging/discharging cycles in the battery life. For example, Lanfranconi et al. [18] present the novel battery chemistry of lead-flow batteries with the problem of dendrite formation resolved. Therefore, a vast range of battery chemistries are available on the market, each with their own defining characteristics that may inhibit the prevalence of one single type. These defining characteristics are the expected lifespan and investment costs. Groppi et al. [19] also performed an analysis of demand response technologies with a focus on energy refurbishments of building stock, transport electrification, and heating electrification, with the conclusion that more intricate sector coupling is required. All of the mentioned examples of flexibility options can be called "sector coupling" since traditionally separate sectors of energy production and demand are related. 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" [20]. It assumes deepening the linkages between various sectors, primarily based on electricity use and energy carriers derived from electricity. These include electricity itself, heat, and various forms of hydrogen-based energy carriers.

The problem that this paper aims to tackle is to provide an insight into what technologies and flexibility options are adequate in achieving certain goals on the pathway towards net carbon neutrality. This is achieved with the use of EPLANopt, an optimization software developed by Prina et al. [21]. The software uses the EnergyPLAN tool in order to perform simulations and a genetic algorithm to achieve the predetermined goals defined by the modellers. Previously published papers using this software or a similar one have all focused on reaching the Pareto front defined by the relations of two variables and thus achieving 2-factor optimization. For example, the creators themselves use EPLANopt to reach a high share of renewables with low system cost [22]. They also perform differing runs with differing shares of transport electrification. Batas Bjelić et al. [23] use similar software GENopt to optimize energy system. The goal of optimization is also to reach as high a share of RES as possible with low costs at the same time. Other examples of multi-objective optimization with EPLANopt or similar tools have focused as well on reaching one predetermined share of RES, such as the paper by Makhlufi et al. [24] that tries to reach a share of 75%. Similarly, the paper by Doepfert [25] presents the results for an optimal energy system in Portugal for the requirement of 100% RES.

The problem some energy systems may face when transitioning towards renewable energy is a drastic increase in the use of biomass, which should be avoided. Biomass is mostly considered carbon-neutral, but only if sustainable harvesting techniques are implemented. Also, biomass is a solid fuel. Therefore, its combustion in poorly equipped boilers may increase the concentration of harmful particulate matter and nitrogen oxides, as presented in Jaworek et al. [26]. However, biomass should be utilized, but not in too extensive a manner. According to Lovrak et al. [27] Croatia has a relatively large sustainable biomass potential, with 6,7 TWh of energy from biogas alone and up to 117 TWh from all types of biomass [28] as stated in the Croatian energy development strategy. Mortenses et al. [29] also propose the use of hydrogen due to this problem. The flexibility of a demand-side in the energy system is also one way of reducing the curtailment of renewable energy as well as avoiding investments in peaking plants [30].

The hypothesis of this research is that the proposed method in this research enables the achievement of an optimal energy system transition pathway through the application of expanded functionalities of the model. The pathway is determined through optimization of input variables such as VRES generating capacities and the capacities of flexibility options. The applied method provides the consistency of energy balances that was lacking in previous iterations of EPLANopt. In previous versions, there was the possibility of optimizing the values of different parameters, but if not applied carefully, the method would result in inconsistent energy balances. An example of such implementation is the transport sector where in order to keep energy balances when transitioning towards electrifeied transport, fossil fuel powered transport has to be reduced in accordance with the rate of electrification and introduction of alternative drivetrains. Furthermore, widespread application of the software is possible after the modifications since it is no longer constrained by the variables that can be optimized.

The contribution of this research reflects through:

- Achievement of multiple stated goals such as energy system cost minimization, CEEP minimization, achievement of targeted share of RES and limitation of biomass use as well as minimization of energy imports. With this in focus, this research aims to present the optimal capacity of each technology or flexibility option presented within the predetermined RES and carbon dioxide (CO_2) limitations. Presented options and technologies range from RES generating capacities, fuels in thermal plants, generation of hydrogen, energy storage and electrification of sectors such as the transport and heating sector.
- Expansion of functionality of EPLANopt optimization software with the introduction of dependent variables. Previously, technologies that require multiple parameters that are correlated with mathematical function had to be inserted manually in the model and were not subject to optimization. An approach of simply inserting all the required parameters into the EPLANopt was not favourable because the system may lose consistency. For example, if multiple fuels for heating purposes are modelled which may in this example be presented by natural gas and biomass. The software would choose the value for both natural gas and biomass independently, not considering that final heating demand has to equal some predetermined value. Usage of such inputs would cause errors in data interpretation. Implementation of this method also helps in the reduction of necessary variables inputted

by the modellers which decrease complexity as well as simulation execution time. For example, this method allows in this case to model 47 differing parameters with the input of only 17 variables. Also, the possibility of further modifications is possible with the utilization of the presented additional code.

- The method enabled the targeted optimization with the model reaching predetermined goals of share of RES and level of CO_2 emissions. An additional contribution is the ability to simulate the development of an energy system since the multiple consequitive optimizations are carried out. Each of them corresponds to different share of RES that is targeted.

2. METHOD

The simulations are carried out with the combination of energy system simulation software EnergyPLAN [31] and multi-objective optimization software EPLANopt [32]. The basic structure of EnergyPLAN is displayed in Figure 1. This tool offers the user the ability to model energy systems with a high penetration of RES. This is achieved through the installation of renewable generating capacities as well as through the introduction and deepening of relations between various sectors. Input data consists of generating capacities, energy demand, and distribution curves. Simulation output consists of a number of parameters describing the energy system, ranging from the share of RES and level of emissions all the way to data on the performance of each technology and their hourly values. The output data of most interest, in this case, is the share of RES, level of emissions, generation of CEEP and biomass consumption.

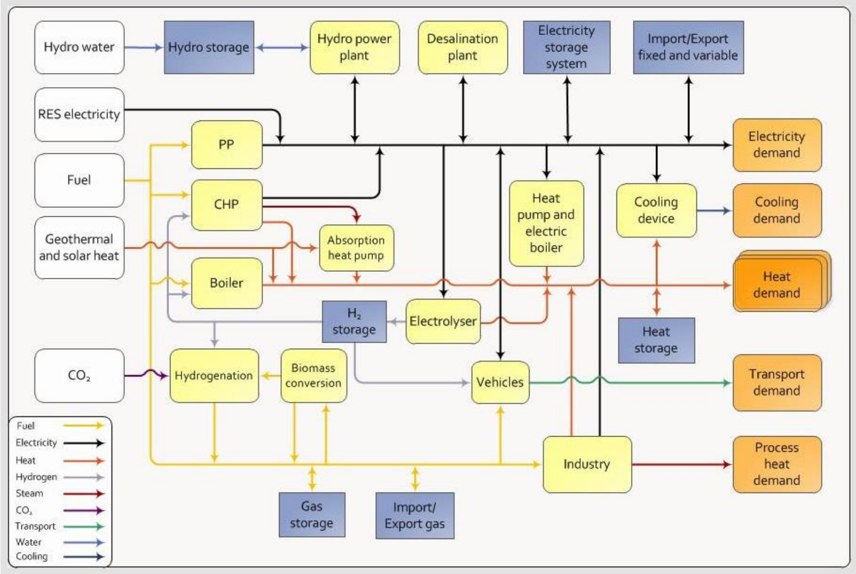

Figure 1. The basic structure of EnergyPLAN [31]

The goal is to examine optimal configurations at various shares of RES and levels of CO_2 emissions. This is done with the optimization of the share of RES in a procedure shown in equations (1) and (2). The function minimizes the absolute value of the difference between the targeted value and the output value.

$$RES = \left|RES_{goal} - RES_{real}\right| \tag{1}$$

Minimize RES

$$CO2 = \left|CO2_{goal} - CO2_{real}\right| \tag{2}$$

Minimize CO2

Where:

- RES_{goal} – targeted share of RES
- RES_{real} – simulation output share of RES
- Minimize RES – objective determined by the weight factor with value -1,0
- $CO2_{goal}$ – targeted level of CO2 emissions
- $CO2_{real}$ – simulation output level of CO2 emissions
- Minimize CO2 – objective determined by the weight factor with value -1,0

Simulations are performed with the goal of a predefined share of RES and a predefined level of emissions. Emissions relate to the emissions originating from the power sector, heating, industry, and transport. The sector of agriculture is excluded from the calculation of CO_2 emissions since it is not included in EnergyPLAN and since the goal is to reach net-zero emissions, which includes CO_2 sequestration.

The other parameter which is being minimized is critical excess electricity generation (CEEP).

$$CEEP_{\%} = \frac{CEEP_{TWh}}{Dem\_el\_tot} \cdot 100 \tag{3}$$

Minimize CEEP

$$\begin{aligned} Dem\_el\_tot = {} & Dem_{basic} + Dem_{EV} + Dem_{P2H} + Dem_{flex} + Dem_{HH\_HP} + Dem_{HH\_el} \\ & + Dem_{H2} + Dem_{Batt\_ch} + Dem_{HTES\_ch} + Dem_{PHS\_ch} \end{aligned} \tag{4}$$

Where:

- $CEEP_{\%}$ - CEEP expressed as in percentages of total electricity demand [%]
- $CEEP_{TWh}$ - output of simulations in EnergyPLAN [TWh]
- Dem_el_tot – total electricity demand [TWh]
- Dem_{basic} – basic electricity demand [TWh]
- Dem_{EV} – demand for EV charging [TWh]
- Dem_{P2H} – demand for P2H [TWh]
- Dem_{flex} – flexible electricity demand [TWh]
- Dem_{HH_HP} – demand for heat pumps [TWh]
- Dem_{HH_el} – demand for electric heaters [TWh]
- Dem_{H2} – demand for hydrogen generation [TWh]
- Dem_{Batt_ch} - demand for battery charging (energy loss between charging and discharging) [TWh]
- Dem_{HTES_ch} - demand for high-temperature thermal storage (energy loss between charging and discharging) [TWh]

- Dem_{PHS_ch} - demand for pumped hydropower storage (energy loss between charging and discharging) [TWh]

The total annual cost of an energy system, as well as emissions, are also being minimized with a weight factor of -1,0.

The limitation on the use of biomass is also included to avoid complete reliance on biomass. The consumption of biomass has a weight factor of -0,1.

After the calculations are performed, post-processing of the results begins to determine the optimal solution. The procedure is as follows. The results featuring larger RES share deviation from 2,5 % are discarded. After that, the results are gradually filtered out. The procedure is based on the mean values of the results. Therefore, the result cases with absoluticaly most prelevant values are kept, while the ones with different values of the examined parameter are discarded. The procedure is performed consequetevley for each of the parameter as described in Figure 2.

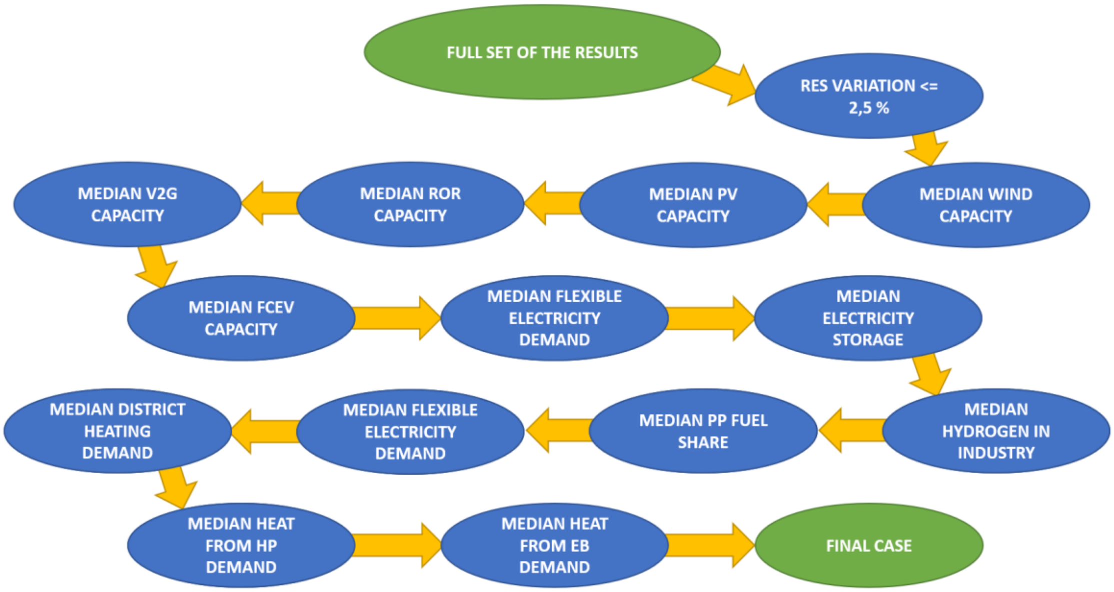

Figure 2. Post-processing of the resultsSome of the variables inserted as variables into EPLANopt do not have significant meaning by themselves, but they do in the context of the energy system. For example, the "Battery storage charging capacity" variable only defines the charging capacity of the battery storage. The battery storage system requires more input parameters to be completely defined, such as discharging capacity and storage capacity. Therefore, all these variables have to be changed in unison to achieve consistent results. The relations between the variables in the modules are displayed in

Table 1.

Table 1. Structure of the modules

MODULE	INPUT FROM EPLANOPT	PROCESSING AND ADDITIONAL INPUTS	INPUT TO ENERGYPLAN

TRANSPORT	ENERGY INPUT FOR SMART CHARGE IN TRANSPORT ELECTRIFICATION	EFFICIENCY	BATTERY CHARGING CAPACITY
	ENERGY INPUT FOR H2	TOTAL DISTANCE TRAVELED	BATTERY DISCHARGING CAPACITY
			BATTERY STORAGE CAPACITY
			USE OF DIESEL FUEL
			USE OF PETROL FUEL
			CAPACITY OF ELECTROLYSER
			NUMBER OF ICE VEHICLES
			NUMBER OF FCEV VEHICLES
			NUMBER OF ELECTRIC VEHICLES
DEMAND-SIDE FLEXIBILITY	DAILY FLEXIBLE ELECTRICITY DEMAND	SHARE OF DEMAND FLEXIBLE DAILY, WEEKLY AND MONTHLY	WEEKLY FLEXIBLE DEMAND
			MONTHLY FLEXIBLE DEMAND
			MAXIMUM POWER DAILY
			MAXIMUM POWER WEEKLY
			MAXIMUM POWER MONTHLY
			BASIC ELECTRICITY DEMAND
STORAGE	BATTERY STORAGE CHARGING CAPACITY	EFFICIENCY	BATTERY STORAGE DISCHARGING CAPACITY
		RATIOS OF CAPACITIES AND STORAGE CAPACITIES	BATTERY STORAGE CAPACITY
			PUMPED HYDRO CHARGING CAPACITY
			PUMPED HYDRO DISCHARGING CAPACITY
			PUMPED HYDRO STORAGE CAPACITY
			ROCK-BED STORAGE CHARGING CAPACITY
			ROCK-BED STORAGE DISCHARGING CAPACITY
			ROCK-BED STORAGE CAPACITY
INDUSTRY	USE OF HYDROGEN IN INDUSTRY	RATIO OF HYDROGEN AND ELECTRICITY IN INDUSTRY ENERGY SUPPLY	USE OF ELECTRICITY IN INDUSTRY
			USE OF NATURAL GAS IN INDUSTRY
			CORRECTION OF BASIC ELECTRICITY DEMAND
			ELECTROLYZER CAPACITY
THERMAL POWER PLANTS	SHARE OF BIOMASS IN THERMAL PLANTS	RATIO OF HYDROGEN AND ELECTRICITY IN INDUSTRY ENERGY SUPPLY	SHARE OF BIOMASS IN CONDENSING POWER PLANTS
			SHARE OF NATURAL GAS IN CONDENSING POWER PLANTS
			SHARE OF BIOMASS IN COGENERATION POWER PLANTS
			SHARE OF NATURAL GAS IN COGENERATION POWER PLANTS
			SHARE OF BIOMASS IN DH BOILERS
			SHARE OF NATURAL GAS IN DH BOILERS
FLEXIBILITY OF THERMAL POWER PLANTS	CONDENSING THERMAL POWER PLANT MINIMUM OPERATING POWER	RATIO OF CONDENSING THERMAL POWER PLANT AND COGENERATION POWER PLANT MINIMUM OPERATING POWER	COGENERATION POWER PLANT MINIMUM OPERATING POWER
HEATING	ENERGY INPUT FROM DISTRICT HEATING	EFFICIENCY	ENERGY INPUT FROM BIOMASS BOILERS
	ENERGY INPUT FROM ELECTRIC BOILERS	TOTAL HEAT DEMAND	
	ENERGY INPUT FROM HEAT PUMPS		
	ENERGY INPUT FROM NATURAL GAS BOILERS		

To improve the realism of simulations and energy system development, limitations on capacity expansion have been implemented. Therefore, the maximum capacity of technology is limited to reflect realistic investments. Also, older capacities are decommissioned, and the lower technology limitation value in subsequent periods is reduced by that amount that is decommissioned.

The transport sector is modelled using two inputs from EPLANopt. These are the energy demand in smart transport electrification and the use of hydrogen in transport. EPLANopt determines the values of the energy demand in smart charge and FCEVs. From the values of these variables and outside parameters such as efficiencies and total distance travelled, the remaining parameters are calculated. Travelled distance is kept the same throughout all of the simulations since this parameter needs to stay at the same value to grant energy system consistency.

Electric vehicles in V2G and smart charge are defined by their charging capacity and battery capacity. The average charging capacity is estimated at 9 kW per vehicle, while battery storage capacity is estimated to be 50 kWh. The remainder of transport demand, not covered by either electric vehicles (EV) or fuel cell electric vehicles (FCEV), is covered by internal combustion engine (ICE) vehicles. The assumption on constant ratio between the share of diesel and petrol fuel in transport sector has been implemented. The reason for implementing such ratio is the similarity to current ratio in examined case study as well as the necessity to minimize the number of variables entering the optimization. EnergyPLAN does not significantly differentiate between petrol and diesel.

The transport module differs in the simulations up to 90% of RES and the ones for 100% RES. The simulations at 100% RES assume no ICE vehicles and all transport demand is shared between EVs and FCEVs. Therefore, the EPLANopt determines the value of energy demand for EVs, and the rest is assumed to be contributed by FCEVs.

Flexible demand is also one of the variables being optimized. Only the demand on a daily basis is being explicitly optimized, while the rest of the parameters are linked to its value. The maximum power that can be utilized is correlated to the maximum yearly load and the share of capacity that is flexible. Basic electricity demand is also being reduced in EnergyPLAN input as more of the demand is switched to flexible demand. In this version of the software, the value of the demand whose parts are being flexibilized is kept constant. Therefore, the value of flexible demand is not affected by the changes to basic electricity demand. This procedure is implemented to limit second-degree optimization problems that could arise if the demand is constantly changing under the influence of demand from EVs, power to heat (P2H), electricity storage, and hydrogen generation.

The relationships in the energy storage model are also displayed in

Table 1. In this case, battery storage charging capacity defines the discharging capacity, storage capacity, as well as capacities and storage data on high-temperature thermal storage and pumped hydro storage systems with linear relations.

The thermal power plant flexibility module assumes the reduction of the minimum operating capacity of thermal power plants from its historical level, all the way to 0 MW. The reduction to 0 MW makes the power plants fully flexible and capable of managing CEEP. Only the minimum capacity of condensing plants is explicitly inserted into the model, while the value for CHP plants is linked to the value for condensing plants.

EnergyPLAN divides input parameters for fuel consumption in the industry sector according to the types of fuels into “coal”, “oil”, “natural gas”, “biomass” and “hydrogen”. For the purposes of this research, all the used fuels represented by the variables “coal”, “oil” and “natural gas” are combined into a single factor representing fossil fuels and inserted into the cell for natural gas. In this model, decarbonization is achieved by switching the consumption of natural gas partly to electricity and partly to hydrogen for the processes that cannot be electrified. Due to simplicity, the ratio between hydrogen and electricity is estimated to be 50-50. The model determines the value for hydrogen use, and to preserve consistency, another part of the code reduces the consumption of natural gas. It also adds electricity demand into the basic electricity demand parameter. The capacity of the electrolyzer is also affected.

In this case, the use of fuels in thermal plants is divided into fossil fuels represented by natural gas and biomass. The system is described with one variable, the share of biomass. The share of natural gas is related to this value. The shares are consistent across all types of thermal plants, ranging from cogeneration power plants to condensing power plants and district heating boilers.

The heating sector is defined by the heat demand supplied by district heating, biomass boilers, natural gas boilers, heat pumps, and electric boilers. The model explicitly defines the supply from district heating, natural gas boilers, heat pumps, and electric boilers. The remainder of the demand is supplied by biomass boilers. The limiting values on energy from various fuel sources are carefully chosen in order not to increase the possibility of getting the sum of supply greater than demand.

Technology prices are evaluated with differing values for the technologies where differences are expected in the future. This encompasses RES generating capacities, prices of fuels, storage and balancing technologies, as well as prices of vehicles. Most of the prices considering generating capacities are sourced from the EnergyPLAN cost database [34], while projections of fuel prices are taken from the results of the Heat Roadmap Europe project [35]. The rest of the specific data is taken from the Danish Energy Agency [36], or papers such as Lutsey et al. [37] for the cost of electric vehicles and reports for the cost of thermal power plant retrofits [38], [39].

The simulation runs are defined by the population and generation number inside a genetic algorithm. The population number represents the number of different cases in each of the generations. At the start, the algorithm chooses random values, while at later generations, mutations and genetic development of the decision-making algorithm is simulated. The used population number, in this case, is 100, while the number of generations is 150. These numbers are determined by the experience of the authors based on the complexity of the problem at hand. Such a combination of populations and generations results in the creation of about 15,000 cases. The simulations are run on a Lenovo Ideapad 330 with a 4 core processor i5-8300H running at 2,3 GHz and 8 GB of DDR4 memory running at 2400 MHz.The execution time for each run is 30 hours.

When the simulations are done, the tables containing the data on all of the run cases are analyzed. Because there are a large number of cases that did not come close to the desired value of the RES share, some of them are filtered out and are not considered in the following steps. The tolerance inside which the cases are considered is 2,5% RES, meaning it is 5% RES wide. Also, cases with emissions of CO_2 of less than 1 Mt from the target value are considered. As a final result, the case that appeared most often as a solution is chosen.

3. CASE STUDY

The simulations are run in an energy system with a restricted transmission capacity of 2500 MW in order not to overstate the reliance on external energy systems for balancing purposes. The studied system represents the Croatian energy system.

The model is based on the model of the Croatian energy system in 2018. Table 2. displays the comparison of achieved values and reference values from IEA and IRENA for the share of renewables, level of emissions and generation from renewables.

Table 2. Calibration of the model in the base year of 2018

Name	**EnergyPLAN**	**Reference**	**Unit**	**Error [%]**	
RES	29,5	29,8	%	-1	IEA [40]
Emissions of CO_2	15,548	15,3	Mt	+2	IEA[40]
Wind CF	0,24	0,238	-	+1	IRENA[41]
PV CF	0,13	0,126	-	+3	IRENA[41]

Installed capacities of power plants are displayed in Table 3

Table 3. Installed capacities of power plants in Croatia [33], [41]

Energy source	**Capacity [MW]**
Wind power	586,3
PV	67,7
Geothermal powers	10
Nuclear power plants	348 (696*)
Thermal power plants	2152
Dammed hydropower plants	1241,9 (1359,4**)
Run of the river hydropower	438,1
Condensing thermal power plants	376,9
Cogeneration thermal power plants	824,5

*Nuclear power plant Krško is shared with the Republic of Slovenia

**1 generator in HE Dubrovnik is shared with Bosnia and Herzegovina

3.1 Limitations and goals in the simulations

The goals of the share of RES and the level of emissions are displayed in Figure 3. The goals are related to the years since the plans for the reduction of CO_2 emissions by 55% by 2030 and 0 by 2050 are respected.

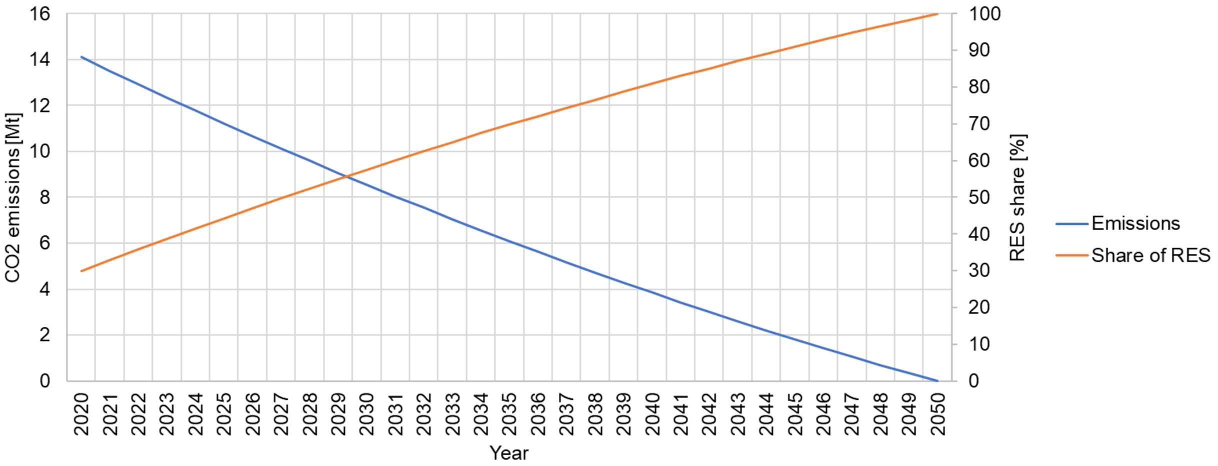

Figure 3. Goals of RES share and CO_2 emissions

3.2 VRES installations

The limits on the installed capacities of VRES differ in each of the cases that are run. The upper limits are displayed in Table 4. whereas the lower limit corresponds with the capacity in the preceding case, which is further decreased by the capacity that is decommissioned. The process of calculating minimum capacity is displayed in Equation 5.

Table 4. Maximum installed capacities in the multiple runs [MW] [28], [42]

RES [%]	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Wind	2000	4000	6000	8000	9000	9000	9000
PV	2000	4000	6000	8000	8000	8000	8000
Offshore wind	1500	3000	4500	6000	7500	9000	10500

$$cap\_min_{n+1} = cap_n - cap_{old} \tag{5}$$

Where:

- cap_min_{n+1} – minimum capacity in the next case
- cap_n – capacity in the preceding case
- cap_{old} – a capacity that is being decommissioned, older than 20 years

3.3 Flexible demand

It is estimated that up to 50 % of electricity demand can be flexibilized and of that, 40% can be made flexible within a 24-hour window. 30% of flexible demand can be moved on a weekly basis as well as a monthly basis.

3.4 Transport sector

Based on historical data and EnergyPLAN conversion factors, the annual travelled distance in the transport sector is 38 billion kilometres. International aviation and shipping are not included.

Electrified transport is divided into "dump" and "smart charge." In historical data, the energy demand for "dump charge" is 0,281 TWh. The same number is used in all of the subsequent cases, and it mainly represents electrified railways and public transport. The fossil fuel section of transportation has been simplified so that it will be represented in all future cases by a combination of diesel and petrol fuel powered transport. The share between diesel and petrol is 70 to 30 in favor of diesel. The reason for implementing such ratio is the similarity to the current ratio in Croatia [33].

3.5 Industry

The demand for fossil fuels in the industry sector is being replaced by the demand for hydrogen and electricity. In this case, the energy supplied by hydrogen and electricity is set to be equal. The maximum energy supplied by hydrogen and electricity is set to be 8,2 TWh.

Table 5. Hydrogen and electricity in industry module [TWh]

RES [%]	**40**	**50**	**60**	**70**	**80**	**90**	**100**
H2 and Electricity	1,5	3	4,5	6	7,5	8,2	8,2

3.6 Heating

The heating sector in EnergyPLAN is divided into district heating and individual. District heating is defined as being able to increase from 1,8 all the way to 5 TWh if the system is more widely applied. The heat supplied from electric boilers can increase to 5 TWh, while heat pumps can increase to 4 TWh. Supply from natural gas can only be reduced to 0 TWh. Complete data on limiting values is displayed in Table 6. The heating demand is assumed to decrease annually by 2% as an effect of energy refurbishments.

Table 6. Limits in heating module [TWh]

RES [%]	**40**	**50**	**60**	**70**	**80**	**90**	**100**
DH	2	2,5	3	3,5	4	4,5	5
HP in HH	1	1,5	2	2,5	3	3,5	4
EB in HH	2	2,5	3	3,5	4	4,5	5
NG in HH	8	6	4	2	0	0	0

3.7 Energy storage

The charging and discharging capacity of battery storage is between 0 and 10000 MW, with a storage capacity of 0 to 50 GWh. It is equivalent to approximately one day of basic electricity demand. High-temperature thermal storage values are also between 0 and 10 GW, while its storage capacity goes up to 160 GWh, which corresponds to 3 days of basic electricity demand. Pumped hydro storage has a storage capacity of 2,93 GWh in the base case and is estimated in this analysis to be able to increase by 50% to a value of 4,4 GWh.

3.8 Flexible power plants

Croatia already has highly flexible thermal power plants with a technical minimum of 100 MW for condensing power plants, while for CHP it is 200 MW. The model considers the reduction of the minimum operating capacity to 0 MW, therefore making thermal power plants fully flexible.

3.9 Parameter limits

The rest of the limits on the installation and implementation of technologies are displayed in Table 7.

Table 7. limiting values for VRES and flexibility options [28], [43]

Variable	**Limiting value**	**Unit**
Wind capacity	9000	MW
PV capacity	8000	MW
Offshore wind	62,82	TWh
Use of electricity for smart charge of electric vehicles	6	TWh
Use of hydrogen in transport	3	TWh
Flexible electricity demand during 24 hours	3,5	TWh
Battery storage charging capacity	10000	MW
Thermal power plant minimum operating power	0	MW
Use of hydrogen in industry	8,2	TWh
Capacity of a heat pump in DH for P2H	15000	MW
DH in heating	5,5	TWh
Share of natural gas in households heating	0	-
Energy from heat pumps in HH heating	4	TWh
Energy from EB in HH heating	5	TWh
Share of biomass in thermal power plants	50	%

4. RESULTS

Results are displayed corresponding to the share of RES for which they are calculated. The results for installations of onshore wind power, PV, and offshore wind power are shown in Figure 4. Nearly the maximum available capacity of 9000 MW for onshore wind and 8000 MW for PV has been reached. Onshore wind power capacity reaches an all-time high of 80% of RES capacity. Between 2040 and 2050, the VRES capacity that was installed before 2025 is decommissioned, which is the reason for the decrease in VRES capacities in the case of 90% RES and 100% RES.

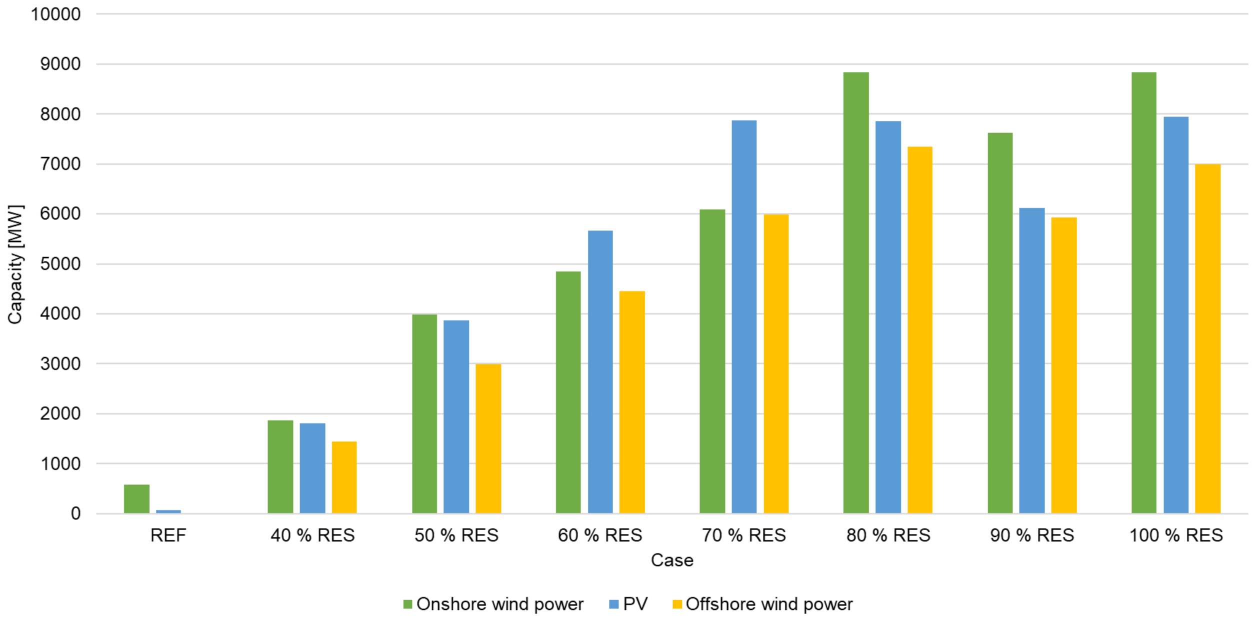

Figure 4. VRES capacity

The distribution of energy sources in the transport sector is displayed in Figure 5. In the reference case, only a dump charge for EV charging is used. This mostly accounts for electrified railway transport and public transport. The remainder of transport demand is supplied from fossil fuels. Smart charge with V2G and FCEVs are introduced in subsequent years. By 2050, the majority of the transport sector is electrified, while 18 % is fueled by hydrogen. The technology of smart charge and V2G offers the capability to a system operator to store energy and retrieve it if required. A similar influence on flexibility is provided by FCEVs since they require the operation of electrolyzers and are as well capable of performing the flexible operation.

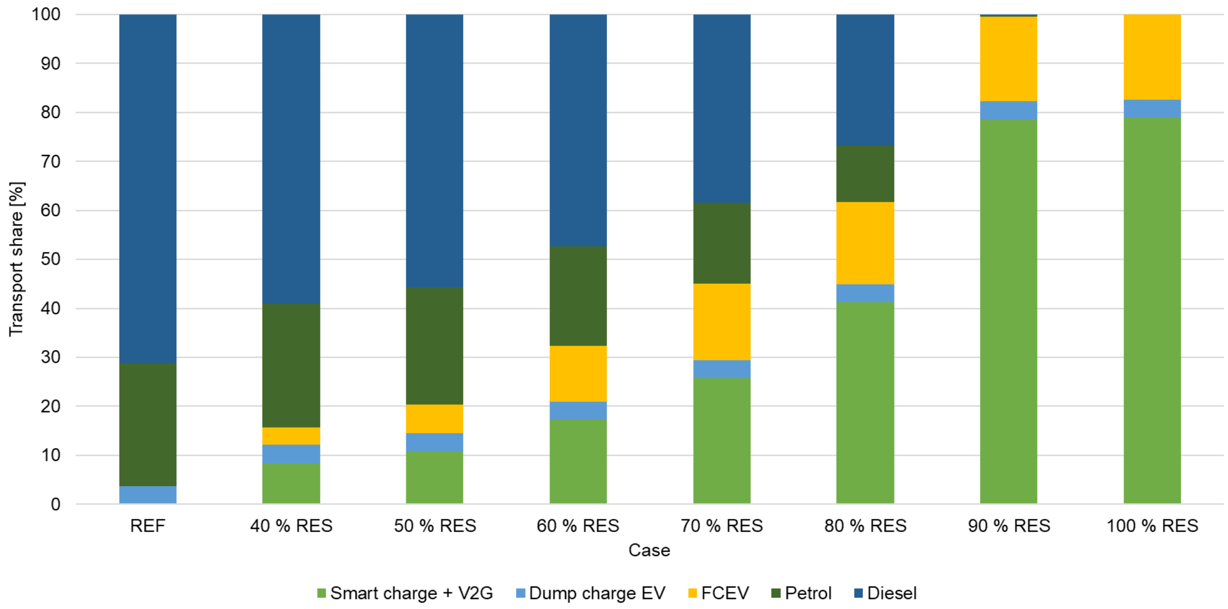

Figure 5. Transport module

Heating demand is modelled to decrease in future years by 2% per year under the influence of energy renovations. The supply of heat from various sources is displayed in Figure 6. While natural gas boilers are decommissioned, district heating systems are expanded to a maximum capacity of 2,4 TWh. The heat generated from electric boilers and heat pumps is the portion of the heating demand that increases substantially. Therefore, electrically driven heating covers more than 50% of the demand in 2050. The rest is supplied by biomass boilers.

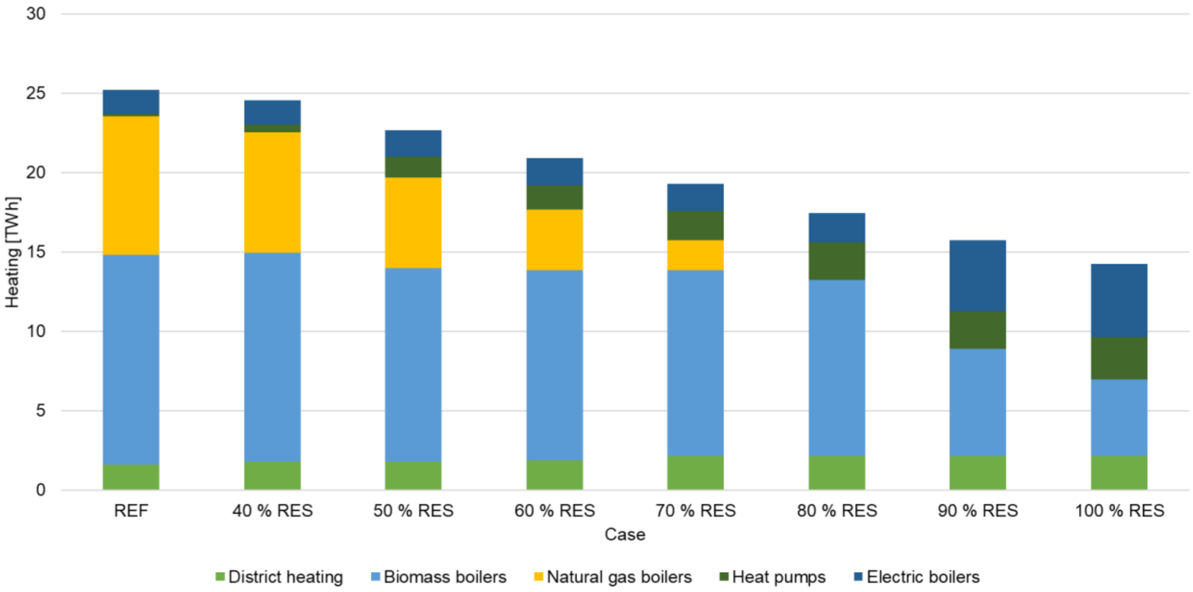

Figure 6. Share of technologies used for heating

Energy storage systems show the greatest applicability when the RES share is high, especially when the system is 100% RES. It is only then that the maximum capacity of battery storage is reached. Results are shown in Figure 7. Used capacity is relatively low in comparison to maximum capacity, and it can meet up to 4,5 days of average basic electricity demand.

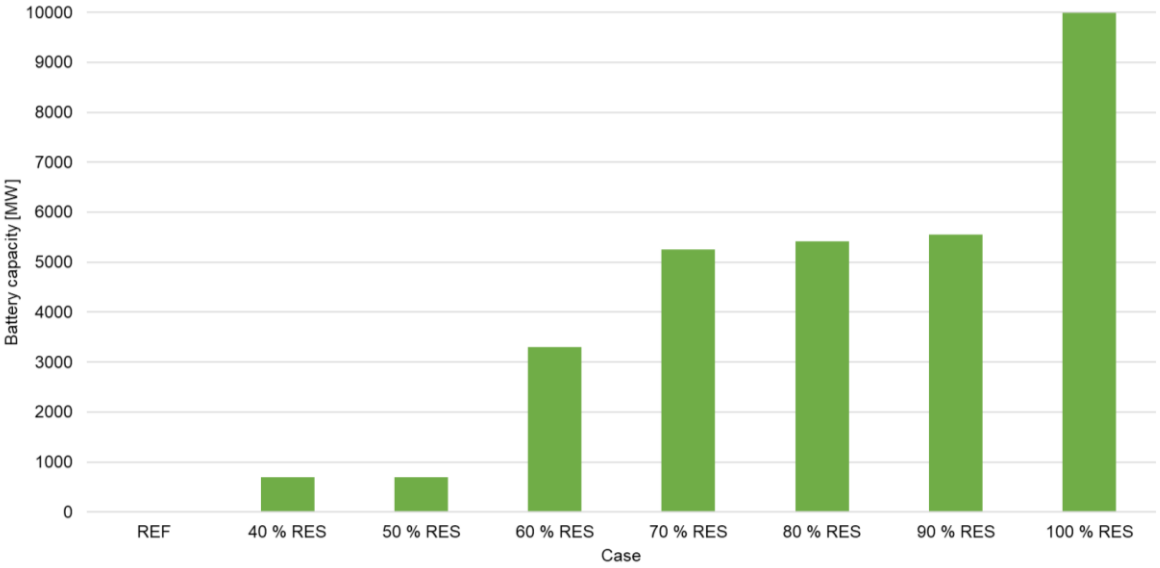

Figure 7. Battery storage capacity

Thermal power plant minimum operating power reduces from the value of 100 MW in the reference scenario to 19 MW in the case representing 40% RES and to 0 MW in all of the subsequent cases. Once it reached 0 MW, this option was not any more considered as an input to EPLANopt and was fixed at 0 MW for the remainder of simulations. The flexibility of thermal power plants is one of the first measures required to enable a transition towards VRES energy generation. The results are displayed in Figure 8.

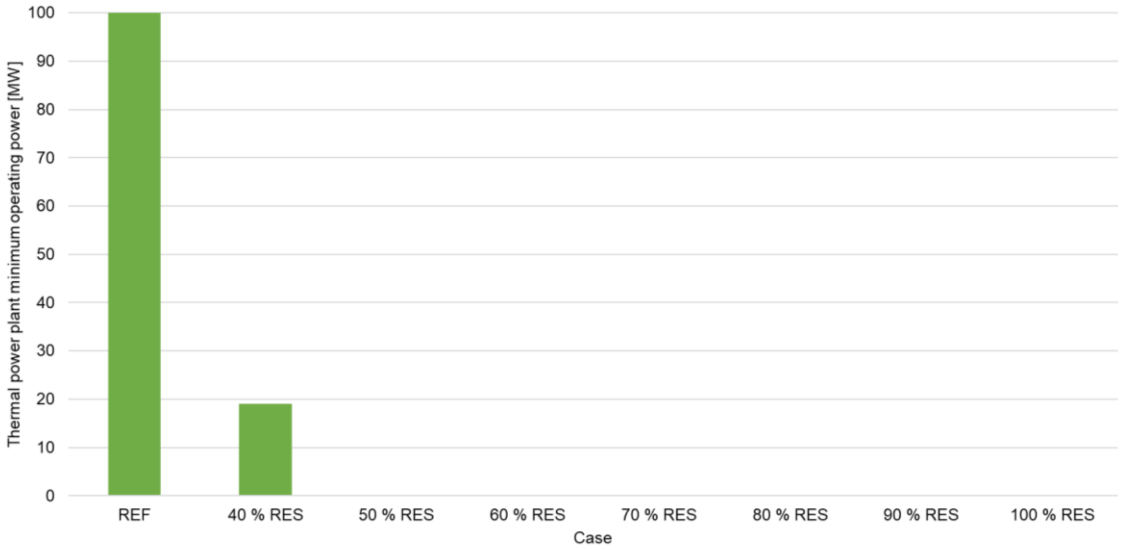

Figure 8. thermal power plant minimum operating power

The use of hydrogen and electrification of the industry is used to replace fossil fuel demand in the industry. In the case of 100% RES, its consumption rises to 8,2 TWh. The generation of hydrogen is preferred by the algorithm due to its noticeable ability of system decarbonization. Also, it is preferred due to the ability to use excess electricity since electrolysis requires vast amounts of electricity. Results are displayed in Figure 9.

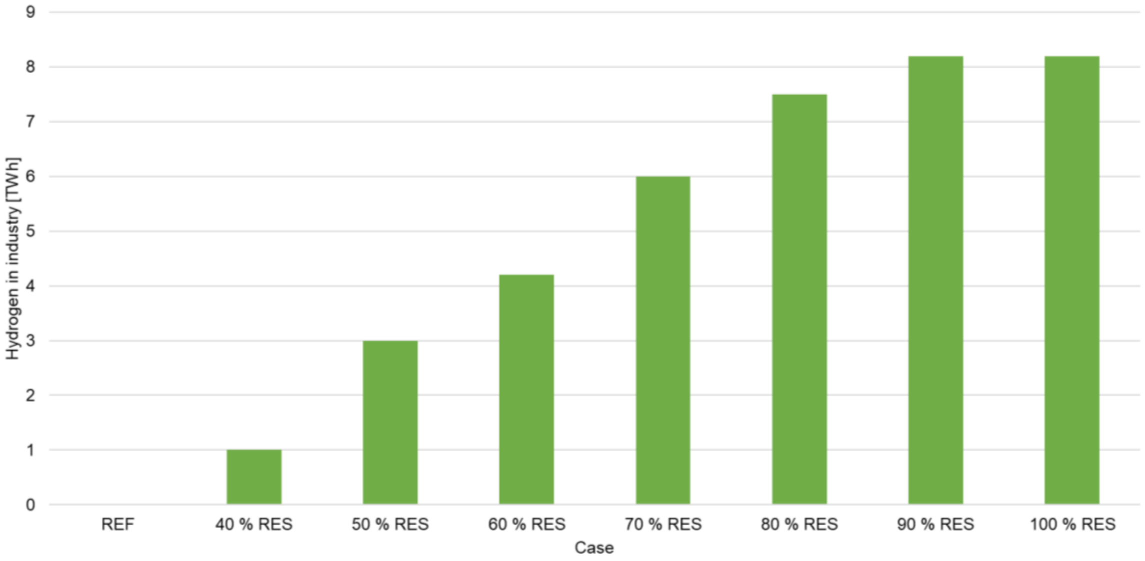

Figure 9. Use of hydrogen in industry

The use of P2H is shown to be sought out in all of the cases. The measure is characterized by its ability to decarbonize since it introduces electricity into district heating networks as well as its ability to provide flexibility. Flexibility is provided by large installed capacities and correlated heat storage. The results are shown in Figure 10. The maximum capacity that this system can reach is 13135 MW.

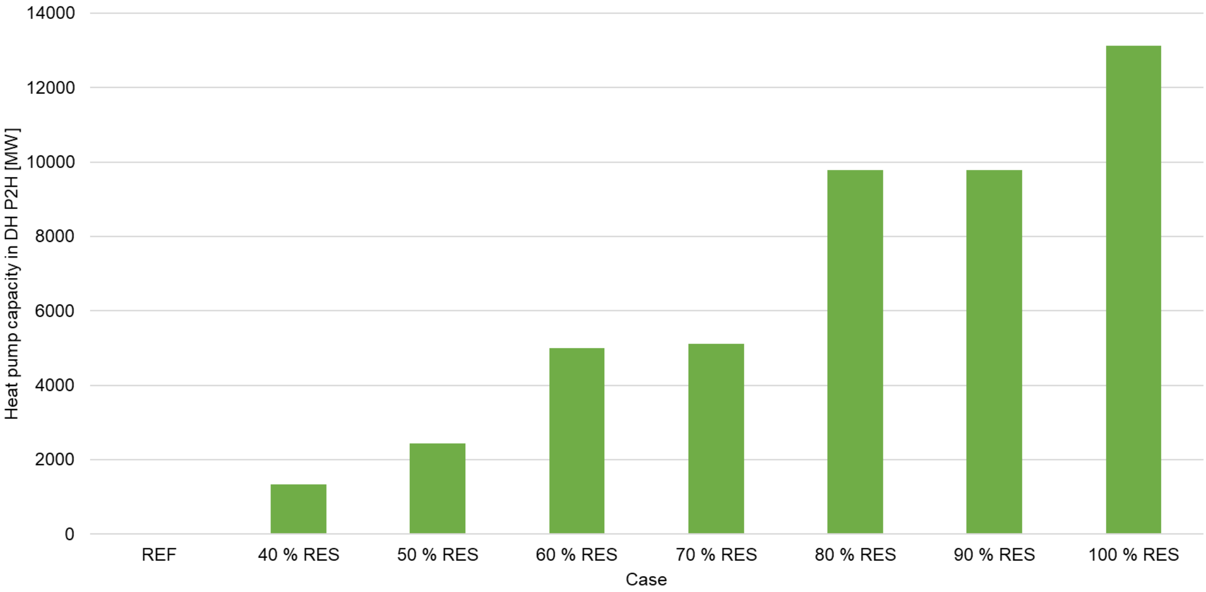

Figure 10. HP capacity in DH – P2H

The fuel mix in thermal plants also changes. Below 60% of RES, natural gas predominates. By 2050, the share of biomass reaches 44%. The system does not undergo complete transition since thermal power plants drastically reduce their energy generation with VRES and storage present. Also, district heating is largely supplied by heat pumps in the P2H system. The results are displayed in Figure 11.

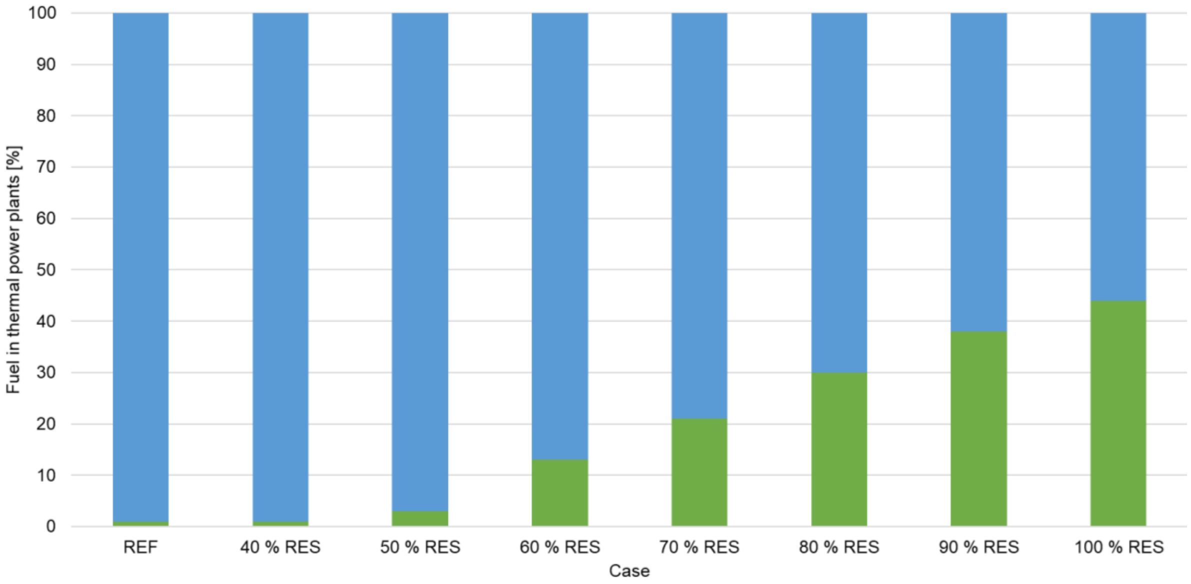

Figure 11. Share of fuels in thermal plants

4.1 Achieved share of RES and level of emissions

The comparison of achieved and targeted shares of RES and the level of CO_2 emissions are displayed in Figure 12. and Figure 13. The level of emissions is constantly lower than the targeted value but within 1 Mt of the goal. On the other hand, the share of RES is lower than the one that is targeted in all of the cases. The difference is less than 2,5%.

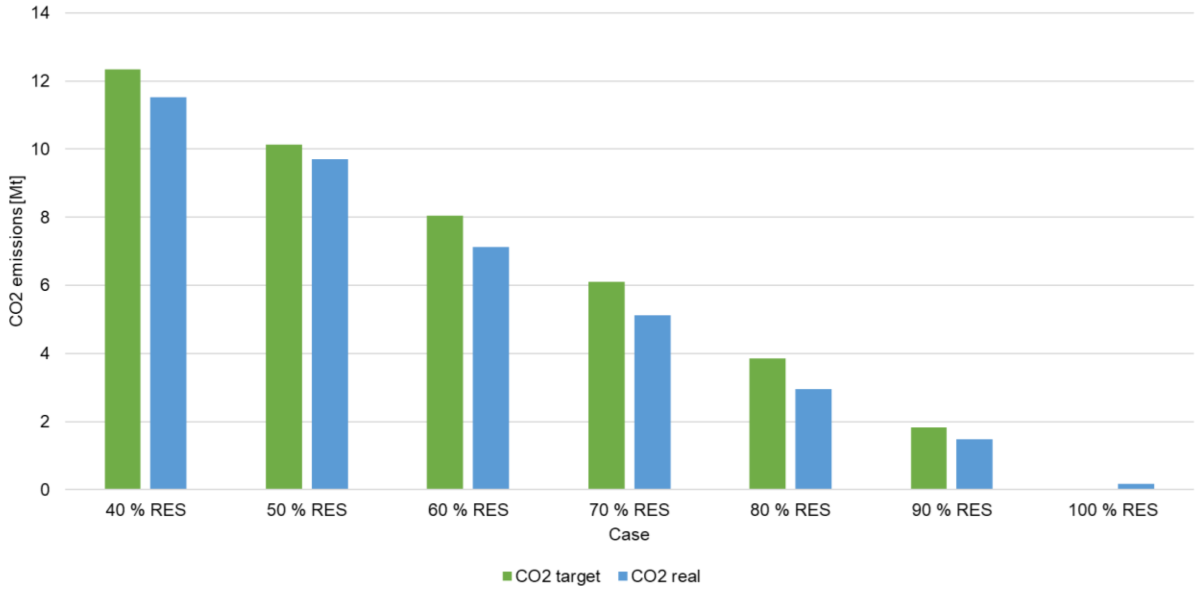

Figure 12. Achieved level of CO_2 emissions

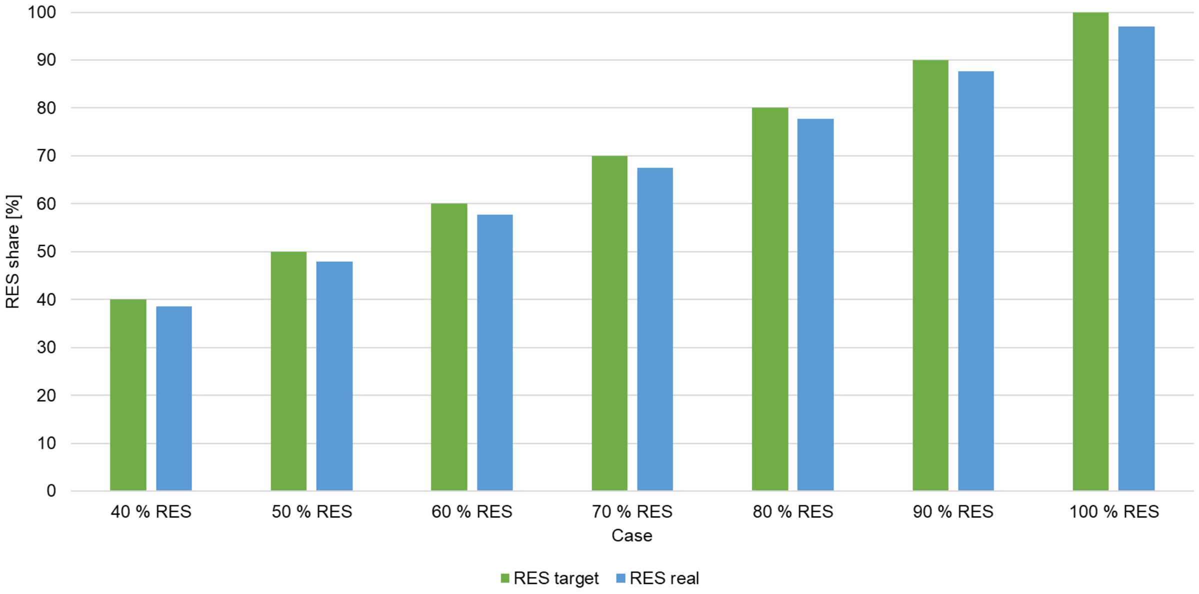

Figure 13. Achieved share of RES

The CEEP is under 5% in all of the cases except for the ones for 70% and 80% RES. In those cases, the high capacities of VRES are used, but not the large capacities of flexibility options. CEEP decreases in the cases of 90% and 100% RES since a portion of VRES capacity are decommissioned and new capacities of flexibility options are implemented. The results are displayed in Figure 14.

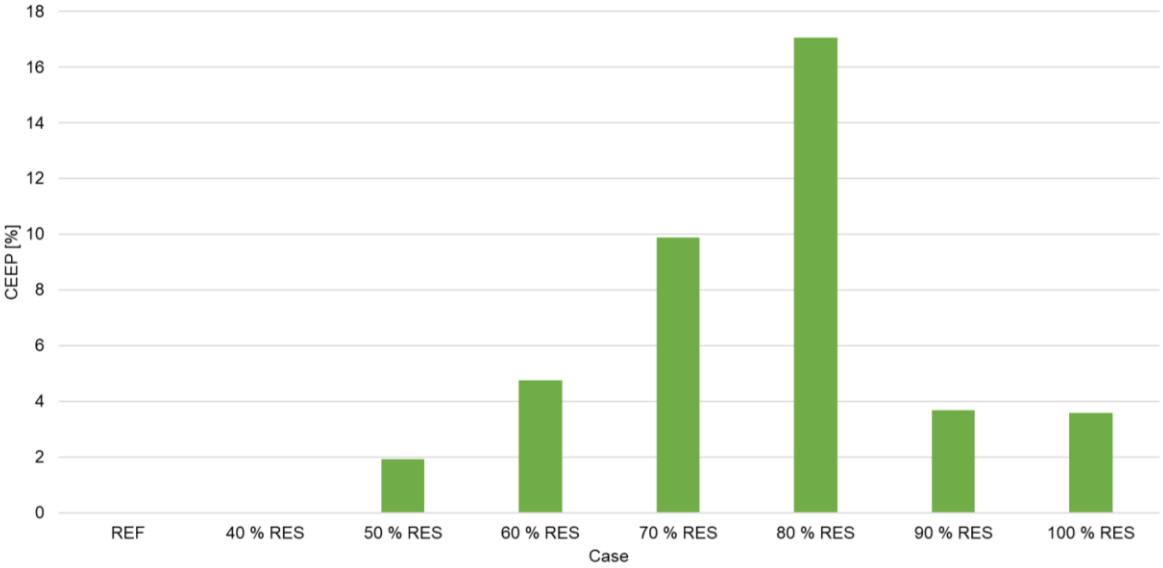

Figure 14. Results for CEEP

4.2 Comparison of the results

The results are compared to the results by Krajačić et al. [45] who examined the possibilities of a 100% renewable energy system. There is no available model or publication that addresses the entire RES range in Croatian energy system. As can be observed in Figure 15., the new model uses much less thermal power plants for energy generation. The generation from CHP and PP in the new model is at or near 0 TWh as opposed to over 6 TWh in Krajačić et al. Another big difference is in the VRES section, where the new model uses much more wind power, especially offshore wind power. Cross-border electricity exchange is lower in the new model as a side effect of limiting the capacity to 2500 MW, whereas the compared model used transmission capacity of up to 10000 MW. An additional major difference and the cause of large wind generation is the discrepancy in the usage of biomass. The new model uses only 8,1 TWh, while referred model uses up to 30 TWh of biomass. Also, the difference, in the results for wind generation is due to the availability of offshore wind in the new model. The model from Krajačić et al. did not consider offshore wind power since it was not available for exploitation at the time of paper writing. The referred model used larger energy storage of 450 GWh as opposed to the total electricity storage of 214 GWh in the new model.

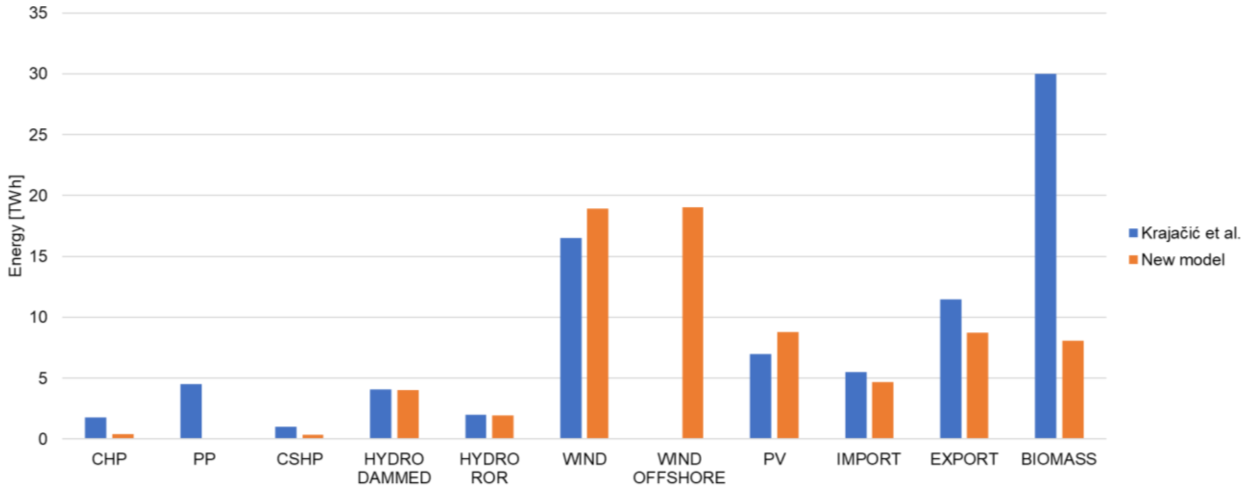

Figure 15. Results for 2050. [45]

5. CONCLUSION

Implementation of this method has allowed the users to examine further relations between various flexibility options. This method represents a step forward in the optimization of the energy system. The modelling procedure is no longer constrained by the use of technologies that can be fully defined with a single data point. Usage of this method provides the capability to reduce the required run time of the simulations by decreasing the number of independent variables as opposed to the case if all of the correlated variables are being modelled individually. Additionally, the relations and the possibility of ensuring consistency are provided with this expansion of the functionalities. For example, in this case, study, the number of variables that are being optimized is 17. Without the implementation of the additional code, the number of variables would be 47 and consistency between the individual simulations could not be granted.

Also, the method is shown to be able to provide results that feature no unrealistically large generation capacity build-ups or technology implementation in a short period. The main reason for the ability to achieve such results is the implementation of gradual progression in RES and CO_2 goals and limits on the input values. Therefore, the next set of simulations differs only by a small amount in the goals, which makes the results more constrained and realistic. Also, the results, such as the ones for the transport sector or heating sector, display consistency and the ability of the model to deliver the results even in cases when the variables are dependent.

Research shows that the most important thing is to guarantee enough VRES generating capacities represented by onshore wind, PV, and offshore wind. Also, sectoral improvements in terms of emissions, especially if they can serve as a flexibility option at the same time, are highly valued. An example of this is the electrification of transport with smart charge and V2G. This action serves two purposes. Firstly, electrification eliminates the use of fossil fuel in transport, which benefits in targeting RES values, reducing emissions and, in most cases, reducing the cost. Secondly, it serves as a flexibility option. Another example is the decarbonization of industry through the use of hydrogen and electricity. Hydrogen is generated with excess electricity, thus reducing CEEP as well as displacing fossil fuels. Also, hydrogen can be stored for later use.

The results on required capacities are comparable to the previously performed research, although reached by an entirely different method. They showed an additional possibility of implementation of flexibility required to reach the goal of a 100% renewable energy system.

Further work on this subject aims to implement automation between subsequent cases. This would enable the modellers to determine the goals of simulations in all of the steps. Also, the modeller will not be required to prepare the model for the next set of simulations after the previous one is finished. The set-up for the next set of simulations can also be improved if the model itself analyses and prints out the solution. This would enable even better performance and require less input from the modeller.

ACKNOWLEDGEMENT

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APENDIX

Additional code in EPLANopt:

For all the cases from 40 % RES till 90 % RES:

```
#transport
    new_data['input_FOM_Various7'] = (36.595 - new_data['input_transport_TWh_V2G']*5 -
new_data['input_fuel_Transport[6]']*3)/1.5
    new_data['input_V2G_Cap_Charge']=new_data['input_transport_TWh_V2G']*2500
    new_data['input_V2G_Cap_Inv']=new_data['input_V2G_Cap_Charge']
    new_data['input_V2G_Battery']=new_data['input_transport_TWh_V2G']*11.4
    new_data['input_fuel_Transport[2]']=new_data['input_FOM_Various7']*0.7
    new_data['input_fuel_Transport[5]']=new_data['input_FOM_Various7']*0.3
    new_data['Input_Size_transport_electric_cars'] = new_data['input_transport_TWh_V2G']/7.319
* 1725 # EV
    new_data['Input_Size_transport_conventional_cars'] = new_data['input_FOM_Various7']/24.397
* 1725 # ICE
    new_data['Input_Size_transport_electric_busses'] =
new_data['input_fuel_Transport[6]']/12.198 * 1725 # H2

#flex dem
    new_data['input_flexible_week_TWh']=new_data['input_flexible_day_TWh']*0.75
    new_data['input_flexible_4weeks_TWh']=new_data['input_flexible_day_TWh']*0.75
    new_data['input_flexible_day_max']=new_data['input_flexible_day_TWh']*172
    new_data['input_flexible_week_max']=new_data['input_flexible_week_TWh']*130
    new_data['input_flexible_4weeks_max']=new_data['input_flexible_4weeks_TWh']*130

#short-mid term storage
    new_data['input_cap_turbine_el2']=new_data['input_cap_pump_el2']
    new_data['input_storage_pump_cap2']=new_data['input_cap_pump_el2']*0.005
    new_data['input_cap_rock_el']=new_data['input_cap_pump_el2']
    new_data['input_cap_rock_steam']=new_data['input_cap_pump_el2']
    new_data['input_rock_store_cap']=new_data['input_cap_rock_el']*0.016
    new_data['input_cap_pump_el']=300+new_data['input_cap_turbine_el2']/20000*300
    new_data['input_cap_turbine_el']=new_data['input_cap_pump_el']
    new_data['input_storage_pump_cap']=2.93+new_data['input_cap_turbine_el2']/20000*2.93

#PPmin & nucl partload
    new_data['input_Nuclear_partload']=1-new_data['input_pp_cap_minimum']/100
    new_data['input_chpgr3_cap_minimum']=2*new_data['input_pp_cap_minimum']

#decarb industry
    new_data['input_fuel_CSHP[3]']=16.4-2*new_data['input_fuel_CSHP[6]']

#electrolyser correction
    new_data['input_cap_ELTtrans_el']= 312*new_data['input_fuel_CSHP[6]'] + 467 *
new_data['input_fuel_Transport[6]']

#P2H storage
    new_data['input_storage_gr3_cap']= 0.05*new_data['input_cap_hp3_el']

#PP CHP fuel
    new_data['input_fuel_PP[3]']= 1-new_data['input_fuel_PP[4]']
    new_data['input_fuel_PP2[3]']= new_data['input_fuel_PP[3]']
    new_data['input_fuel_PP2[4]']= new_data['input_fuel_PP[4]']
    new_data['input_fuel_CHP2[3]']= new_data['input_fuel_PP[3]']
    new_data['input_fuel_CHP2[4]']= new_data['input_fuel_PP[4]']
    new_data['input_fuel_CHP3[3]']= new_data['input_fuel_PP[3]']
    new_data['input_fuel_CHP3[4]']= new_data['input_fuel_PP[4]']
    new_data['input_fuel_dhp[3]']= new_data['input_fuel_PP[3]']
    new_data['input_fuel_dhp[4]']= new_data['input_fuel_PP[4]']
    new_data['input_fuel_Boiler2[3]']= new_data['input_fuel_PP[3]']
    new_data['input_fuel_Boiler2[4]']= new_data['input_fuel_PP[4]']
    new_data['input_fuel_Boiler3[3]']= new_data['input_fuel_PP[3]']
    new_data['input_fuel_Boiler3[4]']= new_data['input_fuel_PP[4]']

#Heating
```

```
    new_data['input_fuel_Households[4]']= ((14.23 - new_data['input_dh_ann_gr3']*0.9 -
new_data['input_HH_HP_heat'] - new_data['input_HH_EB_heat'] -
new_data['input_fuel_Households[3]']*0.85) )/0.7

#el dem correction
    new_data['Input_el_demand_Twh'] = 17.5 -4.694 -1.511 - 0.1 +
new_data['input_fuel_CSHP[6]']-new_data['input_flexible_day_TWh']-
new_data['input_flexible_week_TWh'] - new_data['input_flexible_4weeks_TWh']
```

For the cases at 100 % RES:

```
#transport
    #new_data['input_FOM_Various7'] = (36.595 - new_data['input_transport_TWh_V2G']*5 -
new_data['input_fuel_Transport[6]']*3)/1.5
    new_data['input_fuel_Transport[6]'] = (36.595 - new_data['input_transport_TWh_V2G']*5)/3
    new_data['input_V2G_Cap_Charge']=new_data['input_transport_TWh_V2G']*2500
    new_data['input_V2G_Cap_Inv']=new_data['input_V2G_Cap_Charge']
    new_data['input_V2G_Battery']=new_data['input_transport_TWh_V2G']*11.4
    new_data['Input_Size_transport_electric_cars'] = new_data['input_transport_TWh_V2G']/7.319
* 1725 # EV
    new_data['Input_Size_transport_electric_busses'] =
new_data['input_fuel_Transport[6]']/12.198 * 1725 # H2

#flex dem
    new_data['input_flexible_week_TWh']=new_data['input_flexible_day_TWh']*0.75
    new_data['input_flexible_4weeks_TWh']=new_data['input_flexible_day_TWh']*0.75
    new_data['input_flexible_day_max']=new_data['input_flexible_day_TWh']*172
    new_data['input_flexible_week_max']=new_data['input_flexible_week_TWh']*130
    new_data['input_flexible_4weeks_max']=new_data['input_flexible_4weeks_TWh']*130

#short-mid term storage
    new_data['input_cap_turbine_el2']=new_data['input_cap_pump_el2']
    new_data['input_storage_pump_cap2']=new_data['input_cap_pump_el2']*0.005
    new_data['input_cap_rock_el']=new_data['input_cap_pump_el2']
    new_data['input_cap_rock_steam']=new_data['input_cap_pump_el2']
    new_data['input_rock_store_cap']=new_data['input_cap_rock_el']*0.016
    new_data['input_cap_pump_el']=300+new_data['input_cap_turbine_el2']/20000*300
    new_data['input_cap_turbine_el']=new_data['input_cap_pump_el']
    new_data['input_storage_pump_cap']=2.93+new_data['input_cap_turbine_el2']/20000*2.93

#PPmin & nucl partload
    new_data['input_Nuclear_partload']=1-new_data['input_pp_cap_minimum']/100
    new_data['input_chpgr3_cap_minimum']=2*new_data['input_pp_cap_minimum']

#decarb industry
    new_data['input_fuel_CSHP[3]']=16.4-2*new_data['input_fuel_CSHP[6]']
#electrolyser correction
    new_data['input_cap_ELTtrans_el']= 312*new_data['input_fuel_CSHP[6]'] + 467 *
new_data['input_fuel_Transport[6]']

#P2H storage
    new_data['input_storage_gr3_cap']= 0.05*new_data['input_cap_hp3_el']

#PP CHP fuel
    new_data['input_fuel_PP[3]']= 1-new_data['input_fuel_PP[4]']
    new_data['input_fuel_PP2[3]']= new_data['input_fuel_PP[3]']
    new_data['input_fuel_PP2[4]']= new_data['input_fuel_PP[4]']
    new_data['input_fuel_CHP2[3]']= new_data['input_fuel_PP[3]']
    new_data['input_fuel_CHP2[4]']= new_data['input_fuel_PP[4]']
    new_data['input_fuel_CHP3[3]']= new_data['input_fuel_PP[3]']
    new_data['input_fuel_CHP3[4]']= new_data['input_fuel_PP[4]']
    new_data['input_fuel_dhp[3]']= new_data['input_fuel_PP[3]']
    new_data['input_fuel_dhp[4]']= new_data['input_fuel_PP[4]']
    new_data['input_fuel_Boiler2[3]']= new_data['input_fuel_PP[3]']
    new_data['input_fuel_Boiler2[4]']= new_data['input_fuel_PP[4]']
    new_data['input_fuel_Boiler3[3]']= new_data['input_fuel_PP[3]']
    new_data['input_fuel_Boiler3[4]']= new_data['input_fuel_PP[4]']

#Heating
```

```
    new_data['input_fuel_Households[4]']= ((14.23 - new_data['input_dh_ann_gr3']*0.9 -
new_data['input_HH_HP_heat'] - new_data['input_HH_EB_heat'] -
new_data['input_fuel_Households[3]']*0.85) )/0.7

#el dem correction
    new_data['Input_el_demand_Twh'] = 17.5 -4.694 -1.511 - 0.1 +
new_data['input_fuel_CSHP[6]']-new_data['input_flexible_day_TWh']-
new_data['input_flexible_week_TWh'] - new_data['input_flexible_4weeks_TWh']
```