The Management of an Energy System in The Realm of Rapid Energy Transition and Degasification as a Consequence of Energy Crisis, Examination in H2RES Energy Model

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ABSTRACT

The energy system in Europe faces significant challenges. Though, the transition to renewable energy is under way, still a significant portion of energy is supplied from fossil fuels, mainly natural gas. In the second half of 2021, the supply of natural gas and consequently the rate of replenishment of the reserves dwindled. The scarcity of natural gas has resulted in record-high energy prices as well as an increase in goods prices. Especially hit are the industry sectors highly dependent on natural gas such as the petrochemical industry.

This research investigates the strategies to mitigate the crisis in the European Union energy system while simultaneously ensuring low energy system cost and fulfilment of energy transition goals. The system analysis and simulations are carried out in the liner optimization model - H2RES.

The results display that the system opts for accelerated fulfilment of energy transition goals. Therefore, the dependency on the stable supply of natural gas is decreased. Also, the total cost of an energy system that undergoes transition as compared to the business as usual scenario is 33 % lower even when accounting for the necessary investments by 2050.

Main findings:

1. Required installation of average 400 MW of PV and 200 MW of wind power generation capacity annually.
2. In district heating systems 60 MW of heat pumps and electric heaters annually as well as 165 MW of solar collectors.
3. Average of 85 MW of heat pumps, 132 MW of electric heaters and 1250 MW of solar thermal collectors need to be installed annually in individual heating systems.
4. Average of 82 MW of electrolysers and 600 MWh of hydrogen storage have to be installed annually.
5. Transition scenario is cheaper in all the years except for 2028 and 2029 due to the higher capital investments in that period in the transition scenario.

Keywords:

Energy crisis, energy transition, energy supply, Energy planning, Optimization, H2RES

ABBREVIATIONS

Abbreviation	Meaning	Explanation
BAU	Business as usual	
RES	Renewable energy systems	
ICE	Internal combustion engine	
H2RES	Highway to renewable energy systems	Name of the energy planning and optimization model
CEEP	Critical excess of electricity production	
VRES	Variable renewable energy systems	
CHP	Combined heat and power	
CRO	Croatia	
ZG	Zagreb	
HR	Croatia (Hrvatska)	
HP	Heat pump	
HE	Hydropower plant	
RHE	Reversable hydropower plant	
mTEO Jakusevec	Small thermal power plant Jakuševec	Name of the landfill gas powered power plant
PZ Osatina	Agricultural union Osatina	Name of the biomass power plant
TE Biomass HR	Biomass powered thermal power plants in Croatia	Placeholder name of the aggregated biomass power plants in Croatia
Bovis	Biomass powered thermal power plant Bovis	Name of the biomass power plant
TE Plomin1	Thermal power plant Plomin, unit 1	Name of the thermal power plant
TE Plomin2	Thermal power plant Plomin, unit 2	Name of the thermal power plant
TE-TO Osijek	Thermal power plant and heat plant Osijek	Name of the CHP plant
TE-TO Zagreb	Thermal power plant and heat plant Zagreb	Name of the CHP plant
EL-TO Zagreb	Power plant and heating plant Zagreb	Name of the CHP plant
KTE Jertovec	Combined cycle thermal powr plant Jertovec	Name of the thermal power plant
SolarPP	Solar power plant	Name of the solar power plant
SolarHigh	Solar power plant	Name of the solar power plant
WindPP1	Wind power plant	Name of the wind power plant
WindPP2	Wind power plant	Name of the wind power plant
WindPP3	Wind power plant	Name of the wind power plant
WindHigh	Wind power plant	Name of the wind power plant
Alkaline_EC	Alkaline electrolizer	
PEM_elec	Proton exchange membrane electrolizer	
SOEC_elec	solid oxide electrolyzer cell electrolizer	
H2_storage_tank	Hydrogen storage tank	
Liion_storage	Lithium ion storage	
PEMFC	Proton exchange membrane fuel cell	
SOFC	solid oxide fuel cell	
CAPEX	Capital expenditures	
OPEX	Fixed operational expenditure	
Var_OPEX	Variable operational expenditure	

1. INTRODUCTION

The world faces a looming crisis in the form of climate change. Also, Europe (EU), during 2021 and 2022, has entered a state of energy crisis with low levels of natural gas replenishment and storage [1]. Following the low replenishment rates, the supply of natural gas from the Russian Federation has completely stopped for some of the EU's nations, such as Poland and Bulgaria [2]. Finding the alternate source of natural gas supply, to replace the imports from Russia which accounted for 41 % of the EU's consumption, has been challenging. One of the methods is to increase the supply from the remaining suppliers. These include the supply via pipelines from Algeria, Morocco, Norway, as well as the use of LNG ships [3]. In addition to Russian gas, the EU has already imposed an embargo on oil and oil products [4]. The challenge with supply transitioning lies in the infrastructure that is not ready to take the load. For instance, Germany currently does not operate LNG terminals to be able to diversify its natural gas mix [5]. Part of the solution is, as proposed by the International Energy Agency, to reduce the demand by encouraging practices such as lower temperatures in households, use of public transport, less commuting, and increase of renewable energy installations [6].

In order to accomplish such goals, already enforced decarbonisation strategies will have to be upgraded to account for a faster transition. For that purpose, the H2RES energy system planning model [7] was expanded to be able to integrate policy constraints indicating the emergency of the energy transition, especially in reducing the consumption of natural gas. This research hypothesises states that when the more aggressive transition scenario is implemented, the system will be presented with lower total system costs in comparison to the BAU scenario, even though big capital investments are required. Therefore, the majority of the payback of the necessary investments will come from the reduction in fossil fuels imports.

When creating a system with a high share of variable renewable energy sources (VRES), the modellers may encounter the prominent problems of curtailment or generation of excess electricity [8] and problems with balancing demand and supply. The problem with the integration of VRES is the necessity to match the temporal distributions of generation and demand, otherwise resulting in curtailment [9]. The other negative situation is the necessity to shed load if the generation from the available sources is insufficient to meet the demand which can have dire consequences on the entire economy [10]. The problem can be partially mitigated by the introduction of demand response technologies as demonstrated the case of wind power in the UK where, for example, the curtailment can be reduced by implementing power to heat solutions such as electric heaters or heat pumps in combination with heat storage [11]. This combination will enable more efficient use of renewable electricity in residential sector and help to mitigate curtailment. Also, the changes in the market structure are required for this to be feasible for implementation. This includes the price driven market structure [12], especially when considering the reserves markets to which the downward reserve was proven to be more valuable [13]. Additionally, without the integration of the new technologies, the benefits can be obtained through the geographical dispersion of the generation by making the use of spatiotemporal resource complementarity, as it was done for the case of offshore wind [14]. Overall, to achieve a complete energy transition, the implementation of sector coupling would be required with the connections between the power, gas and transport sectors [15]. For example, the industry sector, especially the high temperature industries can be decarbonized through the use of hydrogen in direct combustion or use as a feedstock where the natural gas was previously been used through steam gas reformation [16]. Also, the replacement of fossil fuels with hydrogen derivatives in the form of electrofuels is a viable strategy to decarbonize industry sector [17]. Their generation is coupled to the power system through the use of electrolyzers that can be run flexibly or have the storage of the fuels and thus improve system flexibility [18]. In this case, the electrolyzers together with their storage provide the possibility for energy storage and consequently the possibility of decoupling the time of energy demand and generation. Generated hydrogen can be used in the industry processes, transport, or energy sector itself, but it can also be used as a feedstock to generate varieties of electrofuels [19]. Using electrofuels adds even more benefits to the effort of system decarbonization. The biggest one is the compatibility with existing equipment and machinery, meaning no or little adaptation is required for the fuel switch [20]. For example, with the implementation of these fuels, the use of existing pipeline infrastructure and fuel terminals can be continued [21], providing the possible pathway with no need to invest in new infrastructure. The situation differs in the case of using pure hydrogen where significant investments in infrastructure upgrade are required as existing pipeline infrastructure does not satisfy the technical requirements for transporting pure hydrogen

[22]. The other significant benefit of using electrofuels is the possibility to additionally decouple energy generation and fuel demand, contributing to the system flexibility due to already existing compatible storage options since fossil fuel and electrofuel variants possess similar storage requirements. Additionally, since some industrial sectors require the supply of heat at certain temperature levels, the applicable list of the technologies or fuels reduces completely disregarding some technologies or making the application prohibitively expensive. For instance, electricity as an energy source in smelting processes in the iron and steel industries is not a feasible option due to the very high equipment cost, while making the hydrogen and electrofuels a viable alternative as this pathway requires only the minor changes to the equipment [23]. Decarbonization of the sectors using hydrogen and hydrogen derived fuels depends on the carbon footprint of the electricity used to generate hydrogen as well as to process it into electrofuel [24]. Therefore, as increasing the share of renewable energy in power generation is the part of the energy transition efforts, the carbon footprint of electrofuels will continue to drop eventually reaching zero.

The decarbonization of the heating sector can be achieved by changing the composition of heating supply. The fossil fuel-powered heating systems can be replaced by electrically powered ones, such as with the use of heat pumps or electric heaters if electricity is generated from renewable sources [21]. Solar heating is viable heat source, especially if combined with seasonal solar energy storage in DH systems but it would need the additional heat source since this is low temperature heat [25]. Biomass is a viable heat source especially if used in CHP plants if it can be locally sourced as it is possible in Croatia due to its forests and agricultural lands as a source of biomass [26]. Geothermal energy is also applicable for the use in district heating systems due to the possibility of centralization of all the equipment around the borehole [27]. In this case, the Croatia has big potential in the Pannonian basin which encompasses most of the continental Croatia together with Zagreb region [28]. Also, the advantage of using district heating is that these systems can more easily change the source of heat compared to the individual systems, due to centralized generation. They can also utilize heat sources that may not be available on the level of individual heating, such as industrial excess heat [29], seasonal solar storage [30], low-temperature heat sources in waterways, sewers [31], data centres [32] and others through the use of heat pumps [33]. An additional advantage of using district heating systems in the decarbonised grid with a high share of variable renewable energy sources is their ability to store energy and thus provide flexible services [34].

Decarbonization of the transport sector can contribute both towards the main goal of reduction of emissions as well as the increase of flexibility with the smart operation of the sector [35] and curtailment reduction with the use of electric vehicles [36], especially in the isolated energy systems such as islands where there is the necessity to solve balancing problems at the local levels and not to rely on the possibility of importing or exporting the electricity if required [37]. The sector can be transitioned to a mixture of electric vehicles, hydrogen-powered vehicles, and internal combustion engine-powered vehicles. Electric vehicles can provide flexibility through smart charging and through the possibility of storing and returning the electricity to the grid with the use of vehicle-to-grid (V2G), vehicle-to-home (V2H) and vehicle-to-building (V2B) technologies [38]. Implementation of these technologies provides the opportunity for the households to benefit from the reduction of energy utility costs by shifting the demand in accordance with the availability of generation [39]. Hydrogen fuel cell electric vehicles (HFCEV) can also provide flexibility due to their capacity to store energy for later use, as well as ICE vehicles that use electrofuels [40].

As mentioned in the previous section, flexibility options from different sectors should be combined and considered as one to successfully decarbonize the system while also keeping CEEP low and minimizing the costs of the system [41].

In this research, an approach to achieve rapid decarbonization is explored with the primary objective of completely eliminating gas consumption by 2035, aligning with European energy development goals of reaching net zero emissions by 2050 as well as with the Croatian environmental group goals [42]. What sets this research apart is the utilization of a detailed energy planning and optimization model operating at an hourly level during the whole year, allowing the comprehensive analysis of interactions among various energy demand sectors and associated technologies. The novelty compared to other research as well as previous publications that use H2RES is the expansion of the model [43]. In this case, for instance, heating sector was divided both into individual and district heating, as well as into multiple geographical zones, each with its own limitations and demands. In the sector of industry, multiple subsectors were created to model different industry branches, each with its own limitations on technology application potential and requirements, for example, high temperature heat. Transport sector was expanded to include other fuels and technologies in contrast to only electric vehicles that are modelled in previous work [44]. In previous works with the use of H2RES model, it was found that the installation of flexibility technologies and demand response was crucial in decarbonization of national energy systems on the example of Italian energy system [45]. Building upon previous work performed for the Study of Degasification in Croatia [46], the focus of this research lies in the application of the H2RES model to compare outcomes of rapid degasification and decarbonization with a business-as-usual scenario. Additionally, in comparison to the previous publications, this research differs by conducting modelling on an hourly level for the whole set of 8760 hours without resorting to conventional time slices as some models like the OSeMOSYS do to avoid very long run times [47]. Therefore, dispatch optimization as performed in the Dispa-SET model [48] is combined with the long-term energy planning and optimization. In this manner, the structure of the model is similar and reflects the goals of the possibility of linking different parts or the model and modelling the zones like PLEXOS Energy Exemplar [49], but in an open-source architecture and completely customizable. While results are presented in 5-year intervals for clarity, the model has the capability to provide annual data across the entire planning horizon. In this case, 5-year intervals were used with the purpose of balancing between the details in modelling and simplification of data visualization to provide a focused analysis of rapid degasification and decarbonization implications.

2. METHOD

H2RES models dispatch and generation from various units in an energy system. Also, it performs capacity investments and decommissioning of units. The system models the whole power system sector. This section includes power plants and energy storage capacities. Also, the heating system is modelled, and it differentiates between individual heating and district heating networks. Further on, both the industry sector and the transportation sector are modelled. Additional defining characteristics of the model are the availability of flexibility options in the form of flexible power plant operation, vehicle-to-grid system (V2G), power-to-heat (P2H), power-to-gas (P2G) and stationary energy storage.

The basic schematic of an H2RES model is displayed in Figure 1. The following sections describe the model and the version that is used for this research work. The version used in this research is available for download at the model website [7].

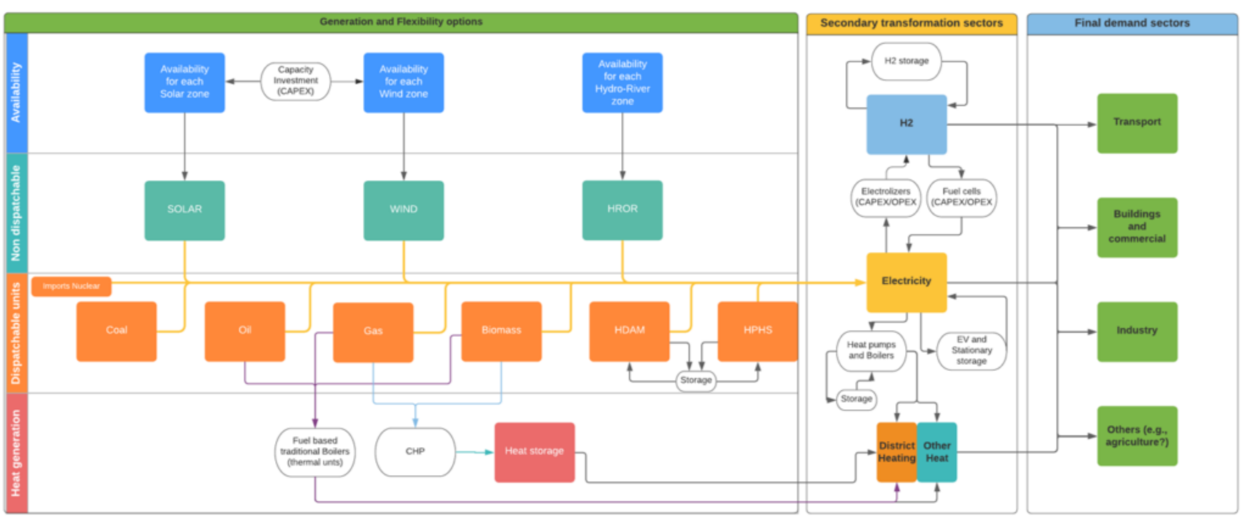

Figure 1. H2RES model [7]

Modelling and optimization are performed on a 30-year planning horizon considering time intervals of 5 years (2020 to 2050). Therefore, the model sees the costs it uses for optimization in only these years as it concentrates the investments in every fifth year. The operational costs are calculated for the exact years that are featured in the results, but for the realistic interpretation in the goal function, the values of the years in between are extrapolated.

2.1 Power sector

The power sector is the backbone of H2RES as it provides the electricity required to satisfy the demands and carry out further energy transformations. Eventually, when all the sectors are decarbonized, they are at least partially connected to the power sector. The system has set up basic “legacy” electricity demand that has to be satisfied. In addition to the basic electricity demand, additional electricity is added for electrified heating, and electricity in transport and industry. Additionally, electricity is required for the generation of hydrogen and the synthesis of electrofuels. Further electricity demand is generated when accounting for energy storage technologies and associated energy losses. The model considers additions of new generating capacities. The implementation of more extensive sector coupling will result in an increase in electricity demand, which will in turn require new generation capacities. Therefore, the model enables investments into new capacities that will satisfy new demands for electricity, help in decarbonizing the existing electricity supply, and serve as a replacement of the decommissioned capacities. The model enables investments both into the new variable renewable energy sources such as wind and PV, but also in fossil technologies if such scenario is implemented. The investing strategy is dictated by the goal function which reduces the total system cost, but also by scenario-defining variable constraints. To model VRES, multiple zones of wind and PV installations are simulated, each with different characteristics representing different locations where the power plant is being built. Different geographical locations in turn influence the availability of generation through hourly distribution functions and constraints on the total installation and installations in individual years.

2.2 Heating sector

The heating sector is modelled through different geographical zones. Each zone is also divided into individual and district heating (DH) portions. Initial data on the composition of the heating, total demand and share between the individual and district heating is modelled in line with historical data. The further years are subjected to optimization, where only data on total demand and share of district heating are given exogenously.

Since the parts of the heating system are modelled as single demands that must be supplied, there is no distinction between single households. This could cause problems and unrealistic results if not taken care of. For example, if the system has a high amount of electricity available at a certain hour, it will opt to supply heating sector as much as possible with this technology. This is not realistic since not every household has an electric boiler installed. Therefore, the restriction on the constant fuel shares in the individual section of the heating in all the hours during the year is implemented. Additionally, for individual heating the maximum capacity factor of each unit is kept to maximum of 70 % to simulate geographical dispersion of the heating supply. The reasoning for this restriction is to limit the prevalence of a single heat source in a given hour. The model does not distinguish between households and the heating systems that each individual household has implemented. In the case where this restriction is not implemented, single heat source such as heat pumps or electric boilers could satisfy entire demand, even though in reality not all households have one installed. The problem is even more prevalent in the times of low heating demand. The implication of this limitation thus forces the model to invest in the higher heating capacities in comparison to the case with no restriction. The additional investments mimic the geographical dispersion of the demand and the practical limitations. For example, the capacities of the heating systems units on the market do not precisely match up with the exact heating requirements of the individual household. In further research this method will be replaced with more advanced approach. The same restrictions in the constant shares between the boilers are not implemented in the district heating section, because in most cases examined in this research, the zone itself overlaps with the single dominant district heating network in the same zone. The operation of district heating systems is in turn governed by the flexibility parameters of the cogeneration power plants, which limits quick changes between the CHP and boilers or heat pumps if required for flexibility.

The technologies that can be used in individual and district heating systems are presented in Table 1. As can be seen, the systems differ in the ability of DH to use derived heat from CHP plants, efficiently utilize solar energy through seasonal solar storage, use storage in the district heating networks and have lower limitations on the implementation of the water source and ground source heat pumps.

Table 1. Technologies in individual and district heating systems (+ if it is included and – if it is not included)

Technology	Individual	DH	Note

CHP	-	+	
Gas boiler	+	+	
Oil boiler	+	+	
Coal boiler	+	+	
Biomass boiler	+	+	
Geothermal heat	-	+	
Electric heater	+	+	
Air source heat pump	+	+	
Water source heat pump	+	+	Limited implementation ability in individual systems
Ground source heat pump	+	+	Limited implementation ability in individual systems
Solar heating	+	+	
Solar seasonal storage	-	+	
Thermal storage	-	+	

2.3 Transport sector

This part of the system is tasked with ensuring that transport demand is met. The demand is given as a travelled distance demand in each hour through hourly distribution. With the use of efficiency parameters which define the energy demand for kilometres driven for various technologies, the energy demand in the sector is calculated. The model uses internal combustion vehicles (ICE), electric vehicles (EV), plug-in hybrid electric vehicles (PHEV), hybrid vehicles and fuel cell electric vehicles (FCEV). Vehicles with ICE engines (ICE, PHEV, and hybrid) can use both oil-derived fuels as well as electrofuel synthesized using electricity. With the investments into plug-in vehicles FCEVs, the model also invests in the charging infrastructure. Additionally, the number of vehicles has to stay consistent through the years. The model invests and decommissions the vehicles based on their age and requirements for meeting CO_2 targets.

The battery-electric vehicles as well as energy storage systems greatly improve the flexibility of an energy system due to the ability to store energy and fill or release the storage in line with the demands of the power system. Fuel cell vehicles also can act as a flexibility option since the generation of hydrogen coupled with storage can also be used. There is no benefit in using fossil liquid fuels in terms of system flexibility, but for the electrofuels, an additional degree of flexibility is utilized. Electrofeuels, same as the hydrogen, have dedicated energy storage. The level of energy storage dictates whether the fuel is available for consumption. Only the storage in the large-scale fuel systems is modelled, while the fuel storage in the vehicles itself is not modelled in this version of the model. All types of vehicles have defined costs in the reference year and corresponding learning curves that modify the prices in later years.

The investments into electric vehicles and fuel cell electric vehicles also activate the investments into EV chargers and hydrogen charging stations. The investments into EV chargers and hydrogen chargers are correlated with the investments into EVs and FCEVs.

2.4 Industry sector

The industry sector is modelled similarly to the heating sector. It consumes the energy represented through the use of different types of boilers or technologies. The sector is divided into multiple sub-sectors, namely petrochemical, refinery, cement, and the remainder of the industry. Each of the industry subsectors has defined hourly energy demand, total demand, legacy capacities, and shares of the energy in demand. The industry is divided into sectors as a consequence of different distributions in the energy demand and requirements for specific conditions such as the high temperature level of the required heat. In sectors such as petrochemical and refinery, the portion of demand consists of non-energy demand for ammonia and hydrogen. In the base year, the hydrogen and consequently ammonia are produced with the processes of steam gas reformation. The model offers the possibility for the replacement of the hydrogen generation from the steam gas reformation process with the hydrogen generated by electrolyzers. The simplification of the industry model is displayed in Figure 2.

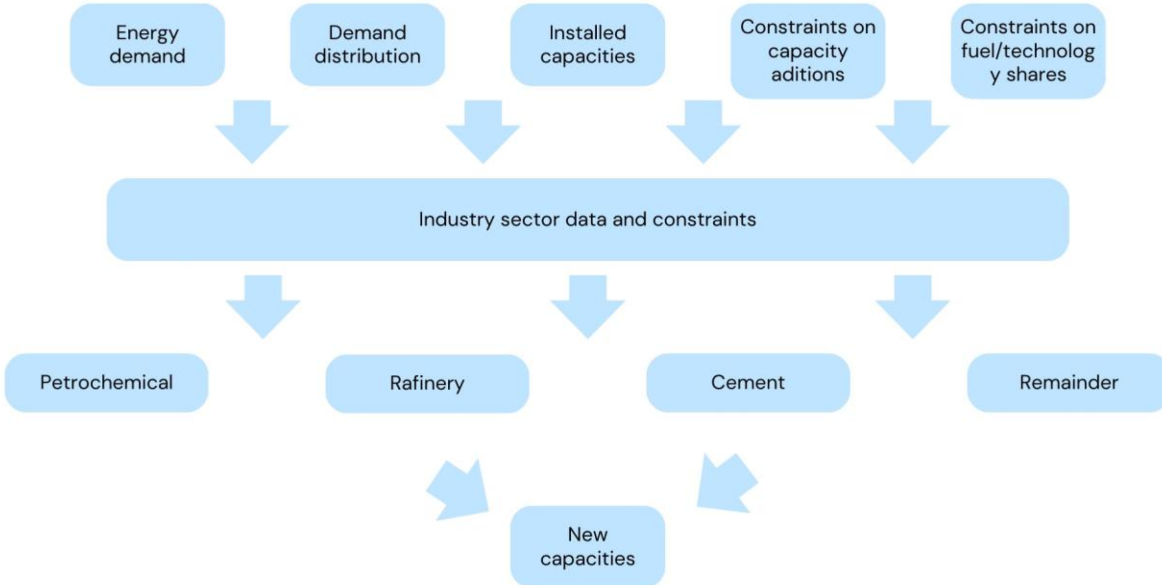

Figure 2. Industry sector

2.5 Fuel and investment cost

Currently, the prices of the fuels and their hourly distributions are entirely exogenous and set up before the simulation is initiated. In order to simulate the supply crunch with fossil fuels, most notably natural gas, the prices used in the simulations have been adjusted to match historical prices recorded during the ongoing 2021/2022 fossil fuel supply crunch in Europe. The projections for the fuel prices up to 2050 are sourced from Energy BrainBlog [50] while the investment and operation cost for the technologies are sourced from Technology Data [51]

3. CASE STUDY

The research is based on the Croatian energy model.

The model assumes that the capacities from 2020 are used as base-year data. The capacities of hydropower plants are displayed in Table 2. The data is acquired from the database of a Dispa-SET [48] model and IRENA [52].

Table 2. Hydropower plant capacities [MW]

Dammed hydropower plants	Capacity	Pumped hydropower plants	Capacity	Run of the river hydropower plants	Capacity
HE Zakucac	538	RHE Velebit	276	HE Varazdin	94,6
HE Senj	216	RHE Orlovac	237	HE Dubrava	79,78
HE Dubrovnik	117	RHE Vinodol	54	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

Thermal power plants are divided based on used fuel.

Table 3. Thermal power plant capacities in [MW] [48]

Fuel source	Power plant	Capacity [MW]	CHP
Biomass	Bovis	1	N
	mTEO Jakusevec	2	N
	PZOsatina	1	N
	TE BiomassHR	24,6	N
	Bovis	1	N
Coal	TE Plomin1	110	N
	TE Plomin2	192	N
Natural gas	TE-TO Osijek	90	Y
	TE-TO Zagreb	440	Y
	EL-TO Zagreb	90	Y
	KTE Jertovec	78	N

Table 4. VRES capacities [MW] [52]

Variable renewable	Capacity	Unit
Solar	85	MW
Wind onshore	646	MW

The assumptions in multiple sectors are implemented as follows.

3.1 Electricity

The case study uses historic data on the electricity demand in Croatia. As described in the methods section, the electricity demand consists of multiple layers and therefore electricity demand given to the model is stripped of demand that covers heating, industry, and transport sectors in accordance with the historic data. Therefore, the basic electricity demand, covering demand for household devices, lighting and public infrastructure, is assumed to encompass efficiency, but also the increase of device number. For this reason, general demand is set to gradually increase in total. VRES generators are modelled with the distributions obtained from the website Renewablesninja [53] and this case study uses 4 different geographical zones for modelling wind power and 2 zones for modelling solar power plants, each with different distribution curves.

3.2 Heating sector

The heating sector is in this case divided into 3 geographical regions as displayed in Figure 3. These are the Zagreb region with its surroundings, the region of continental Croatia and the region of coastal Croatia. Each of these regions is modelled both as an individual heating and as a district heating. Overall assumptions for the total heating demand is a decrease in heating demand of 1 % per year as a consequence of the gains in energy efficiency which are in line with the national energy efficiency improvement goals [54] and the decrease of population. Also, for the transition scenario, the part of the demand is transitioned from individual heating systems to the district heating. The increase in the district heating by 2035 corresponds with the 10 % of the demand that used to be covered by gas boilers in the base year. In the base year, the composition of the heating supply and ratio between individual and district heating differ by region. The demands in the heating sector and distribution between the technologies and fuels are sourced from the annual report on the energy system in Croatia – Energija u Hrvatskoj [55].

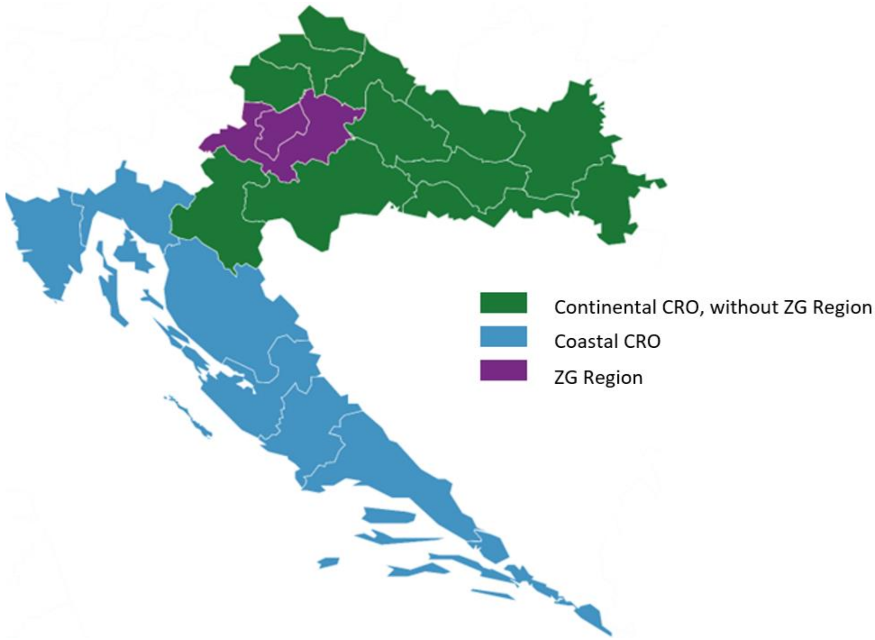

Figure 3. Regions for heating demand

3.3 Industry sector

Energy demand in the industry is supplied by fuels or energy carriers such as coal, oil, biomass, natural gas, waste, hydrogen and electricity. The demand shares are displayed in Table 5 and are modelled after historical data from Eurostat [56].

Table 5. Fuel shares in industry sectors [%]

Unit	Petrochemical	Cement	Refinery	Rest
Gas	30	22	26	38
Biomass	0	1	0	6
Oil	0	24	70	3
Coal	0	26	0	1
Hydrogen	0	0	0	0
Electricity	7	17	4	52
Non--energy industry (H2)	63	0	0	0
Waste	0	10	0	0

3.4 Transport sector

The transport sector can use electric vehicles, hydrogen fuel cell vehicles or internal combustion vehicles. The number of vehicles is assumed to remain the same through the years. Croatia currently has 2 312 280 registered vehicles [57]. The average connection capacity of 7 kW per vehicle is used, as this is the most common available power output when using type 2 home charger[58] and battery capacity of 50 kWh, as it is an EU average for 2023 [59]. Also, the limitation on the maximum share of 90 % of electric vehicles in 2050 is implemented to account for heavy transport that cannot easily be electrified. Despite depopulation, the average number of vehicles per person grows [60], therefore, no change in total number of vehicles is considered in the future years. The assumption on constant demand and travelled distance is based on the historic demand in transport sector which is mostly consistent in the last 20 years [56].

3.5 Constraints on fuel use share of renewables, level of CO_2 emissions, and CEEP

In order to ensure energy transition, the minimum share of renewable energy generation as a share of demand, maximum level of emissions, CEEP, and the use of fuels are defined.

3.5.1 Business as usual scenario (BAU):

In this scenario, the historical data was used to set electricity generation from different types of power plants. Also, the ratios in the transport, heating and industry sectors were kept constant to the ones in the base year. The only differences from year to year are caused by the increase in energy efficiency and due to depopulation, which is consistent with the transition scenario.

3.5.2 Transition scenario:

The limit on CO_2 emissions in 2020 is set to 15 Mt [61] and it gradually decreases towards 2050 reaching 0 Mt. It should be noted that the goal of 0 tonnes of CO_2 emissions in the model encompasses the sectors of power generation, heating, industry, and transport. Therefore carbon-negative sectors such as forestry and agriculture are not considered in this version. The model does not use carbon removal technologies as well. The minimum share of renewable energy in electricity supply in the base year is 40 % and it steadily increases to 100 % by 2050. It should be noted that this constraint does not limit power to be completely supplied only by domestic renewable generation, but it balances the total sums of renewable generation and total demand. Thus, it allows for electricity imports and exports even in the case of 100 % RES constraints. Another constraint is the degasification by 2035 meaning the sum of gas consumption in 2035 must be equal to 0. The system stability constraint of CEEP is kept to the level of 5 % for all years. It should also be noted that other constraints limit the uptake of the technologies or decommission of the existing ones to reflect the real-world limits and difficulties in the uptake of new technologies. For example, the uptake of heat pump installation or PV installation should be limited if there is no sufficient installation capacity and available workforce in the economy.

4. RESULTS

The next section presents the results for the power generation sector, heating, industry, transport, storage, and hydrogen technologies. Also, the costs are displayed for both scenarios, alongside the scenario comparasion.

4.1 Power generation and capacities

The results for the business as usual (BAU) scenario are displayed first. In this scenario, the only prominent changes in the generation of electricity relate to the reduction of total electricity demand as a result of depopulation trends. The results are displayed in Figure 4.

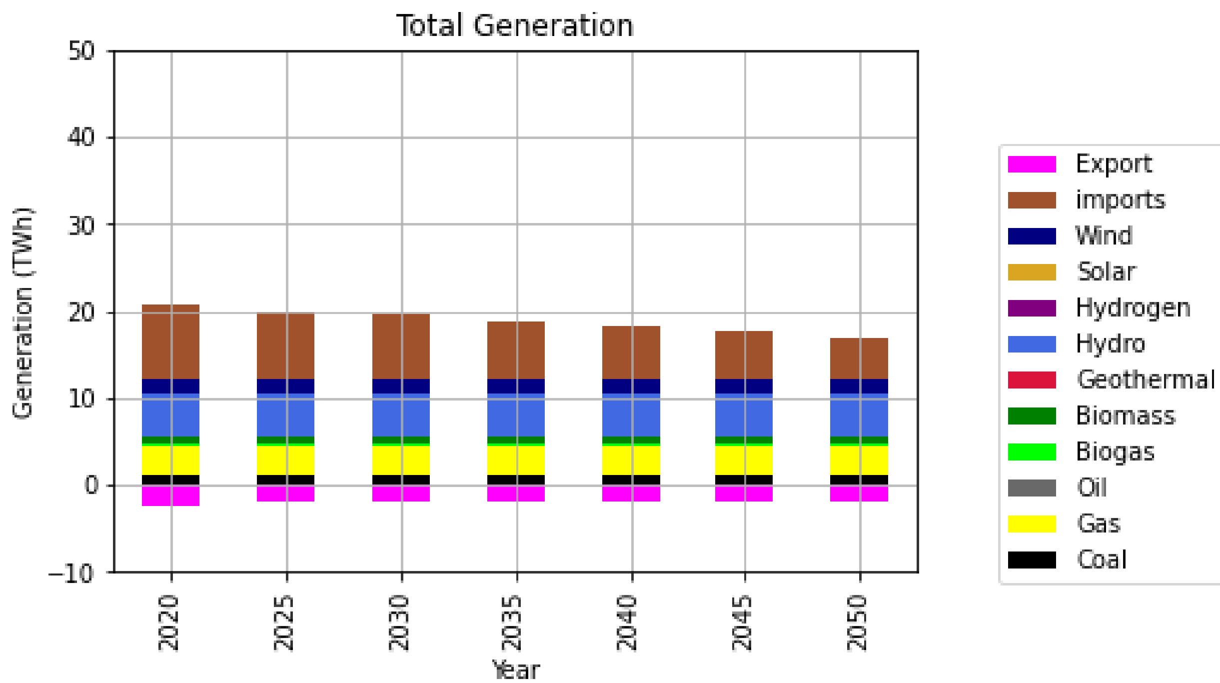

Figure 4. Summation of energy generation in the case of BAU scenario

As it is observed in the generation data, the system just replaces the existing capacities that are being decommissioned to keep up with the requirement for consistent generation in the BAU scenario. The results are displayed in Table 6.

Table 6. Investments into electricity generation capacities in the BAU scenario [MW]

Unit	2020	2025	2030	2035	2040	2045	Total
TE-TO-Zagreb	0	0	124,56	51,04	10,12	36,45	222,17
EL-TO-Zagreb	0	0	16,53	3,36	0	5	24,89
KTE Jertovec	0	0	0	0	1,54	0,39	1,93
TE-TO-Osijek	0	0	0	6,16	2,07	0,45	8,68
TE-TO-Sisak	0	0	78,77	45,94	9,11	23,64	157,46
BE-TO	0	4,39	0	0	0	0	4,39
TE Plomin 2	17,44	109,06	17,38	51,11	69,54	35,04	299,57

The results for the scenario of energy transition with degasification by 2035 and the BAU scenario are displayed in the following figures. The results for the evolution of electricity generation, imports and exports in the case of energy transition are displayed in Figure 5. It is visible that in this scenario, the model will already stop using coal and oil for electricity generation in 2025. Gas will be used till 2030, but is being steadily reduced in power generation. The majority of the gas use in this period is by cogeneration power plants which have not yet been replaced by renewable heating solutions such as heat pumps, geothermal heating or solar energy. Also, in the same period, there is an increase in the generation from wind energy followed by solar PV which will take over the majority of the power generation by 2035. The total generation also increases in this period as a result of the system-wide introduction of electricity-based solutions, ranging from heat pumps in heating, electricity in industry and transport to the generation of hydrogen and electro fuels. The demand stagnates after 2040 and even starts to slowly decrease. This is the result of the increase in energy efficiency, as well as the reduction in the total population in Croatia.

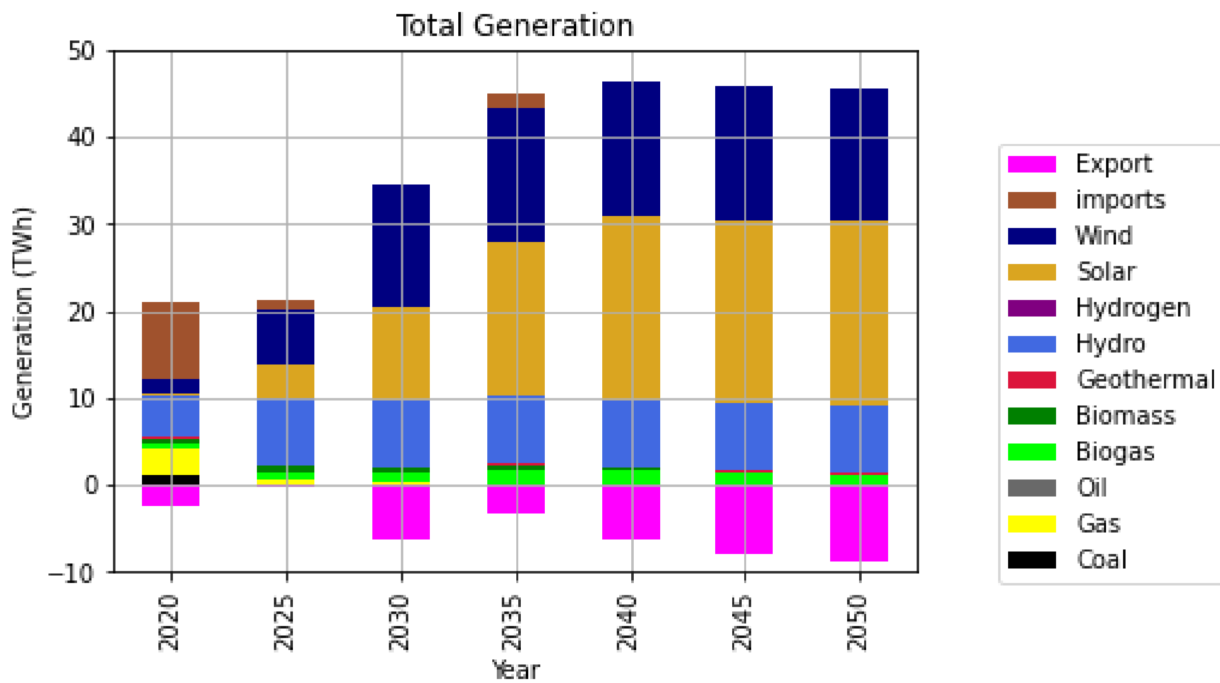

Figure 5. Summation of energy generation in the case of energy transition

As can be observed in the generation figure, the system mostly invests in PV and wind power with a total of 11964 MW in PV and 6015 MW in wind power. The results are displayed in Table 7. Also, it must be noted that the model had the opportunity to invest more into the capacities, but it opted only to install the capacities at the most favourable locations or zones presented with SolarHigh for PV and WindPP2 for wind power. These zones offered the highest capacity factors and thus greatest profitability of investment. The model invested more into solar PV generation as opposed to wind power despite the higher availability factors for wind. The reason for this ratio is the lower cost of solar PV and the availability of energy storage and flexibility systems that can tackle the challenges of variable generation. To achieve these results, the average investments of 400 MW of solar PV and 200 MW of wind power per year are required. In reality, the investments are concentrated in the earlier years of the planning horizon.

Table 7. Investments into electricity generation capacities in the transition scenario [MW]

	2020	2025	2030	2035	2040	2045	2050	Total
BE-TO	0	10,02	3,86	0,12	0	0,01	0,01	14,02
HR_Biogas	0	50,02	50,02	44,88	0	0	0,01	144,93
HR_SolarPP	0	0	0,03	0,1	0,03	0,05	0,04	0,25
HR_SolarHigh	0	2000	4000	4000	1963,84	0,12	0,38	11964,34
HR_WindPP	0	0	1,02	2,73	0,58	0,11	0,1	4,54
HR_WindPP1	0	0,02	1517,9	0,41	0,08	0,06	0,11	1518,58
HR_WindPP2	0	1999,98	1965,5	523,07	0,03	0,09	0,07	4488,74
HR_WindPP3	0	0	0,03	3,3	0,02	0,11	0,03	3,49

The total hourly distribution results for the electricity generation in the case of energy transition are displayed in Figure 6. In this figure, the evolution of electricity supply is prominent, both in the total summed hourly values and in the shape of the curves. Between 2025 and 2030, the curve increases in peak values as a consequence of the installation of VRES capacities. The generation from VRES is variable and therefore, the distribution displays the high peak values. Also, the values on the negative y-axis displaying the export of electricity change their shape from a more spread-out distribution on an annual level to the periods where the export is highly pronounced as a result of the excess in the generation. The generation profile is similar in all years after 2030, since most changes of power generation system were accomplished by then. On the contrary, the Figure 7. displays the results for the business-as-usual scenario and therefore features very similar distribution in each year. The similar distribution is the result of keeping the same configuration of power system throughout the years.

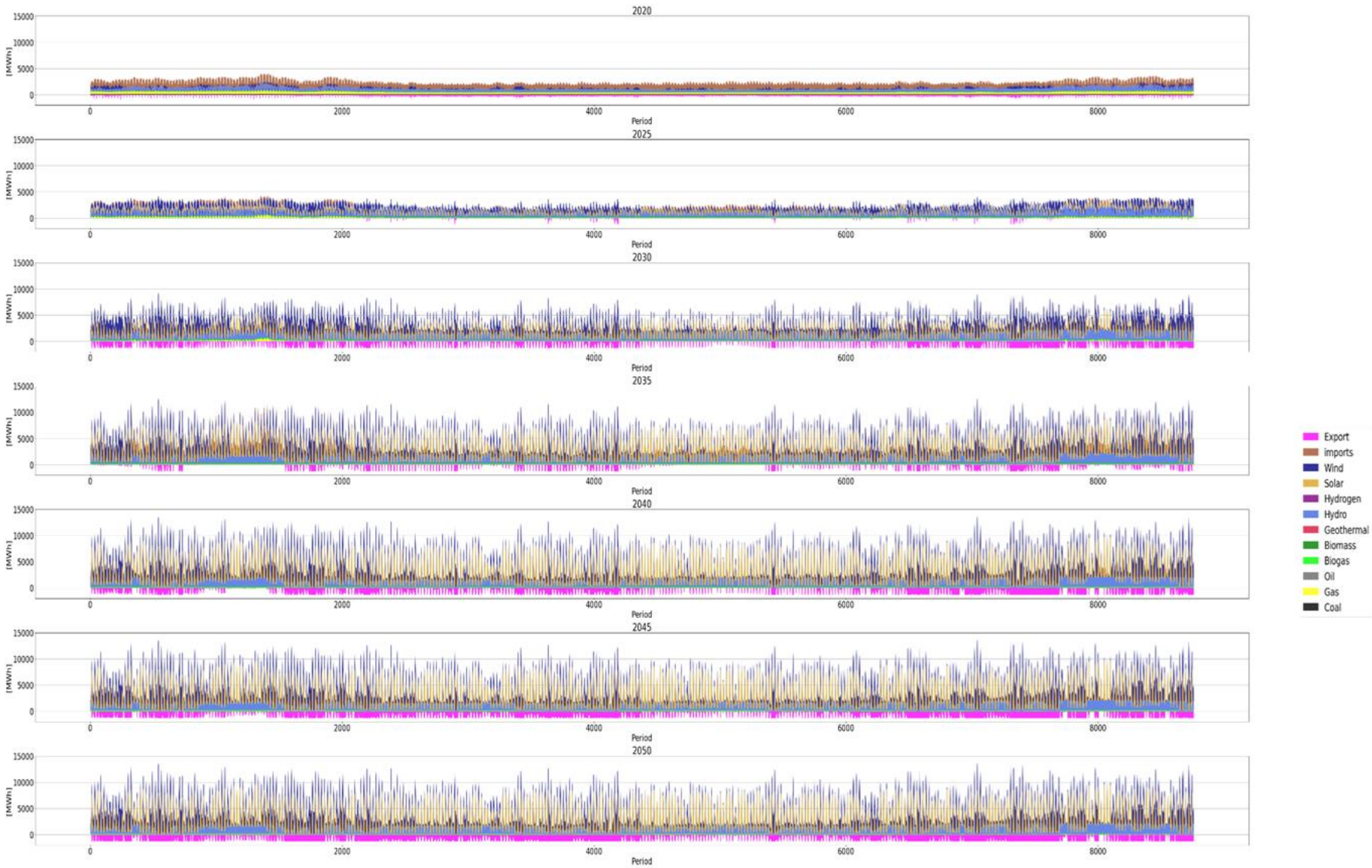

Figure 6. Hourly generation distribution in the case of energy transition

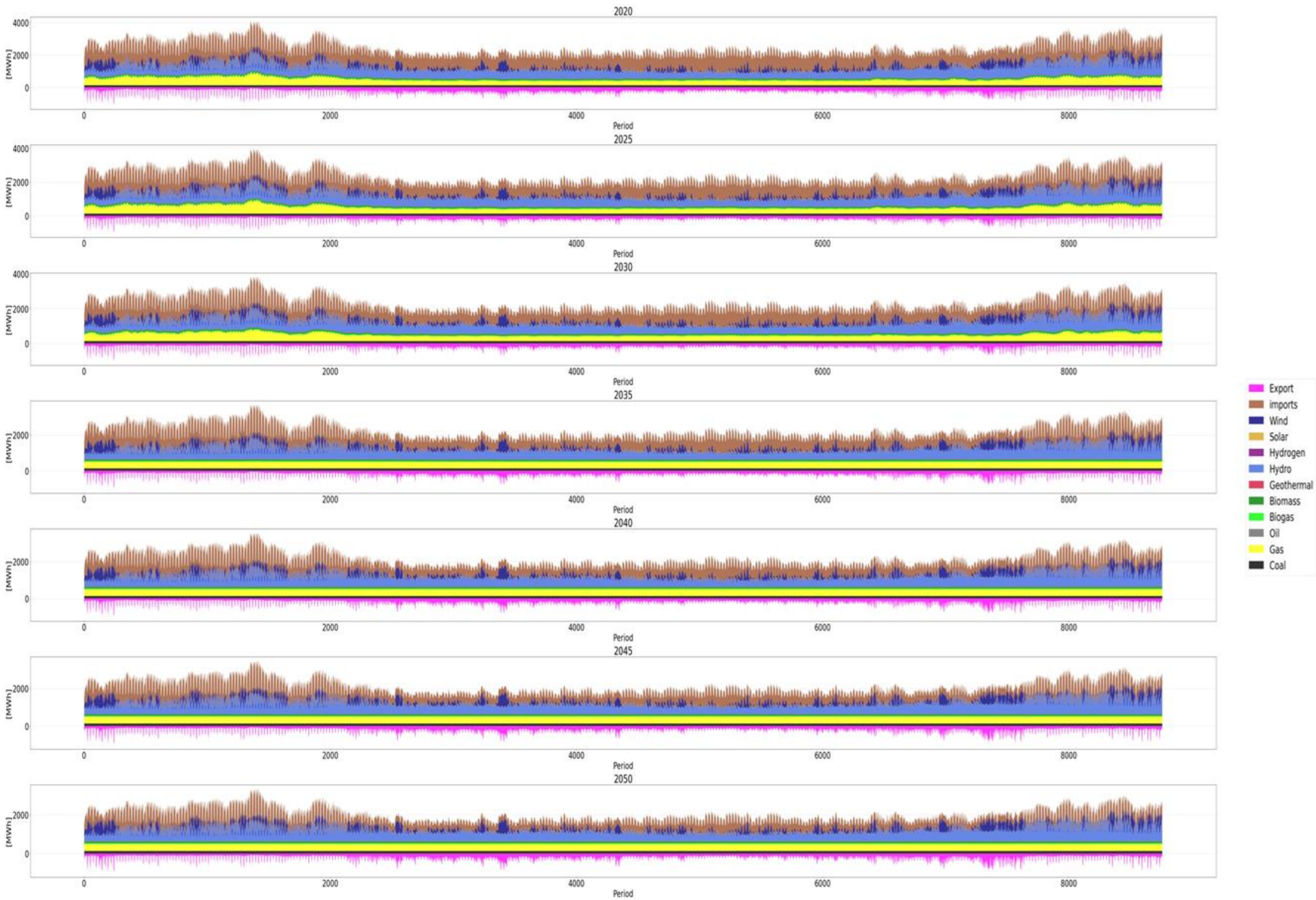

Figure 7. Hourly generation distribution in the case of BAU scenario

4.2 Heating in district heating systems

The results for the evolution of the heating demand and composition of the supply for both individual and district heating are displayed in the following figures.

Figure 8 displays the evolution of heating in district heating systems in the area of the city of Zagreb and its surroundings for the case of BAU scenario. In this case, the gas-powered CHP units and boilers continue to be used till 2050, mostly reflecting the current composition of the heating supply. Total heat demand reduces as a result of the reduction in demand due to energy efficiency gains and depopulation.

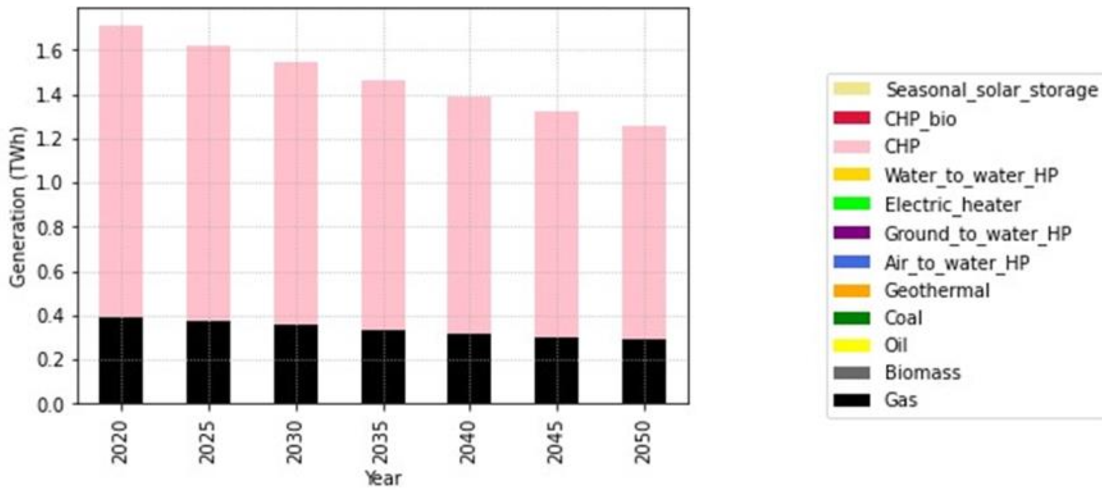

Figure 8. Heating in the case of Zagreb region in the case of BAU scenario

The results for the case of energy transition for the evolution of the heating in district heating systems in the area of the city of Zagreb and its surroundings, are displayed in Figure 9. As discussed in the case study section, district heating takes over 10 % of the individual heating demand initially supplied by gas in the base year. This is the reason for the increase in the generation till 2030. From 2035, the effect of the increase in energy efficiency and the decrease in the population starts to become more pronounced and causes a decrease in the heating demand. The composition of the heat supply starts to change from the system supplied entirely by the gas-powered CHP plants and gas boilers. The system utilizes more of the geothermal resources as well as the solar thermal energy through the use of seasonal solar energy storage. The most important contributor to the change in the energy supply is the introduction of water-to-water heat pumps, which take over majority of heat supply by 2050. The CHP heat generation decreases since the low carbon and more efficient technologies start to be available. Also, the heat generation in CHP is interlinked with the power generation in CHP which also decreases due to the introduction of VRES. Air to water heat pumps are highly utilized in the first years, especially in 2025 as an response to the high fuel prices while at the same time minimizing the investment cost compared to other types of heat pumps. As more of the more efficient water to water heat pumps are installed and available in the system, the use of air to water heat pumps reduces. Also, system makes use of the available renewable electricity during the times of overproduction by utilizing the electric heaters, especially in 2035.

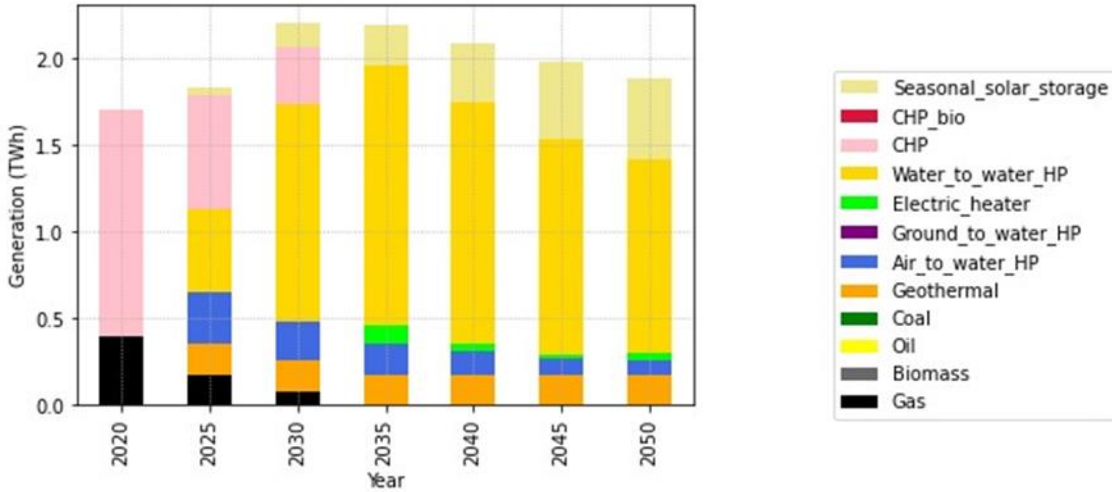

Figure 9. Heating in DH systems in the Zagreb region in the case of energy transition

The results for the BAU scenario for DH systems in coastal Croatia are displayed in Figure 10. In this region, heating in DH systems is based on gas boilers in 2020. The total generation decreases, and the ratios stay consistent throughout the years meaning no new technologies are introduced, and gas boilers keep providing the entirety of supply.

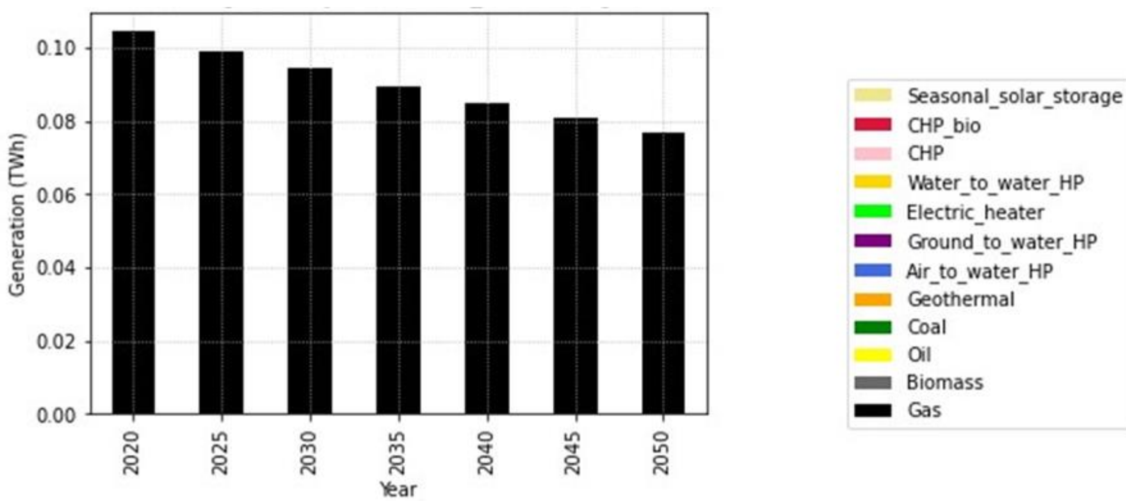

Figure 10. Heating in the case of coastal Croatia in the case of BAU scenario

The results for the same region for energy transition scenario are displayed on Figure 11. Similarly, Zagreb region experiences a reduction in the use of gas, while the majority of the demand starts to be supplied by the water-to-water heat pumps. Also, the solar heating is extensively used. In this case, it was exogenously inputted that the new CHP capacity will be employed between 2020 and 2025 as that is stated in the development plans of the local heating utility, but when left for the model to optimize the dispatch, due to the use of gas, this plant ceases operation by 2035.

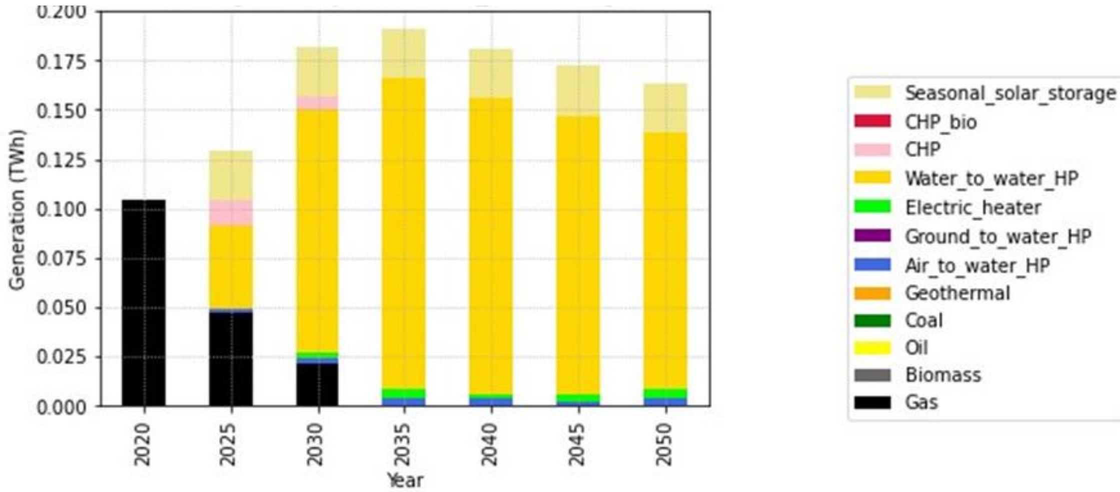

Figure 11. Heating in the case of coastal Croatia in the case of energy transition

Similarly, as in previous regions, in the continental Croatia region, the total demand in the BAU scenario decreases and the ratios between the generators stay constant throughout the years, as displayed in Figure 12. In this region, the heat is supplied by the mix of gas-powered CHP, biomass powered CHP, gas boilers and a small amount of geothermal energy.

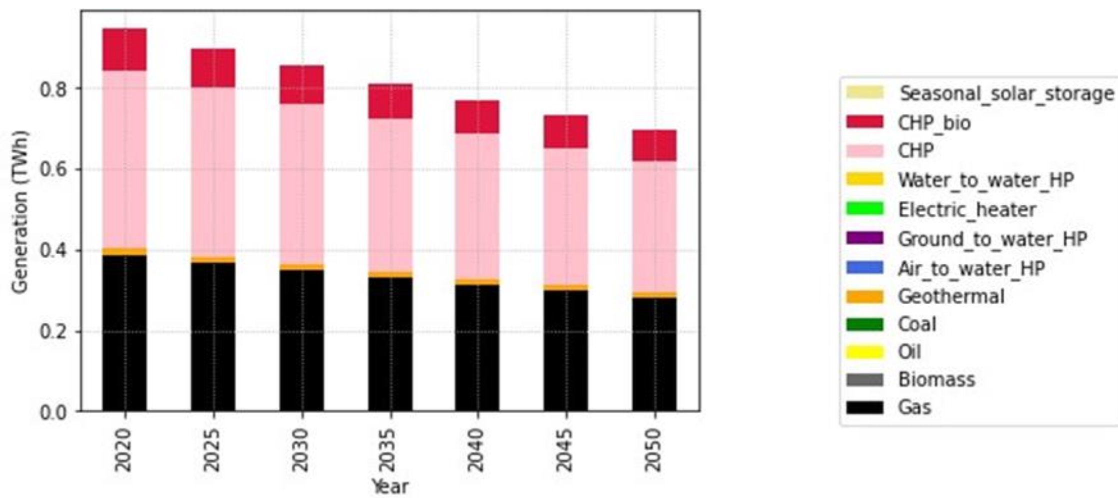

Figure 12. Heating in the case of continental Croatia in the case of BAU scenario

The results of the evolution of the generation and demand in the district heating systems in continental Croatia are displayed in Figure 13. The evolution sees the increase of the geothermal energy use, solar seasonal heating use and the application of water-to-water heat pumps which take over most of the demand by 2050. As a result of the transition towards DH, the demand rises till 2035 after which starts to decrease as a result of energy efficiency gains and the depopulation. In this case, gas powered CHP reduces and is completely outphased by 2035, whereas biomass powered CHP increases the heat supply between 2025 and 2035. This increase is due to the necessity to displace the heat generation from gas powered CHP combined with the inability of the system to rapidly replace the gas CHP with heat pumps or solar heating.

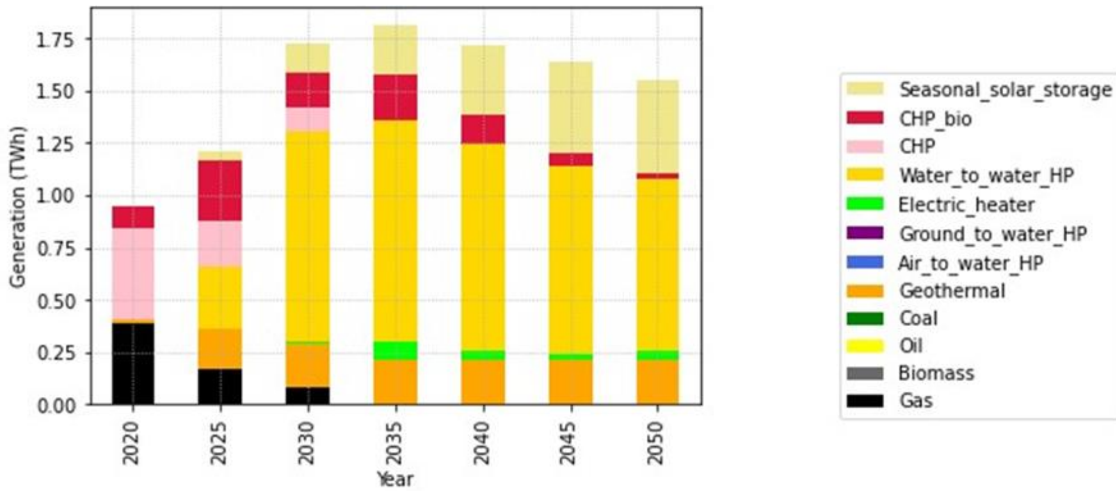

Figure 13. Heating in the case of continental Croatia in the case of energy transition

Total installations in the district heating systems in transition scenario are displayed in Table 9. Total of 1791 MW are invested into heat pumps and electric heaters, 71 MW into geothermal heat, 4935 MWh into seasonal heat storage and 3000 MW into solar heating systems.

4.3 Individual heating systems

In this section, the results for the same zones of continental Croatia, coastal Croatia and Zagreb region are analysed, but for the portion of the demand that is supplied by individual heating systems.

The results for the BAU scenario in the case of the Zagreb region are displayed on Figure 14. The composition of the supply is dominated by the gas boilers followed by the biomass boilers. Also, electric heating and air to water heat pumps are used. The BAU scenario presents only the reduction of demand while the ratios stay consistent till 2050.

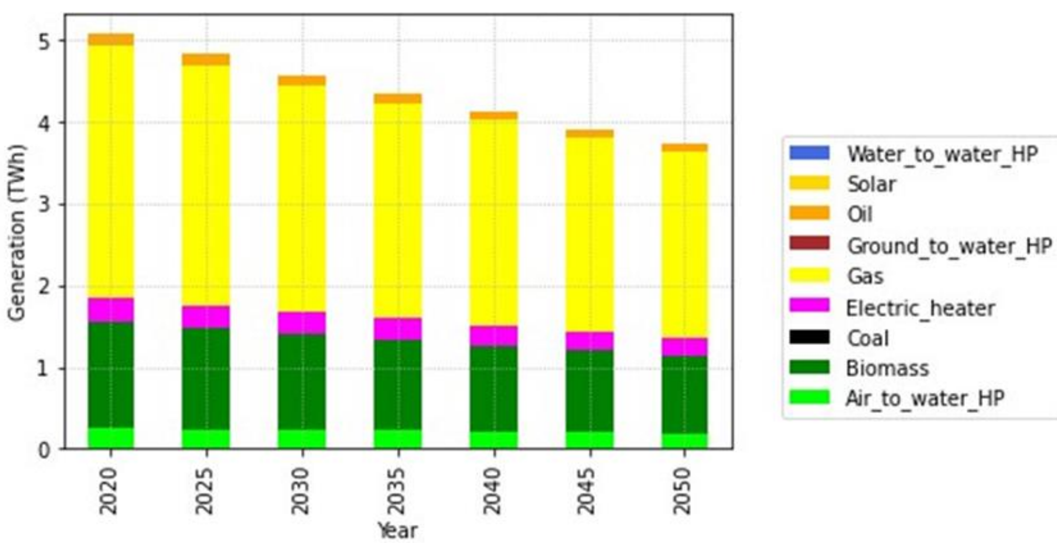

Figure 14. Heating in the case of the Zagreb region in the BAU scenario in individual systems

Individual heating systems in Zagreb region have also a decrease in demand in the case of energy transition scenario. The first cause is the switch of part of the demand towards DH and the second one is the increase in efficiency combined with depopulation. The results for the area of the City of Zagreb and its surroundings are displayed in Figure 15. It can be seen that the majority of the demand in the base year is supplied by gas boilers. Their share rapidly decreases as they are replaced by the combination of air-to-water heat pumps and electric heaters. Heat pumps take over most of the demand by 2050. As opposed to the results for district heating, in this case, heat pumps are dominated by the air to water heat pumps due to the different levels of availability for installation and use of different types of heat pumps depending on the region. Households for example do not have the access to the water bodies as district heating utilities do.

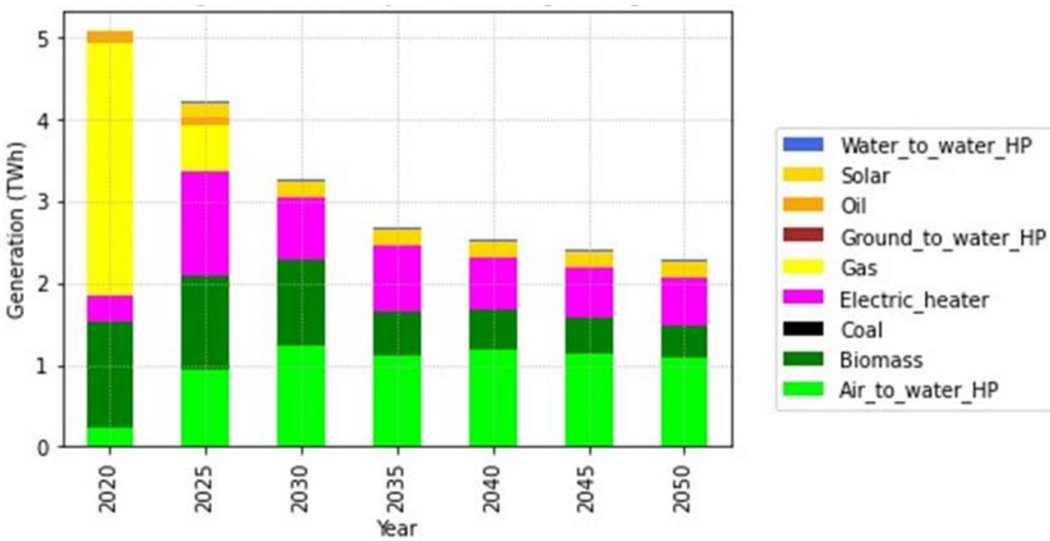

Figure 15. Heating in the case of Zagreb region in the case of energy transition in individual systems

The results for the region of coastal Croatia in the BAU scenario are displayed on Figure 16. Similarly as in other regions, the shares of the supply stay consistent and the total demand reduces. The supply is dominated by biomass boilers, but electric heaters, air to water heat pumps, solar energy and oil boilers are also used.

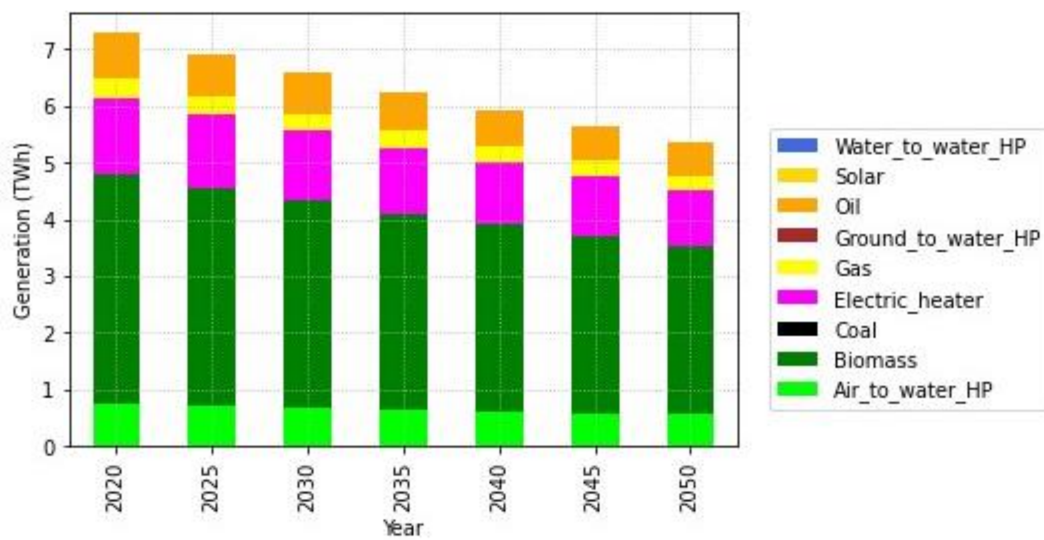

Figure 16. Heating in the case of coastal Croatia in the BAU scenario in individual systems

In the case of energy transition scenario, region of coastal Croatia displays the shift from mainly biomass powered heating towards heating supplied mostly by air source heat pumps, followed by the electric heaters. Also, solar heating is used, but only to provide a domestic hot water supply. The results are displayed in Figure 17. In this case, the model did not completely cover the demand with the heat pumps since the heating season in this region is shorter and therefore the number of working hours of the equipment is lower which affects the economics of installing the heat pump as opposed to electric heater.

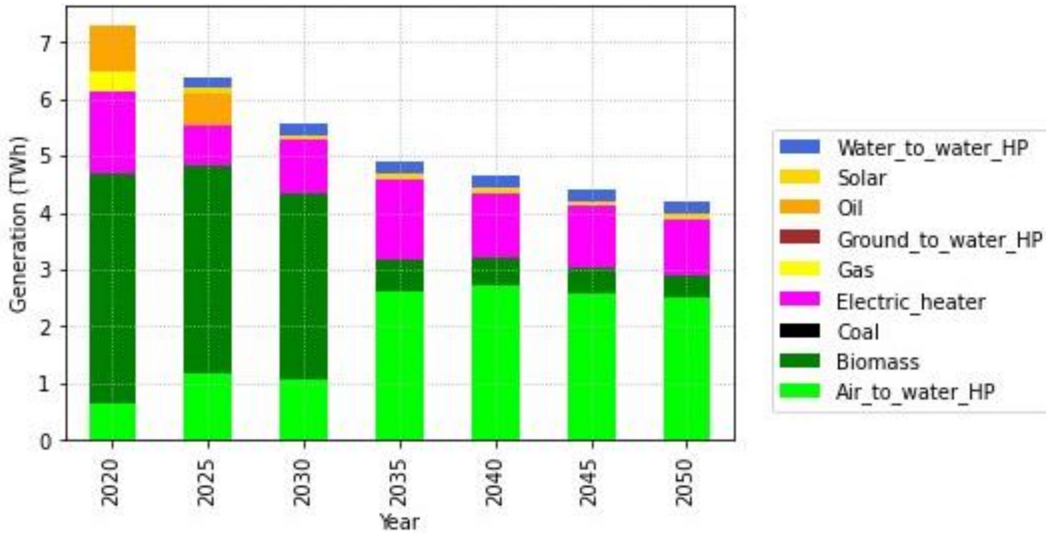

Figure 17. Heating in the case of coastal Croatia in the case of energy transition in individual systems

The results for the continental Croatia region in BAU scenario are displayed on Figure 18. They feature the reduction of demand and consistent shares of supply technologies. The composition of the supply is dominated by biomass and followed by gas boilers indicating the demand for more than 3 TWh of gas in 2050.

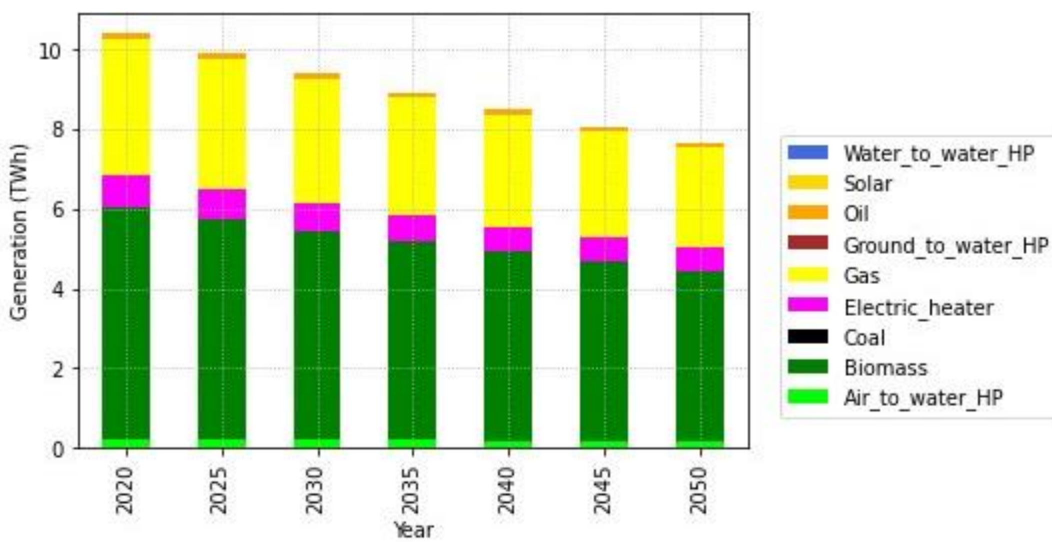

Figure 18. Heating in the case of continental Croatia in the BAU scenario in individual systems

The results for the energy transition scenario in the individual heating of continental Croatia are displayed in Figure 19. The gas is being rapidly replaced mostly by air-source heat pumps and electric heaters, and will be completely out-phased by 2035. Biomass share is also reduced and replaced by electrically powered heating solutions. Also, solar energy is being used to supply part of the domestic hot water demand.

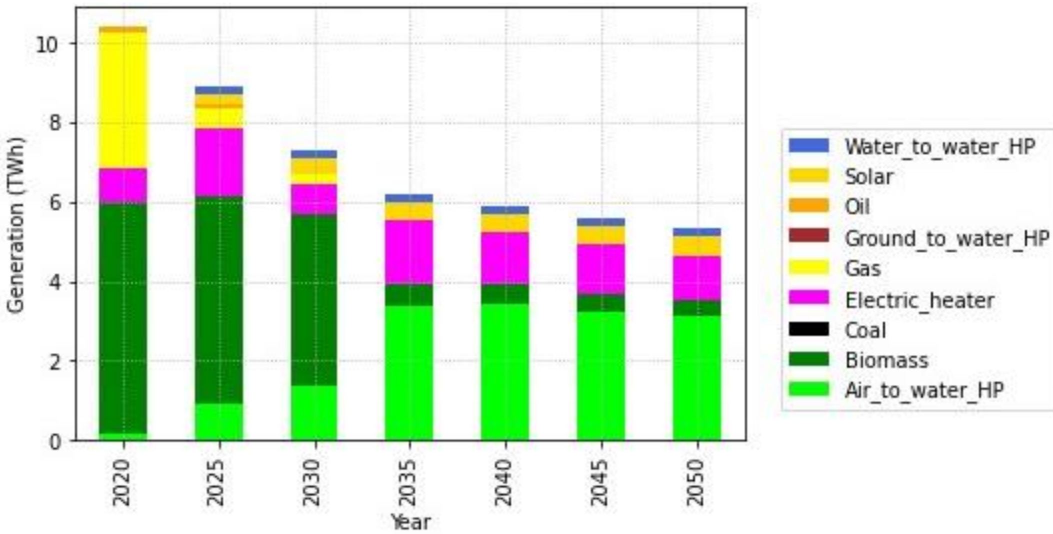

Figure 19. Heating in the case of continental Croatia in the case of energy transition in individual systems

For the individual heating systems, the total installations for transition scenario are displayed in Table 10. In this case, total of 6516 MW of heat pumps and electric heaters are installed, 661 MW of biomass boilers and 37500 MW of solar collectors.

In the presented transition scenarios, the rapid change is present between the 2030 and 2035, with the prominent increase of heat pumps share. This is the result of big investments into this type of heat generation in 2035. Presented change occurred as a consequence of the constraint to remove gas demand by 2035. Therefore, the model had the possibility to invest as late as possible, and use existing systems as long as possible. Late investment reduces the necessity to plan for equipment replacement at the end of the life during the planning horizon, as well as use of the ever decreasing prices of the equipment. In the future research, the stricter limits will be implemented on the annual investments in order to limit rapid changes, especially near the start of the planning horizon.

4.4 Industry sector

The results for the BAU scenario in the cement industry subsector are displayed in Figure 20, and it can be seen that the fuel shares stay consistent, while the total demand decreases as the assumption of energy efficiency increase for both scenarios.

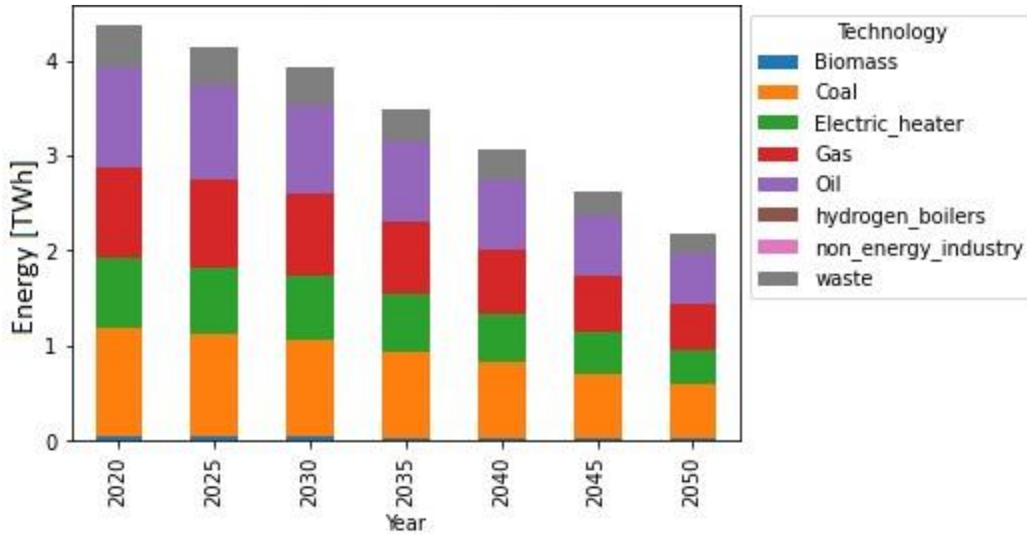

Figure 20. Energy balances in the cement industry for the case of a BAU scenario

The results of the transition of the industry cement subsector are displayed in Figure 21. In the base year, the fuels were dominated by coal, oil, and gas. By 2035 the use of these fuels will be eliminated, when hydrogen and electricity take over most of the demand with rest being supplied by the non-renewable and non-recyclable waste which is used as a fuel.

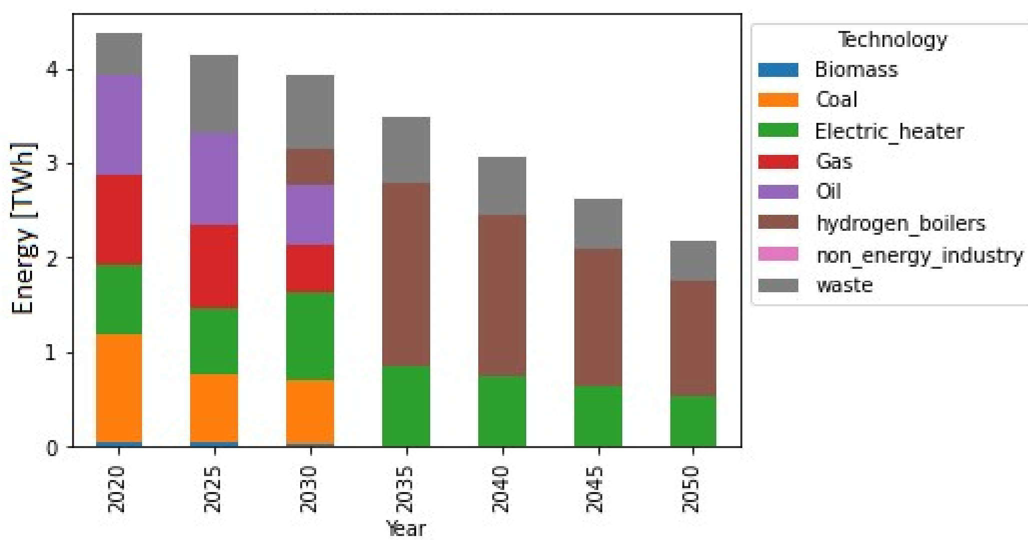

Figure 21. Energy balances in the cement industry for the case of energy transition

The results for the BAU scenario of the petrochemical industry are displayed in Figure 22. Fuel and energy demands in the petrochemical industry consist of the biggest part for hydrogen non-energy demand, which is used as a feedstock in the production of fertilizers. Therefore, the non-energy demand occupies biggest share, followed by the gas demand. Non-energy demand presents the demand for gas used to generate hydrogen by steam gas reformation. Further on, the hydrogen is used in the next stages of fertilizer production.

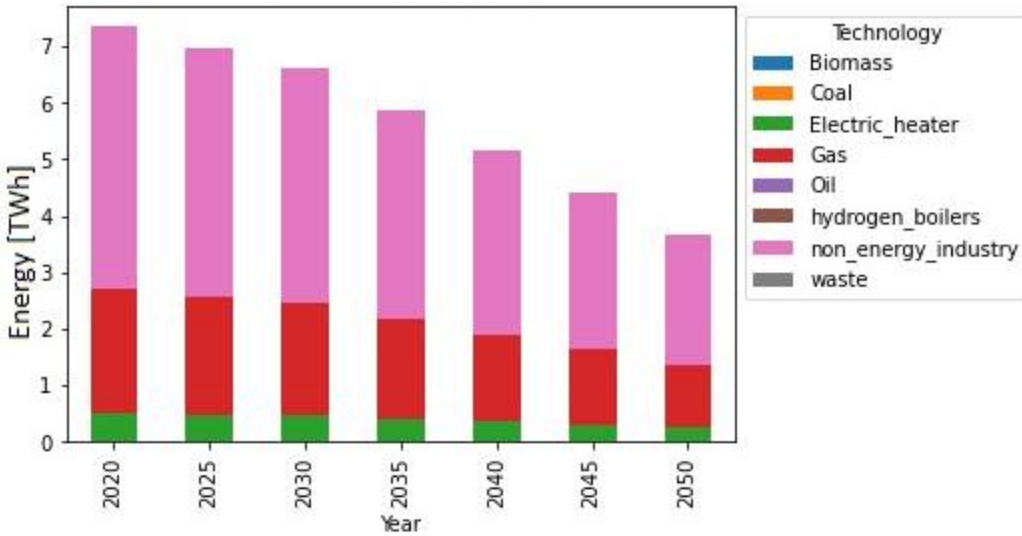

Figure 22. Energy balances in the petrochemical industry for the case of a BAU scenario

The results for the petrochemical sector in the transition scenario are displayed in Figure 23. In this scenario, the remainder of the demand, which consists mainly of gas, is converted to hydrogen while the production of hydrogen feedstock is steadily switched from steam gas reformation to the electrolyzer production. The transition of the hydrogen generation is displayed in the Figure 28.

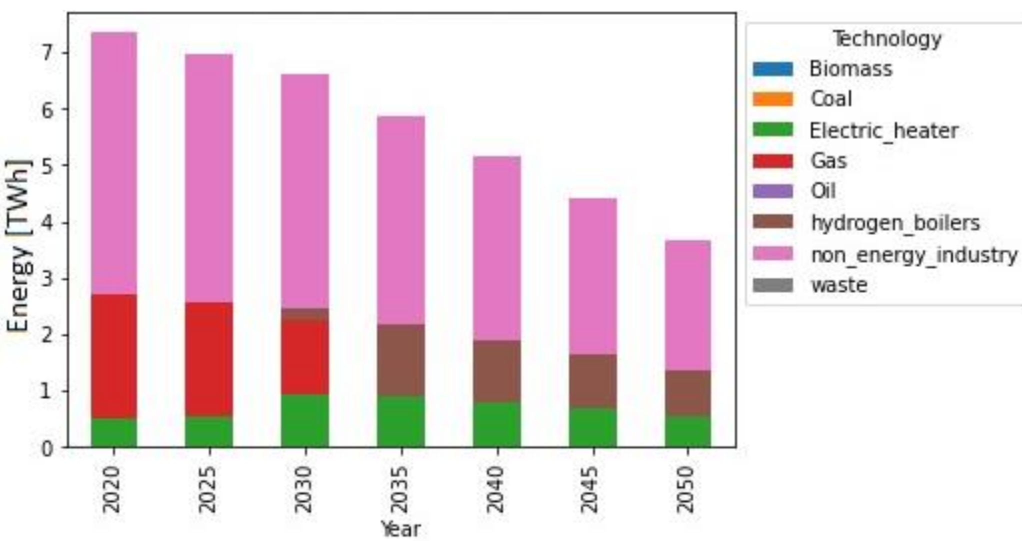

Figure 23. Energy balances in the petrochemical industry for the case of energy transition

The results for the refineries in the BAU scenario are displayed in Figure 24. In the base year, the supply is dominated by the oil and gas. In this scenario, the sector keeps using the same fuels, but the used amount is being reduced as a result of gains in energy efficiency.

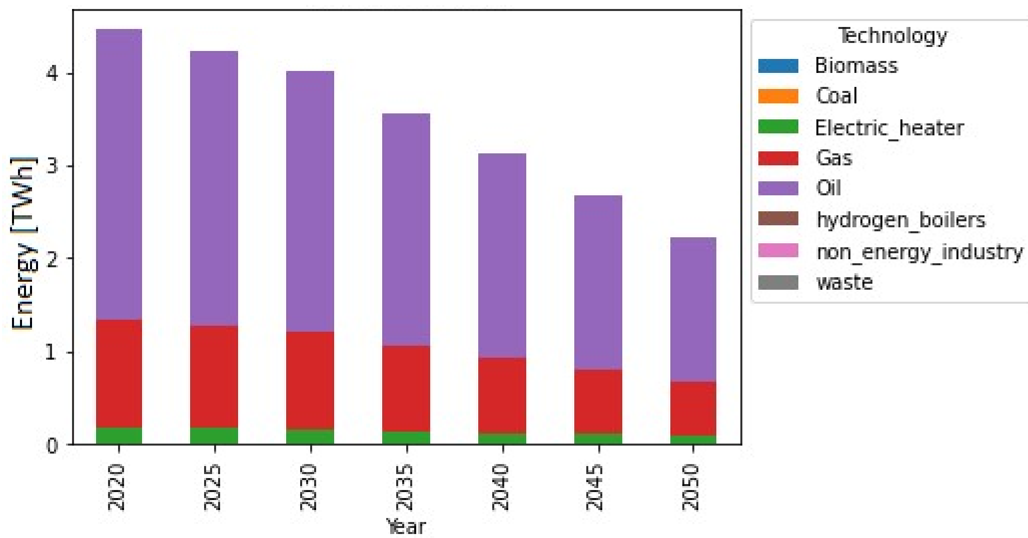

Figure 24. Energy balances in the refineries for the case of a BAU scenario

The evolution of the energy demands in the refinery subsector in the case of transition scenario is presented in Figure 25. The supply of the sector changes with the reduction and subsequent elimination of the demand for the production of oil-derived fuels, and they are steadily replaced by hydrogen-based fuels causing the shift in the share of used fuels. It should be noted that the presented demand is energy demand of industry branch and not the input of crude oil for processing.

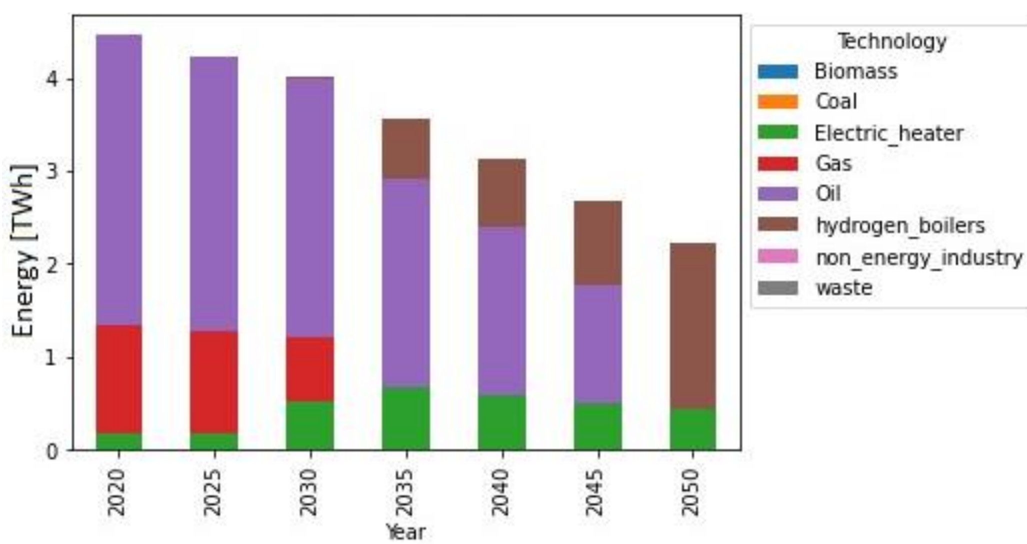

Figure 25. Energy balances in the refineries for the case of energy transition

In the BAU scenario, the shares of the fuels in the remainder of the industry stay the same which means that this sector will continue using gas, oil, and coal till 2050 as displayed in Figure 26.

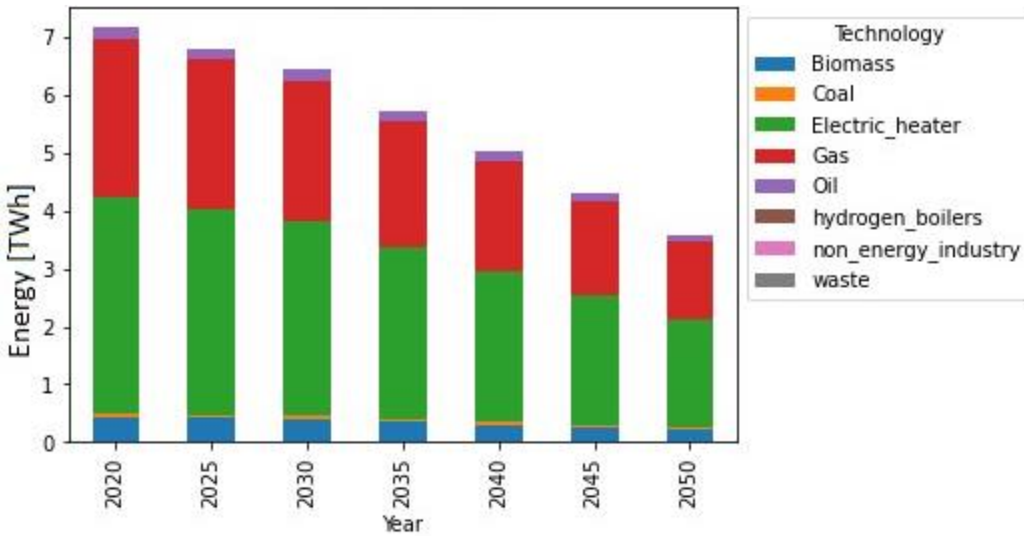

Figure 26. Energy balances in the remainder of the industry for the case of a BAU scenario

The remainder of the industry consists mostly of processes that do not require high temperatures and therefore the use of electricity in this subsector is more prevalent in the future years. As displayed in Figure 27, electricity takes over almost the entire demand with the rest being hydrogen.

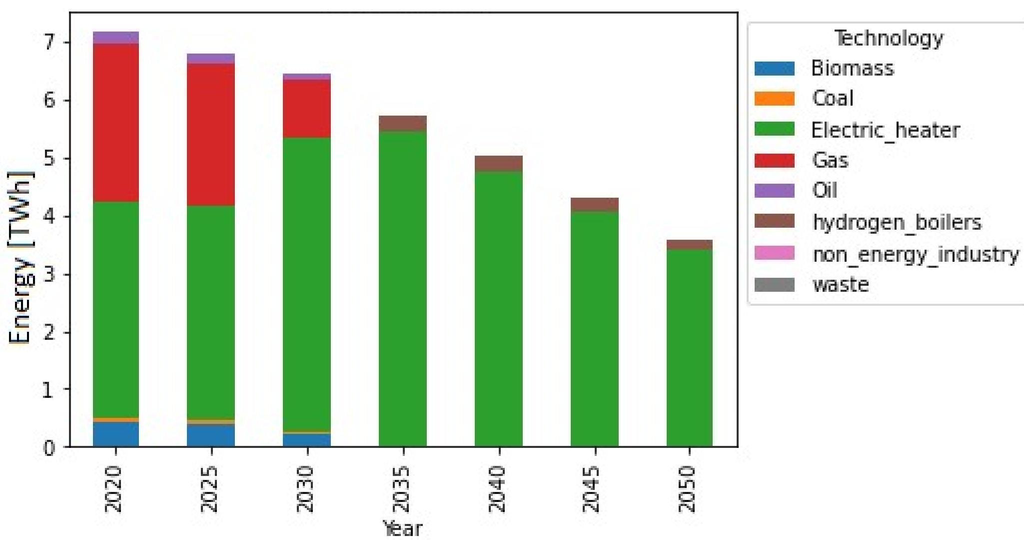

Figure 27. Energy balances in the remainder of the industry for the case of energy transition

In general, transition of the industry sector is carried out in two ways. This is mandated by the capabilities of different industry branches to apply certain technologies, such as requirements for high temperature heat. Therefore, in those that require high temperature heat, hydrogen prevails, while in the branches that do not require such conditions, the model opts to use electricity since it is both cheaper and more energy efficient as fewer energy conversion steps are required. The hydrogen is introduced in the petrochemical and cement industry in 2035, but by 2035 it greatly increases in its share. This is the consequence of the restrictions on the end of the use of gas by 2035. Due to the perfect foresight architecture of the model, it saw that it could make majority of the investments as late as possible and still satisfy the conditions. The late investments are preferred due to the discounting which reduces the present value of future investments as well as the ability to use as long as possible the existing equipment and thus save on the possibility of having to replace the new equipment by the end of the planning horizon.

4.5 Storage technologies, electrolysers, and fuel cells

From the side of energy storage systems, in transition scenario model mostly invested in hydrogen storage. Also, there are big investments into hydrogen generation, mostly using alkaline electrolysers. The investments into hydrogen infrastructure are mandated by the necessity to decarbonize the hard to electrify sections of the industry sector. When integrating hydrogen into energy system, it is crucial to enable flexible operation of those systems. Therefore, hydrogen storage is used as a buffer between hydrogen generation and consumption, thus enabling the decoupling of generation time mandated by availability of renewable generation from the consumption time. The investments are displayed in Table 8. In the BAU scenario, there are no investments in these technologies since it does not require additional hydrogen and flexibility. The model invested very little in the battery storage systems since the system already possesses the battery storage system through the use of electric vehicle batteries through smart charge and V2G technologies. As can be observed, the investments into hydrogen storage are almost constant from 2025. This is the result of the set-up boundary condition on the investment into hydrogen storage. The restrictions were set up in line with the results of previous works that tackled the energy transition modelling with H2RES of the Croatian energy system [44]. The results from the previous work displayed the lower investment values than the ones that are used as a boundary condition in this research. In further research, the limits should be increased to accommodate for the possibility of expansion since the hydrogen storage was presented as a viable source of flexibility. Also, a step towards the variable limits that consider the learning curves through the years instead of strict limits will be made. The model invested in total of 2444 MW of electrolysers and 17997 MWh of H2 storage. These installed capacities allow for flexible operation of the hydrogen generation and supply system. The maximum annual demand for H2 in the model is 9,3 TWh meaning that in the system 17 hours of H2 storage is available and that the electrolysers work at an average capacity factor of 43 %.

Table 8. Investments into hydrogen technologies and energy storage in transition scenario. Expressed in [MW] and [MWh]

Year	2020	2025	2030	2035	2040	2045	2050
Alkaline_EC	0	41,03	284,59	1948,84	168,33	0,04	0,01
PEM_elec	0	0	0,01	0,8	0,34	0,01	0,01
SOEC_elec	0	0	0	0,39	0,01	0	0
H2_storage_tank	0	2998,87	2999,99	2999,89	2999,47	2999,6	2999,66
Liion_storage	0	0	0,01	1,44	1,26	0,75	0,27
PEMFC	0	0,16	0	0,72	0,03	0	0,01
SOFC	0	0,06	0,04	0,44	0,05	0	0

The impact of electrolysers and hydrogen technology's introduction, can be observed in Figure 28 as they displace hydrogen demand that corresponds to the steam gas reformation by 2035.

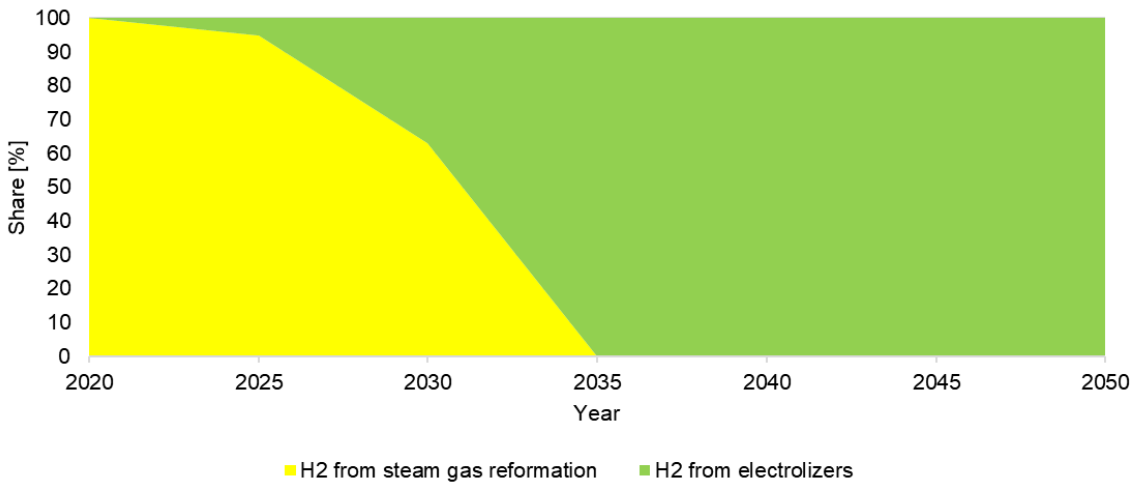

Figure 28. H2 generation processes

4.6 Transport sector

In the transport sector, for the BAU scenario, the shares stay constant, and the sector continues to use mostly fossil fuel-powered vehicles. It should be noted that in this case, the transport sector was modelled only as a single category of personal vehicles. Therefore, the restrictions that were implemented in the maximum share of electrification consider the transport sector as a whole, most notably concerning heavy-duty road transport, long-distance shipping and aviation which require the use of highly energy-dense fuels to be economically viable. The results of the BAU scenario are displayed in Figure 29. The transition scenario offers the transition towards mostly electrified sector. Although the sector is not completely electrified, it is decarbonized since the fuel used by ICE-powered vehicles in 2050 is replaced by synthetically generated electrofuels. The results are displayed in Figure 30. Investments for the transition case are displayed in Table 11. Whereas for the BAU scenario in Table 12. The total investments in both scenarios are approximately the same with 1,33 million, but the composition differs. Therefore the 75,5 of the investments in the transition scenario refer to the EV’s, 15 % to the hybrid vehicles and 9 % to the plug-in hybrid vehicles. The investments into EV’s are concentrated mostly in 2030 and 2035. For the BAU case, most of the investments, 98 % are into internal combustion vehicles.

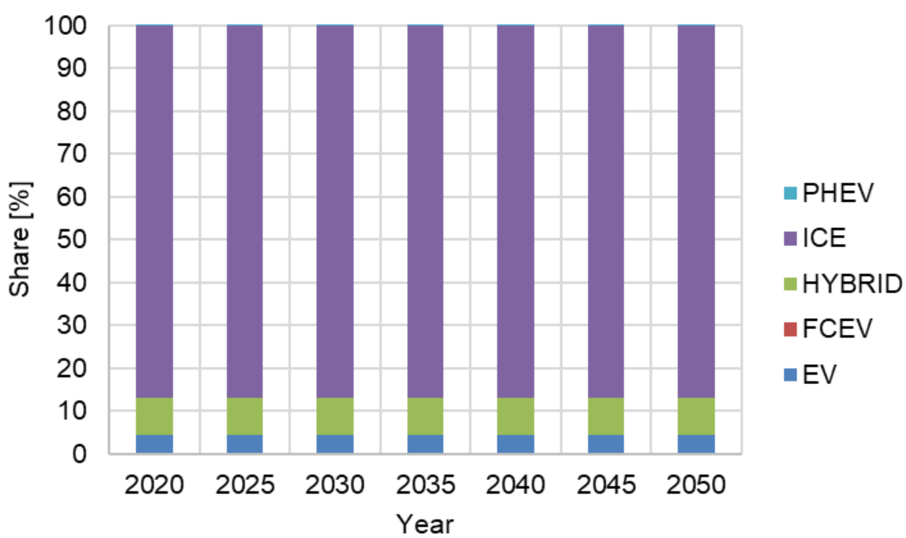

Figure 29. Shares in the transport sector in the BAU scenario

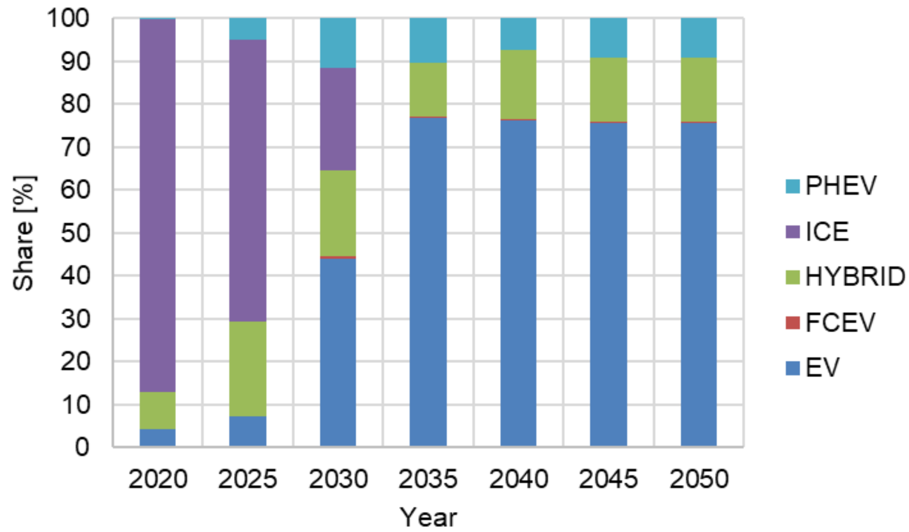

Figure 30. Shares in transport sector in transition scenario

4.7 System costs

The results for the system costs are displayed in the following figures. The results for the BAU scenario are displayed in Figure 31. This scenario features capital investments into new capacities (CAPEX) for power generation and other equipment such as boilers, but they are mostly replacements of the old equipment. The investments reach a peak between 2030 and 2035 with replacement of decommissioned capacities. Since in this scenario there are no big changes in the generation composition of all sectors, the fixed operational (OPEX) portion of the costs, tied to the maintenance of the equipment stays almost constant throughout the years. Variable operational costs (Var_OPEX) that are mandated by the fuel costs and tied to the dispatch of the equipment, experience a peak during 2022 as a consequence of the energy crisis in Europe and therefore very high gas and oil prices.

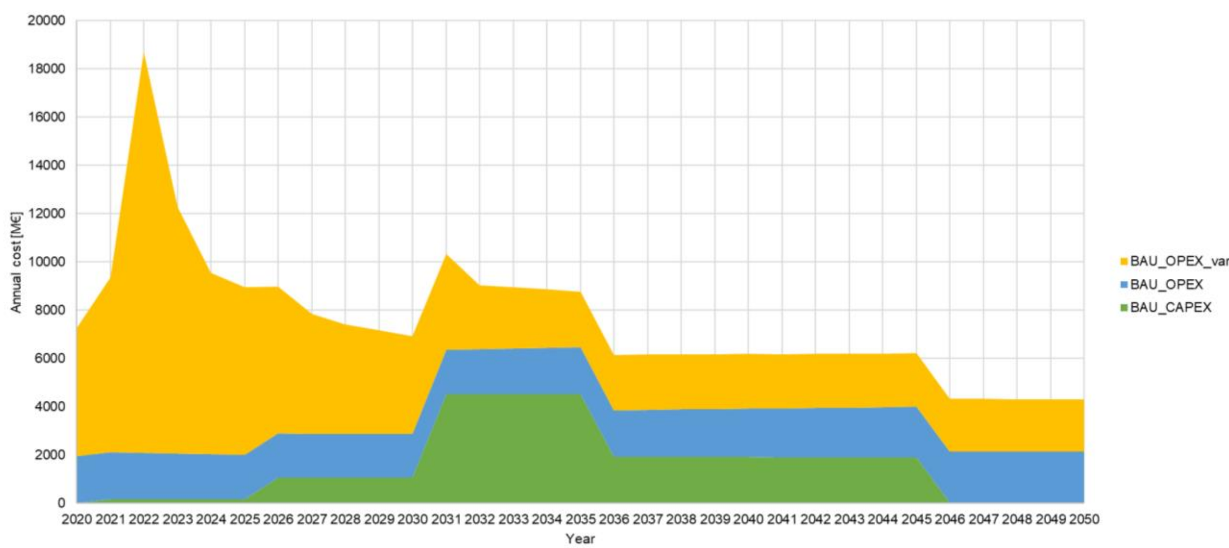

Figure 31. Total costs for the BAU scenario

Figure 32 displays the costs for the scenario in the case of energy transition. The investments represented as capital investments (CAPEX) reach a peak between 2025 and 2030 when majority of new capacities are installed. The operational (OPEX) portion of the costs is tied to the installed capacities and presents ongoing maintenance of the equipment. This part of the expenses becomes dominant in the later years. Also, in this scenario, variable operational costs (Var_OPEX) experience a peak during 2022 as a consequence of the energy crisis. It should be noted that because of already initiated transition, the peak is lower in this case than in the BAU scenario. This portion of the costs steadily decreases as more of the energy generation is switched to renewable energy, which does not require additional fuel to run.

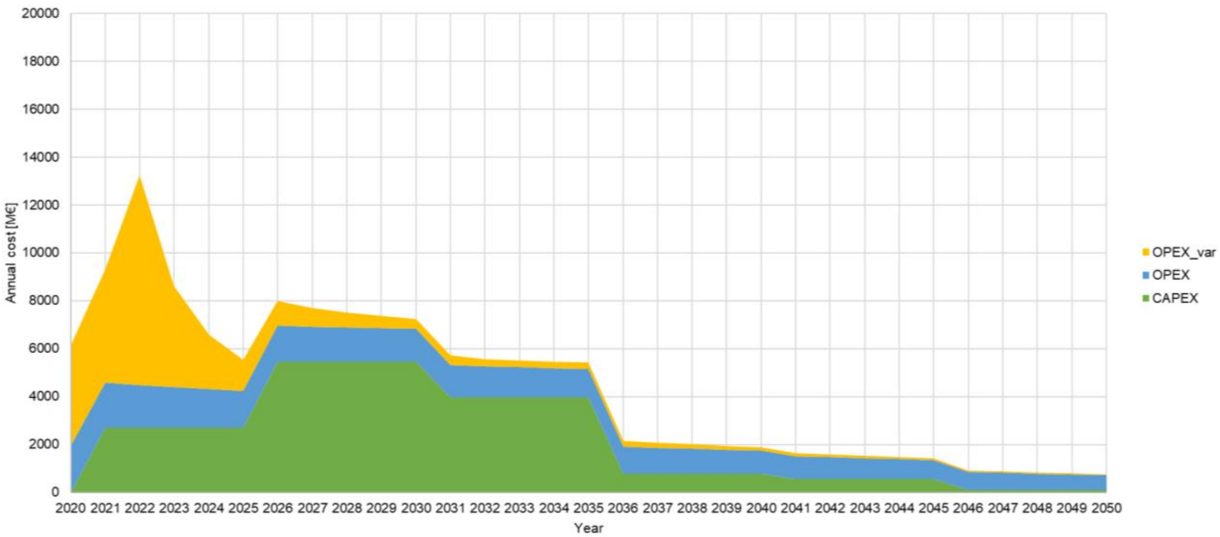

Figure 32. Total costs for the scenario of energy transition

The comparison between the scenarios is displayed in Figure 33 It can be seen that the transition scenario features lower costs for almost every year except for the slightly higher costs for 2028, 2029 and 2030. These higher costs are caused by the intensive investments into new capacities and infrastructure in the transition scenario during this period.

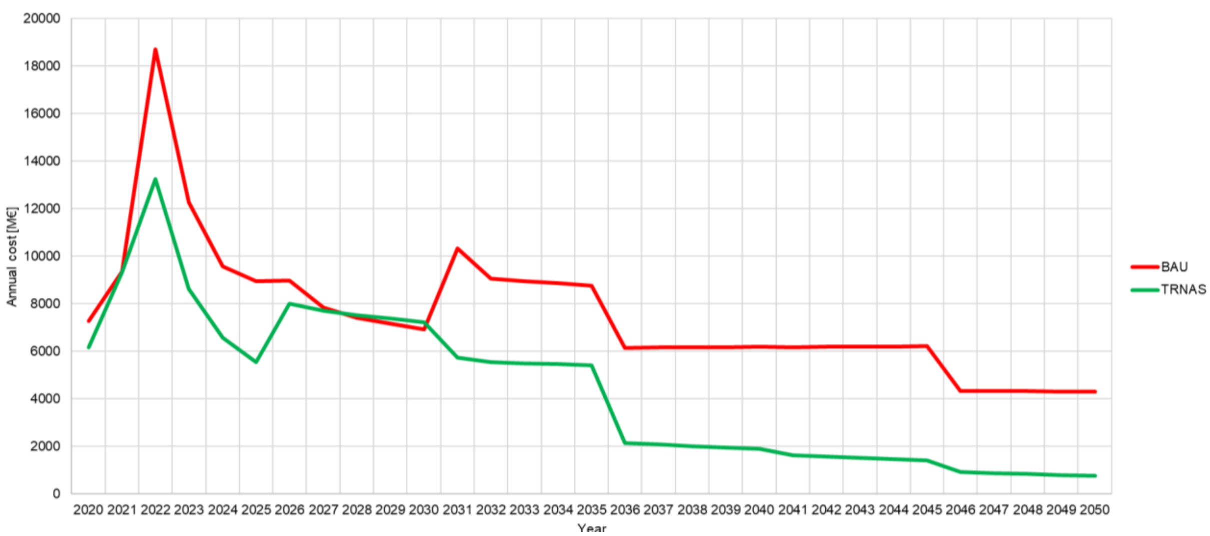

Figure 33. Comparison of the total costs in the transition and BAU scenario

When transitioned to the present value, the results feature the net present value (NPV) of all costs, amounting to 92,6 B€ in the transition scenario and 138,29 B€ in BAU scenario, with an assumption of the discount rate of 5 %. This value for the discount rate was used as it is in the usual value range for the renewable energy projects, but on lower end since the range is between 3 and 10 % [62]. Using higher discount rate would try to shift the investments into later stages of planning horizon which is opposite to what was the goal here in conducting fast transition. In the transition scenario, when accounting for all the years, total of 50 % of the costs correspond to CAPEX, 27 % to OPEX and 23 % to variable OPEX. The shares in BAU are 20,5 % for CAPEX, 26 % for OPEX and 53 % for variable OPEX. The differences in the distribution of the costs indicate that even though the capital investments in the transition scenario are much higher, they result in savings predominantly in the variable OPEX section. The ratios between the costs components differ drastically throughout the years in both scenarios. In the first years, as a consequence of very high fuel prices, variable OPEX took over most of the total costs. In the following years for transition scenario, CAPEX is the biggest part of the total costs since big investments into the new generating capacities and other equipment are required. Investments into the new capacities allowed the reduction of the variable operational costs so the most of the remaining costs in 2050 are fixed operational costs related to the maintenance of the equipment. BAU scenario also presents high investment cost, but they do not result in the decrease of operational costs. The cumulative total costs for transition and BAU scenarios brought to present value are displayed in Figure 34. Both of the lines start steep increase in the first couple years since at the beginning they have the same energy system composition. The steep rise in the first years is the result of a very high var_OPEX costs during the energy crisis. In both of the scenarios the rise is continued but at the slower pace, since the fuel costs stabilize and now the majority of the cumulative increase is due to the capital investments. In the case of transition scenario, the investments had an effect on reducing both fixed and variable operation costs, while this is not the case for the BAU scenario as it continues to rise even in 2050. Tapering at the end of the planning horizon in both scenarios is the result of lack of investments in 2050 since the model did not plan for systems development after 2050. This is the point of further research where the method will be modified to make the model plan for the development after the end of planning horizon. Additionally, since these are the values at the present value of monetary unit, the influence of the values in distant future is much lower than the influence of the monetary flows in the present. Additionally, the detail results for the costs by its components are displayed in Appendix. As can be observed in Figure 51, most of the CAPEX in transition scenario relates to the installation of the new power generation equipment, new types of vehicles and electrolysers, while in BAU, the replacements of the old units consist the majority of CAPEX as shown in Figure 67. The fixed OPEX, as displayed in Figure 52 for transition and Figure 68. For BAU scenario are similar. The total values in the transition scenario are higher due to the bigger total capacity of all the units installed and used while also not completely decommissioning the old units that are not used by that time. The most notable difference is in the variable OPEX where the values related to the transition scenario displayed on Figure 53. reduce drastically when compared to the variable OPEX for BAU scenario on Figure 69.

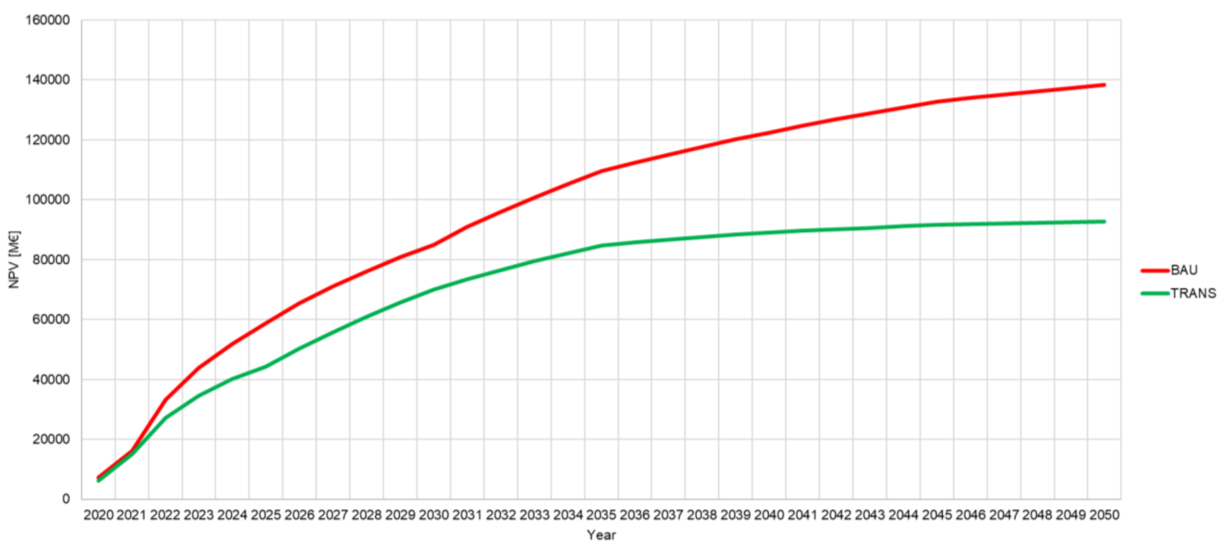

Figure 34. NPV of transition and BAU scenarios

5. CONCLUSION AND POLICY IMPLICATIONS

During this research, the model was developed and upgraded to provide the possibility of modelling and optimizing the transition towards renewable based energy system on the hourly level with the planning horizon of 30 years. The research compared two scenarios, one that enforced the transition towards a carbon-neutral energy system with the specific goal of eliminating gas consumption by 2035. The other was the BAU scenario which served as mainly an economics comparison to assess the cost of transition.

The model successfully decarbonized the system by 2050 and eliminated the gas use by 2035. To achieve this goal, investments into generating capacities consisting of 11964 MW in PV and 6015 MW in wind power were required. Also, investments into hydrogen generation, storage and transformation technologies were necessary to decarbonize industry and parts of the transport sector. These include 2444 MW of electrolysers and 17997 MWh of H2 storage which is sufficient for 17 hours of operation at maximum load. In the heating sector, part of the demand was transitioned to district heating where most of energy is supplied by the water-source heat pumps. In the individual systems, most of the demand was taken over by the air source heat pumps which are more applicable in the circumstances where the access to water and groundwater to extract ambient heat is limited. To achieve these goals, 1042 MW of heat pumps in district heating systems, 749 MW of electric boilers, 71 MW of geothermal heating, and 3000 MW of solar collectors are installed. In the individual systems, the installation are 2558 MW of heat pumps, 3958 MW of electric heaters and 37500 MW of solar thermal collectors. Due to the variability of the power supply in the system, both district heating and individual heating systems have installed significant quantities of electrical heaters that are aiding in energy system flexibility.

The total net present value of the transition scenario is 92,6 B€ and 138,29 B€ in BAU scenario. Therefore, the transition scenario displayed a significant decrease when compared to the BAU scenario resulting in the total net present value savings in the amount of 46,3 B€ by 2050. The BAU scenario is more expensive for almost all the years in the planning horizon, indicating the greater profitability of the transition scenario. With that said, the hypothesis is confirmed as the energy transition scenario is cheaper even though the large investments are required.

Main findings:

1. Required average annual installation of 400 MW of PV and 200 MW of wind power generation capacity.
2. In district heating systems annual installation of 60 MW of heat pumps and electric heaters, as well as 165 MW of solar collectors.
3. Average of 85 MW of heat pumps, 132 MW of electric heaters and 1250 MW of solar thermal collectors need to be annually installed in individual heating systems.
4. An average of 82 MW of electrolysers and 600 MWh of hydrogen storage have to be annually installed.
5. Transition scenario is cheaper in all years except for 2028 and 2029 due to the higher capital investments in the transition scenario for that period.

6. ACKNOWLEDGEMENT

This work has received support and funding by the Croatian Science Foundation through the project IP-2019-04-9482 INTERENERGY.

Felipe Feijoo was also supported by FONDECYT REGULAR 1221894, funded by ANID Chile.

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8. APPENDIX 1 - Additional results from transition scenario

Figure 35. Hourly distribution of heating in DH systems in Zagreb region inn transition scenario

Figure 36. Hourly distribution of heating in DH systems in the region of costal Croatia in transition scenario

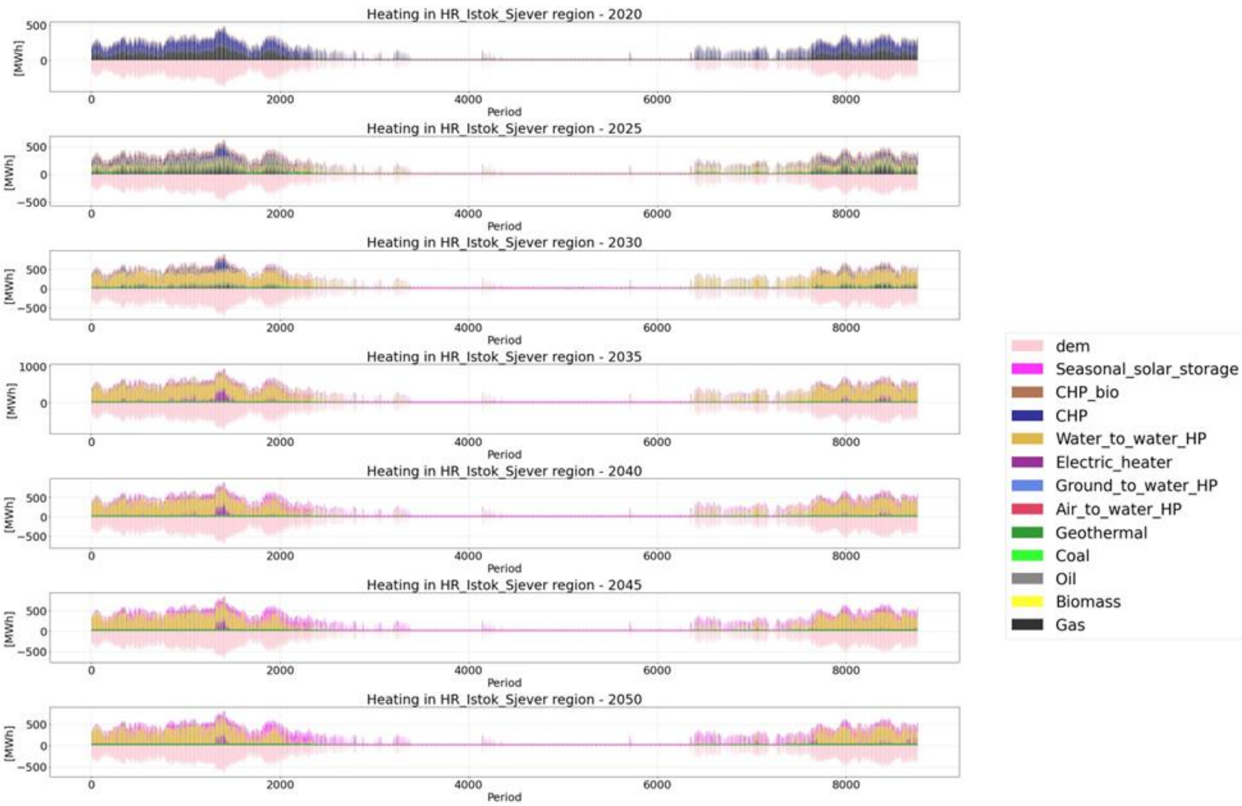

Figure 37. Hourly distribution of heating in DH systems in the region of continental Croatia in transition scenario

Table 9. Investments into district heating system generation capacities

Year	Zone	Air_to_water_HP	Electric_heater	Ground_to_water_HP	Water_to_water_HP	Biomass	Coal	Gas	Geothermal	Oil	Seasonal_solar_storage	Solar
2020	Continental Croatia	0	0	0	0	0	0	0	0	0	0	0
2025	Continental Croatia	1.3	4.51	0	100.02	0	0	0	49.66	0	50.05	50
2030	Continental Croatia	0.01	32.37	0	251.51	0	0	0	0.01	0	100.06	100
2035	Continental Croatia	0.01	314.2	0	52.75	0	0	0	0.03	0	200.07	200
2040	Continental Croatia	0	0.09	0	0.01	0	0	0	0.01	0	300	300
2045	Continental Croatia	0	0.2	0	0	0	0	0	0	0	499.97	300
2050	Continental Croatia	0	0.09	0	0	0	0	0	0	0	499.72	50
2020	Costal Croatia	0	0	0	0	0	0	0	0	0	0	0
2025	Costal Croatia	0.47	2.33	0	7.09	0	0	0	0	0	49.2	50
2030	Costal Croatia	0.46	3.5	0	26.11	0	0	0	0	0	98.67	99.99
2035	Costal Croatia	0.24	0.03	0	9.24	0	0	0	0	0	198.44	199.98

2040	Costal Croatia	0	0.29	0	0	0	0	0	0	0	297.16	299.89
2045	Costal Croatia	0	0.87	0	0	0	0	0	0	0	497.33	299.49
2050	Costal Croatia	0	0.15	0	0	0	0	0	0	0	494.68	50.4
2020	Zagreb region	0	0	0	0	0	0	0	0	0	0	0
2025	Zagreb region	80.75	2.83	0	100.06	0	0	0	20.07	0	50	50
2030	Zagreb region	0.01	4.18	0	297.95	0	0	0	1.55	0	100.01	100
2035	Zagreb region	0.07	383.14	0	113.98	0	0	0	0	0	200.04	200
2040	Zagreb region	0	0.08	0	0.01	0	0	0	0	0	299.97	300
2045	Zagreb region	0	0.17	0	0	0	0	0	0	0	499.95	300
2050	Zagreb region	0	0.09	0	0	0	0	0	0	0	499.7	50

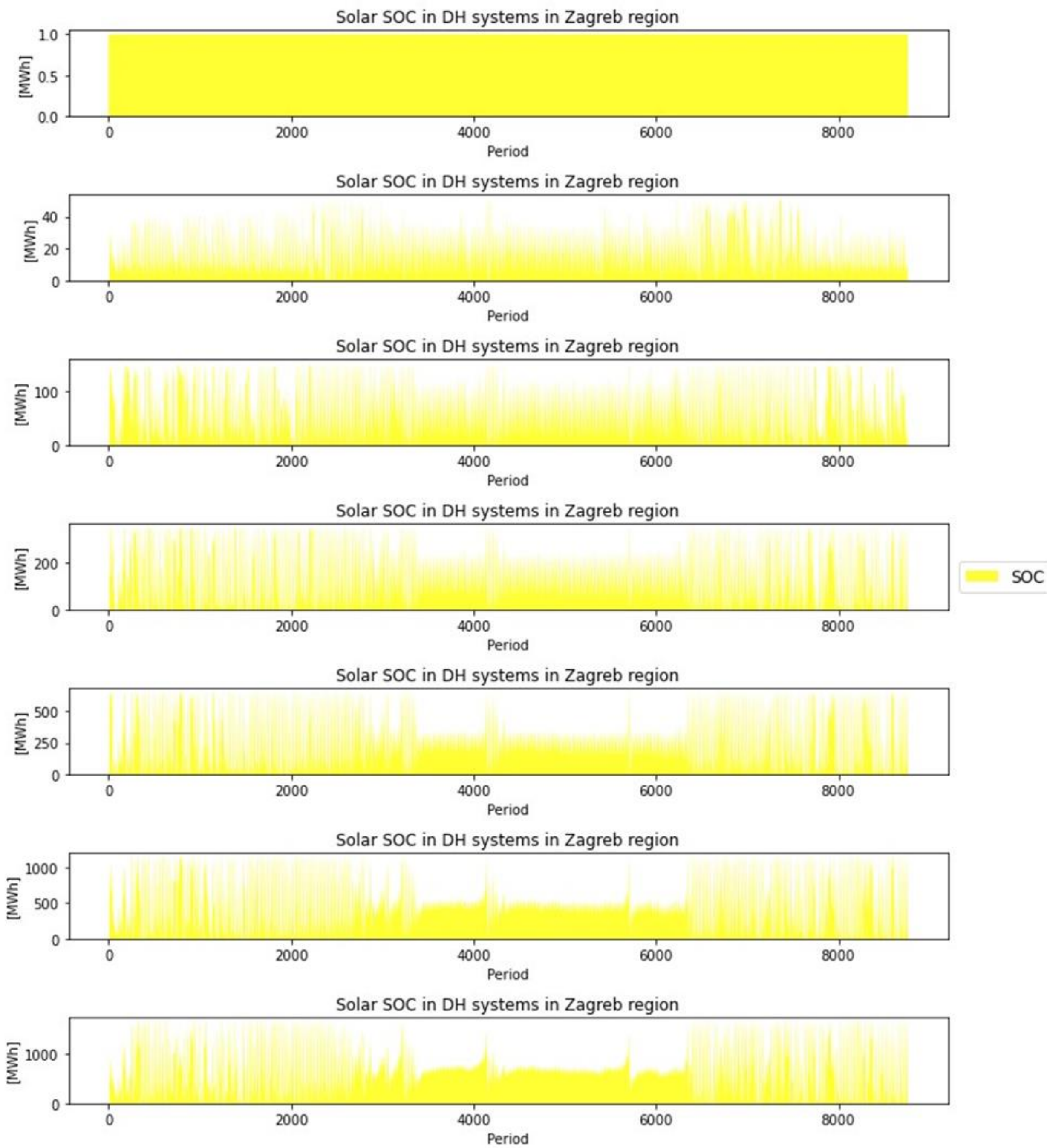

Figure 38. SOC of solar heat storage in Zagreb region in transition scenario

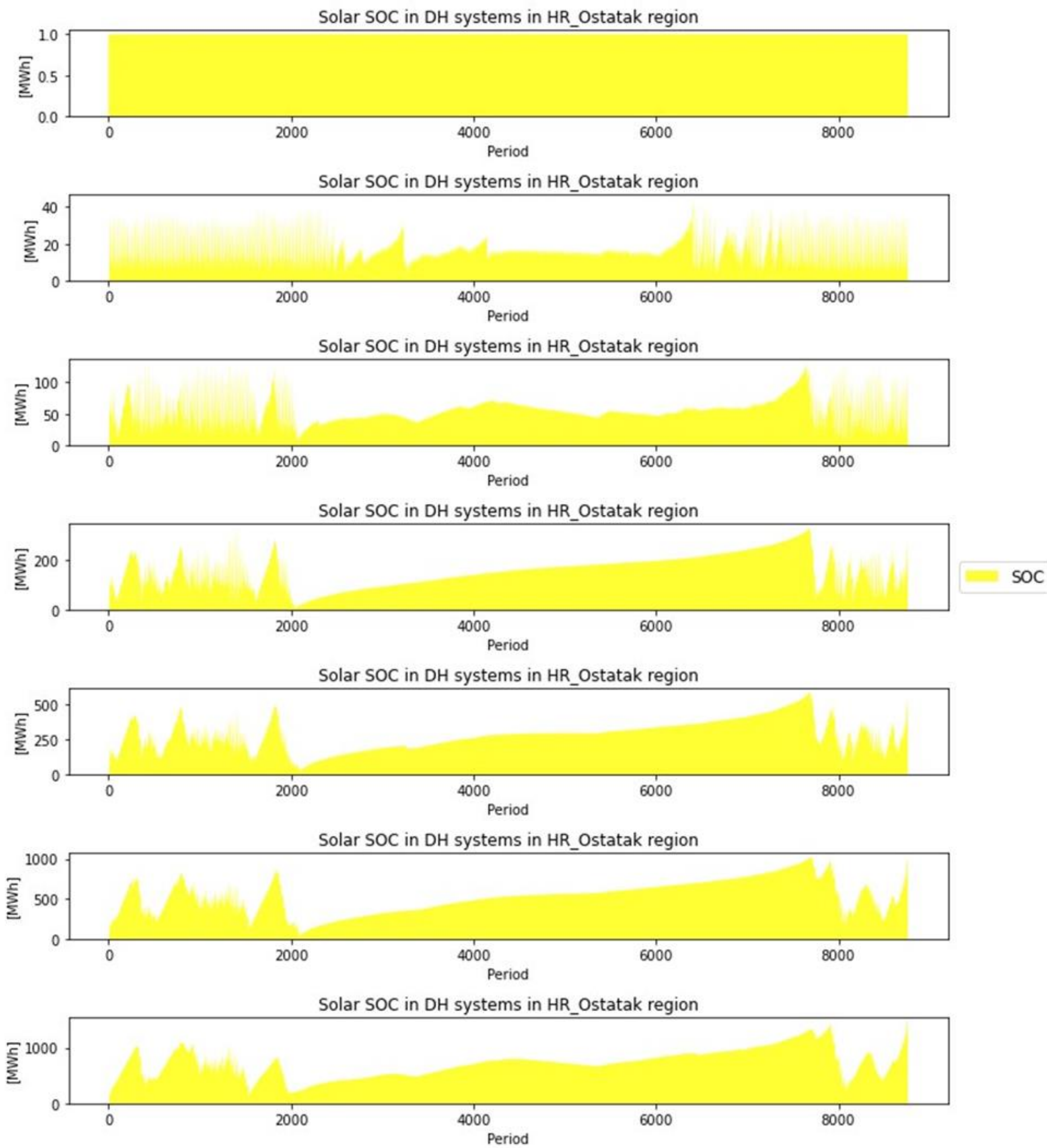

Figure 39. SOC of solar heat storage in the region of costal Croatia region in transition scenario

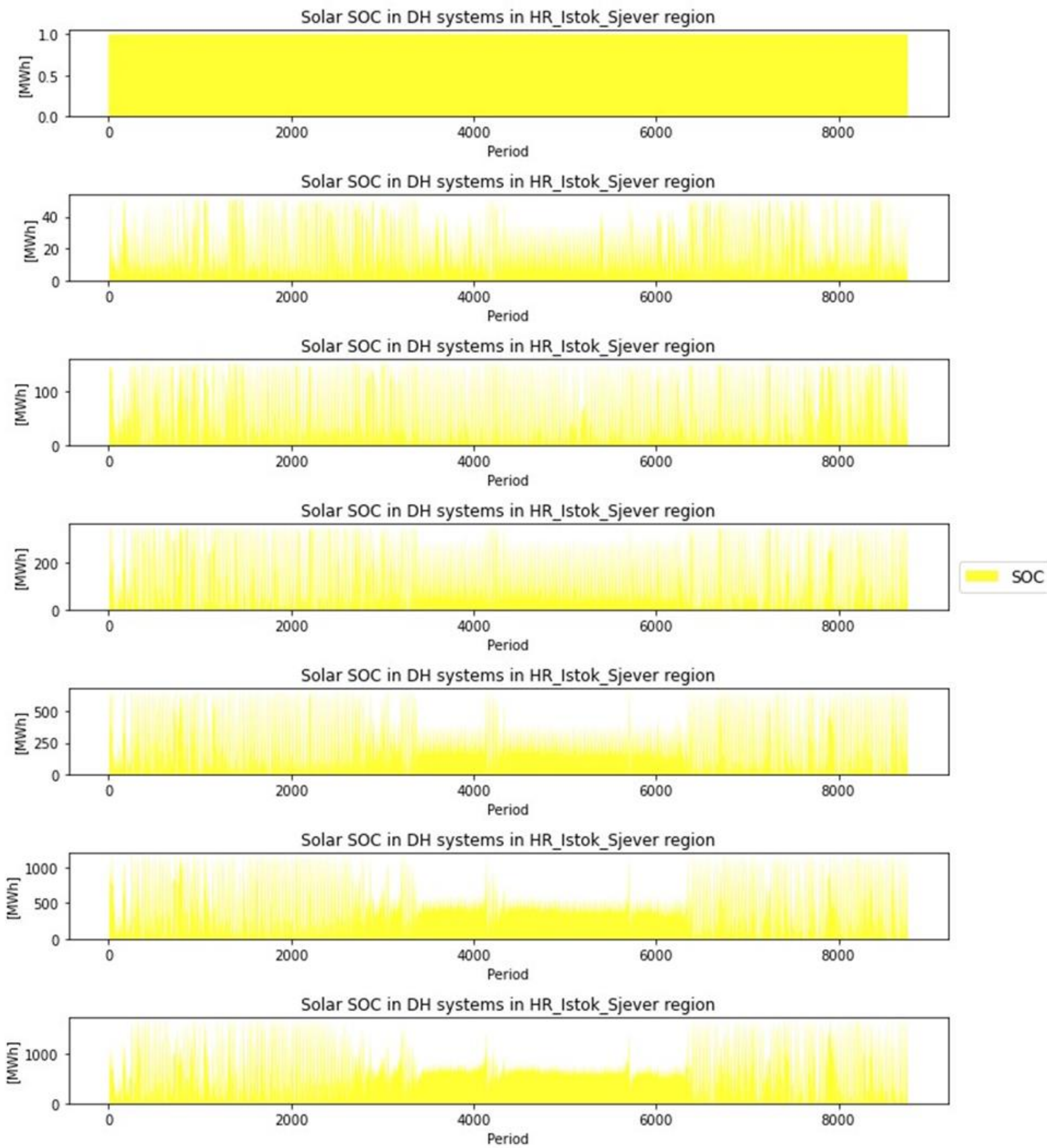

Figure 40. SOC of solar heat storage in the region of continental Croatia in transition scenario

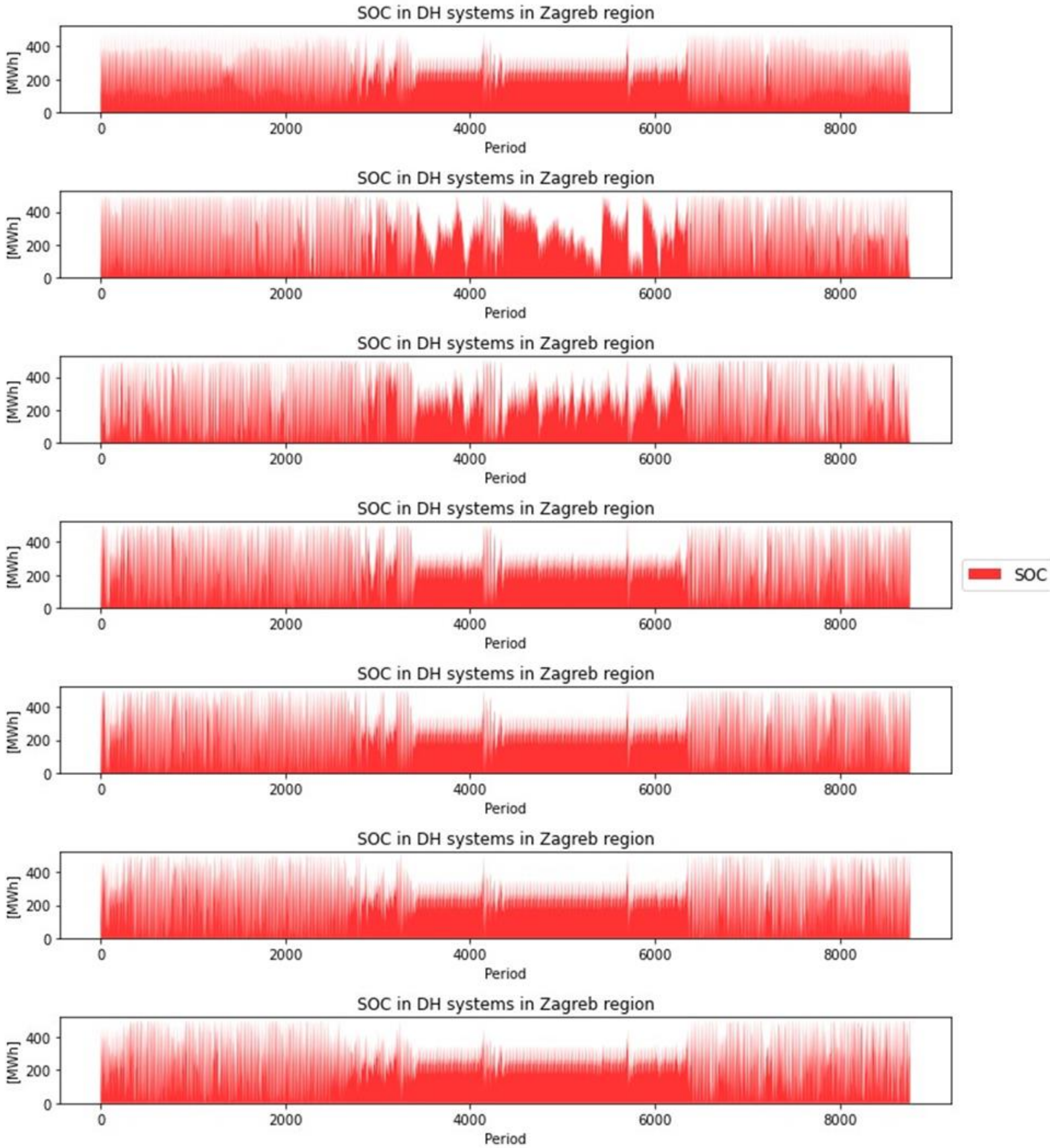

Figure 41. SOC of heat storage in Zagreb region DH system in transition scenario

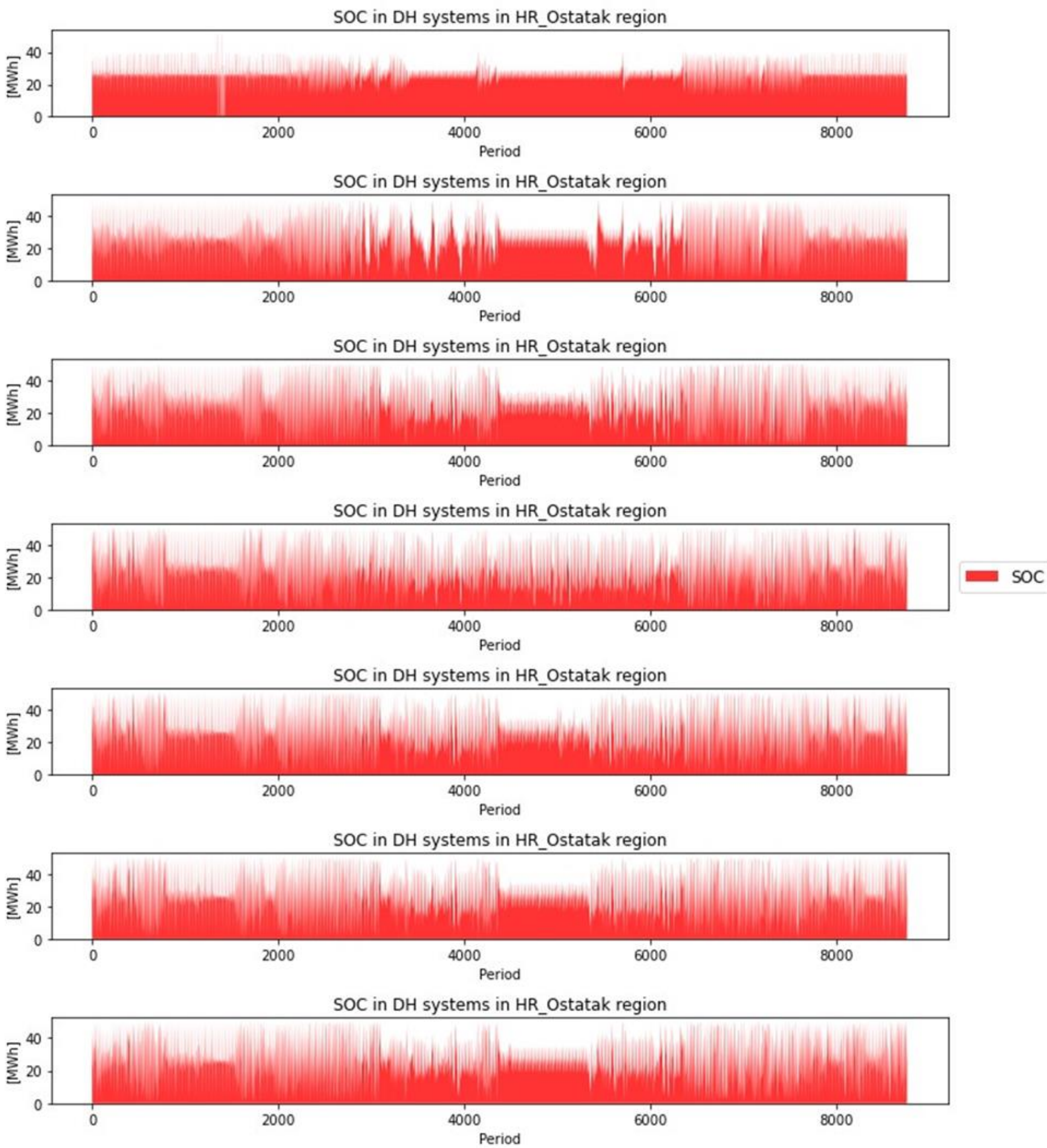

Figure 42. SOC of heat storage in the region of costal Croatia DH system in transition scenario

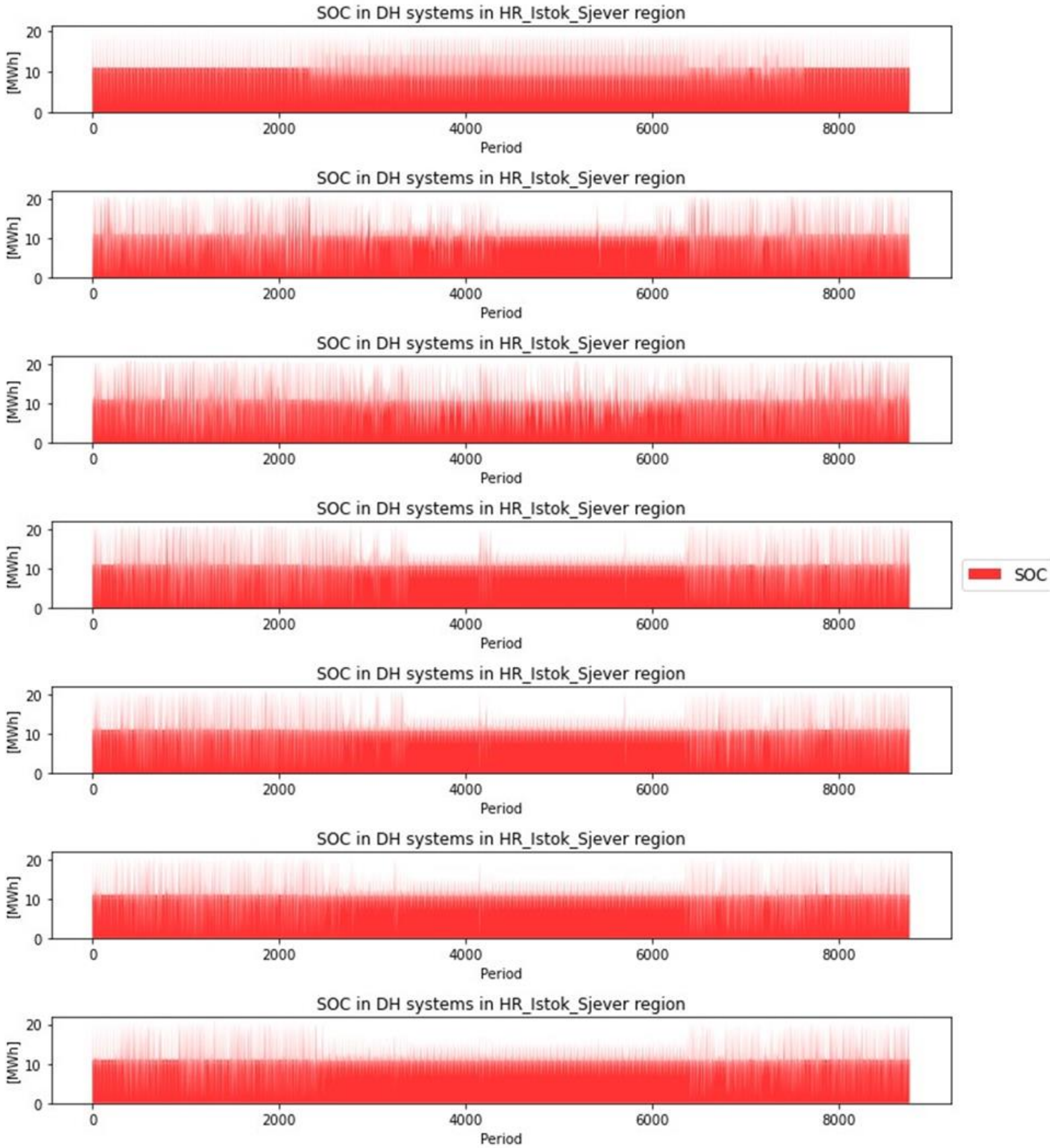

Figure 43. SOC of heat storage in the region of continental Croatia DH system in transition scenario

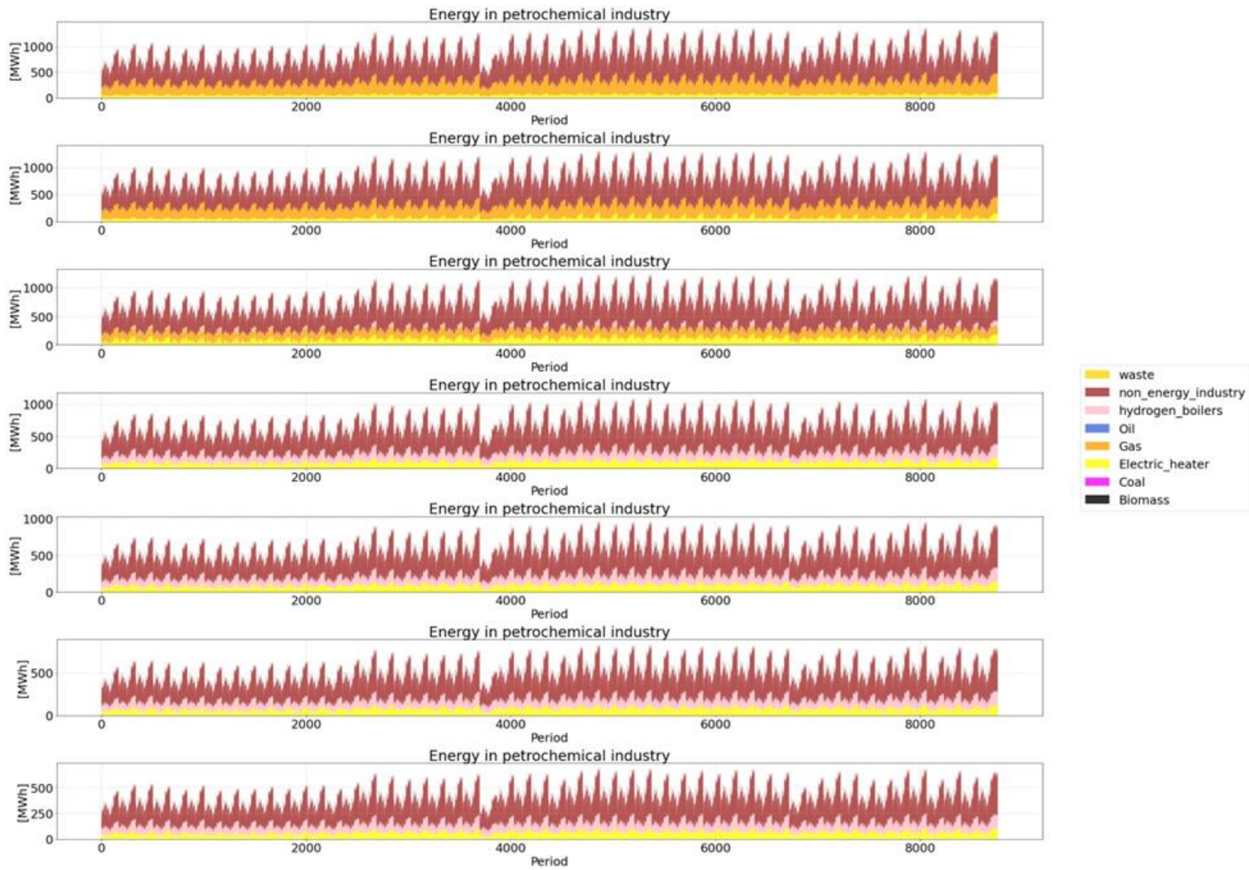

Figure 44. Energy use in petrochemical industry subsector in transition scenario

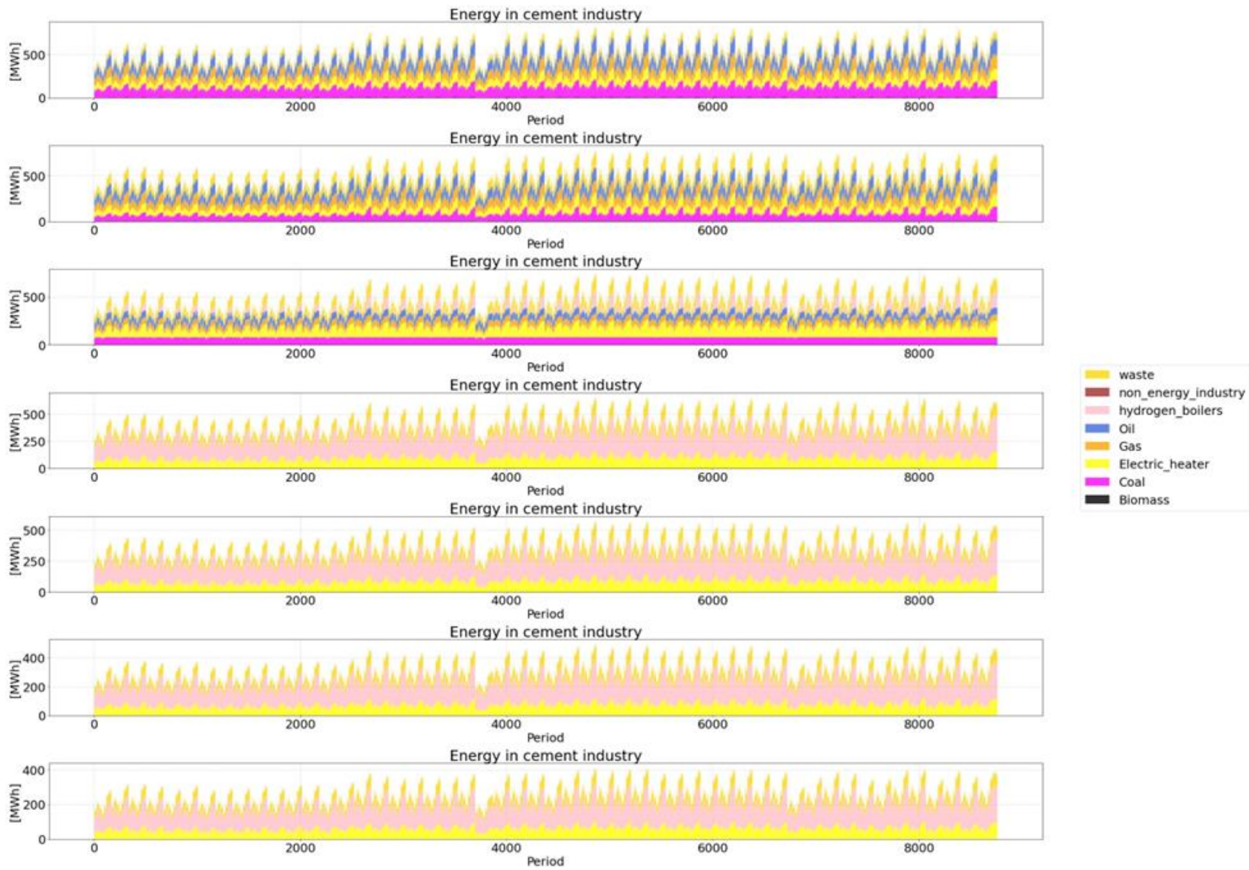

Figure 45. Energy use in cement industry subsector in transition scenario

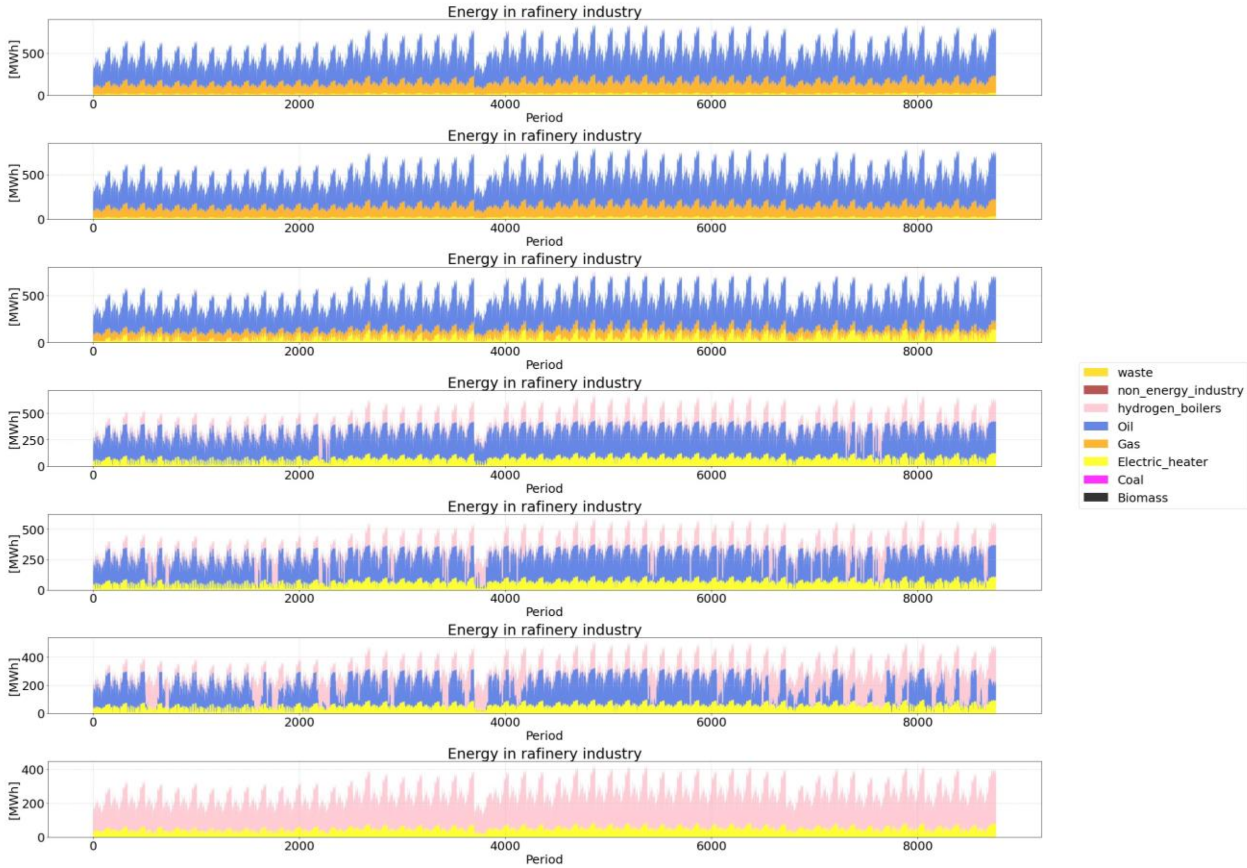

Figure 46. Energy use in refinery industry subsector in transition scenario

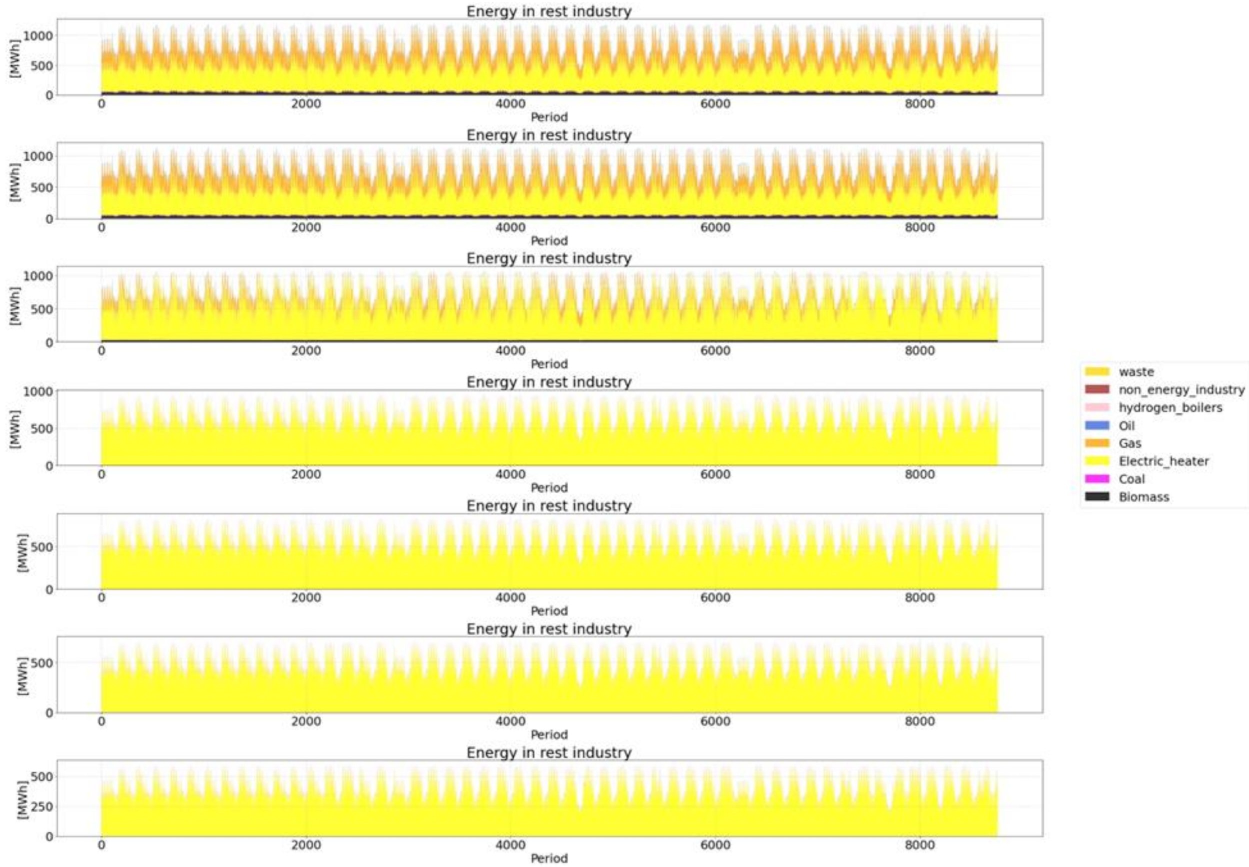

Figure 47. Energy use in the remainder of industry in transition scenario

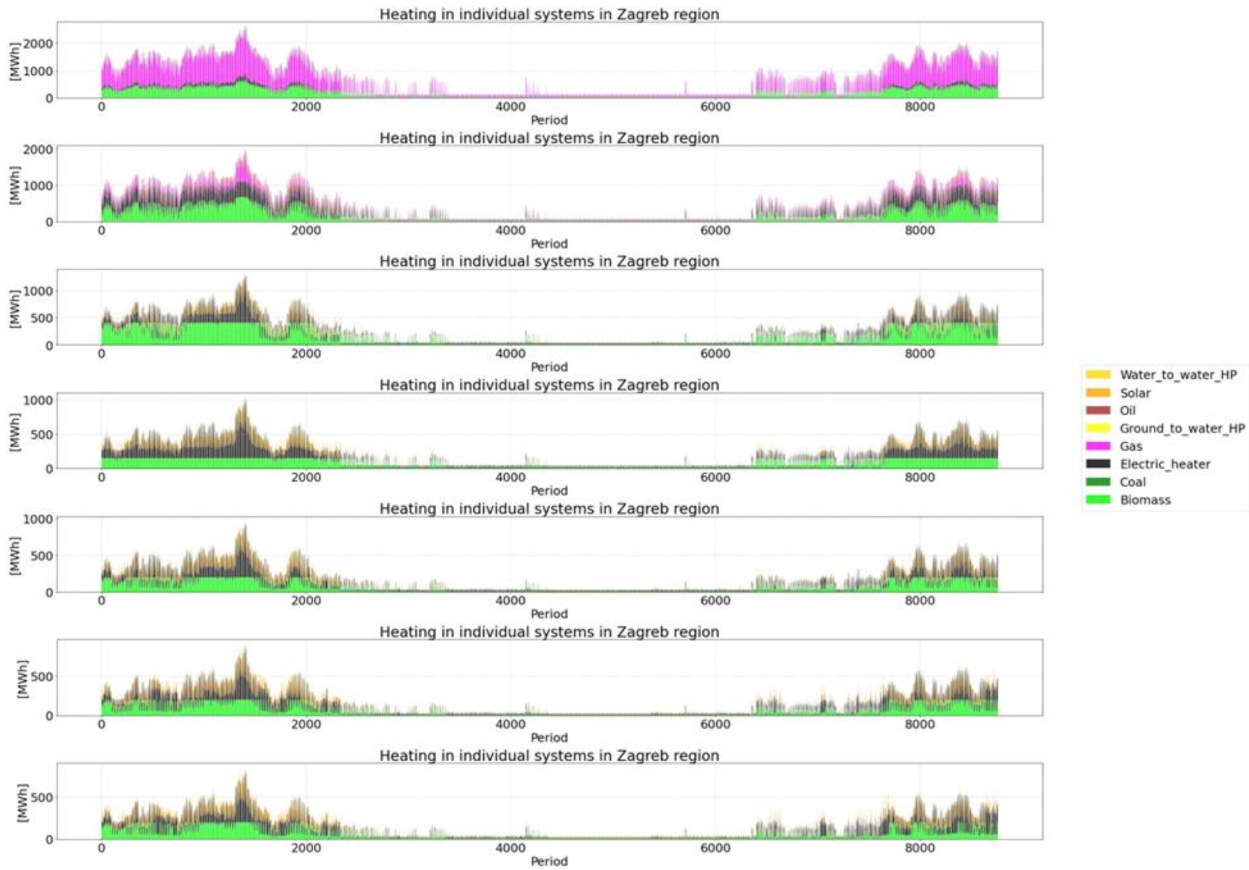

Figure 48. Heating in individual systems in Zagreb region in transition scenario

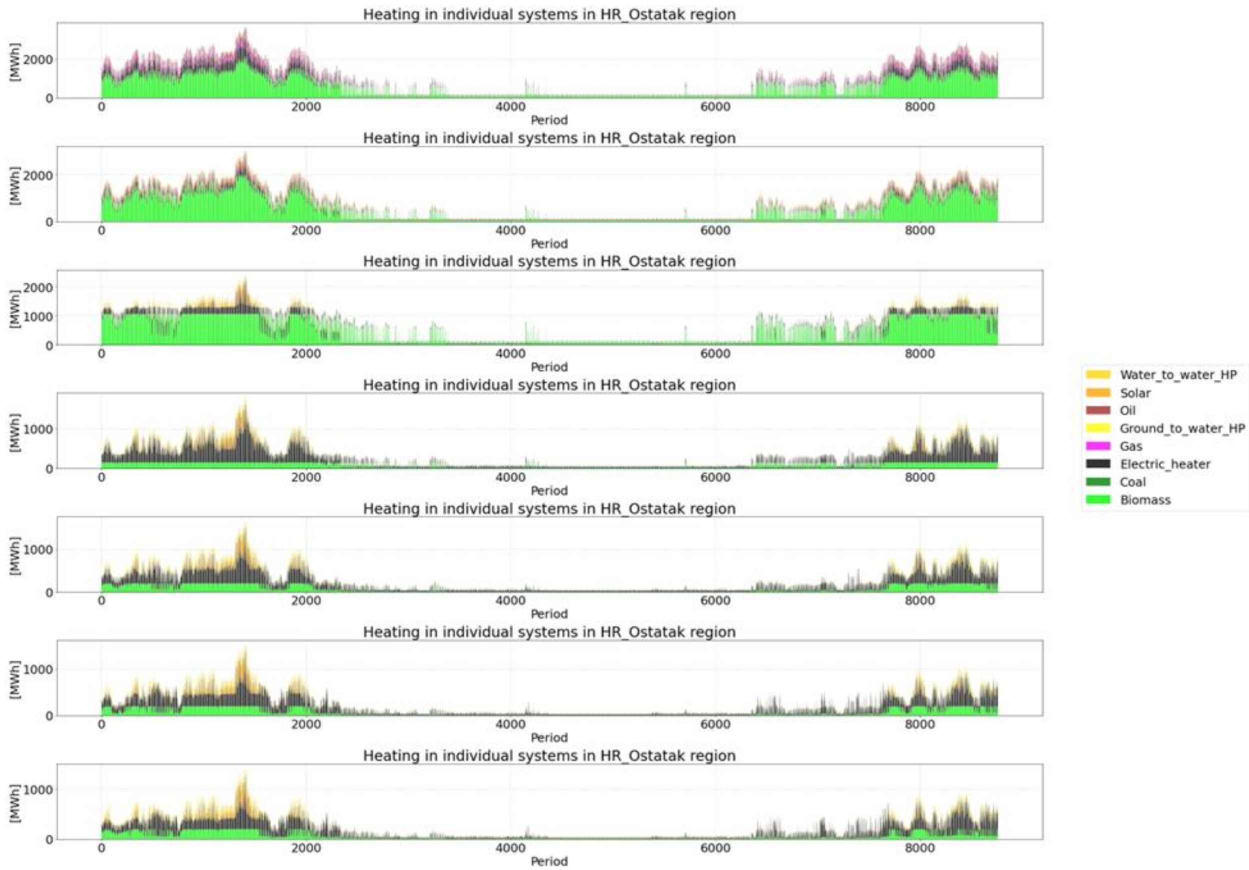

Figure 49. Heating in individual systems in the region of costal Croatia in transition scenario

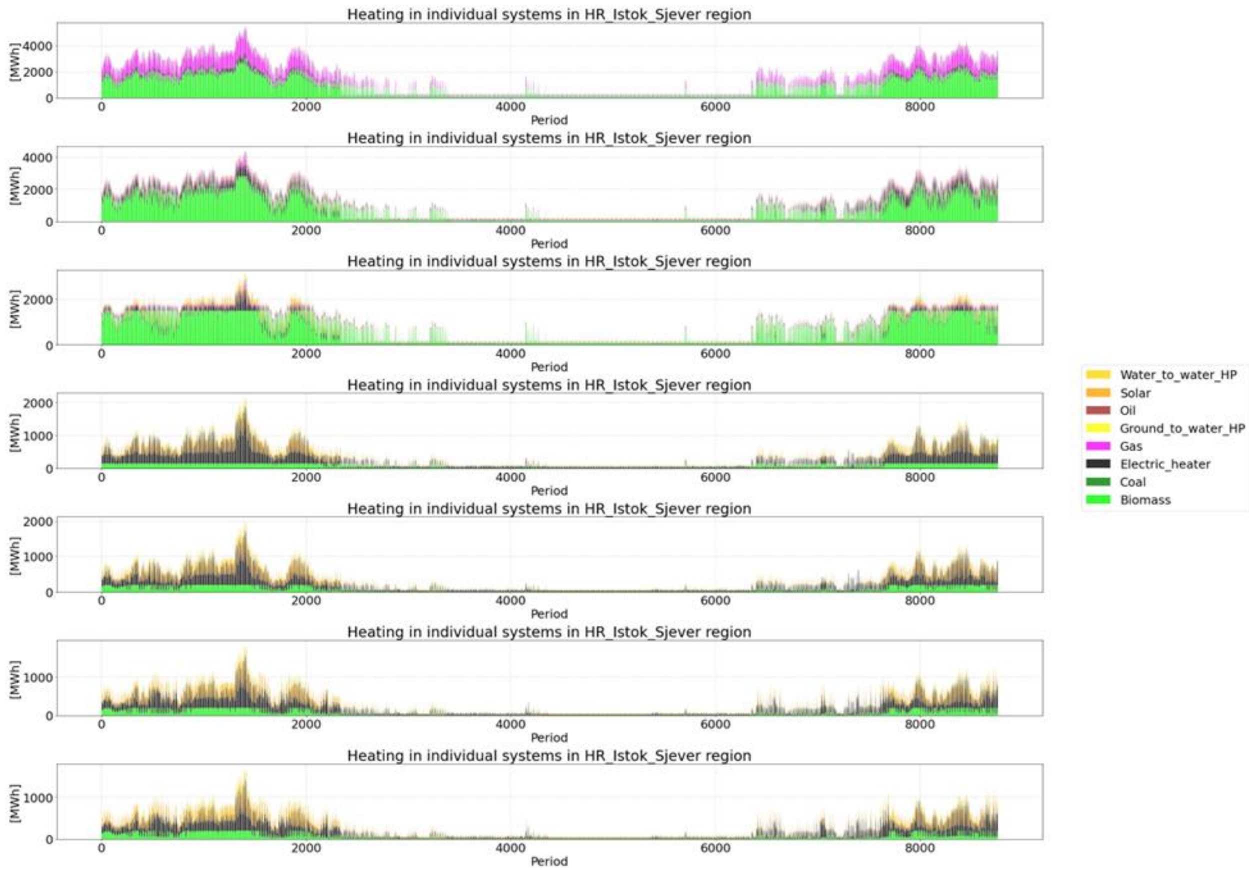

Figure 50. Heating in individual systems in the region of continental Croatia in transition scenario

Table 10. Investments into individual heating system generation capacities

Year	Zone	Air_to_water_HP	Electric_heater	Ground_to_water_HP	Water_to_water_HP	Biomass	Coal	Gas	Geothermal	Oil	Solar
2020	Continental Croatia	0	0	0	0	0	0	0	0	0	0
2025	Continental Croatia	0	0	0	44.75	0	0	0	0	0	500
2030	Continental Croatia	0	0	0	156.79	0	0	0	0	0	1000
2035	Continental Croatia	200.04	200.04	0	0.01	50.13	0	0	0	0	2000
2040	Continental Croatia	200	200.01	0	0.01	50.12	0	0	0	0	3000
2045	Continental Croatia	200	175.86	0	0.01	50.12	0	0	0	0	3000
2050	Continental Croatia	158.7	497.99	0	0	50.13	0	0	0	0	3000
2020	Costal Croatia	499.82	500.05	0	0	50.13	0	0	0	0	0
2025	Costal Croatia	246.58	499.87	0	42.75	50.12	0	0	0	0	500
2030	Costal Croatia	0.03	116.36	0	52.79	50.12	0	0	0	0	1000

2035	Costal Croatia	411.77	1000.01	0	0.03	50.12	0	0	0	0	2000
2040	Costal Croatia	339.4	766.42	0	0.02	50.12	0	0	0	0	3000
2045	Costal Croatia	0.03	0.04	0	0.01	49.97	0	0	0	0	3000
2050	Costal Croatia	0.05	0.16	0	0	49.97	0	0	0	0	3000
2020	Zagreb region	0.03	0.01	0	0	50.01	0	0	0	0	0
2025	Zagreb region	0	0.24	0	3.93	0.04	0	0	0	0	500
2030	Zagreb region	0	0.13	0	0.35	0.05	0	0	0	0	1000
2035	Zagreb region	0	0.12	0	0.01	0.04	0	0	0	0	2000
2040	Zagreb region	0	0.09	0	0.03	0.02	0	0	0	0	3000
2045	Zagreb region	0	0.07	0	0.01	0.02	0	0	0	0	3000
2050	Zagreb region	0	0.09	0	0	0.01	0	0	0	0	3000

Table 11. Investments into vehicles

Year	EV_car	FCEV_car	HYBRID_car	ICE_car	PHEV_car
2020	0	0	0	0	0
2025	51024	500	199795	0	20000
2030	499739	5000	103	0	99759
2035	452583	0	7	0	1
2040	2	0	1	8	1
2045	5	0	9	15	2
2050	0	0	0	0	0

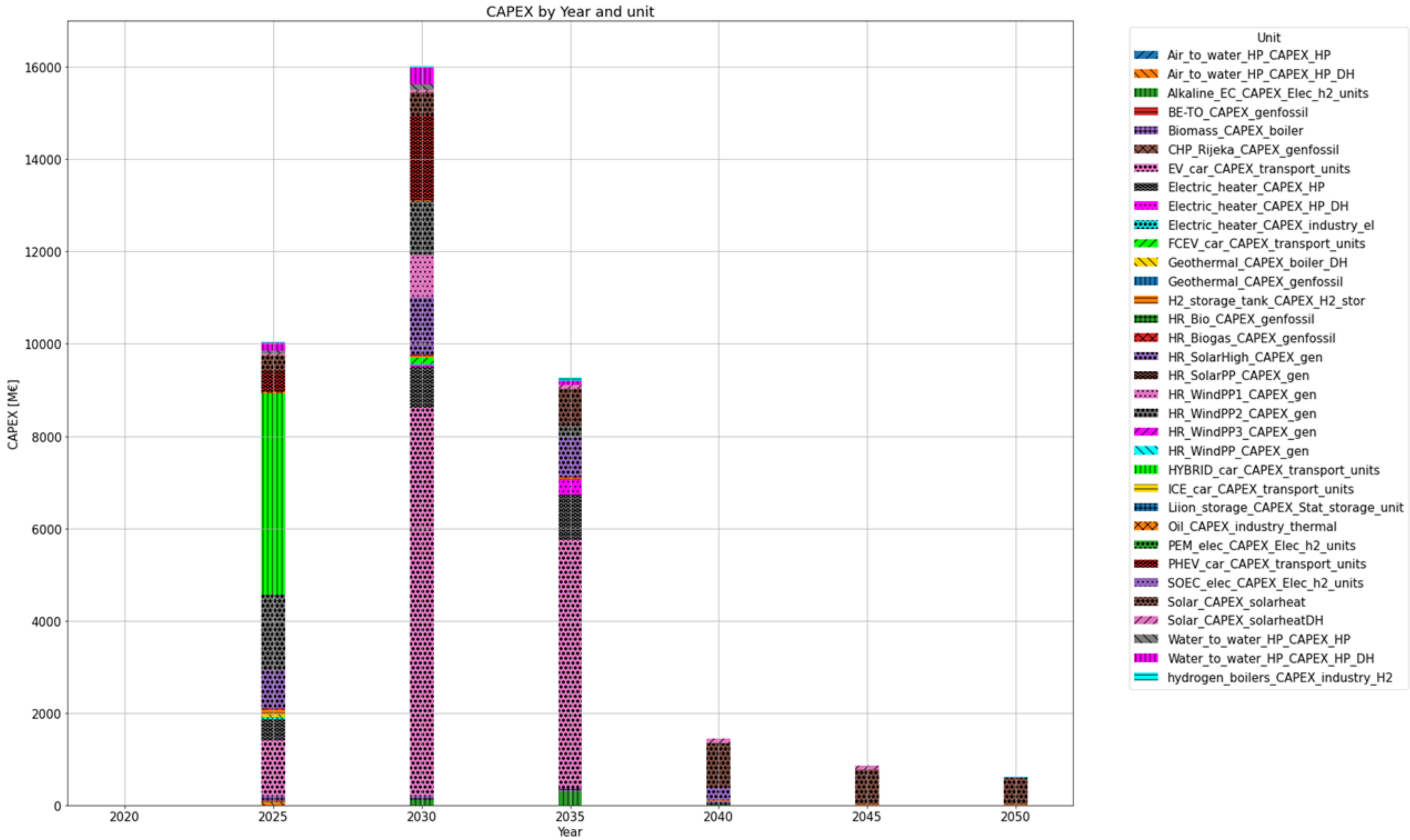

Figure 51. CAPEX in transition scenario

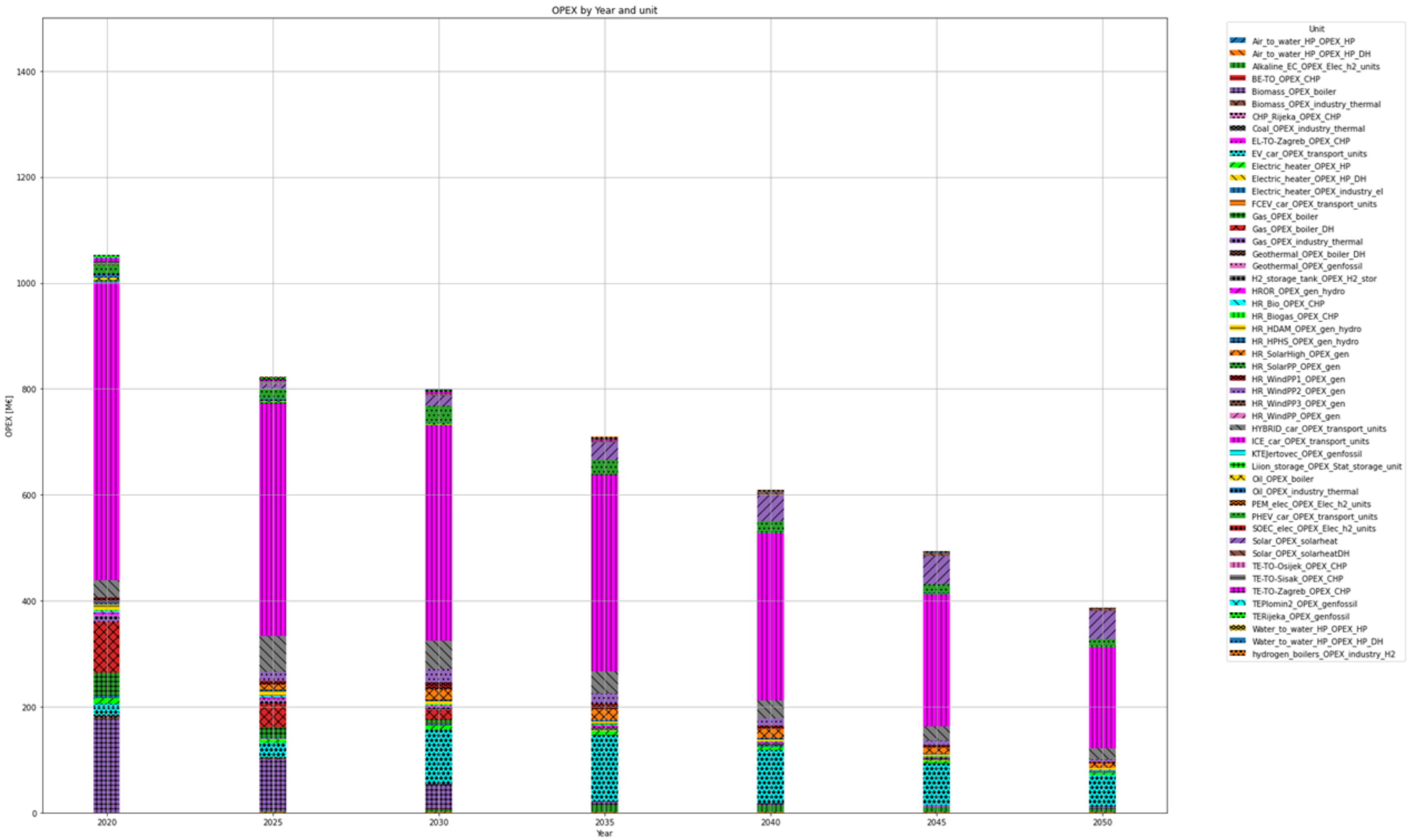

Figure 52. Fixed OPEX in transition scenario

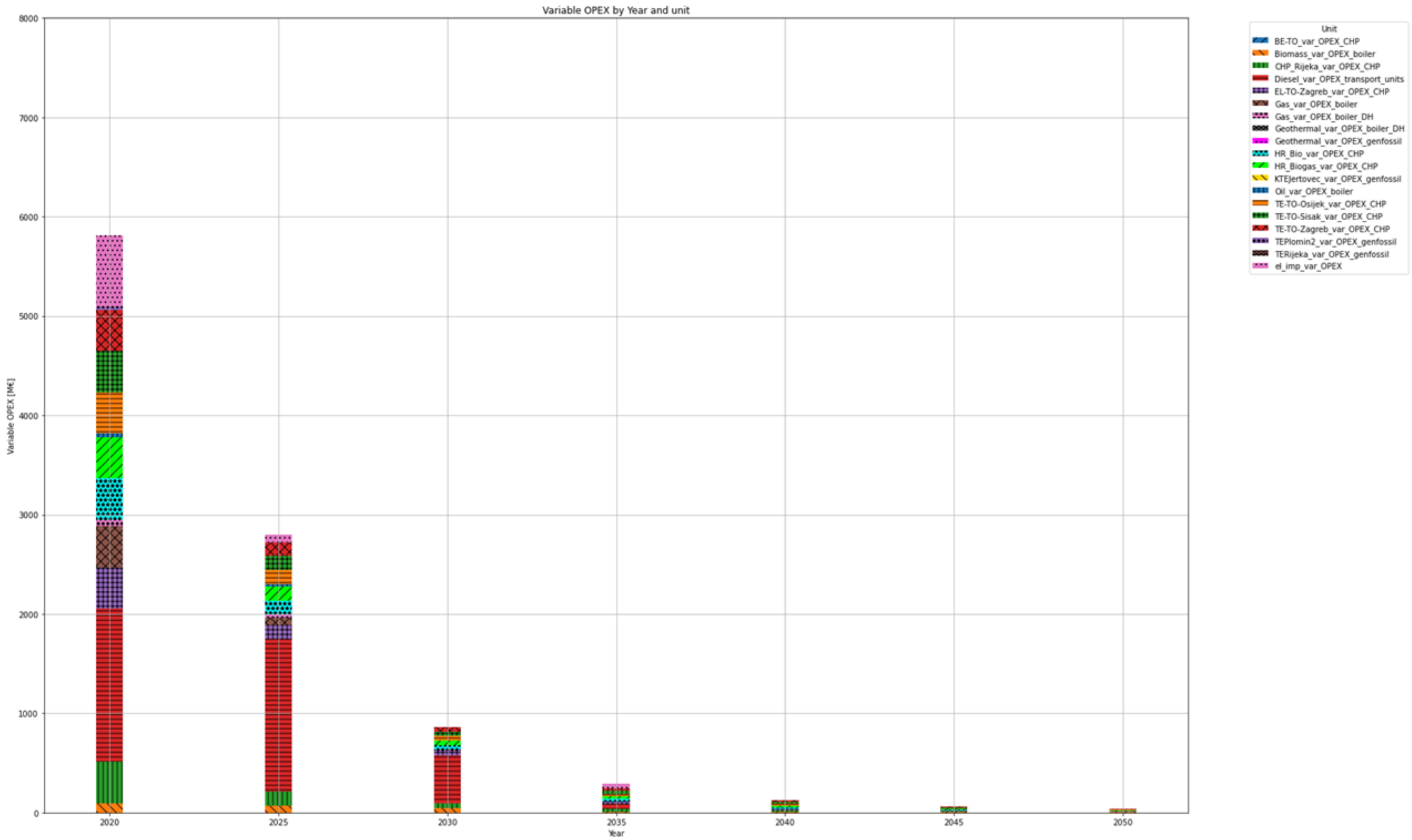

Figure 53. Variable OPEX in transition scenario

9. APPENDIX BAU - Additional results from BAU scenario

Figure 54. Hourly distribution of heating in DH systems in Zagreb region in BAU scenario

Figure 55. Hourly distribution of heating in DH systems in the region of costal Croatia in BAU scenario

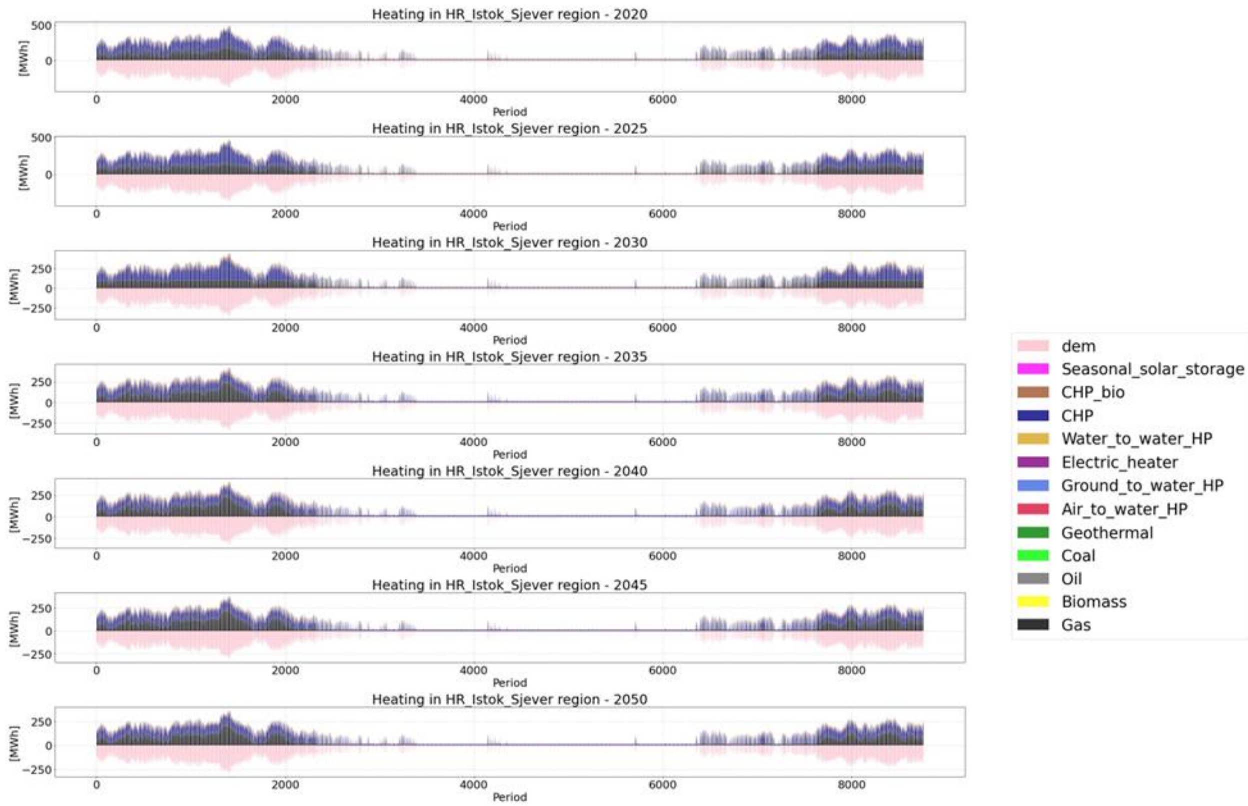

Figure 56. Hourly distribution of heating in DH systems in the region of continental Croatia in BAU scenario

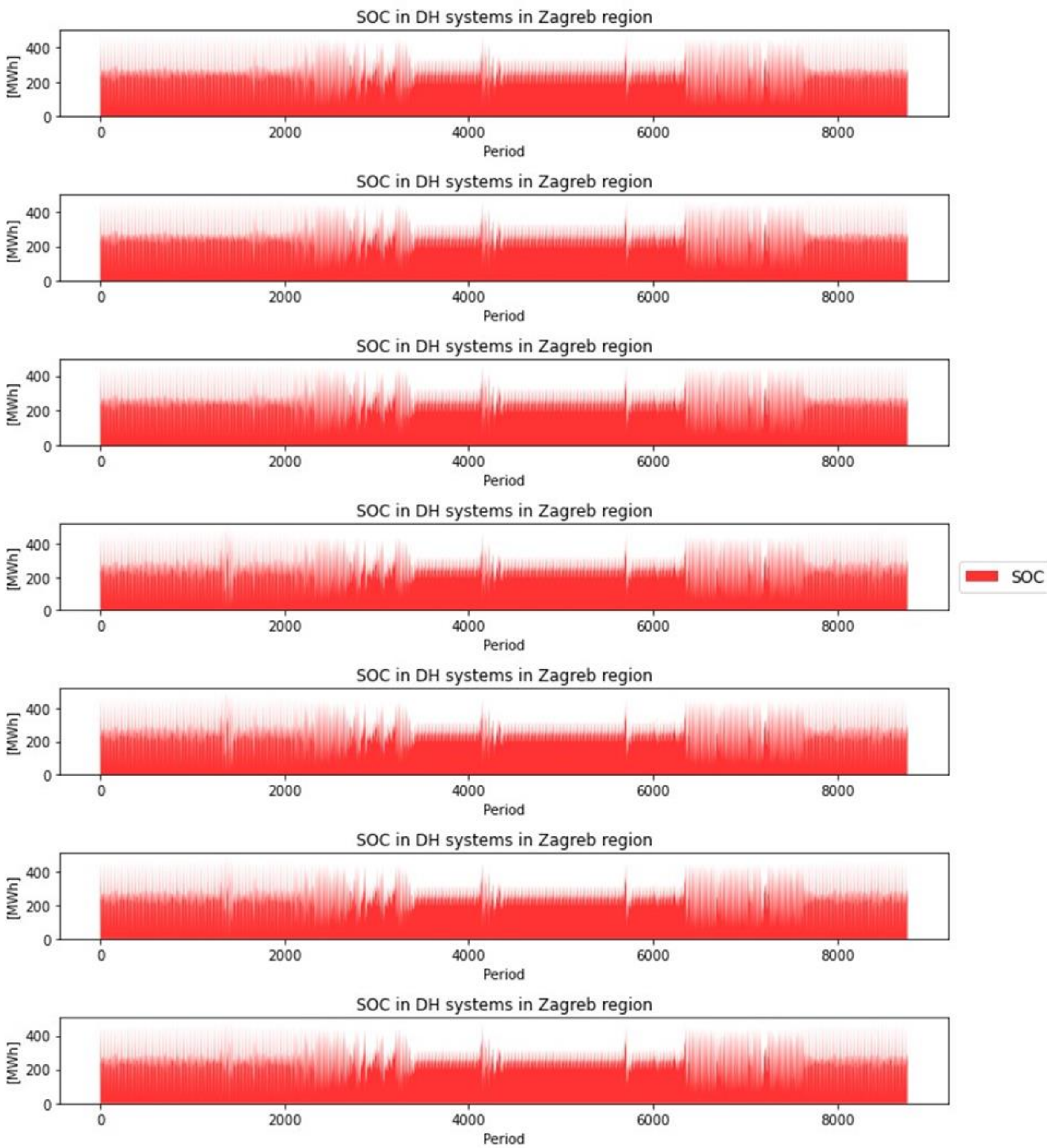

Figure 57. SOC of heat storage in Zagreb region DH system in BAU scenario

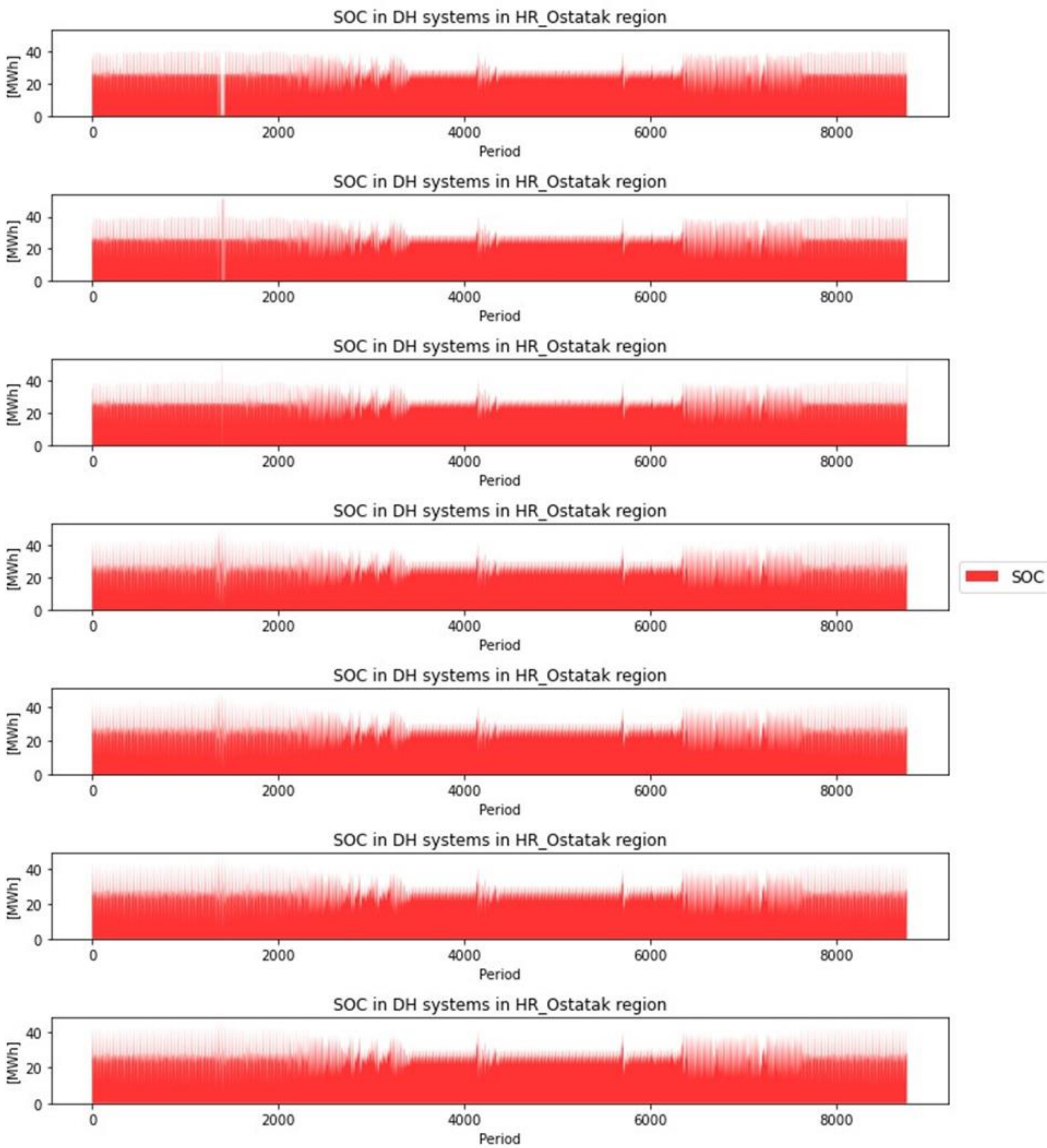

Figure 58. SOC of heat storage in the region of costal Croatia DH system in BAU scenario

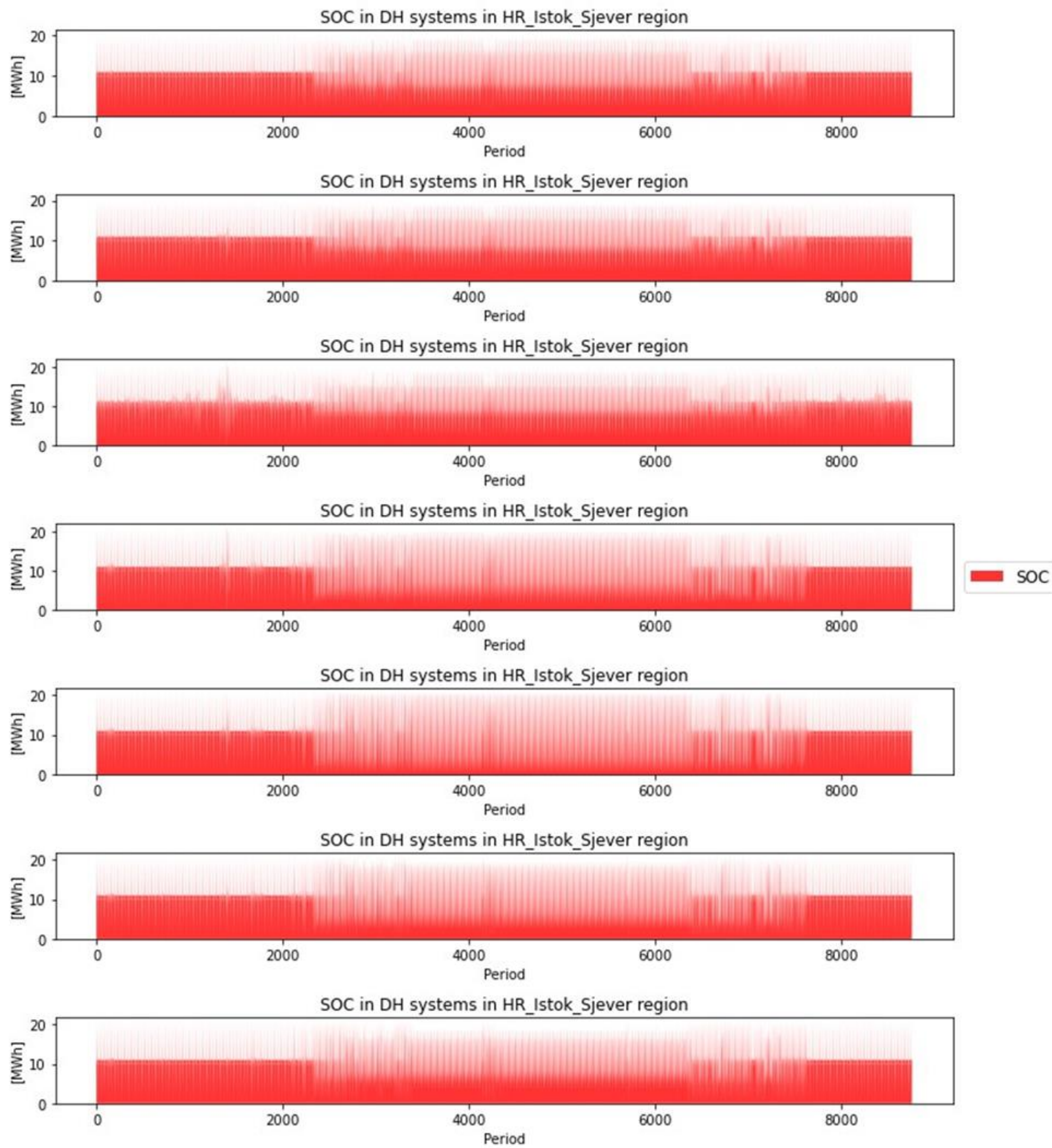

Figure 59. SOC of heat storage in the region of continental Croatia DH system in BAU scenario

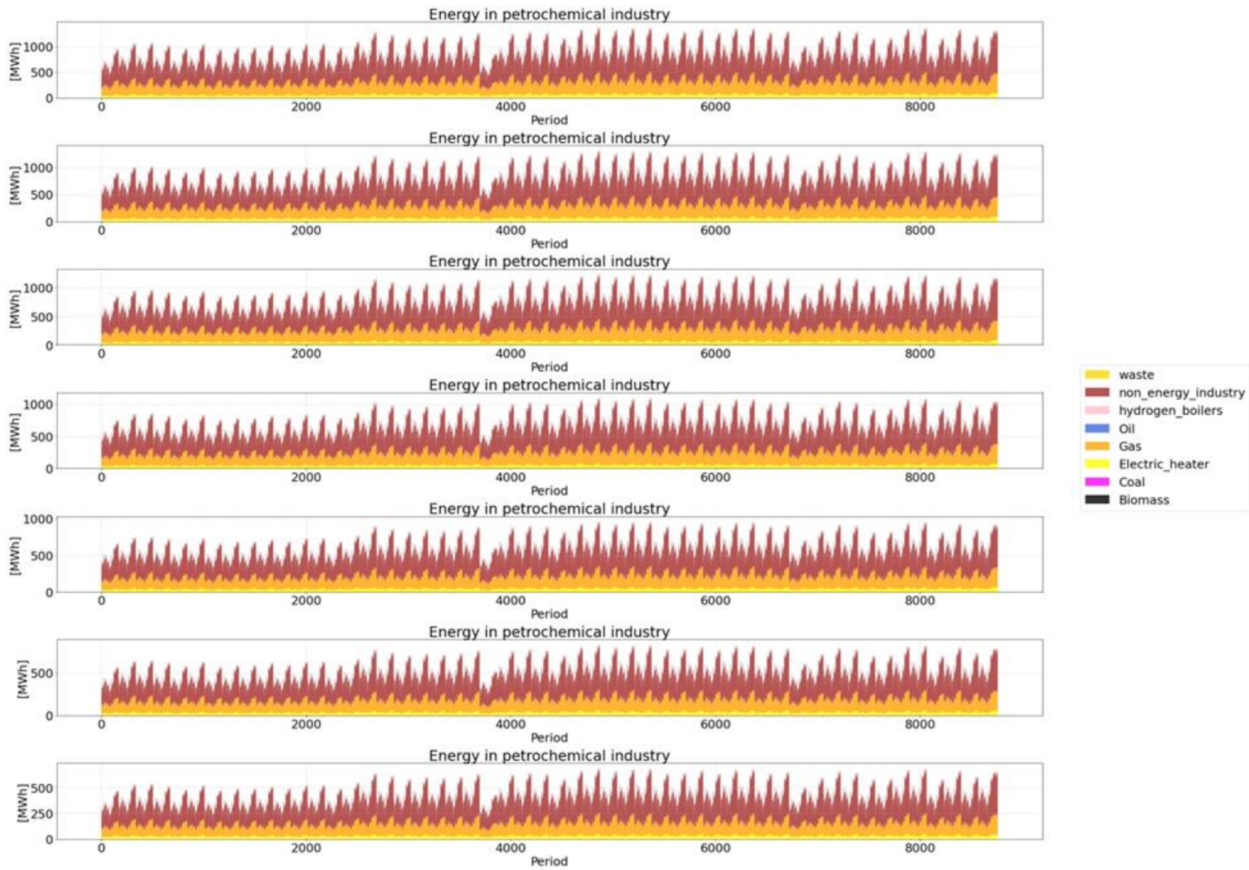

Figure 60. Energy use in petrochemical industry subsector in BAU scenario

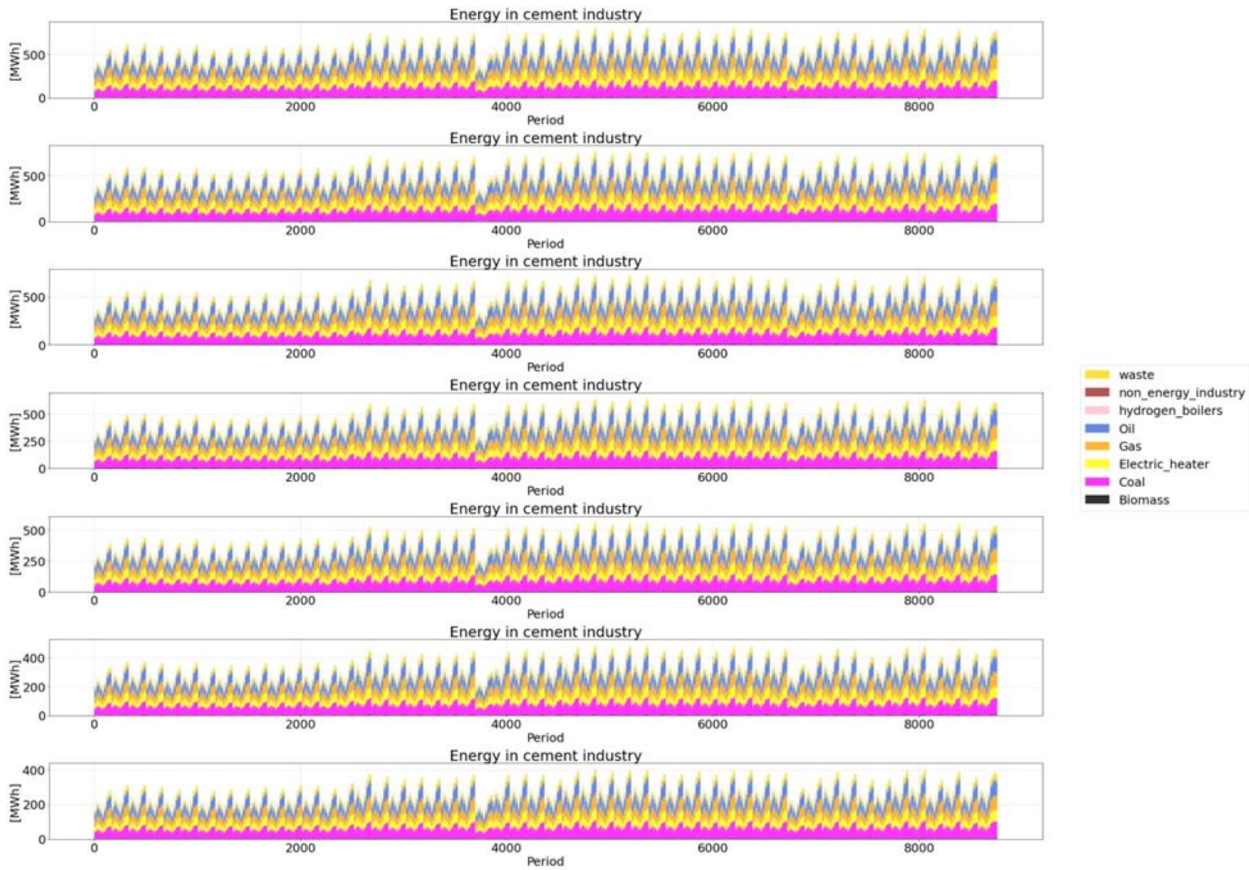

Figure 61. Energy use in cement industry subsector in BAU scenario

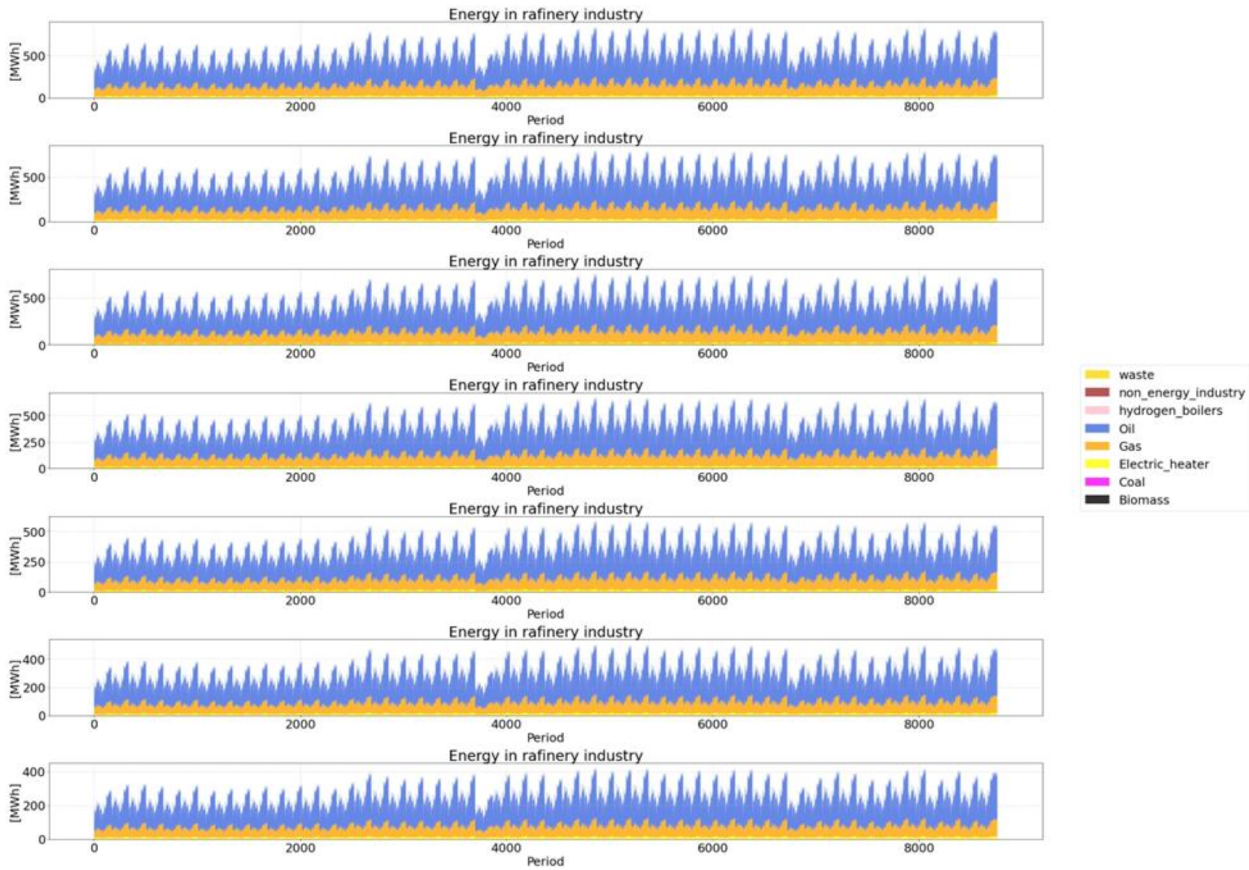

Figure 62. Energy use in refinery industry subsector in BAU scenario

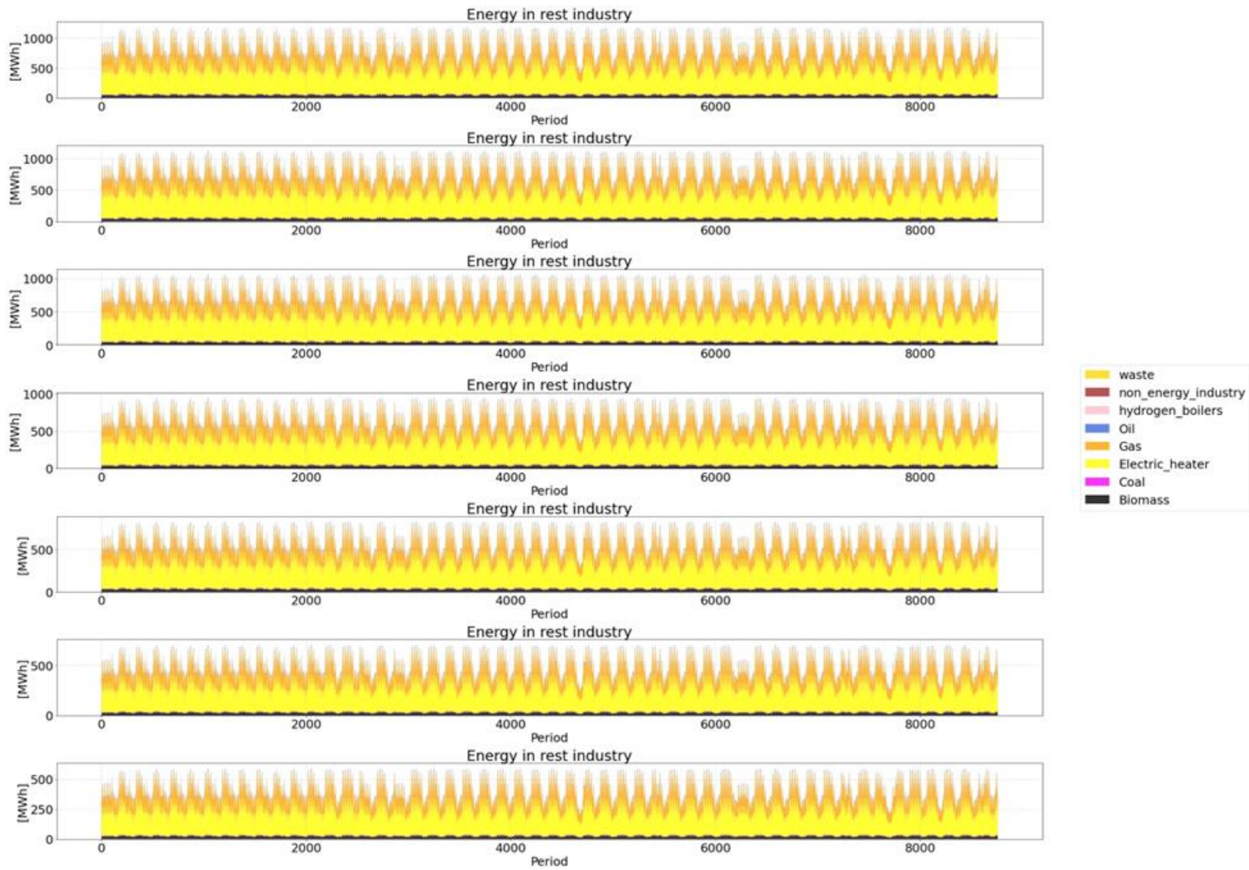

Figure 63. Energy use in the remainder of industry in BAU scenario

Figure 64. Heating in individual systems in Zagreb region in BAU scenario

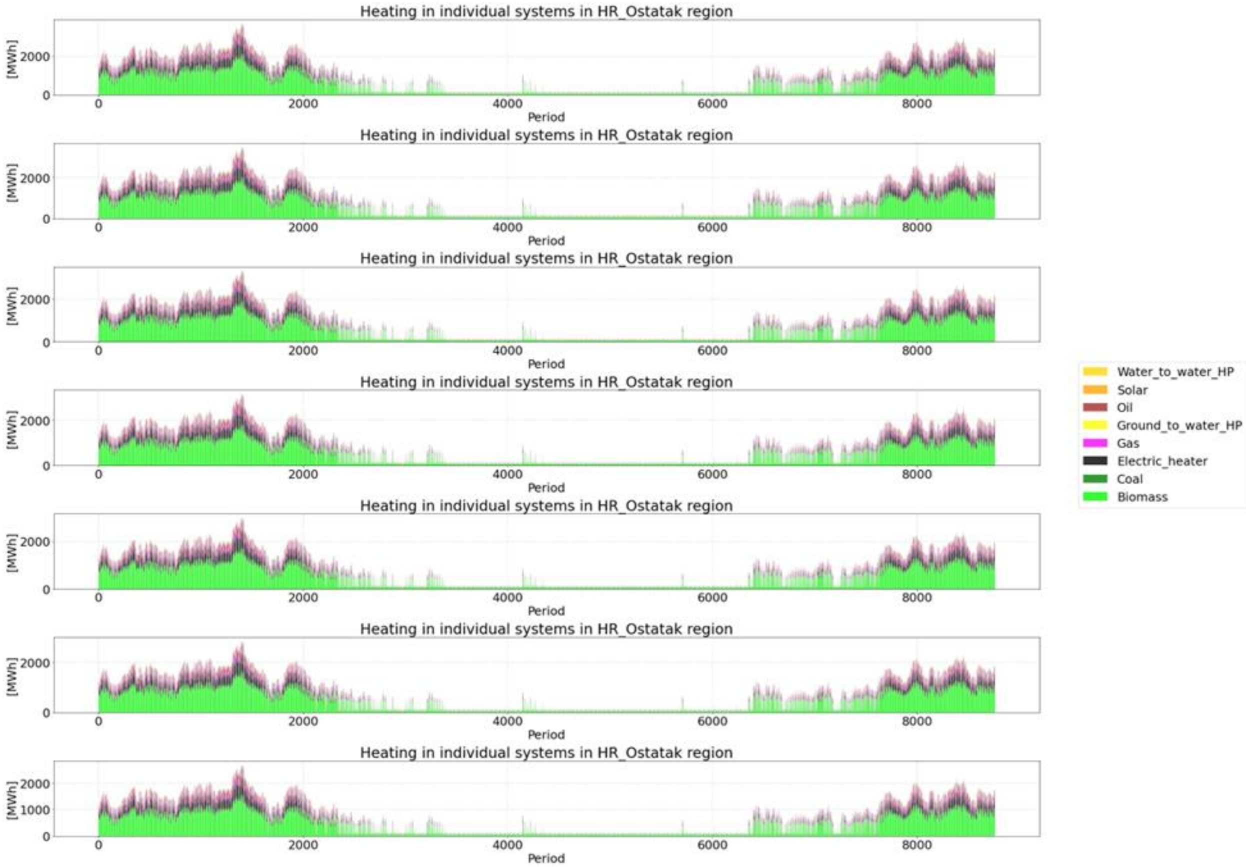

Figure 65. Heating in individual systems in the region of costal Croatia in BAU scenario

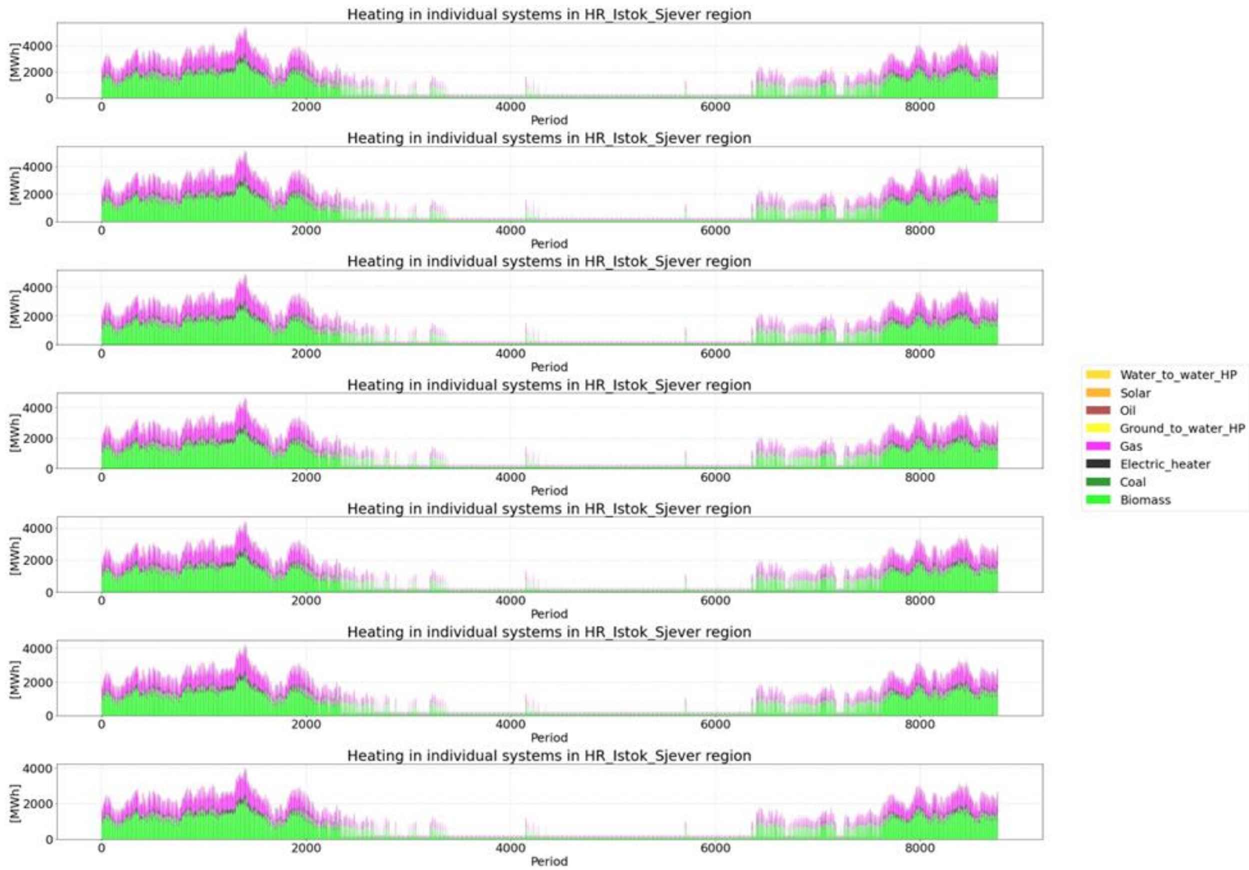

Figure 66. Heating in individual systems in the region of continental Croatia in BAU scenario

Table 12. Investments into vehicles in BAU scenario

Year	EV_car	FCEV_car	HYBRID_car	ICE_car	PHEV_car
2020	0	0	0	0	0
2025	925	0	3700	0	0
2030	925	0	3700	0	0
2035	1387	0	5550	618099	0
2040	694	0	2775	343374	0
2045	694	0	2775	343374	0
2050	0	0	0	0	0

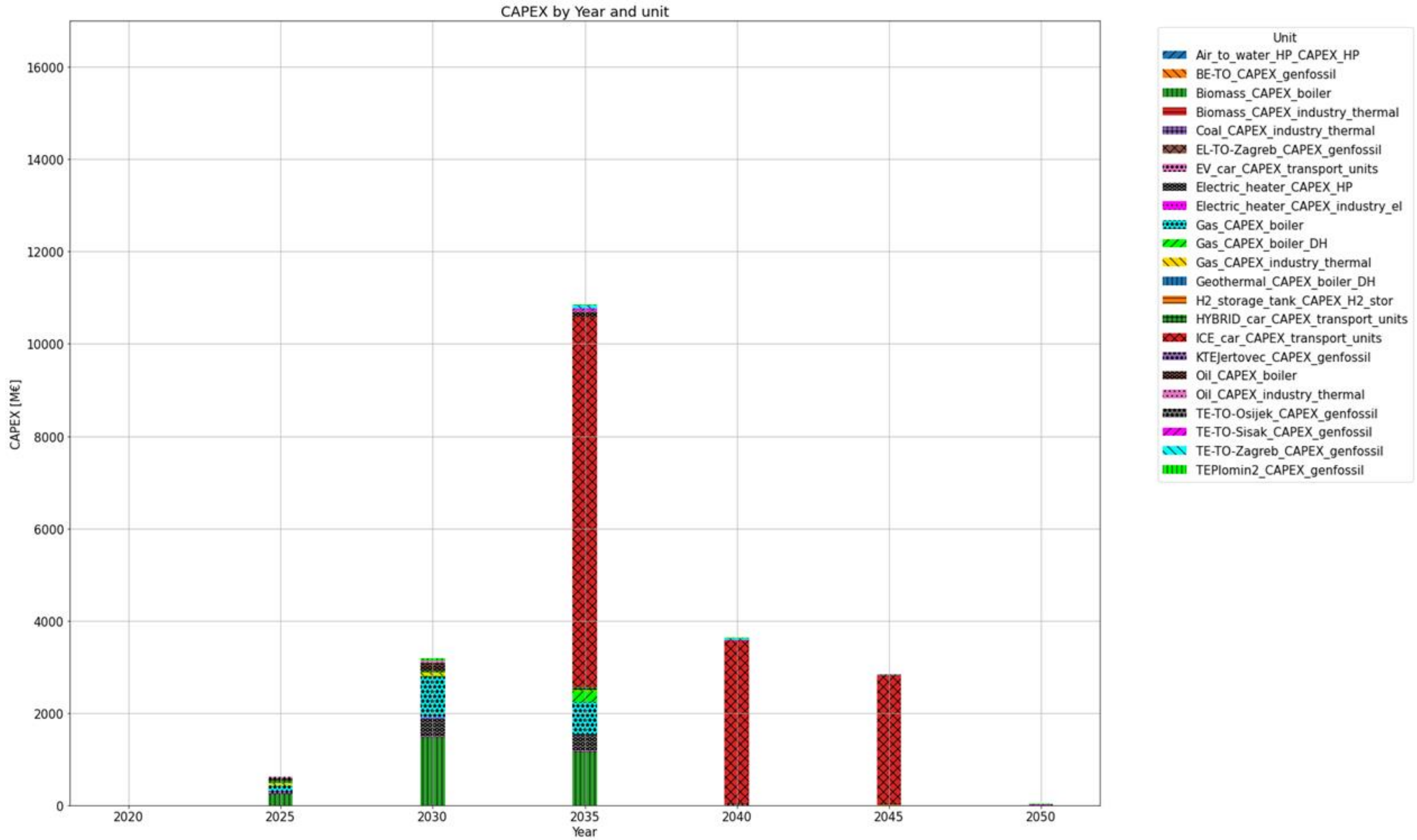

Figure 67. CAPEX in BAU scenario

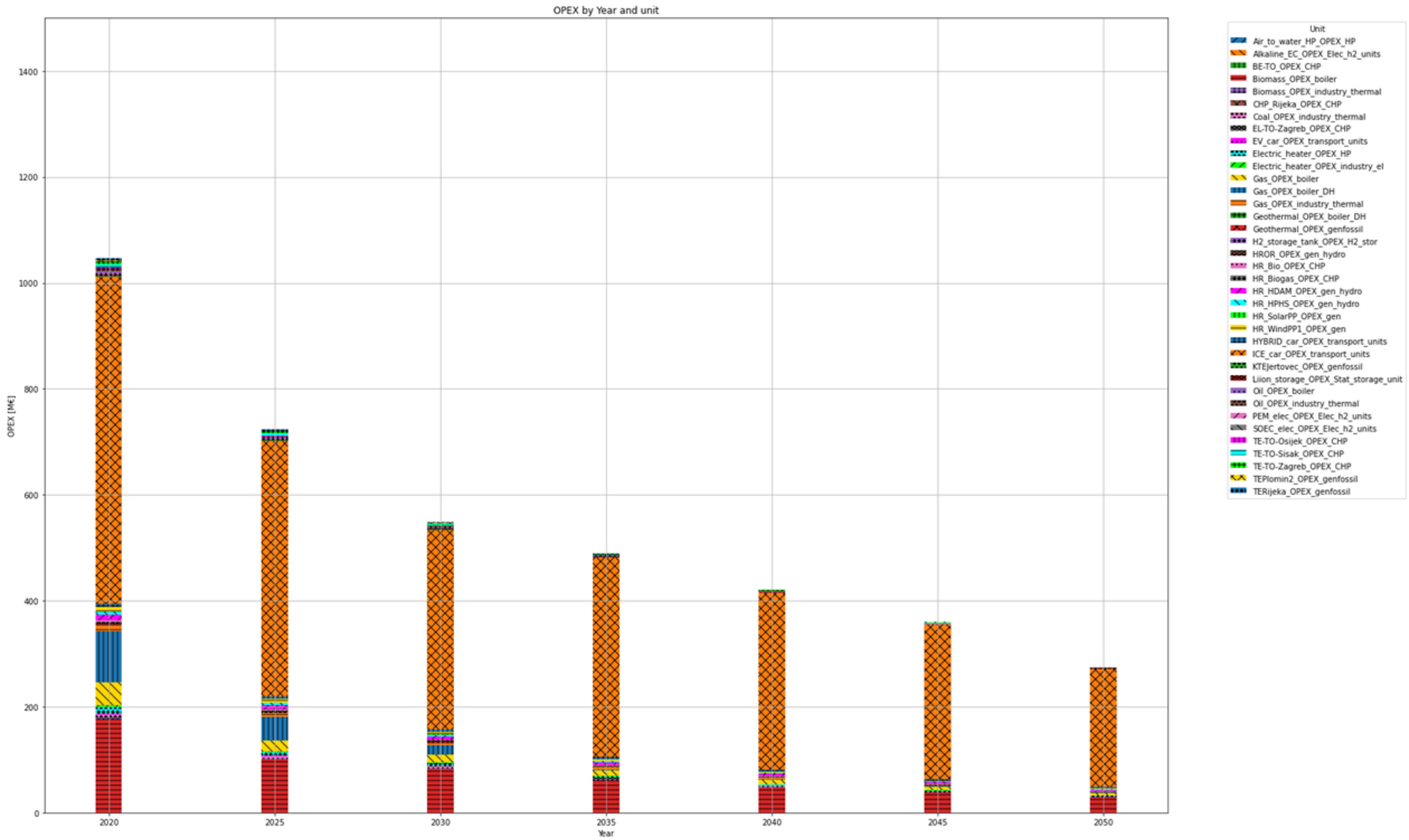

Figure 68. Fixed OPEX in BAU scenario

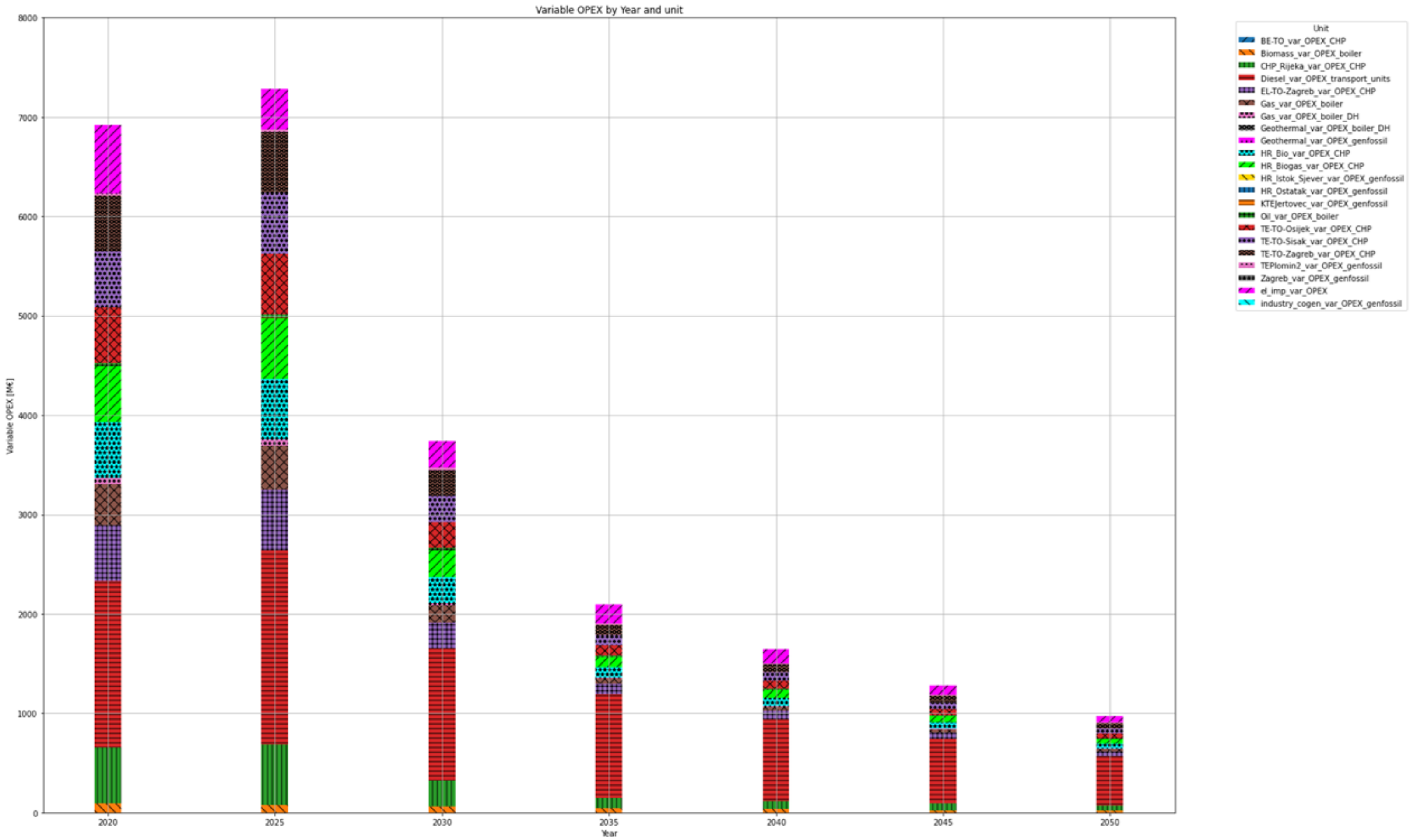

Figure 69. Variable OPEX in BAU scenario