STUDY OF DEGASIFICATION IN THE REPUBLIC OF CROATIA

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ORES
UDRUGA ZA ODRŽIVI RAZVOJ ENERGETSKIH SUSTAVA

ZELENA AKCIJA
FRIENDS OF THE EARTH CROATIA

STUDY PREPARED BY:
Association for Sustainable Development
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Zagreb, Jun 2023

SUMMARY OF THE STUDY

Modelling of the development of the energy sector in the Republic of Croatia showed that it is possible to replace fossil gas with renewable sources by 2035, with a return on costs by 2037.

The accelerated transition of the electric power sector enables complete decarbonisation by 2035 by abandoning all fossil sources of energy, gas, coal and oil derivatives. They are replaced primarily by domestic production from variable renewable energy sources with a total capacity of 6488 MW of wind power plants and 6304 MW of photovoltaic power plants. At the same time, there is an increase in electricity consumption due to the transformation of the heating, industry and transport sectors. The industrial sector is also undergoing significant changes, where gas and coal can be replaced by electricity and hydrogen and hydrogen-based fuels.

Fossil gas consumption in the household and service sectors was modelled at a high geographic resolution. The results showed that the greatest potential for degassing is in the area of Gradska plinara Zagreb Ltd., which covers the cities of Zagreb, Zaprešić and Velika Gorica and the municipalities of Brdovec, Marija Gorica, Pušća and Dubravica. This distribution area consumes 39% of the total gas consumption in households and 41% of the total gas consumption in the service sector in the Republic of Croatia. The obtained results were used as input data for the analysis of the expansion potential of existing and the construction of new district heating systems.

The analysis carried out showed that there is a high potential for the expansion of existing and the construction of new district heating systems. Fossil gas is often used for heating in densely populated areas. The results showed that 45% of fossil gas consumption for heating can be replaced by district heating systems, whereby the discounted cost of the heating network is 14.1 EUR/MWh.

The results of the possibility of expanding the heat network were used for the scenario analysis procedure of the construction of new and expansion of existing district heating systems, along with the analysis of the development of individual systems. The range of total costs and the resulting levelised cost of thermal energy production (LCOH) is shown according to the percentage share of the possibility of replacing the existing fossil gas consumption in the percentages of 45%, 24%, 10% and 1%. The study showed that the degasification of the entire heating sector is possible in the entire Republic of Croatia. The approach to full degasification of the heating sector depends on the region of application and the type of system, whether it is a district heating system or an individual heating system.

The total cost of the transition until 2035 is 39 billion euros. This amount refers to the installation of 5695 MW of wind power plants, 6187 MW of photovoltaic power plants and 120 MW of geothermal power plants. Also, a total of 3415 MW heat pumps are being installed. At the same time, networks of district heating systems are being expanded and investments are being made in hydrogen production systems needed in industry. In the transport sector, investments are made in electric vehicles.

INTRODUCTION

Fossil gas, or as it has been called natural in marketing for the last decades, is one of the fossil fuels with a significant impact on climate change. Although it produces less greenhouse gases than coal and oil during combustion itself, if we add methane emissions during production and carbon dioxide emissions that occur during the preparation of gas for use, then the impact of gas on the climate can be comparable to coal when it is used for heat production. If fugitive emissions of methane are above 4%, and if we look at the lifetime of methane in the atmosphere, i.e., about twenty years, gas has the same impact on the climate when it is used for heating as coal. As there are alternative methods for heating, heat pumps and centralized heating systems, there is no justification for further use of gas in heating systems, therefore, the ban on installing gas boilers is feasible immediately, and their replacement is possible in a reasonable period with public funds. As for the use of gas in industry, part of it can be replaced by electricity, but the greater part must wait for green hydrogen, for which the share of renewable sources in electricity production needs to be significantly increased, and for which Croatia has a great potential. Only in the electricity production is fossil gas less harmful on the environment, especially if used in cogeneration. Gas cogenerations can balance renewable sources and supply centralised heating systems with waste heat for a while, until electricity is replaced by wind and solar, and hydropower becomes sufficient for balancing. At the same time, cogeneration on fossil gas is replaced by geothermal and solar energy and heat from heat pumps. Cogeneration power plants can replace fossil gas with hydrogen and remain as a reserve in the system after they are no longer needed for the production of electricity and heat, in order to ensure secure system operation. As this study shows, the transition can be made by 2035.

Until 2021, the European Union imported 40% of fossil gas from Russia, thus putting itself in the current unenviable position of suddenly having to find new supply routes, which is expensive and will push it into recession. Although Russian gas was cheap compared to the alternatives, it was very wrong to create such dependence on a single source. Dependence on cheap fossil fuels is bad as it complicates the fight against climate change, slows down innovation and does not contribute to security of supply. It can be expected that the EU will go on the path of accelerated transition, despite the enormous efforts of the gas lobby to slow down the transition, and that increased financial resources will be available for this accelerated transition.

The Republic of Croatia, as a part of the EU, will have obligations related to the reduction of fossil gas consumption. To create long-term guidelines for an energy transition based on the reduction of fossil gas consumption, an analysis was carried out of the full degasification of the Republic of Croatia, including electricity production, industry, heating and transport sectors.

METHOD AND INPUT DATA

Energy planning and modelling requires modelling on a long-term level (several decades) in order to be able to make strategic decisions related to investment and the creation of strategies and policies. One of the basic parts of energy planning refers to the integration of renewable energy sources whose production is variable and changes from hour to hour. For this reason, energy planning and modelling is carried out on an hourly basis in order to capture the complex dynamics of the system. For the purposes of this study, we did not go into the dynamics in shorter periods of time because it is considered to be a technical problem. For the purposes of balancing the system, it will be necessary to establish a 15-minute intraday electricity market, which is a much cheaper solution than using a tertiary reserve for balancing. The problem of lack of inertia in a system powered mostly by wind and solar can be solved transitionally by connecting the generator to the grid in idle mode, without coupling to the turbine. Since the existing cogeneration plants will probably be used for some years as a backup, then they, as well as hydroelectric plants, are candidates for such role in the system. When it is no longer possible to use generators for inertia, that function will need to be taken over by strong electronics (grid forming inverters, etc.). The details on system operation are beyond the scope of this study.

The goal of developing the system while meeting restrictions on reducing emissions or environmental pollution is to achieve a system that is also attractive from an economic point of view. The process of energy planning is actually a process of cost optimisation – searching for the cheapest solution while taking into account various boundary conditions, which was achieved using a tool called H2RES [1]. It can be used to find the best scenarios for implementing the energy transition, and the results can be used to define policies that will help achieve the desired goals. The aim of this study is to create an energy system of the Republic of Croatia that does not use fossil gas as fuel, and the electricity generation, industry, heating and transport sectors are modelled. Modelling the consumption of fossil gas in heating is particularly demanding because its consumption is linked to spatial coordinates. GIS (Geographic Information System) methods were also used for the purpose of modelling gas consumption and identifying potential expansion zones of centralised heating systems. These results served as input data for detailed modelling in the H2RES tool.

In the following chapters, the methods used in the analysis of the degassing of the Republic of Croatia are presented in more detail.

H2RES model

For the purpose of modelling the electric power system and heating, industry and transport, the computer model H2RES was used. The H2RES model is an open-source linear optimisation model programmed in Python, and uses the Gurobi solver to perform the optimization.

H2RES consists of three basic levels. The first part refers to the optimisation of capacity expansion on an annual basis. The second part refers to the balancing of generation and consumption at the hourly level, while the third part refers to the modelling of flexibility and energy storage technologies. This includes technologies such as reversible hydropower plants, flexible electric heating systems, energy storage in stationary batteries, hydrogen storage and electric energy storage in electric vehicle batteries. The energy accumulation within each of the mentioned systems is also modelled on an hourly basis, while the capacities are optimized.

The main objective of the model is the minimisation of the total discounted costs of the system within the planning horizon. Costs related to capital investments, fuel costs, other operating costs, energy import or export costs, and CO2 emission costs are considered.

Where:

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

▲ Equation 1
Shows the general expression of the objective function.

$C_{t,p,y}$ $D_{t,p,y}$ – operating cost of technology at hour p and year y.
$TC_{t,y}$ K_t $Inv_{t,y}$ – annualized capital costs of technology t in year y
$R_{t,p,y}$ $Ramp_{t,p,y}$ – the cost of changing generation output
$I_{p,y}$ $Imp_{p,y}$ – cost of import
CO_2 $Price_y$ CO_2 $Levels_{t,p,y}$ – the cost of CO_2 emissions.

In order to model a realistic energy system, constraints have been introduced that can be divided into four categories:

- Operating and technical limitations – production units and storage systems are limited in operation by their technical characteristics of maximum capacity, minimum power at which they can operate, rate of change of output power and availability of technology on the grid. Technology availability factors are particularly important in the modelling of variable energy sources, and in their application, the modelling of these two types of technologies differs. With variable energy sources, production availability is defined by the hourly availability curve, while production from other technologies is available regardless of weather conditions.
- Energy storage system operating constraints – storage systems are modelled on an hourly basis for each of the modelled years. Limits are set on the capacity of the storage and on the charging or discharging capacity. Also, the state of charge is regulated between two limiting values, one of which represents the minimum state and the other the maximum state of charge.
- Demand constraints – this is a set of relations that dictates the conditions that must be respected on the side of the need for electricity, heating and energy in transport and industry.
- Political goals of system development – H2RES has several basic limitations on the side of system operation that can be used separately or in some combination. Limitations include:
  1. Maximum level of excess electricity production (Critical excess electricity production) – expressed as a percentage of the entire load of the power system.
  2. The minimum share of electricity produced from renewable energy sources in the total electricity consumption in a given year.
  3. The maximum level of CO_2 emissions in a given year.
  4. Maximum consumption of a particular fuel in a given year.

For the purpose of modelling the heating and domestic hot water sector through the H2RES program, the Republic of Croatia is divided into three regions, and the division is based on NUTS-2 and NUTS-3 divisions. The region of continental Croatia includes all counties of continental Croatia with the exception of the City of Zagreb and Zagreb County. The Zagreb region includes the City of Zagreb and Zagreb County, while the coastal Croatia region includes the coastal counties. Figure 1 shows the considered regions.

Figure 1
Considered regions

Electricity production sector and industry

The electricity generation system within the H2RES model consists of units that produce energy. They can be divided into two types with regard to the availability of production in a certain hour of the year. Thermal power plants, storage and reversible hydropower plants belong to the first group that can provide electricity production regardless of weather conditions. The rest are variable sources whose production is directly conditioned by the availability of resources in a certain hour.

Table 1
Production units in 2020 [1]

UNIT	FUEL	CAPACITY [MW]
HR_HDAM	-[Water]	1043,5
HR_HPHS	-[Water]	518,4
HROR	-[Water]	520
TE Zagreb	Gas	362
KTE Jertovec	Gas	78
TE-TO_Osijek_Sisak	Gas	280
BE-TO	Biomass	6
Geothermal	Geothermal energy	20

TEPlomin2	Coal	192
TERijeka	Fuel oil	303
HR_SolarPP	-[Solar Energy]	108,5
HR_SolarHigh	-[Solar Energy]	0
HR_WindPP	-[Wind]	0
HR_WindPP1	-[Wind]	801,3
HR_WindPP2	-[Wind]	0
HR_WindPP3	-[Wind]	0
HR_Bio	Biomass	74,2
HR_Biogas	Biogas	55,1

Table 1 shows data on production units used in the H2RES model. According to the table, it can be seen that the individual units presented in the model consist of several production units whose capacities are combined for the purposes of the calculation. For example, HR_HDAM combines capacities and other characteristics such as storage capacities of hydropower plants. HR_HPHS combines reversible hydropower plants, and HROR combines flow hydropower plants. TE Zagreb represents all capacities of cogeneration power plants in Zagreb. TE-TO_Osijek_Sisak represents the combined capacities of gas power plants located in Osijek and Sisak, while BE-TO combines the capacities of biomass cogeneration power plants located in the same cities. Several units of energy production from wind and solar energy are used, and they differ in availability distributions conditioned by different resource availability in examined locations. HR_Bio and HR_Biogas represent the combined capacities of biomass and biogas power plants that are used in some of the industries or agriculture. Capacities and historical generation are modelled accordingly to the data from the Energy in Croatia report [1], data from Eurostat [3] and IEA [4]. Limitations on the rate of expansion of wind and solar energy capacity are assumed, and they are presented in Table 2.

Table 2
Limitations in system development [MW]

	Wind	PV
From 2021 to 2025	1500	2000
From 2026 to 2030	2000	2500
From 2031 to 2035	5000	5000

Heating sector

MODELLING OF GEOSPATIAL (GIS) INFORMATION ON FOSSIL GAS CONSUMPTION

With the aim of defining the areas that need to undergo a degasification process of the heating sector, the first step was to model the consumption of fossil gas in the household and service sectors, at a high spatial resolution.

With the aim of defining the spatial distribution of fossil gas consumption in the household and service sector, in the first step, data was collected on the annual gas distribution of each distributor that provides service in the territory of the Republic of Croatia. The above data were collected from the document Gas Industry in the Republic of Croatia, issued by the Croatian Gas Association [5]. Data on annual fossil gas distribution are georeferenced, that is, assigned to all cities and municipalities where gas consumption exists in the Republic of Croatia. In this way, areas of interest were defined at a lower spatial resolution. With the aim of distributing aggregated gas consumption data at a spatial resolution of 100x100 m, a georeferenced population distribution map of the Republic of Croatia was used as a basis, and it was exported from the Hotmaps tool, created as part of the Hotmaps Horizon 2020 project [6].

The next step was to define the areas covered by centralised heating systems (CTS) and closed heating systems (ZTS). More precisely, the existing networks of centralised and closed heating systems (district heating systems) located in Zagreb, Karlovac, Zaprešić, Velika Gorica, Samobor, Rijeka, Sisak, Osijek, Slavonski Brod and Vukovar are georeferenced, and the areas covered by those district heating systems are excluded from further consideration, since in the mentioned areas, the thermal needs for heating and domestic hot water production are covered to the greatest extent by the existing district heating systems. For georeferencing the district heating system networks, the documents Comprehensive assessment of the potential for efficiency in heating and cooling in Croatia under Annex VIII to Directive 2012/27/EU [7], Analysis of the heating sector and exploitation of the potential of geothermal sources in the area of the Zagreb Urban Agglomeration [8] and Zagreb Geoportal [9].

Aggregated data at the level of distribution areas were then spatially distributed to a spatial unit of 100x100 m, where the weighting factor used for the distribution was the population distribution in areas where fossil gas is consumed, which are not covered by district heating networks.

In this way, the spatial distribution at the hectare level (100x100 m) of fossil gas consumption was obtained for the following categories:

- fossil gas consumption in the household sector (m3/ha);
- fossil gas consumption in the service sector (m3/ha);
- total fossil gas consumption (m3/ha).

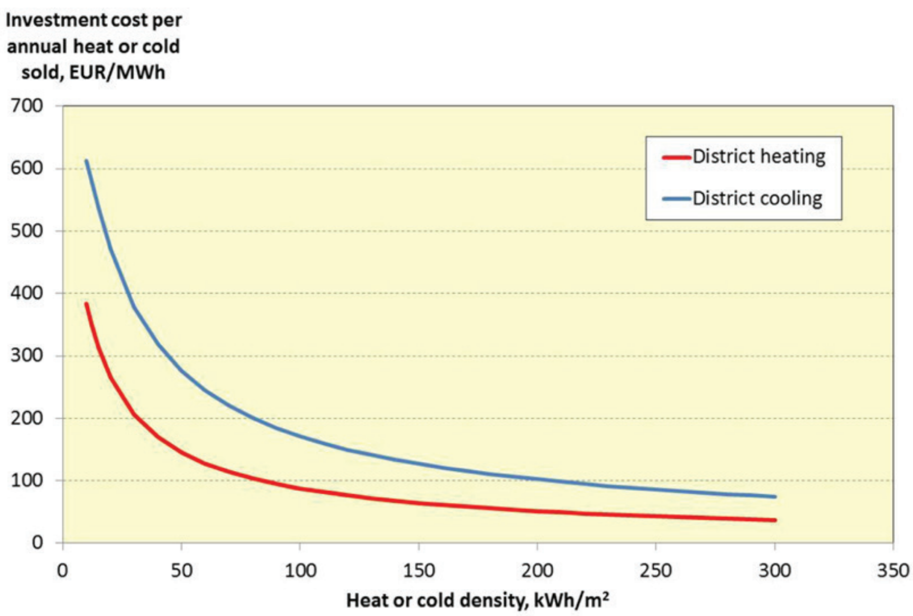
The aforementioned modelling was performed in the QGIS tool [10].

DEFINING SUITABLE AREAS FOR THE INSTALMENT OF NEW AND EXPANSION OF THE EXISTING HEATING NETWORK

In order to carry out an analysis of the suitable areas for instalment of new and expansion of the existing heating network, it is necessary to know the heat demands in the area where fossil gas is being used. The total consumption of fossil gas in the Republic of Croatia in the household and services sector amounts to 928 million m3 [5]. According to data from [7], 91% of gas consumption in the household and services sector is for space heating and preparation of domestic hot water (DHW). In the document, the heating sector includes space heating and DHW. The share of DHW in the heating sector is 16%. In other words, degasification of the household and service sectors is reduced to the decarbonisation of the heating sector. Knowing the total fossil gas consumption for the heating sector and the average lower heating value of fossil gas (9.64 kWh/m3) [5], the total fossil gas consumption for the heating sector can be calculated, which equals 8017 GWh.

The density of thermal energy consumption is a key parameter for defining the zones in which the expansion of the existing heat network or the instalment of new district heating networks will

Figure 2
The relationship between the density of heat demand and specific investment in the heat network [11]



be carried out. Generally speaking, areas with a higher density of thermal energy consumption are more suitable for the expansion of the existing heat network or the instalment of new district heating as the specific investment for these areas is lower, as shown in Figure 2.

A few things can be noticed from Figure 2. First, for very low densities of heat demand, the specific cost of investment in the heating network is very high and can amount to more than 400 EUR/MWh, while for relatively high densities of heat demand (>100 kWh/m2, i.e., >1000 MWh/ha) the specific investment cost is four times lower and equals around 100 EUR/MWh. It is important to emphasize that Figure 2 is only an illustration and for the purposes of this analysis a detailed analysis was made for the Republic of Croatia using the method shown in [11] and [12].

The method includes the following steps:

- define the density of heat demand [MWh/ha]
- calculate the ratio of the total floor plan area of the buildings to the ground area (so called plot ratio) [-]. The ratio shows the degree of "urbanity" of a certain area, and equals: for sparsely populated areas (0 – 0.3), for densely populated areas (0.3 – 0.5) and for urban settlements (0.5 – 2.0)
- determine the effective width – a value that is equal to the ratio of the surface of the area [m2] and the length of the heat network excavation [m]. According to [11], [12] and [13], there is a relationship between the ratio of the total floor plan area of buildings to the ground area and the effective width
- calculate the linear density of heat demand [MWh/m], which is equal to the ratio of the total heat demand in a certain area and the total length of the excavation of the heating network. The product of the density of heat demand and the effective width is equal to the linear density of heat demand
- determine the mean size of the heating network pipes [m]. According to [11], [12] and [13], there is a relationship between the linear density of heat demand and the mean size of the pipes of the heating network
- determine a specific heating network investment [EUR/MWh]. By knowing the specific prices of heating network [EUR/m] [14], the total length of the network and the density of a heat demand, a specific investment for a heating network can be determined
- with a certain discount rate of 3% and a lifetime of 30 years, the discounted cost of a heating network can be determined.

CALCULATION OF THE COSTS OF HEAT ENERGY PRODUCTION IN EXPANDED AND NEW DISTRICT HEATING SYSTEMS AND INDIVIDUAL HEATING SYSTEMS

Results on the percentage share of the possibility of connecting to DH systems, which is defined according to the method in paragraph 2.3.3.1., are the input data for the scenario analysis of the calculation of the cost of heat energy production which is divided into DH systems and individual heat systems. It should be noted that the calculation of costs includes the costs of new centralized heating systems and the expansion of existing ones, as well as the cost of degasification of individual systems that cannot be connected to the existing or newly proposed DH system. The costs shown in this paragraph do not refer to the procedure of degasification of the existing DH system.

The method considers a separate calculation of the costs of the new DH system and individual heating systems. The calculated costs for both cases can be divided into:

- capital investment costs (CAPEX) which represents the annualized cost according to the selected discount rate and lifetime of the used technology.
- annual operating expenses (OPEX) which can be divided into fixed annual operating expenses (FOM) and variable annual operating expenses (VOM). The difference between FOM and VOM is that VOM is generally presented as a cost that depends on the production of the system (expressed per MWh of energy produced), while FOM is independent of the amount of energy produced. Also, the cost of the energy consumption needed to operate the system is often expressed as a share of the OPEX cost, and such an approach will be present in this study as well.

As an indicative result of the proposed solutions, the levelised cost of heating (LCOH) will be presented, and the realized savings due to reduced CO2 emissions will be presented according to the current state of the emissions trading system (ETS) [15].

DISTRICT HEATING SYSTEM SCENARIO

In order to cover a wide range of possibilities, a scenario analysis was chosen for the case of DH systems and individual heating systems. For the case of the new and the expansion of the old DH systems, four scenarios were selected considering four possible heating energy generation technologies. Technologies considered for the DH case included the use of high capacity heat pumps (DT), geothermal sources (GEO), solar collector fields (SOL) and biomass cogeneration plants (CHPB). Each of the four selected scenarios actually represents a series of sub-scenarios that represent different shares of the use of the selected technologies in a defined percentage share. Therefore, four scenarios were selected, where in each scenario one of the technologies represents the base technology, while the share of the other two selected technologies changes in the range of 100% minus the percentage of the base technology. Thus, for each percentage of the base technology, a series of 11 sub-scenarios is created depending on the share of the other two selected technologies. The percentage shift of the base technology was considered in the range from 0% to 100%. Therefore, it can be concluded that each of the four scenarios represents a series of 11x11 sub-scenarios, i.e., a total of 121 sub-scenarios. In order to further clarify the selected scenario approach, Figure 3 visually presents an example of Scenario 1 where DT is selected as the base technology in a percentage of 10%, while SOL and GEO are used as additional two technologies in the percentage range of up to a maximum of 90 %. The figure shows a series of 11 sub-scenarios for the example of a 10% share of the base technology DT.

Sub-scenario	SOL share	GEO share
1	90%	0%
2	81%	9%
3	72%	18%
4	63%	27%
5	54%	36%
6	45%	45%
7	36%	54%
8	27%	63%
9	18%	72%
10	9%	81%
11	0%	90%

+ DT = 10 %

Figure 3
Example of displaying the percentage share of technologies for Scenario 1 where DT represents the base technology, while the share of SOL and GEO changes according to the presented sub-scenarios

The four selected scenarios represent specific performances of future DH systems that do not take fossil fuels into account. Therefore, the scenarios can be divided into:

- scenario 1: Base technology DT, different share of the remaining percentage share for SOL and GEO – without using CHPB
- scenario 2: Base technology CHPB, different share of the remaining percentage share for SOL and GEO – without using DT
- scenario 3: Base technology GEO, different share of the remaining percentage share for SOL and CHPB – without using DT
- scenario 4: Base technology GEO, different share of remaining percentage share for SOL and DT – without using CHPB

The input data for the selected technologies within the CTS solution were used from available references and databases, primarily using the catalogue of the Danish Energy Agency [16].

INDIVIDUAL HEATING SYSTEMS SCENARIO

Section 3.4.4 presents the results based on the considered assessment method of expanding the existing and building a new DH system. Based on the obtained results, it is concluded that a maximum of 45% of consumers who are not currently connected to DH, can be connected to the DH system in the expansion of existing ones or the construction of new ones. Therefore, depending on the percentage of expansion or construction of a new DH, it is necessary to consider other consumers who cannot be connected to the DH, and the process of degasification needs to be realized at the facility level using individual heating systems. Similar to the scenario approach presented in the paragraph before, four scenarios were selected where each of them represents a series of 121 sub-scenarios. The four selected scenarios are based on the use of solar collector technologies (SOL), air-to-water heat pumps (DTA), water-to-water heat pumps (DTW) and ground-to-water heat pumps (DTE). Each of the scenarios contains one of the base technologies, while the other two are selected technologies with a variable percentage of application. Therefore, the following four scenarios were selected:

- scenario 1: Base technology DTE, different share of the remaining percentage share for SOL and DTA – without using DTW
- scenario 2: Base technology DTW, different share of remaining percentage for SOL and DTA – without using DTE
- scenario 3: Base technology DTA, different share of remaining percentage share for SOL and DTE – without using DTW
- scenario 4: Base technology DTA, different share of remaining percentage share for SOL and DTW – without using DTE

The input data for the selected technologies within the CTS solution were used from available references and databases, primarily using [16] and [17].

RESULTS

Electricity production sector and industry

The year 2020 was used as the base year. By 2025, 1500 MW of wind, 2000 MW of solar and 30 MW of geothermal power plants will be put into operation. After 2025, 2000 MW of photovoltaic power plants, an additional 40 MW of geothermal and 2000 MW of wind power plants will be commissioned. Between 2030 and 2035, 2187 MW of photovoltaic power plants, 2195 MW of wind power plants, and 50 MW of geothermal power plants will be put into operation.

Electricity production is increasing because of increased demand due to the electrification of the industry, heating, and transport sectors. Figure 4 shows the total annual production by energy source.

Figure 4
Electricity production

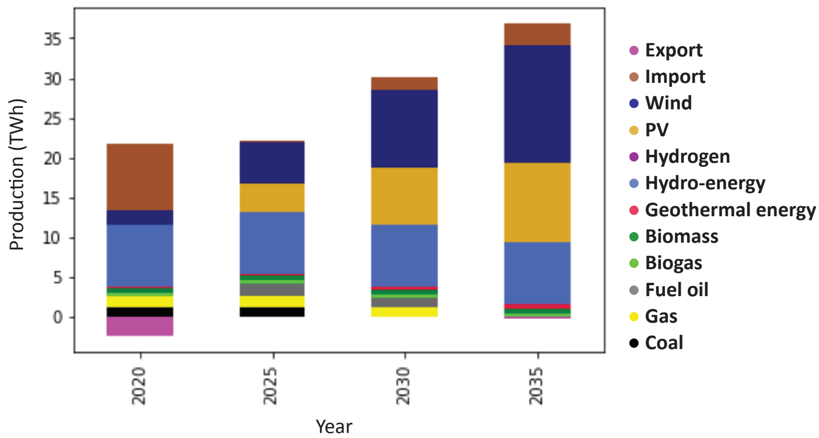


Figure 5 shows the hourly distribution of electricity generation. There is a visible connection between the production of thermal energy and electricity from gas cogeneration power plants during the heating season. Also, it should be noted that the scale on the y-axis of the diagram changes as additional energy-intensive technologies are introduced that increase the demand for electricity.

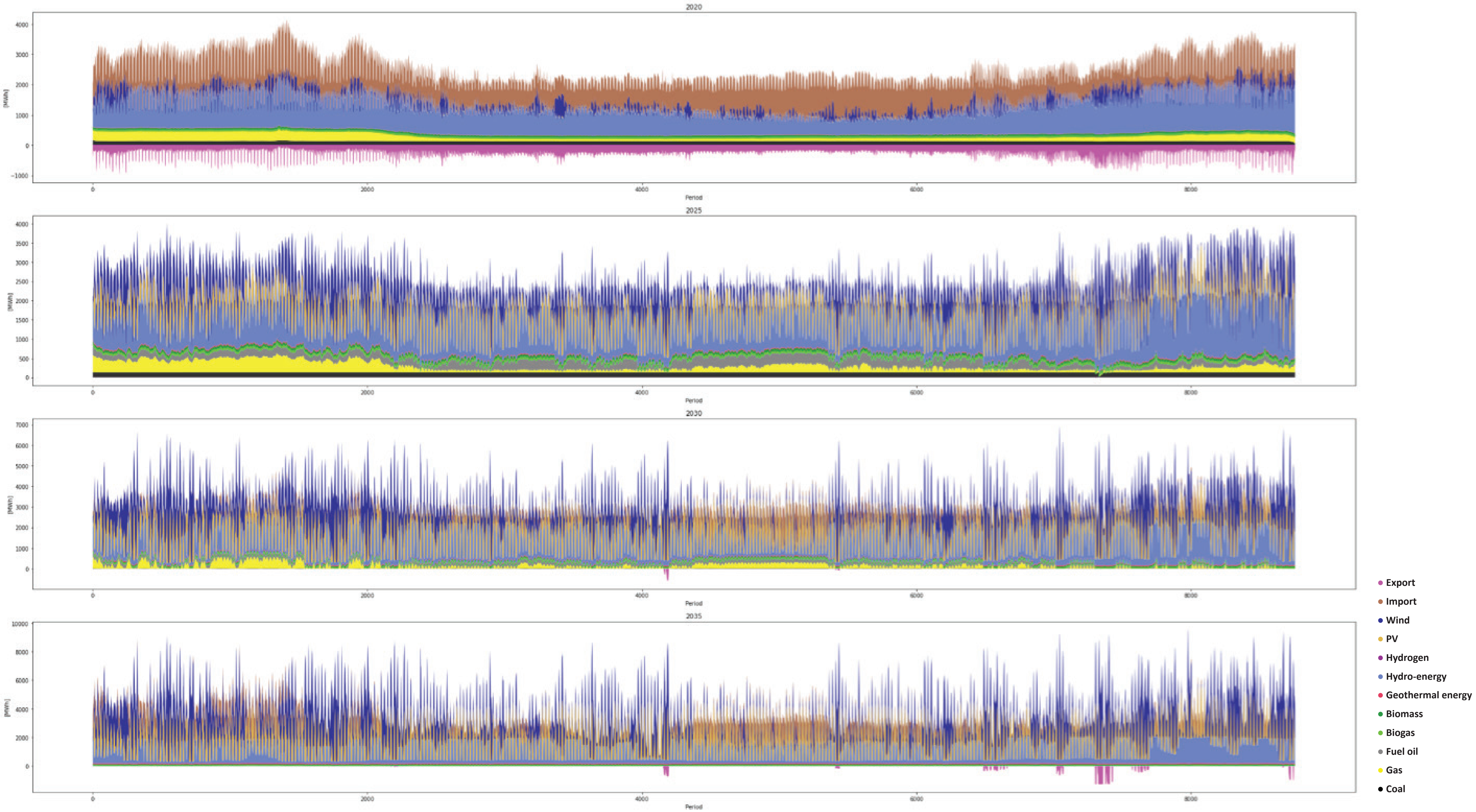


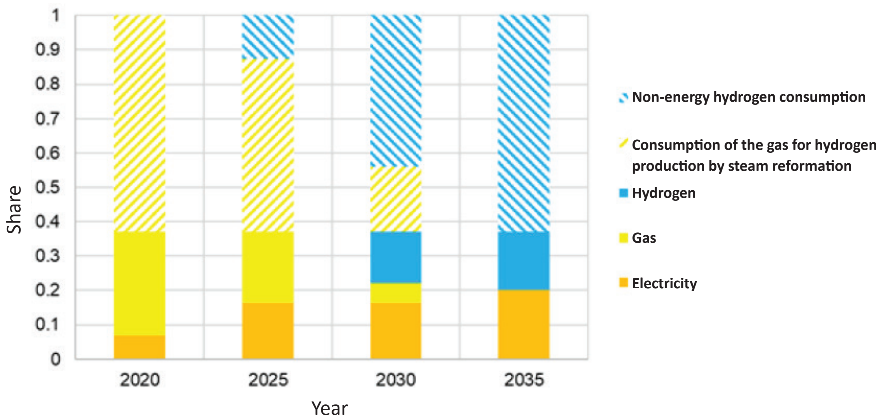
Figure 5
Distribution of electricity production

Industry sector

The industry sector is also undergoing transformation. Primarily, there is a gradual reduction of the use of fossil gas and coal use, and later in some sectors the reduction of the use of oil derivatives. It should be noted that the following representations do not include thermal energy from centralized heating systems, as this part of consumption is modelled together with the rest of the heating sector.

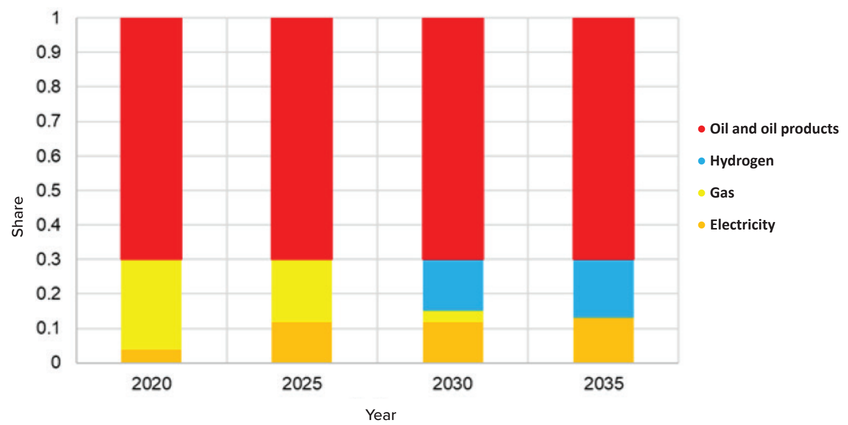
Figure 6 shows the transformation of the petrochemical and chemical industry subsector. The largest share of this sector's consumption corresponds to non-energy consumption. Non-energy demand in the base year consists exclusively of fossil gas used for the purpose of obtaining hydrogen used as a feedstock in the process. The development of the energy system leads to the gradual replacement of fossil gas in the hydrogen production system, and hydrogen generated with the use of electrolysers powered by renewable energy takes over this part of demand. The rest of the sector also uses fossil gas in the first part, which is replaced by electricity and hydrogen in the consequent years.

Figure 6
Petrochemical industry



The refinery subsector is shown in Figure 7. 70% of energy consumption in this sector comes from oil and oil products. Total of 32% of demand belongs to non-energy consumption. Fossil gas covers 26% of demands in the base year and it decreases to 18% in 2025, 3% in 2030 and 0% in 2035. At the same time, there

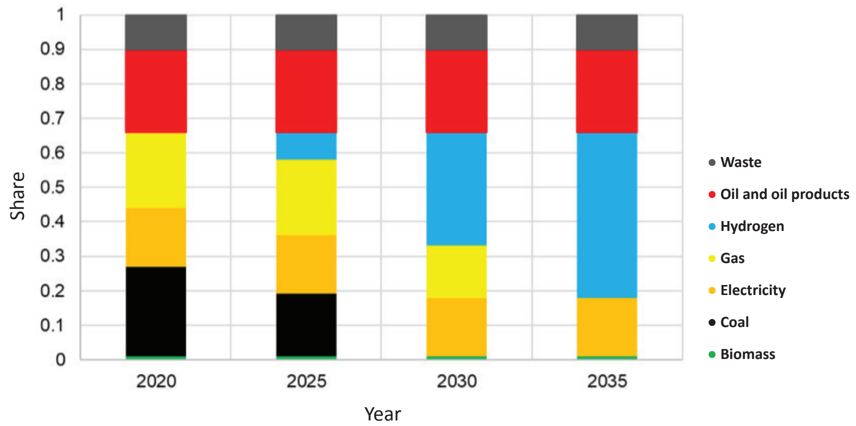
Figure 7
Refineries



is an increase in the use of electricity and hydrogen. In 2035, hydrogen will cover 17% of needs and electricity will cover 13%.

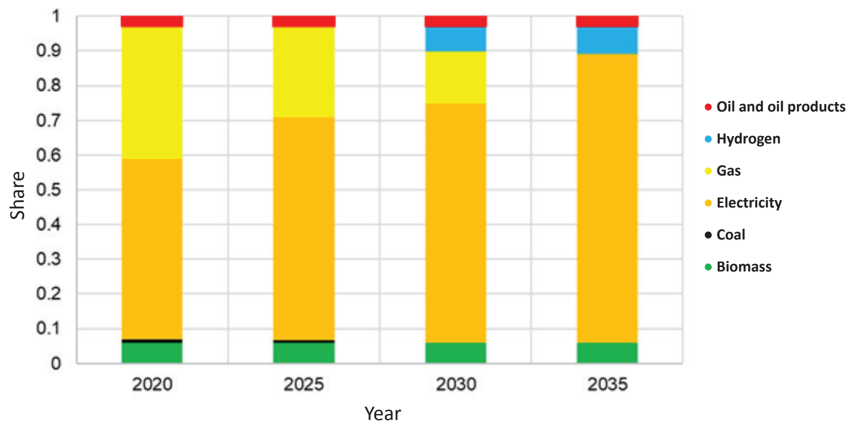
The transition of the cement industry sector is shown in Figure 8. From 2025, coal and fossil gas will begin to be replaced by hydrogen. The share of gas is reduced to 0% by 2035 as well as coal by 2030. In 2035, hydrogen will cover 48% of needs, and electricity will remain at 17%.

Figure 8
Cement plants



The remaining part of the industry, characterised primarily by low-temperature processes, is gradually transitioning to electricity, which makes up 83% in 2035, and to hydrogen with 7%. The remaining 10% is covered by biomass and oil derivatives, of which biomass accounts for 7%, and oil and oil derivatives 3%.

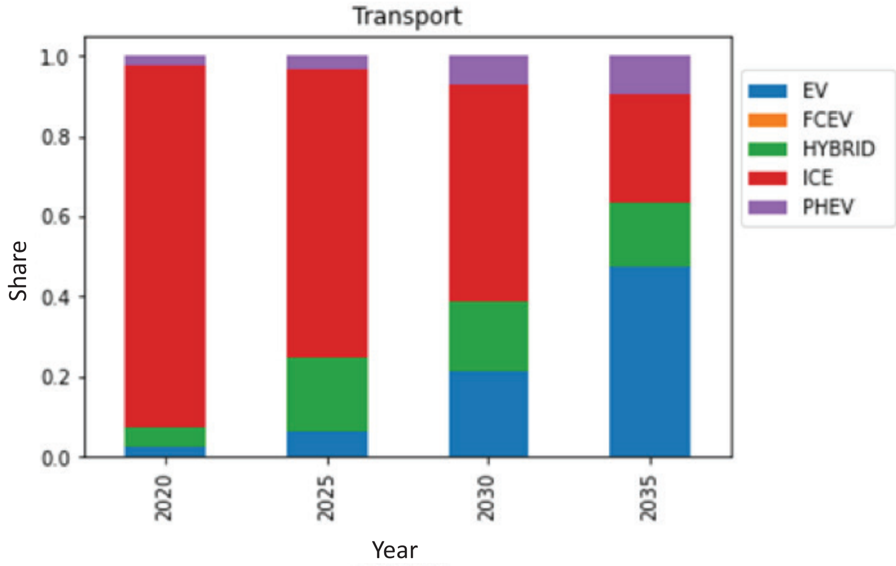
Figure 9
Rest of the industry



Transport sector

The transport sector is undergoing electrification. The share of electric vehicles increases to 48% by 2035. At the same time, there is also an increase in the share of hybrid and plug-in hybrid vehicles (PHEV), while the share of vehicles with internal combustion engines decreases to 27%.

Figure 10
Transport sector

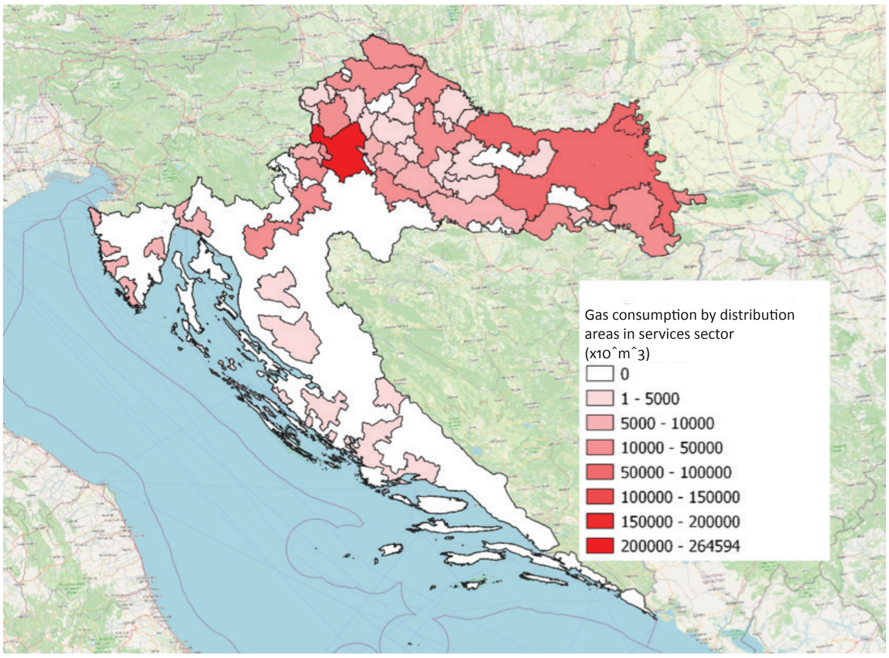


Heating sector

FOSSIL GAS CONSUMPTION MAP

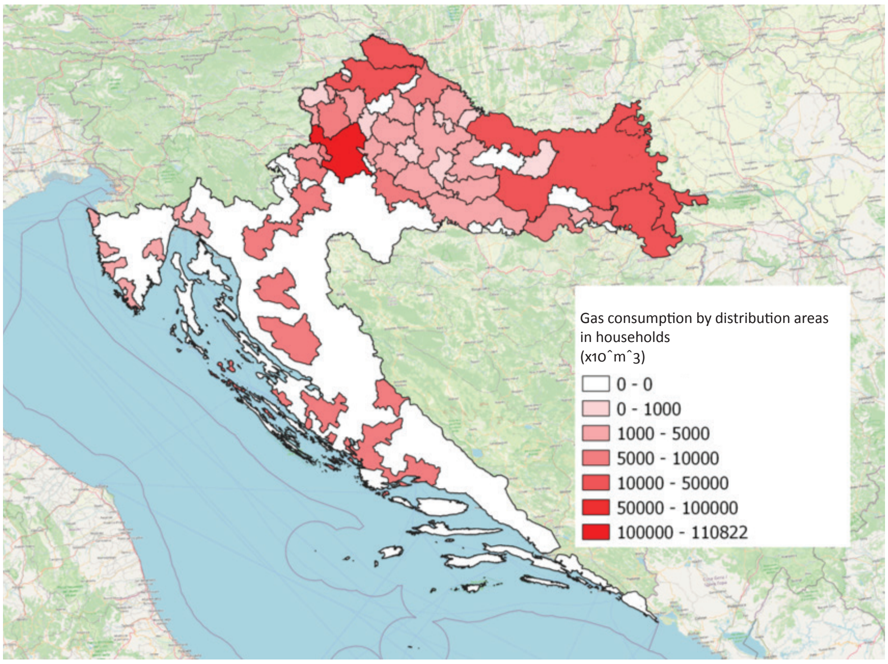
Based on the method described in the Method section, the spatial distribution of gas consumption in distribution areas is defined. Figure 11 shows the distribution of gas consumption in households, by distribution areas.

Figure 11
Gas consumption by distribution areas in households



As Figure 11 shows, the majority of fossil gas consumption in households takes place in the distribution area of Gradska plinara Zagreb Ltd., with a share of 39% in the total fossil gas consumption in households in the Republic of Croatia. Figure 12 shows fossil gas consumption by distribution areas in the service sector.

Figure 12
Gas consumption by distribution areas in the service sector

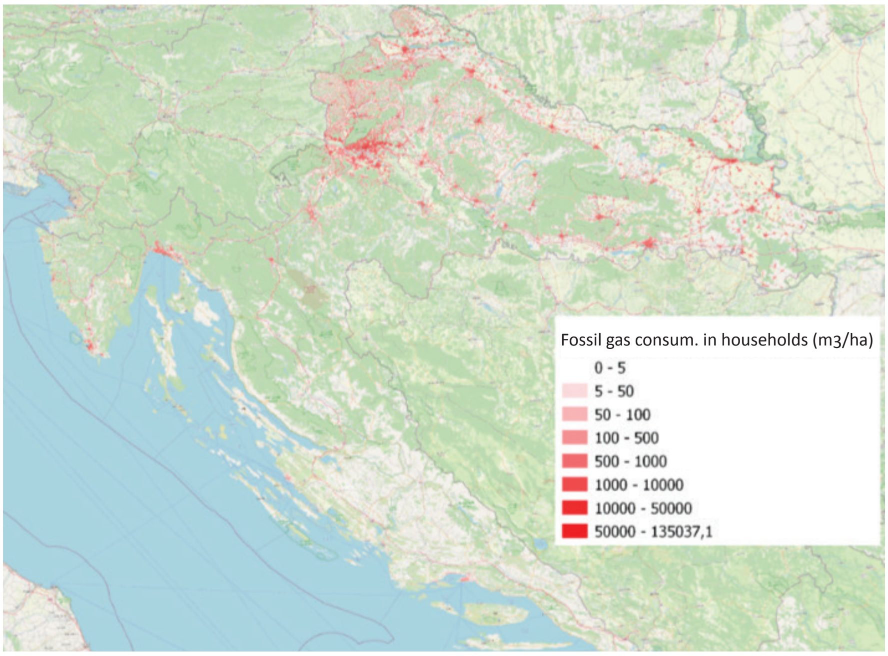


Similar to the first case, Figure 12 shows that the majority of fossil gas in the service sector is consumed in the distribution area of Gradska plinara Zagreb Ltd. with a share of 41% in the total gas consumption in the service sector of the Republic of Croatia.

Based on fossil gas consumption in distribution areas, spatial distribution of the population and georeferenced areas covered by district heating systems, the distribution of fossil gas consumption at the hectare level (100 x 100 m) was modelled. The modelling was performed for consumption in households, the service sector and total consumption.

Figure 13 shows the spatial distribution of fossil gas consumption in households at a spatial resolution of 100 x 100 m.

Figure 13
Spatial distribution of fossil gas consumption in households



As Figure 13 shows, the majority of fossil gas consumption in households takes place in the cities of continental Croatia. In the coastal part of Croatia, the cities of Split, Rijeka and Pula have the highest consumption of fossil gas. Figure 14 shows an enlarged view of the spatial distribution of fossil gas consumption in households in the City of Zagreb.

Figure 14
Enlarged view of the spatial distribution of fossil gas consumption in households in the City of Zagreb

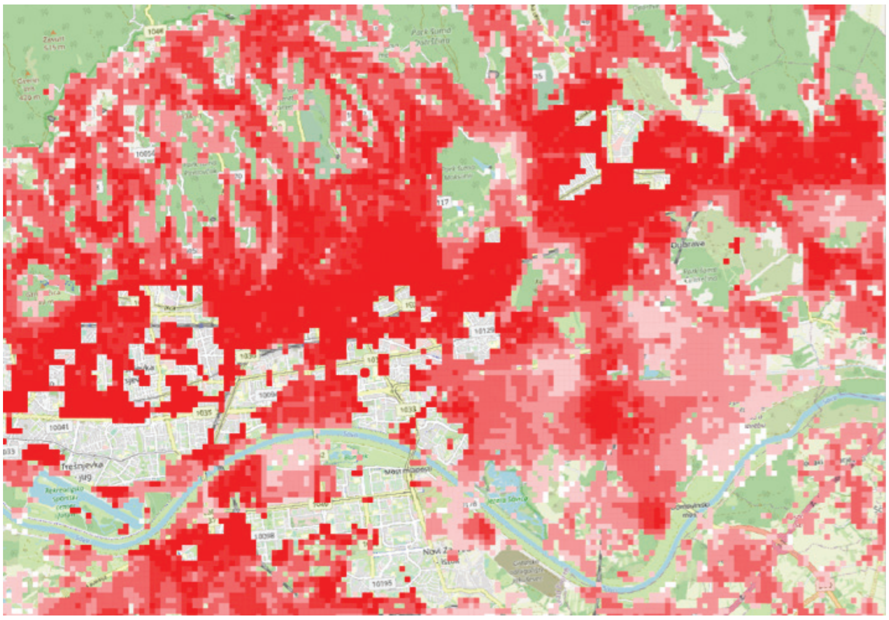
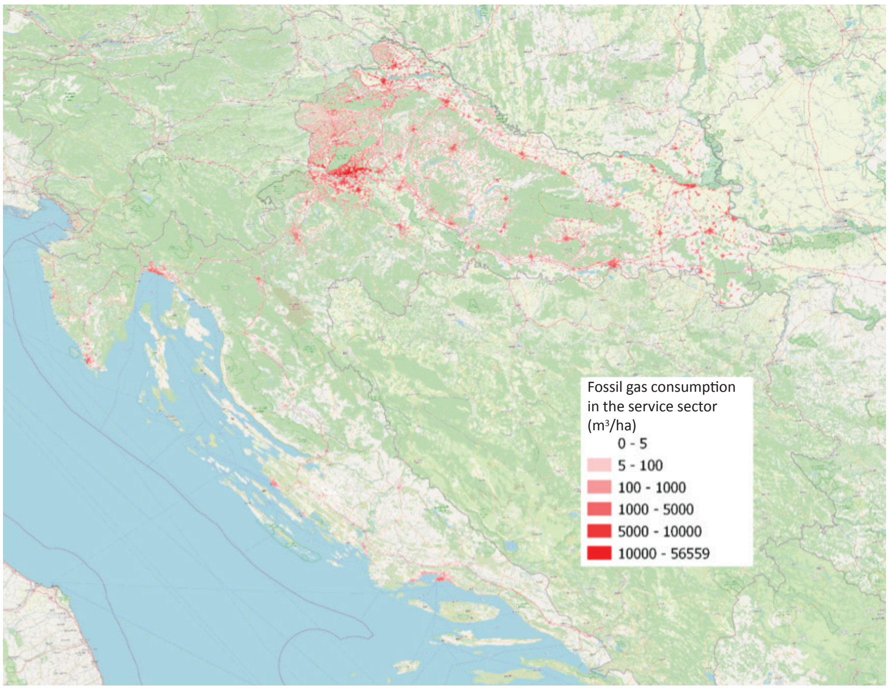


Figure 15 shows the spatial distribution of fossil gas consumption in the service sector at a spatial resolution of 100 x 100 m.

Figure 15
Spatial distribution of fossil gas consumption in the service sector



As expected, the spatial distribution of fossil gas in the service sector is similar to consumption in households, and the majority of fossil gas consumption takes place in the cities of continental

Croatia. The consumption of fossil gas in the service sector in coastal Croatia is more intense, compared to the consumption of fossil gas in households, as can be seen from the comparison of the last two figures. This is mainly due to the fact that, based on data on fossil gas consumption in 2020, gas consumption in the service sector is in the distribution area of the distributor EVN Croatia Plin Ltd. 11 times higher than gas consumption in households. This distribution area covers the cities of Otočac, Gospić, Trogir, Kaštela, Zadar, Biograd na Moru, Benkovac, Šibenik, Drniš, Knin, Split, Solin.

In order to obtain the total consumption of fossil gas in households and the service sector, the values contained in the layers shown in Figure 13 and Figure 15 are merged. Figure 16 shows the spatial distribution of the total fossil gas consumption at a spatial resolution of 100 x 100 m.

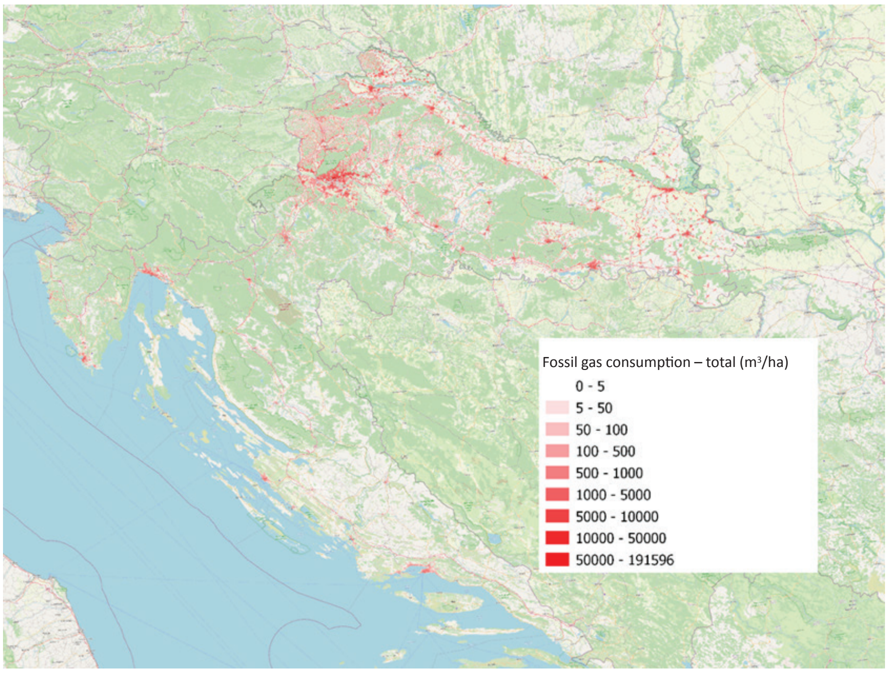
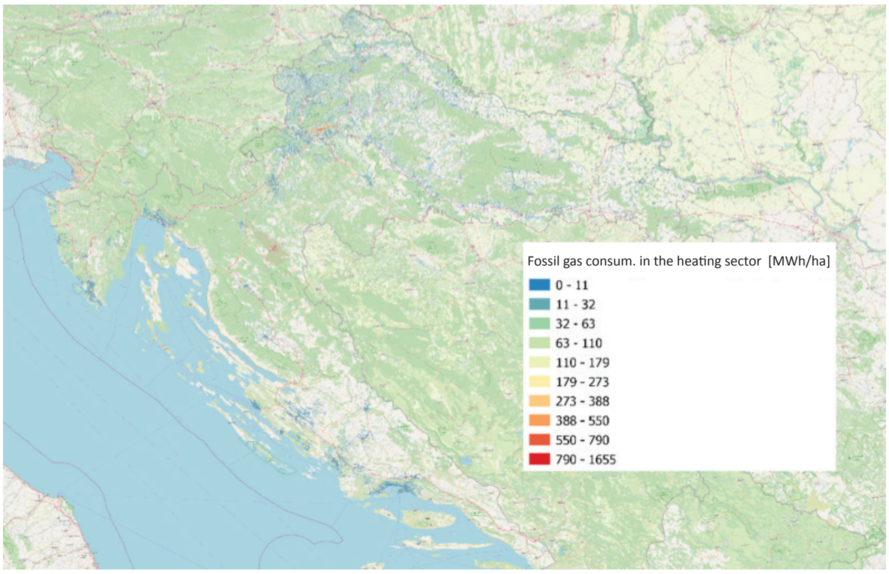


Figure 16
Spatial distribution of total fossil gas consumption

FOSSIL GAS CONSUMPTION MAP FOR THE HEATING SECTOR

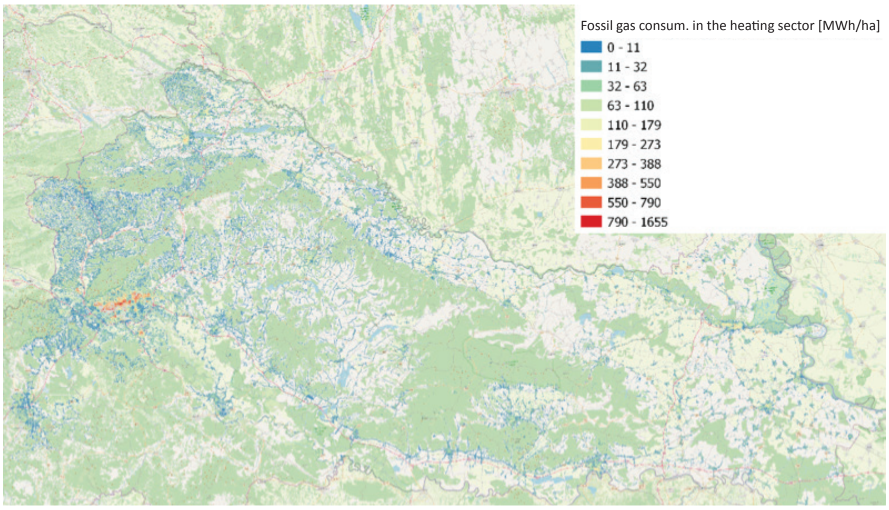
Using the input data presented in Chapter 3.4, a gas consumption map for the heating sector was created. Figure 17 shows the consumption of thermal energy in the household and services sector that use fossil gas. It can be observed that the spatial distribution of heat energy consumption density is similar to the distribution of fossil gas consumption, Figure 17. It is important to note that heat demand density is often very low and equals less than 11 MWh/ha.

Figure 17
Fossil gas consumption for the heating sector in the Republic of Croatia



The highest density of heat demand is in the larger urban areas of Northern and Pannonian Croatia and in the City of Zagreb, as shown in Figure 18. The highest density of heat demand was recorded in the City of Zagreb and its surroundings. According to this, it can be concluded that the urban areas in Northern Croatia and in the City of Zagreb and its surroundings are the most suitable for the expansion of the heating network. In order to accurately determine the suitable areas for the expansion of the heating network, an economic analysis was made, presented in the next chapter.

Figure 18
Fossil gas consumption for the heating sector in Pannonia and Northern Croatia and the City of Zagreb



INSTALLATION OF NEW AND EXPANSION OF EXISTING DISTRICT HEATING SYSTEMS

Figure 19 shows the relationship between the specific investment in the heating network and the density of heat demands. The presented results are similar to those shown in Figure 2. Furthermore, it is important to note that the model is not valid for heat demands density values of less than 50 MWh/ha, and the highest specific investment in the heat network is more than 500 EUR/MWh. For relatively high densities of heat needs, the specific investment drops rapidly and amounts to around 150 EUR/MWh, while the value stagnates around 100 EUR/MWh.

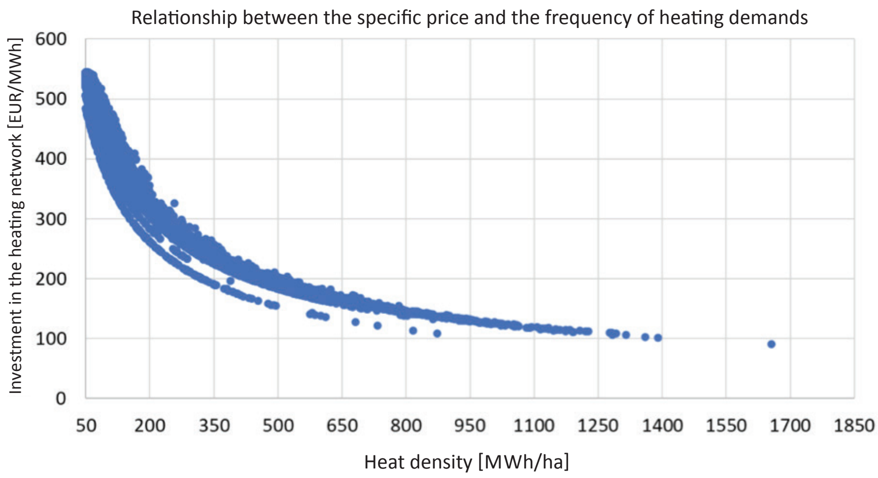


Figure 19
Specific investment of the heating network depending on the frequency of heating needs

Figure 20 shows the share of heating in relation to the specific discounted investment in the heating network. The specific investment increases with the total heating potential, with the highest discounted investment being around 28 EUR/MWh. The lowest prices are around 50 EUR/MWh, applicable for the densest urban areas, i.e., the highest density of heat demands.

First, it is important to note that 36% of fossil gas consumption for the heating sector cannot shifted to district heating as the density of heat demands is less than 50 MWh/ha. In a case if areas with a density of heat demands higher than 100 MWh/ha are shifted to district heating, around 45% of fossil gas consumption could be shifted to district heating. For densities of heat demands greater than 250 MWh/ha, this share is lower and equals to 24%, whereby the maximum investment is equal to around 18 EUR/MWh. If areas with a density higher than 500 MWh/ha are heated, then it is possible to cover only 10% of the demand. Finally, if only the areas with the heat demand density higher than 1000 MWh/ha are shifted to district heating, then only 1% of the consumption could be covered.

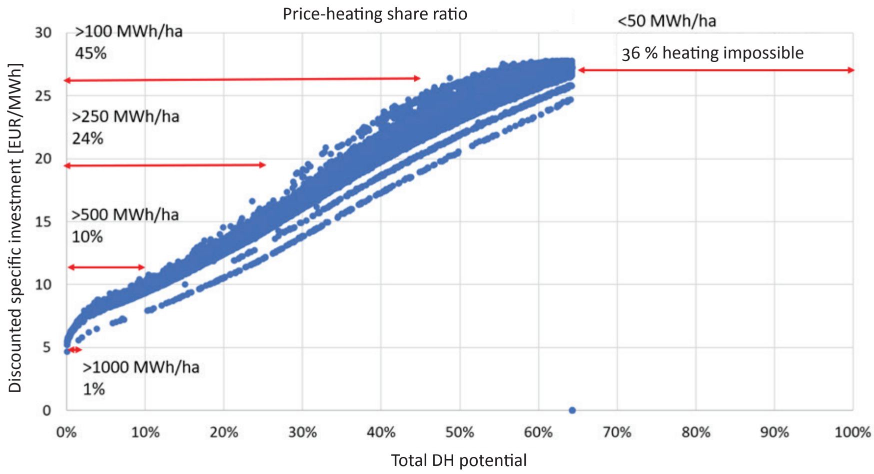


Figure 20
Specific investment price in relation to the total heating potential of fossil gas consumers

Figure 21 and Figure 22 show the spatial distribution of heated areas. It is important to note that these are mainly the areas of Northern and Pannonian Croatia and the City of Zagreb.

For the lowest defined density of heat demand of 100 MWh/ha, in most urban settlements in Northern and Pannonian Croatia district heating systems can be installed, and the expansion of the district heating system in Rijeka can be recommended. When the density of heat demands is above 250 MWh/ha, the range of district heating network installations and extension is reduced to Northern Croatia and the City of Zagreb, while in Pannonian Croatia only suitable cities are Osijek, Slavonski Brod, Đakovo, Vinkovci and Vukovar. For the density of heat demands higher than 500 MWh/ha, the expansion of the district heating network is limited to the City of Zagreb, Samobor, Zaprešić and Velika Gorica. Areas with a density of heat demand greater than 1000 MWh/ha are located only in the City of Zagreb, where only the expansion of the existing heating network is recommended.

Figure 23 shows a comparison of different heating scenarios, the length of the heating network and the associated investments. For the heating scenario with a heat demands greater than 500 MWh/ha, the specific discounted cost equals to 8.3 EUR/MWh, while the total investment is equal to 132 million EUR. The installations and extension of district heating network in the areas with the highest heat demands results in the discounted specific cost of 5.9 EUR/MWh, whereby the total investment is equal to 7.2 million EUR. For comparison, the total investment in revitalisation of the 69 km hot water network of the City of Zagreb is 93 million EUR [18].

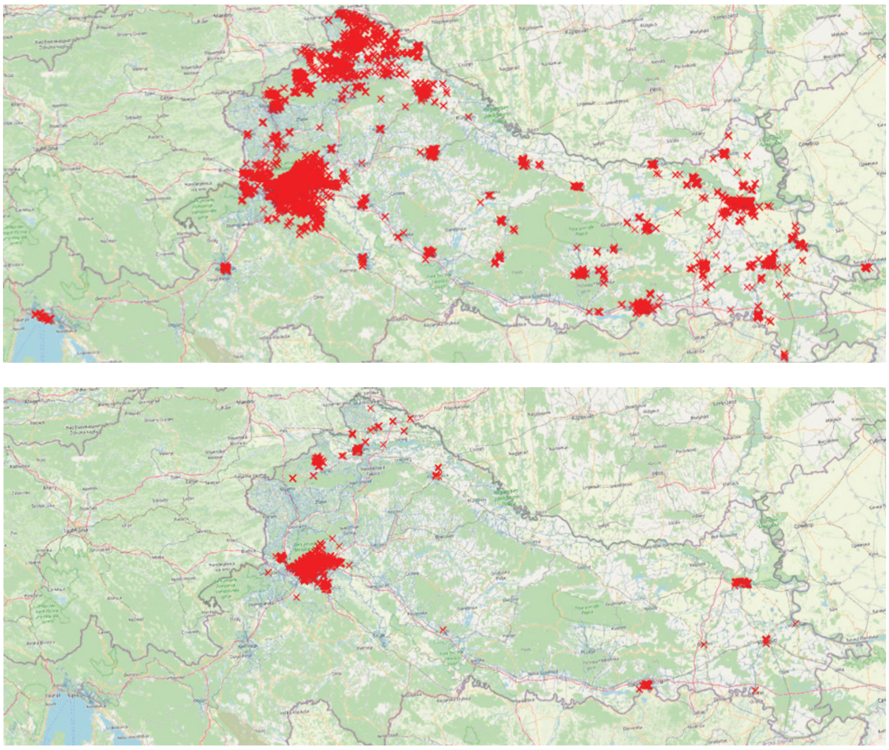


Figure 21
Locations of new and expansion of existing centralised heating systems for densities of heat needs: above 100 MWh/ha (figure above), above 250 MWh/ha (figure below)

Figure 22
Locations of new and expansion of existing district heating systems for densities of heat demands: above 500 MWh/ha (figure above), above 1000 MWh/ha (figure below)

Table 3
Investment cost in the heating network for different heating demand levels

	> 100 MWh/ha	> 250 MWh/ha	> 500 MWh/ha	> 1000 MWh/ha
Share of current fossil gas heating switching to district heating [-]	45%	24%	10%	1%
Investment [million EUR]	993,4	397,9	131,8	7,2
Specific investment [EUR/MWh]	276,4	204,8	162,2	116,4
Discounted cost [EUR/MWh]	14,1	10,5	8,3	5,9
Network length [km]	1954,2	626,5	184,2	8,9

SCENARIO ANALYSIS OF NEW AND EXPANSION OF EXISTING DISTRICT HEATING SYSTEMS

Based on the proposed method in paragraph 2.3.3, the following section presents the results for the process of degasification of the heating sector, which includes the expansion or construction of new DH systems and individual heating systems based on fossil gas. The heating sector, according to the results from paragraph 3.4.3, and more precisely in Table 3, is divided into four scenarios where the percentage of new consumers that can be connected to the expansion of the existing or a new DH system is pre-defined. Thus, the results can be divided into:

- scenario 45% (S45%)
- scenario 24% (S24%)
- scenario 10% (S10%)
- scenario 1% (S01%)

Each of the scenarios defines how much of the total fossil gas consumption can be covered by the new or expanded DH systems, while the rest of the total gas consumption must be covered by individual heating systems. Within each of the above-mentioned scenarios, an additional intra-scenario analysis was carried out, which is explained in more detail in paragraph 3.4.4. Each of the scenarios includes an intra-scenario analysis depending on the type of heat energy generation technology used. Table 4 shows the requirements for useful heating energy for each of the scenarios, taking into account the consumption of fossil gas as 8017 GWh, and the average efficiency of the gas boiler of 95% [19]. Useful heating energy from the consumption of fossil gas amounts to 7616 GWh.

Table 4
Amount of useful thermal energy for the observed scenarios

SCENARIOS	DH [GWh]	INDIVIDUAL HEATING SYSTEMS [GWh]
Scenario 45%	3427	4189
Scenario 24%	1828	5788
Scenario 10%	762	6855
Scenario 1%	76	7540

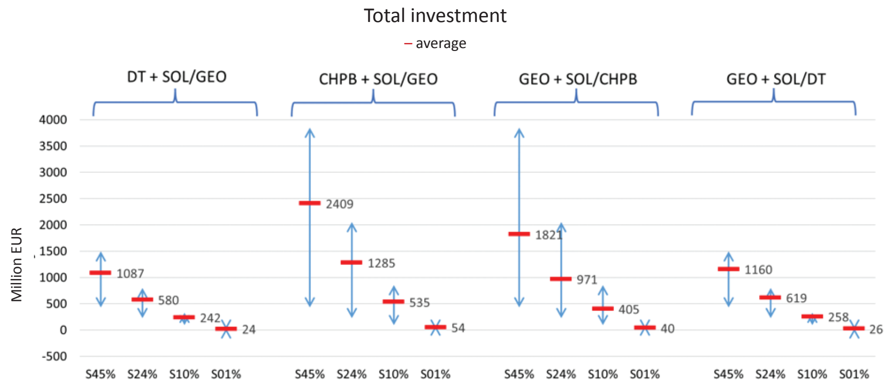
The following section presents the aggregate results for the case of the new and expanded DH and for the case of individual heating systems. Results for the scenario of percentage use of DH solutions according to the amounts in the table above, and for each of the sub-scenarios of the used technology explained in paragraph 3.4.4, are presented separately for DH solutions and individual heating solutions.

EXPANSION OF THE EXISTING DISTRICT HEATING SYSTEMS AND CONSTRUCTION OF NEW ONES

Within the considered solution in the form of DH system, four scenarios were observed depending on the technologies used. The scenarios are divided according to the method in paragraph 2.3.3.1. The ranges of total investment costs, CAPEX and OPEX costs, and total LCOH are shown depending on the percentage of use of the considered technologies.

Figure 23 shows the total investment cost according to the observed scenarios and sub-scenarios. The figure shows the range of the total investment cost, where the upper arrow shows the maximum amount depending on the percentage share of a certain technology, while the lower arrow represents the minimum amount of the total investment. The red lines represent the average values of the total investment of the observed scenarios. It is noticeable that on average, the lowest investment cost is achieved in scenario 1, which includes the base use of DT and a variable share of solutions in the form of SOL and GEO. It can also be noted that the investment cost of scenario 4, which includes the base usage of GEO and a variable share of the solution in the form of SOL and DT, is close to the cost of scenario 1, but the slightly higher investment cost is due to the higher cost of the GEO solution.

▶ Figure 23
The cost of the total investment of the DH solution depending on the scenarios of application of different technologies and the scenario of percentage use of DH systems



Related to the total investment cost shown above, Figure 24 shows the annual discounted investment cost – CAPEX. The discount rate used is 6%. Similar to the conclusions from the figure above, the figure below shows the same results just reduced to an annualised discounted cost.

▶ Figure 24
CAPEX cost of DH solutions depending on the scenarios of application of different technologies and the scenario of percentage use of DH systems

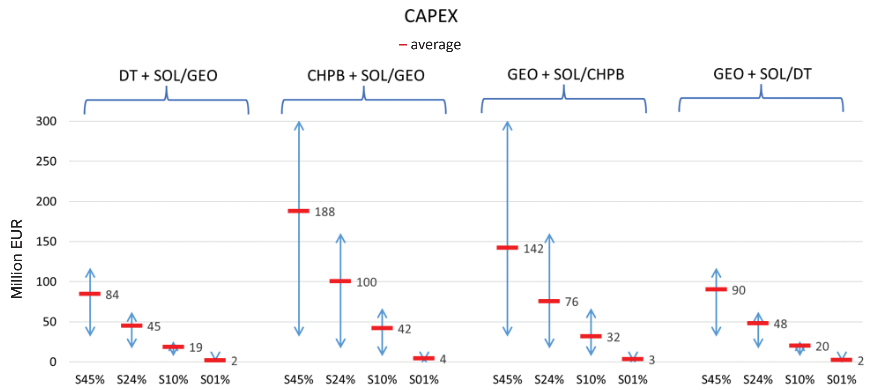


Figure 25 shows the ranges of annual operating costs – OPEX. Annual operating costs are divided into fixed annual costs, variable annual costs that are related to the annually produced energy, and the cost of the energy required to operate the system. Regarding the energy needed for the system operation, it primarily refers to the cost of electricity for the DT and the cost of biomass for the CHPB plant. In the figure below, it can be seen how the minimum operating cost is related to scenarios 1 and 4. In scenario 1, DT is the base technology used, while the share of SOL and GEO is being changed. In scenario 4, the GEO is base technology, while the shares of SOL and DT change proportionally. The primary reason for the significantly lower OPEX cost in scenarios 1 and 4 is due to the higher biomass cost present in scenarios 2 and 3, where CHPB is used in certain percentages. A significant part of the OPEX cost is made up of energy costs for plant operation, where in the case of using DT the cost of electricity amounts to 93% of the total OPEX cost, while when using CHPB the cost of biomass amounts to 77% of the total OPEX cost. It is also necessary to note that when using the CHPB solution, there is a share of the income from the sale of electricity, and the used price of the electricity being sold was 100 EUR/MWh. The realized income from the sale of electricity reduces the total OPEX cost, i.e., the final result in the form of LCOH.

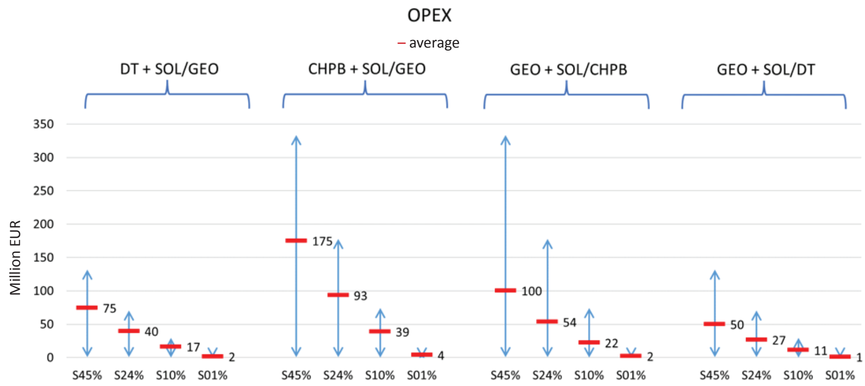


Figure 25
OPEX cost of DH solutions depending on the scenarios of application of different technologies and the scenario of percentage use of DH systems

As a final comparison of the considered scenarios, Figure 26 shows the total levelised cost of heating – LCOH. Again, the range of solutions for the observed scenarios is given according to the selected technologies and percentage use of DH systems. It is noticeable that the primary difference within the scenario of percentage use of the DH solution is the discounted cost of the required DH network in Table 3. Therefore, it can be observed that the LCOH increases with an increased share of DH application. It is noticeable that the minimum average LCOH is present in scenario 4, i.e., the base application of GEO with a percentage change in the use of SOL and DT. The average amount of LCOH for scenario 4 is 52.16, 48.56, 46.36 and 43.96 EUR/MWht for scenarios S45%, S24%, S10% and S01%. Slightly higher results of the total LCOH are noticeable in scenario 1 compared to scenario 4 due to a slightly higher OPEX cost that is present as a result of a significant use of DT, i.e., a higher consumption of electricity. Significantly higher LCOH results are noticeable in scenarios 2 and 3 due to the significant impact of the biomass cost resulting from the application of CHPB.

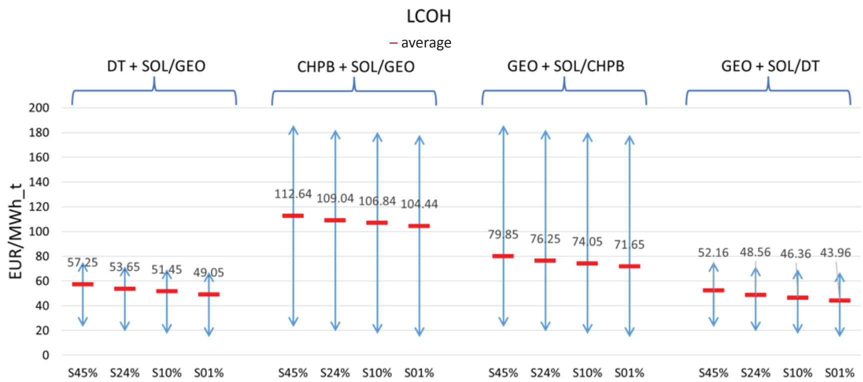


Figure 26
LCOH of DH solutions depending on the scenarios of application of different technologies and the scenario of percentage use of DH

After the presentation of the results for individual thermal systems, the results for the average solution in the scenario of using DH systems in the amount of 10% will be presented. The following section presents the results for the case of individual heating systems.

APPLICATION OF INDIVIDUAL HEATING SYSTEMS

Within the considered solution in the form of individual heating systems, four scenarios were observed depending on the technologies used. The scenarios are divided according to the method in paragraph 2.3.3.2.. In this chapter, as well as for the case of DH systems, the ranges of costs in the case of using individual heating systems are presented. The costs of the total investment, CAPEX and OPEX costs and the total LCOH are shown depending on the percentage of use of the considered technologies.

Figure 28 shows the total investment cost according to the observed scenarios and sub-scenarios. The figure shows the range of the total investment cost, where the upper arrow shows the maximum amount depending on the percentage share of a certain technology, while the lower arrow represents the minimum amount of the total investment. The red lines represent the average value of the total investment of the observed scenarios. It is noticeable that on average the lowest investment cost is achieved in scenario 2, which includes the base use of DTW and a variable share of solutions in the form of SOL and DTA. Such a result primarily derives from the assumed investment costs according to [20], where the specific investment cost per kW of thermal output for DTW is 1371 EUR/kWt, while for DTE and DTA it is 1714 EUR/kWt and 1741 EUR/kWt, respectively. Also, according to reference [16], the share of SOL in individual heating systems is limited to a maximum share of 20%.

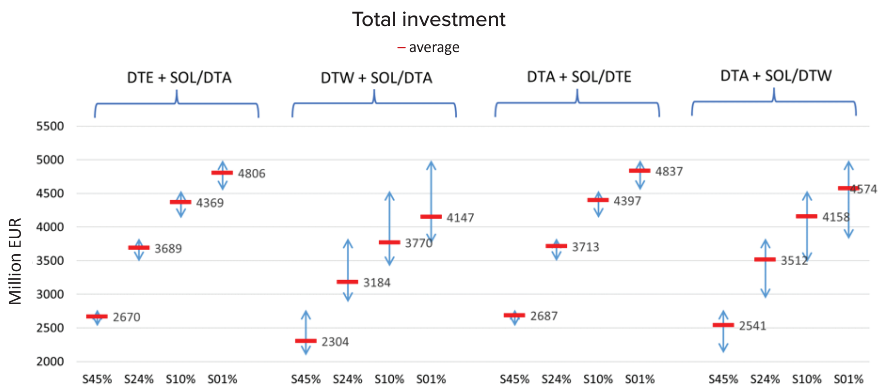


Figure 27
Total investment cost of individual heating systems depending on the scenarios of application of different technologies and the scenario of percentage use of DH systems

Related to the total investment cost shown above, Figure 28 shows the annual discounted investment cost – CAPEX. The discount rate used is 6%. As there is a difference in lifetime between the considered technologies, the above presentation of the total investment is not fully proportional with the figure where the annual discounted investment cost is presented. The lifetime of DTA is 16 years, DTE 20 years, while DTW and SOL technology have a lifetime of 25 years. As the specific investment cost for DTW is the lowest and the lifetime is the highest, scenario 2 results in the lowest average CAPEX cost. The range of CAPEX costs for scenario 2 where DTW is used as a base with a percentage change of SOL and DTA for scenario S45%, S24%, S10% and S01% amounts to 196, 270, 320 and 352 million EUR per year. It should be noted that the scenarios S45%, S24%, S10% and S01% symbolize the DH system percentage use, that is, the share of individual heating systems for the scenarios is 55%, 76%, 90% and 99%.

▸ Figure 28
CAPEX cost of individual heating systems depending on the scenarios of application of different technologies and the scenario of percentage use of DH systems

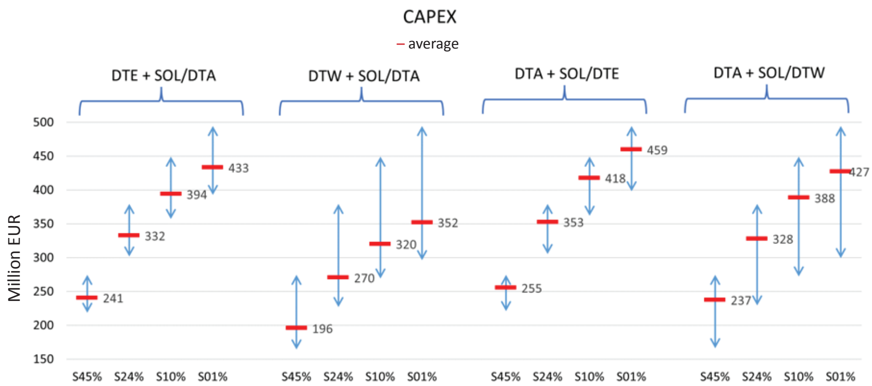
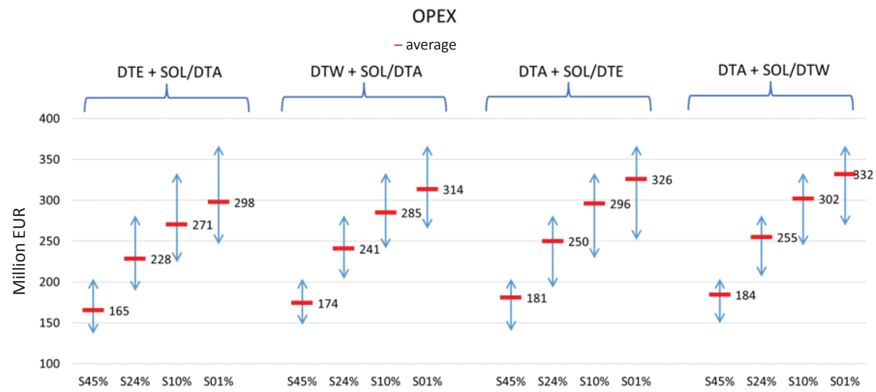


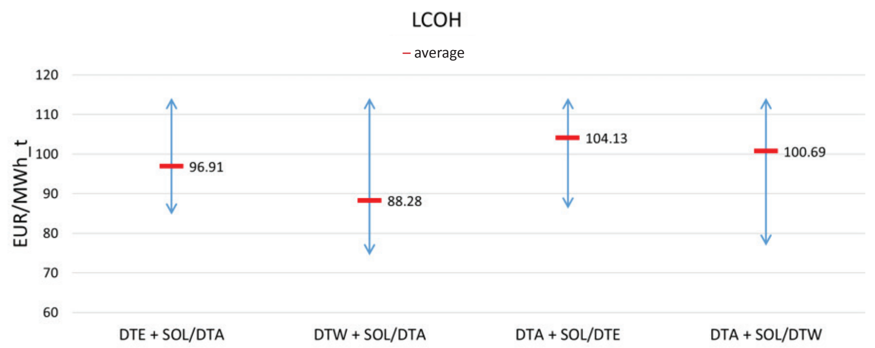
Figure 29 shows the ranges of annual operating costs. It can be observed that the difference in the average amounts of OPEX costs between the scenarios is relatively small. Furthermore, it is noticeable that the average minimum OPEX cost is noticeable in scenario 1, where the DTE technology is used as a base with a percentage change in the share of SOL/DTA technologies. According to the available references [16], [20] and [21], it is noticeable that DTE has the lowest FOM costs per kW of thermal output, amounting to 41 EUR/kWt. The FOM cost of DTW is slightly higher and is 43 EUR/kWt, while the FOM cost of DTA is 45 EUR/kWt. Also, a larger share of the total OPEX cost falls on the cost of electricity needed to operate the DT. The share of electricity costs in the total OPEX cost is 60.3%, 61.8% and 65.2% for the case of using DTE, DTW, and DTA technologies, respectively. The basic cost of 100 EUR/MWh was chosen as the cost of electricity. It should be noted that the COP of DTE technology additionally contributes to the minimum OPEX cost of scenario 1. The COP values for DTE, DTW, and DTA technologies are 4.2, 3.8, and 3.15.

Figure 29
OPEX cost of individual heating systems depending on scenarios of application of different technologies and scenario of percentage use of DH systems



As a final comparative presentation of the considered scenarios, Figure 30 shows the total levelised cost of heat energy production for the case of individual heating systems. As there is no additional cost of DH network in the scenario of individual heating systems, there is no difference between the levelised costs of heat for the scenarios of the percentage share of the DH systems. Therefore, the figure below shows the results according to the scenarios depending on the selected technologies. It can be noted that the minimum average LCOH was achieved in scenario 2 where the DTW technology is used as a base with a percentage change in the SOL and DTA technologies. The minimum amount of average LCOH is 88.28 EUR/MWh. The average LCOH for scenario 1, 4 and 3 is 96.91, 100.69 and 104.13 EUR/MWh, respectively.

Figure 30
LCOH of individual heating systems depending on the scenarios of application of different technologies and the scenario of percentage use of DH systems



In the continuation of the paragraph, the LCOH results will be presented for the case of the average solution in the S10% scenario, that is, in the scenario of the percentage share of DH systems in the amount of 10%.

RESULTS FOR SCENARIO S10%

Figure 31 shows the results in the form of LCOH for the S10% scenario for the DH case. The diagram shows the average results for the four observed scenarios according to the selected technologies. The results in the form of LCOH are divided into specific parts. The total LCOH is therefore divided into specific – CAPEX cost (EUR/MWh); specific fixed annual operating cost – FOM (EUR/MWh); specific variable annual operating cost – VOM (EUR/MWh); the specific cost of the required energy to operate the system minus the income generated from the sale of electricity when using the CHP solution – FUEL – REV (EUR/MWh); and the specific cost of the required DH network – DH network (EUR/MWh).

Figure 31
LCOH by items for the case of scenario S10% – DH systems

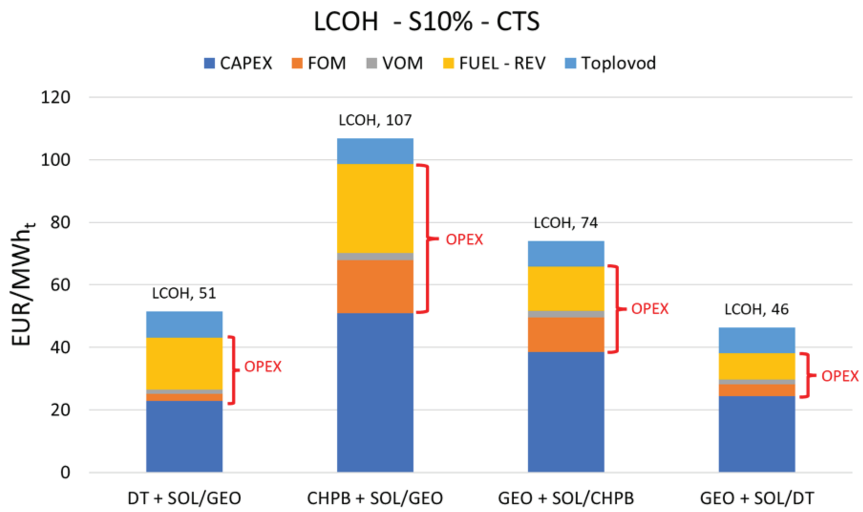
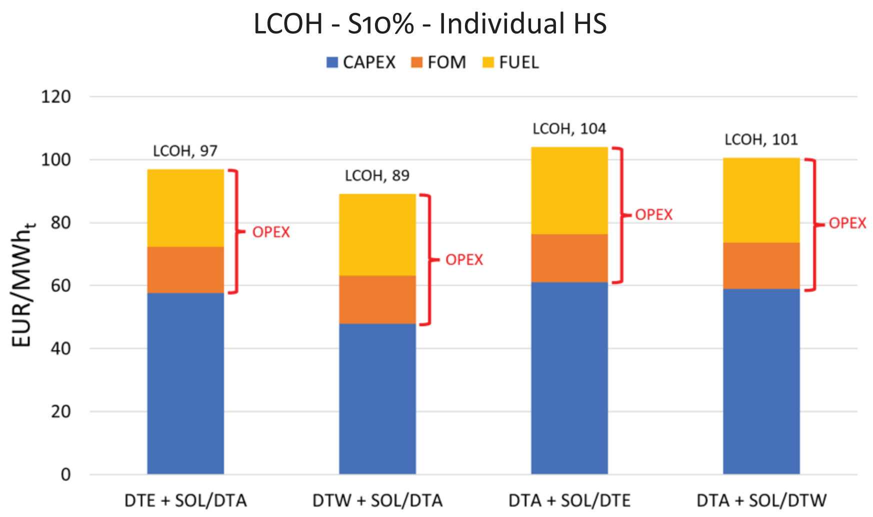


Figure 32 shows the results in terms of LCOH for the S10% scenario for an example of individual heating systems. The diagram shows the average results for the four observed scenarios according to the selected technologies. The total LCOH is divided into specific parts. The total LCOH is therefore divided into specific – CAPEX cost (EUR/MWh); specific fixed annual operating costs – FOM (EUR/MWh); and the specific cost of the required energy to operate the system – FUEL (EUR/MWh). As the key variable cost of the considered individual solutions is the cost of the necessary energy to drive the system, in this example, according to the references used, the variable annual operating costs are negligible. Also, as the individual solutions do not include the cost of the necessary thermal distribution, it is not indicated in the diagram below.

Figure 32
LCOH by items for the case of scenario S10% – Individual heating systems

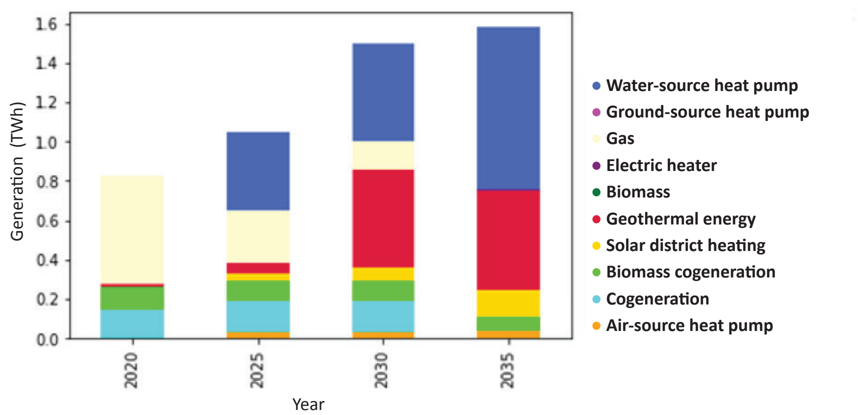


Scenario analysis of heating sector degasification

CENTRALISED HEATING SYSTEMS

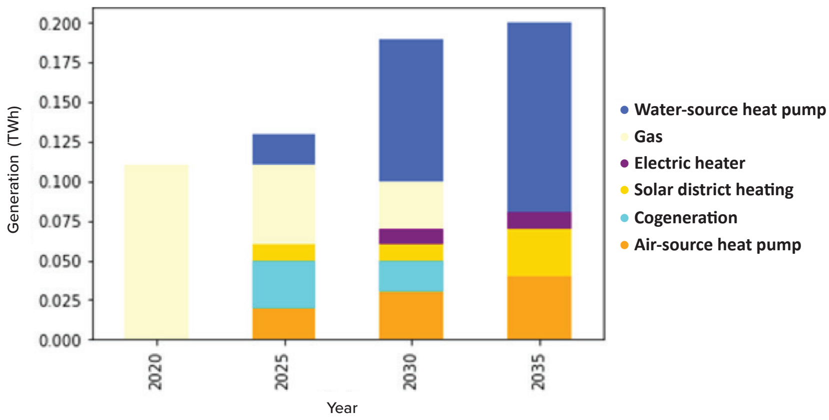
In the base year, heating and DHW supply for centralised heating systems in the region of continental Croatia is supplied from cogeneration power plants with a share of 31%. Most of the remaining needs are covered by fossil gas boilers. Also, the system uses solar energy with a share of less than 1%. The development of the system leads to a gradual reduction and complete elimination of the use of fossil gas and oil derivatives by 2035. Also, after 2030, there is a reduction in heat generation from cogeneration plants as a result of the reduction in the use of fossil gas. Cogeneration plants that use biomass continue to operate. At the same time, there is an increase in the share of heat supplied by heat pumps, solar energy, and geothermal energy. The primarily used type of heat pumps in centralised heating systems is water source heat pump.

Figure 33
Heating and DHW supply in centralized heating systems in continental Croatia, excluding the Zagreb region



Heating and DHW supply for centralised heating systems in the region of coastal Croatia is in the base year provided by fossil gas boilers. The development of the system leads to a gradual reduction and ends in the use of fossil gas and oil derivatives by 2035. At the same time, there is an increase in the share of heat pumps and solar energy. Also, there is an increase in the use of electrical resistive heaters.

Figure 34
Heating and DHW supply in centralised heating systems in coastal Croatia



Heating and DHW supply for centralised heating systems in the region of the City of Zagreb and Zagreb County in the base year is provided by cogeneration power plants with a share of 77%. Most of the remaining demands are covered by fossil gas boilers. The development of the system leads to a gradual reduction and end of the use of fossil gas and oil derivatives by 2035. Also, there is a reduction in heat generation from cogeneration plants as a result of the reduction in the use of fossil gas. At the same time, there is an increase in the share of heat supplied from heat pumps, solar energy and geothermal energy.

Figure 35
Heating and DHW supply in centralized heating systems in the Zagreb region

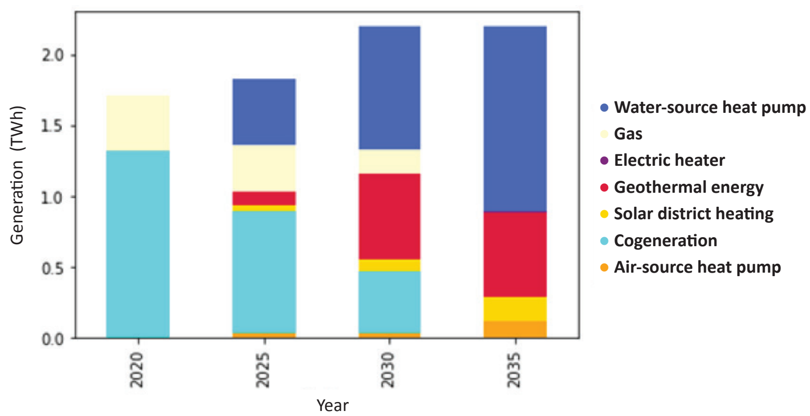


Table 5 shows newly installed capacities in centralised heating systems. As can be seen from the comparison of the table and the diagrams featuring heat generation, some of the capacities such as electric heaters are installed with the intention of supplying only the peak demand for a small number of working hours per year, while for example heat pumps work in base load.

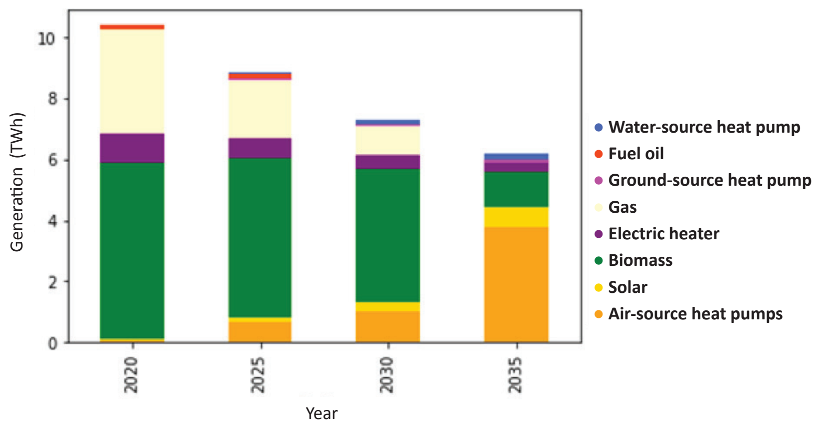
Year	Region	Air-water heat pumps	Electrically resistant heater	Ground-water heat pumps	Water-water heat pumps	Geothermal energy	Biomas boiler	Coal boiler	Gas boiler	Oil derivatives boiler	Solar collectors	Solar seasonal tanks [MWh]
2025	Continental Croatia	4	2	0	50	5	0	0	0	0	24	2443
2030	Continental Croatia	0	0	0	107	54	0	0	0	0	29	2352
2035	Continental Croatia	0	37	0	137	0	0	0	0	0	31	2367
2025	Coastal Croatia	4	2	0	6	0	0	0	0	0	10	4590
2030	Coastal Croatia	3	0	0	26	0	0	0	0	0	7	1863
2035	Coastal Croatia	0	7	0	0	0	0	0	0	0	0	59
2025	Zagreb and surroundings	2	0	0	58	11	0	0	0	0	27	7244
2030	Zagreb and surroundings	5	1	0	193	63	0	0	0	0	35	12093
2035	Zagreb and surroundings	12	35	0	147	0	0	0	0	0	9	33956

▲ Table 5
Installation of new capacities in centralised heating systems [MW]

INDIVIDUAL SYSTEMS

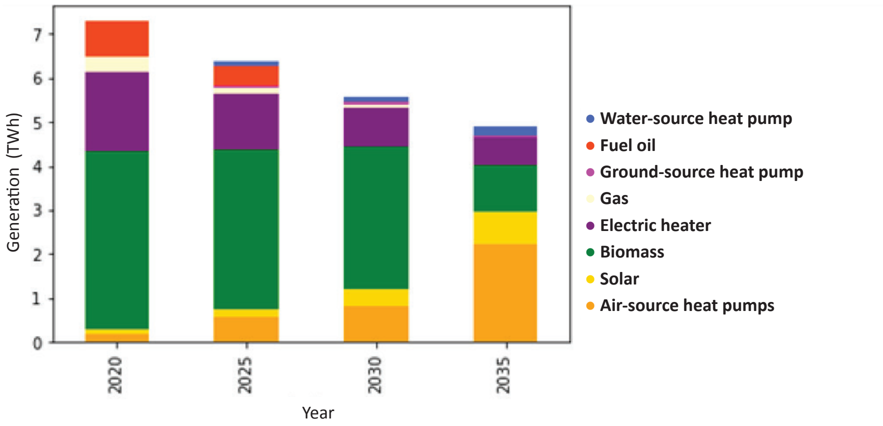
In the base year, heating and DHW supply of individual systems in the region of continental Croatia is provided by biomass with a share of 53%, fossil gas with 29%, and electrical heaters with 12%. The rest corresponds to the share of oil products. The development of the system leads to a gradual reduction and end of the use of fossil gas and oil derivatives by 2035. At the same time, there is an increase in the share of heat pumps and solar energy. The use of biomass is also decreasing. In the case of individual systems, the role of air source heat pumps is higher due to the limited availability from technical and legal side in implementation of higher efficiency water-source and ground-source heat pumps.

▶ Figure 36
Heating and DHW supply in individual heating systems in continental Croatia, excluding the Zagreb region



Heating and DHW supply in individual systems in the region of coastal Croatia in the base year is provided by biomass with a share of 47%, fossil gas with 20% and electricity with 28%. The rest corresponds with petroleum products. The development of the system leads to a gradual reduction and end of the use of fossil gas and oil derivatives by 2035. At the same time, there is an increase in the share of heat pumps and solar energy, while the use of biomass decreases as well. The use of electric resistive heaters also decreases as an effect of the introduction of more efficient alternatives in the form of heat pumps.

Figure 37
Heating and DHW supply in individual heating systems in coastal Croatia



In the base year, heating and DHW supply of individual systems in the Zagreb region and Zagreb County is provided by the use of fossil gas with a share of 45%, biomass with 42% and electricity with 8%. The rest goes to petroleum products. The development of the system leads to a gradual reduction and end of the use of fossil gas and oil derivatives by 2035. At the same time, there is an increase in the share of heat pumps and solar energy. The use of biomass is also decreasing.

Figure 38
Heating and DHW supply in individual heating systems in the Zagreb region

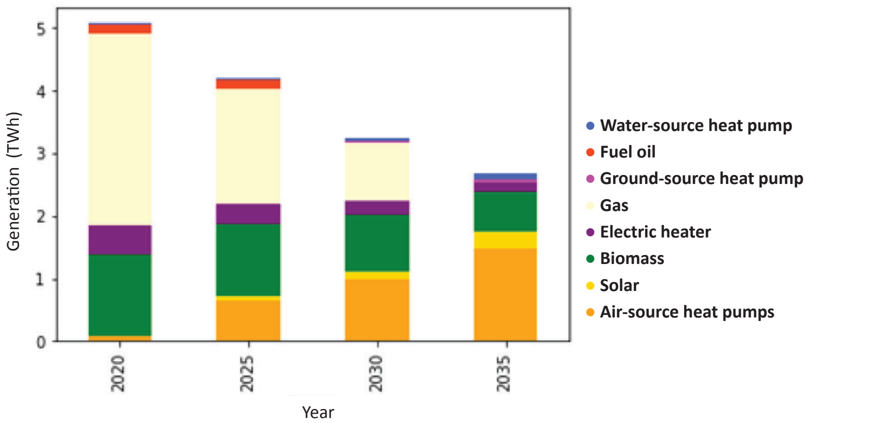


Table 6 shows data on new installations in individual heating systems. Similarly to centralised systems, investments are divided into base and peak heat production technologies.

Year	Region	Air-water heat pumps	Ground-water heat pumps	Water-water heat pumps	Electrically resistant heater	Biomass boiler	Oil derivatives boiler	Coal boiler	Gas boiler
2025	Continental Croatia	61	10	1	0	0	0	0	0
2030	Continental Croatia	165	23	95	0	0	0	0	0
2035	Continental Croatia	961	27	42	307	0	0	0	0
2025	Coastal Croatia	0	6	1	0	0	0	0	0
2030	Coastal Croatia	279	19	75	0	0	0	0	0
2035	Coastal Croatia	391	1	34	446	0	0	0	0
2025	Zagreb and surroundings	61	6	1	0	0	0	0	0
2030	Zagreb and surroundings	198	14	6	0	0	0	0	0
2035	Zagreb and surroundings	137	3	44	130	0	0	0	0

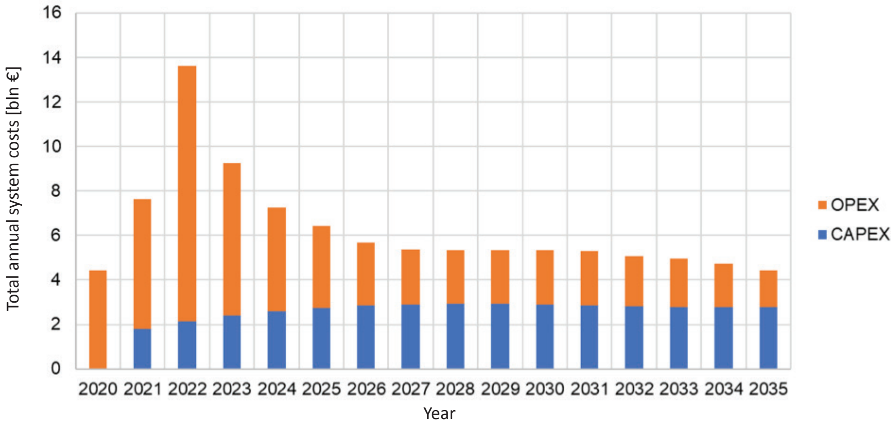
▲ Table 6
Installation of new capacities in individual heating systems [MW]

ECONOMY AND INVESTMENTS

Total system costs

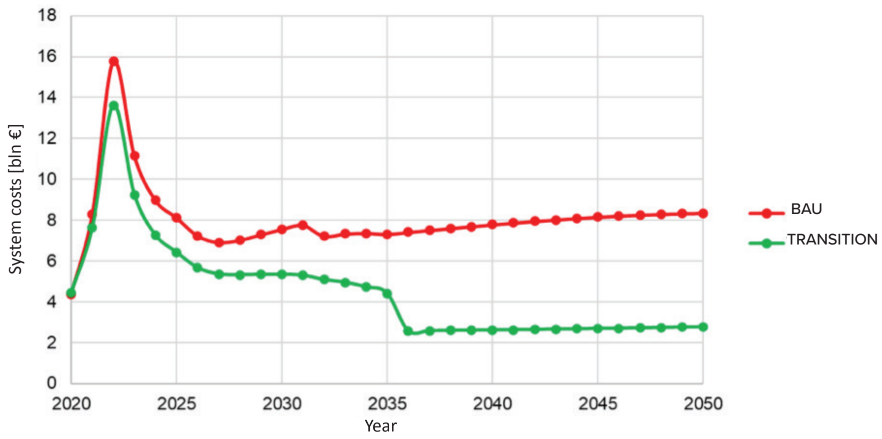
The total annual costs of the system reach the maximum around 2022 with a level of 13.5 billion. €/year and are reduced in consequent years with the total annual cost in 2035 being 4.2 billion €/year. The reason for the extreme peak in costs in 2022 is due to the difficulties in the supply of gas and other fossil fuels and the resulting energy crisis featuring high cost of the fuels. Figure 39 shows the evolution of total costs. The share of capital costs (CAPEX) increases as most of the system cost structure is in investments into new technologies such as the new capacities of variable renewable energy sources, flexibility technologies, energy storage and new production technologies in heating systems and in industry. Also, there is a replacement of the vehicle fleet with mostly electric vehicles. At the same time, there is a visible reduction in operating costs (OPEX) as a result of the reduction in the use of fossil fuels. The total discounted sum of the capital investments between 2020 and 2035 sums to 39 billion. €.

Figure 39
Total costs



A comparison of the implemented scenario with the BAU scenario, which assumes the continued use of existing technologies, was made. To the greatest extent, this represents the need for the renovation and maintenance of the existing gas infrastructure and the retention of the use of vehicles with internal combustion engines. At the same time, there is an increase in emission costs, which further increases operating costs in the period from 2030 to 2050. Due to the need to consider economics, system development and costs are assumed after the end of the simulation in 2035. In the transition scenario, the amount of capital costs is assumed in the amount of 33% compared to the last simulated year 2035 with the assumption of a 15-year replacement interval of the existing systems. This amount was chosen because it represents the number of investments needed to maintain and replace worn-out parts of the system. Figure 40 shows the comparison of the transition and BAU scenarios and the cost decrease in the transition scenario is visible, as well as the increase in cost difference in future years of the system development.

Figure 40
Total costs of the transition scenario and the BAU scenario



The difference is further increased by increasing the cost of emissions as shown on Figure 41 and reduced by reducing the price of emissions, which is shown in Figure 42.

Figure 41
Total costs of the transition scenario and the BAU scenario with an increase in emission costs by 50%

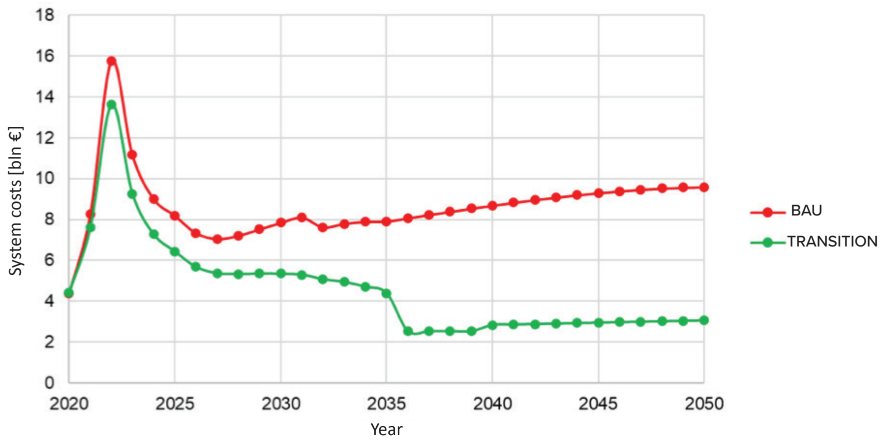
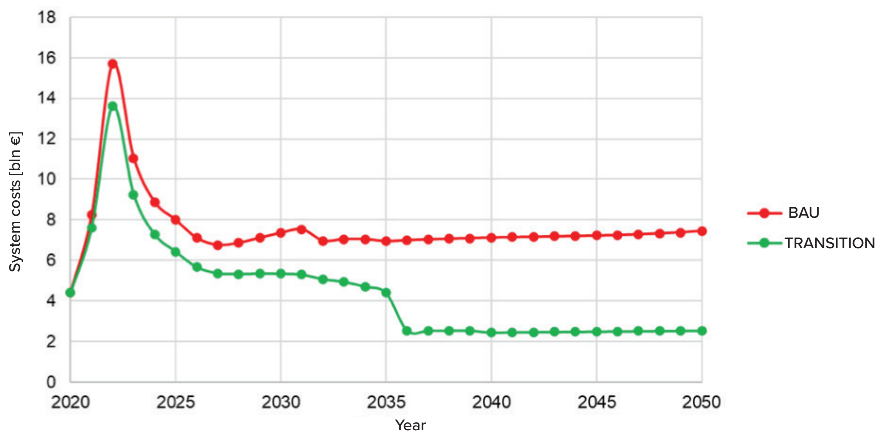
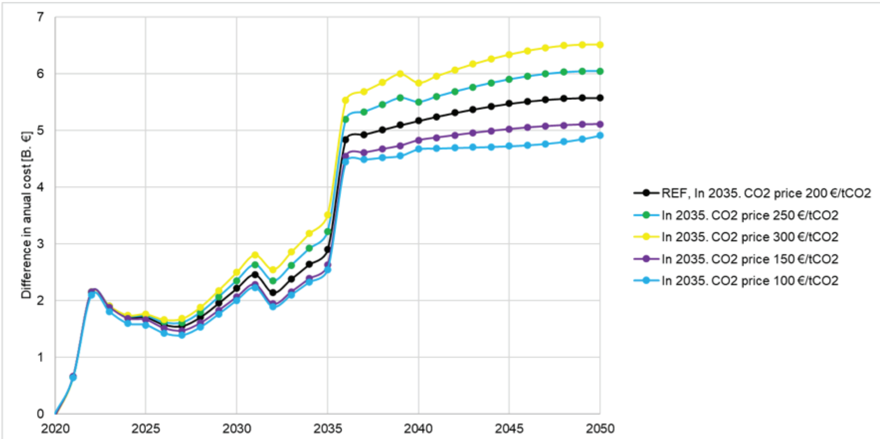


Figure 42
Total costs of the transition scenario and the BAU scenario with a 50% reduction in emissions costs



The comparison of total annual costs with regard to the applied level of emission costs is shown in Figure 43. As expected, the scenario with the higher emission prices shows higher difference in the total annual costs of the system and thus greater profitability of the transition scenario. All the examined cases of the transition scenario are profitable and thus present lower annual costs than the BAU scenario. The transition scenario features lover annual total cost in all years.

Figure 43
Comparison of total annual costs for the reference case, the case of increasing emission costs by 25 and 50% and for reducing emission costs by 25 and 50%



KEY MESSAGES

The presented results of the analysis can be turned into key messages that can be used to define guidelines for the development of strategies and policies that would help to achieve the goal of performing full degasification the Republic of Croatia.

HOW TO FULLY EXPLOIT CERTAIN ENERGY SECTORS?

- The electricity generation sector can be fully degasified using already known technologies: wind power plants and solar power plants. Along with the massive integration of variable renewable energy sources, it is necessary to enable energy storage in different forms and to increase the flexibility of the system. Energy storage primarily refers to short-term hydrogen storage systems to ensure the smooth operation of industrial processes and optimisation of the charging of electric vehicle batteries.
- The industry sector is fully degasified by the gradual replacement of technologies and energy sources. Gas is currently used as an energy source and for non-energy consumption. Gas is used for non-energy consumption in refineries and the petrochemical industry. This part of the consumption can be completely replaced by green hydrogen, while the energy consumption is replaced depending on whether it is low-temperature or high-temperature processes. In the case of low-temperature processes, replacement is primarily carried out by introducing electrically powered processes, while replacement of high-temperature processes with electricity is impossible or impractical. In this case, a fuel switch with green hydrogen is carried out.
- Today, a large amount of fossil gas is used for heating in individual gas boilers. The analysis proposes the expansion of existing district heating systems and the installation of new ones in densely populated urban areas. The study showed that 45% fossil of gas consumption for heating can be transferred to district heating systems. The existing systems need to be decarbonized using locally available heat sources: geothermal energy, solar energy with a combina-

tion of seasonal heat storage tanks, aquifer energy, ground and surface water energy, and biomass (locally available while paying attention to its sustainability). In addition to the mentioned heat sources, it is also necessary to use heat pumps, which are powered by green electricity. In this way, the flexibility of the system is further increased and the possibilities of highly efficient conversion of electrical energy into thermal energy are available. Areas that are not densely populated and use gas boilers for heating should switch to heat pumps while using air, ground, or water as a heat source.

WHAT POLICIES AND STRATEGIES NEED TO BE IMPLEMENTED IN ORDER FOR THE REPUBLIC OF CROATIA TO FULLY DEGASIFY?

- It is necessary to encourage the expansion of existing heating networks and the installation of new systems. In addition to the above, it is necessary to invest in the decarbonisation of existing heating systems, which today are mostly based on fossil gas (cogeneration and gas boiler).
- Subsidise the replacement of gas boilers with heat pumps and the upgrading of heating systems in houses and apartments (installation of fan convectors or underfloor heating). In the heating sector, it is necessary to install 245 MW of heat pumps per year.
- Accelerate the construction of renewable energy sources, especially wind and solar power plants. Annually, it is necessary to build 380MW of wind power plants and 410 MW of photovoltaic power plants by 2035.
- Encourage the local manufacturing of electrolysers and the production of green hydrogen. In order to meet the needs for hydrogen, it is necessary to install 60 MW of electrolysers and 30 MWh of hydrogen storage annually.

CONCLUSION

By 2035, the development of the electric power sector will lead to the end of the use of fossil energy sources represented by gas, coal and oil derivatives. They are replaced primarily by domestic production from variable renewable energy sources with a total capacity of 6488 MW of wind power plants and 6304 MW of photovoltaic power plants. At the same time, there is an increase in electricity consumption due to the transformation of the heating, industry and transport sectors. The industry sector is also undergoing significant changes, especially in branches that rely on gas and coal.

By modelling the spatial distribution of fossil gas consumption in the household sector and the service sector, the areas where the heating sector needs to be fully degasified are defined. The results showed that the largest consumption of fossil gas takes place in continental Croatia, with the area of Gradska plinara Zagreb d.o.o. leading the way, with a share of 39% in total consumption by households and 41% in consumption by the service sector. In the coastal part of Croatia, the cities of Split, Rijeka and Pula have the highest consumption of fossil gas in households. In the distribution area of the distributor EVN Croatia Plin d.o.o., the consumption of fossil gas in the service sector is significantly (11 times) higher than the consumption of gas in households. This distribution area covers the cities of Otočac, Gospić, Trogir, Kaštela, Zadar, Biograd na Moru, Benkovac, Šibenik, Drniš, Knin, Split, Solin.

The heating sector in cities and urban areas is often based on individual gas boilers. The analysis showed that 45% of the current consumption of fossil gas for heating can be transferred to centralised heating systems, whereby the discounted cost of the heating network is equal to 14.1 EUR/MWh. It is important to emphasise that this is a long-term process, whereby the expansion of the existing heating networks in areas with a high density of heat needs, i.e. greater than 500 MWh/ha, is required first.

The cost of the additional expansion of the heating network was used in the scenario analysis of the construction of new and expansion of existing centralised heating systems, along with the analysis of the degasification of individual systems. For the case of replacing 45%, 24%, 10% and 1% of gas heating, the results of the costs of the transition are calculated and divided into capital costs (CAPEX), operating costs (OPEX) and the cost of expanding existing or building new DH systems. The levelised cost of heat energy production (LCOH) for the case of building the new and expansion of the existing DH is the smallest for the case of using geothermal sources as a base technology in combination with solar heating systems and central heat pumps. The LCOH of this system variation ranges from EUR 52.16 to EUR 43.96 /MWht.

The optimisation of the heating sector for the transition of 45% of existing gas heating to centralised heating systems has shown that most of the transition can be achieved by introducing heat pumps. Most of the demands are taken over by water-source heat pumps in centralised heating systems, while in individual systems most of the demands are transferred to air-source heat pumps. Also, with centralised heating systems, geothermal energy takes over a large part of the needs. The reason for the different outcomes for centralised heating systems and individual systems, as well as for different regions, is due to different levels of resource availability.

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ATTACHMENTS

Capital costs of investments

Table 7
Capital costs of investments in production technologies [million €/MW] [16]

YEAR	WIND	PV	GEOTHERMAL POWER PLANTS
2020	1,1	0,56	3,4
2025	1,07	0,47	3,2
2030	1,04	0,38	3,1
2035	1,01	0,35	3

Year	Air-water heat pump	Water-water heat pump	Ground-water heat pump	Electric heaters	Gas	Biomass	Oil and oil derivatives	Coal	Solar heating systems
2020	0,86	0,48	2,07	0,07	0,06	0,52	0,28	0,47	0,30
2025	0,86	0,48	1,97	0,07	0,06	0,49	0,27	0,46	0,29
2030	0,76	0,38	1,87	0,06	0,05	0,45	0,27	0,45	0,28
2035	0,76	0,38	1,82	0,06	0,05	0,44	0,26	0,44	0,28

Table 8
Capital costs of the heating system [million €/MW] [16]

Table 9
Investments in vehicles [€/vehicle] [22]

YEAR	ICE	EV	FCEV	HYBRID	PHEV
2020	27000	34000	45000	28000	30000
2025	29000	30600	42750	28000	29250
2030	31000	27540	40613	28000	28519
2035	32000	24786	38582	28000	27806

Table 10
Investments in hydrogen technologies and energy storage technologies [16]

YEAR	PEM ELECTROLYZERS	ALKALINE ELECTROLYZERS	SOEC ELECTROLYZERS	HYDROGEN STORAGE	LITHIUM-ION BATTERIES
2020	0,925	0,65	4,491	0,057	1,042
2025	0,79	0,55	3,196	0,047	0,874
2030	0,65	0,45	1.901	0,038	0,664
2035	0,55	0,35	1,06	0,038	0,508

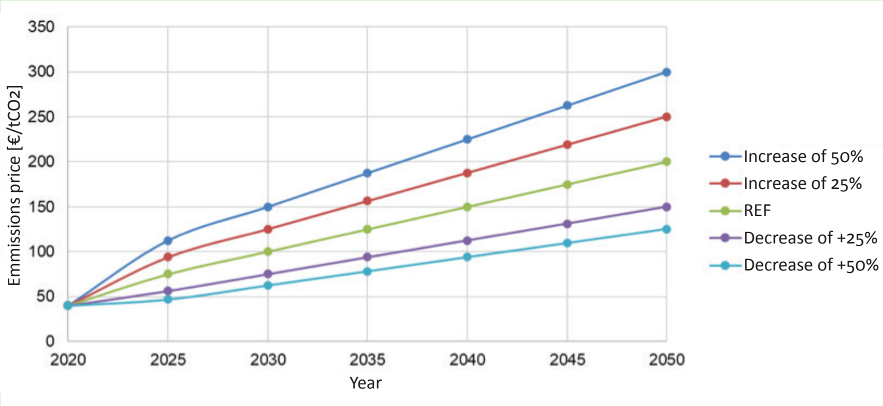


Figure 44
Costs of emissions

Description of technologies

THERMAL POWER PLANTS

Thermal power plants are thermal energy plants that produce electrical and/or thermal energy from the chemical energy of the fuel. The production is carried out first by burning fuel in furnaces, which produces flue gases with high internal energy, i.e. gases with high temperatures. Then, most often in the steam generator, the heat is transferred from the flue gases to steam, and the final product is steam with high parameters. This steam can be used to produce work on a turbine which is connected to a working machine, e.g. an electric generator where electricity is generated. The basic purpose of thermal energy plants is the production and transformation of primary forms of energy into useful work, which is then used in the form of mechanical energy for the production of electricity. Mechanical energy is produced with the help of a heat engine that transforms heat energy. Chemical energy is converted into thermal energy, which is transferred to a working medium through various processes. The working medium serves as a transmitter of this energy, often by burning fuel, into rotational energy. The most important parts that form a closed unit within a thermal power plant are: steam generator, turbine, electricity generator and condenser. We distinguish three large groups of thermal power plants: steam-turbine plant, gas-turbine plant and combined process composed of gas-turbine and steam-turbine parts.

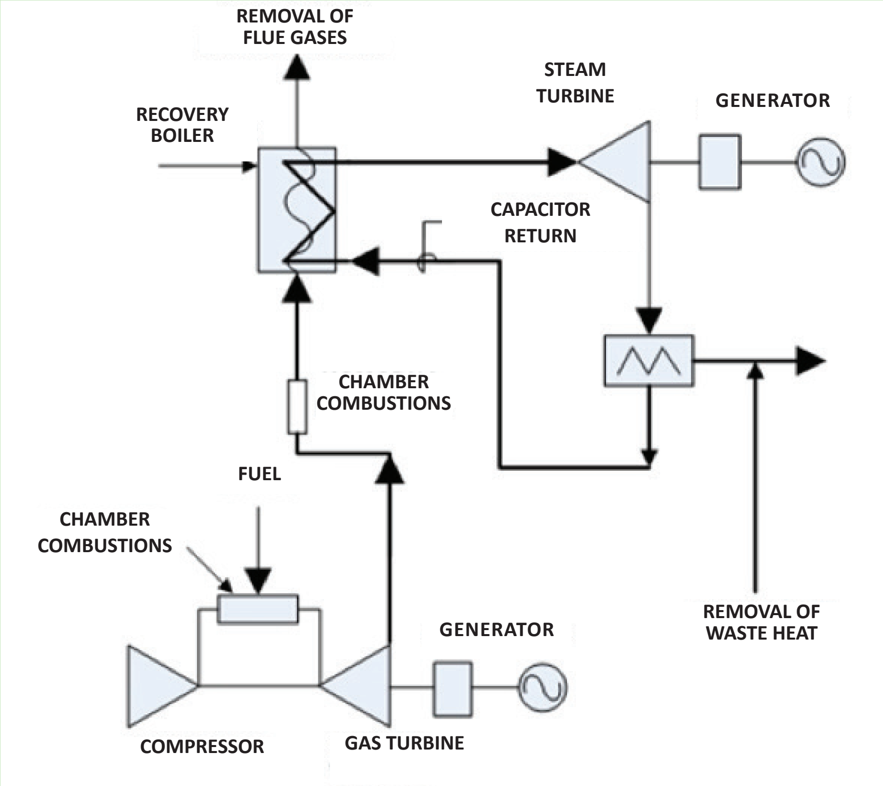


Figure 45
Scheme of the combined process of the thermal power plant [23]

COGENERATION

Cogeneration or co-production (Combined Heat and Power or CHP) is the simultaneous production of two useful forms of energy (electrical and thermal) in a single process. Thermal energy that remains unused in a conventional power plant (or is released into the environment with negative effects) is used for needs in various production processes or, which is more often the case, for heating individual buildings or entire settlements. Thermal energy can be used to produce steam, heat water or air. The total efficiency of cogeneration is from 70 to 85% (from 27 to 45% of electricity and from 40 to 50% of thermal energy), in contrast to conventional power plants where the total efficiency is from 30 to 51% (of electricity). In addition, network losses, transmission congestion and harmful effects on the environment are reduced, and the voltage quality and reliability of electricity supply have increased. The cogeneration plant, in terms of connection and operation in relation to the distribution network, is most often designed for parallel operation with the electric distribution network, meeting its own needs for electricity, while possible surpluses are transferred to the external network. However, the cogeneration plant can also work in a separate (island) operation, when it exclusively meets the consumption of electricity at the facility (complex). Typical cogeneration power plants are: back pressure turbine plant, condensation turbine plant with regulated steam extraction, gas turbine plant using flue gas waste heat and fuel cells with molten carbonates.

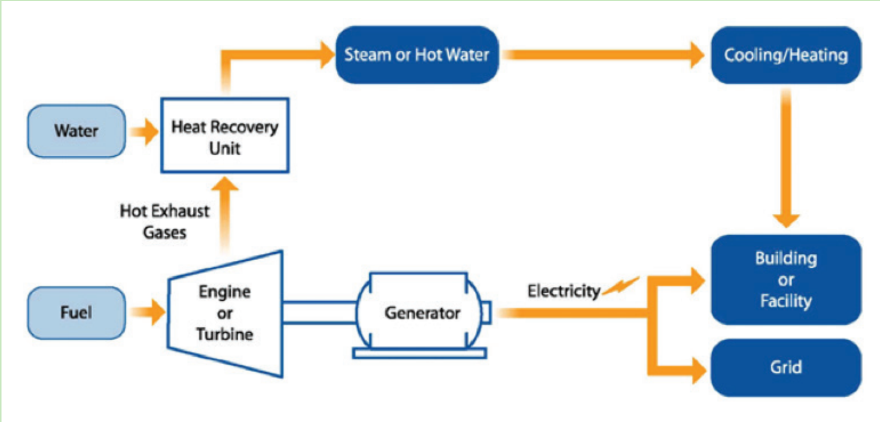


Figure 46
Scheme of a common cogeneration process [23]

WIND POWER PLANTS

The term wind power plant implies a system for the transformation (conversion) of moving air mass, i.e. wind into electricity, which as an energy resource is characterised by variability and the inability to store it. A wind power plant consists of a turbine that converts the kinetic energy of the wind into mechanical energy and an electric generator that converts the mechanical energy into electricity. The kinetic energy of the wind is transferred to the rotor blades of the turbine, which drives the slow-rotating shaft, which drives the fast-rotating shaft through the transmission and transmits mechanical energy to the shaft of the electric generator, which provides electricity at its terminals. In some versions of the wind turbine (depending on the configuration type), the transmission may be missing, and in this way the turbine rotor shaft is directly connected to the generator shaft. The structural forms of wind power plants can differ according to the position of the

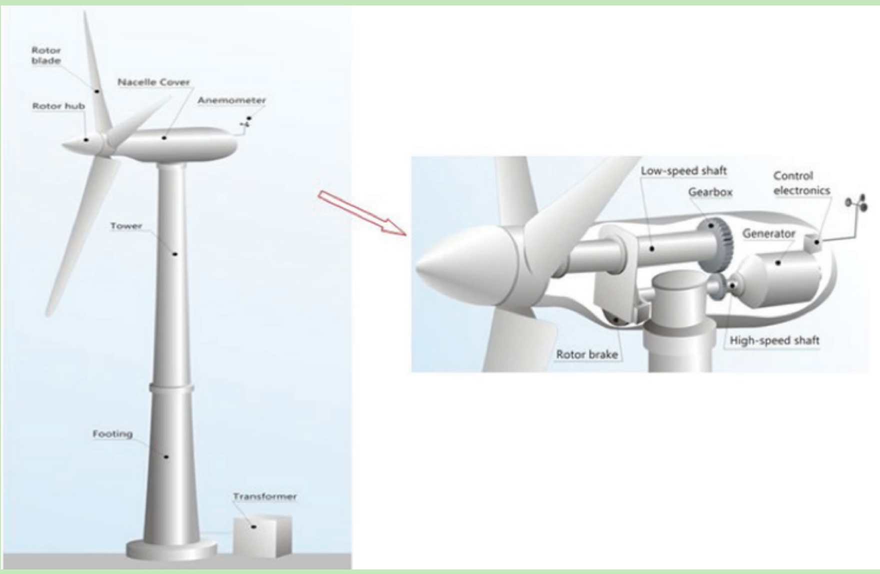


Figure 47
Scheme of the wind power plant [24]

shaft and the number of blades. According to the position of the shaft, there are two basic types of wind turbines: wind turbines with a horizontal rotor shaft and wind turbines with a vertical rotor shaft. Depending on the place of installation, wind power plants are divided into those that are installed on land and those that are located offshore. The basic parts of a wind turbine are the rotor, blades, generator, casing, column and transformer.

PHOTOVOLTAIC SYSTEMS

Photovoltaic cells or photocells are semiconductor elements that directly convert the energy of solar radiation into electricity. The basic element of the photovoltaic system is the photovoltaic module. The photovoltaic module consists of a series of cells connected in series, the number of which varies depending on the power and desired electrical characteristics of the module. By exposing the cell to solar radiation, an electric current is generated and thus the cell becomes a source of electricity. Cells are produced in amorphous, monocrystalline, multilycrystalline or banded crystalline silicon technologies and in thin film technology. The efficiency of solar cells ranges from just a few percent to 40%. Photovoltaic modules generate direct current and converters are used to convert it from direct current to alternating current, suitable for transmission to the power grid.

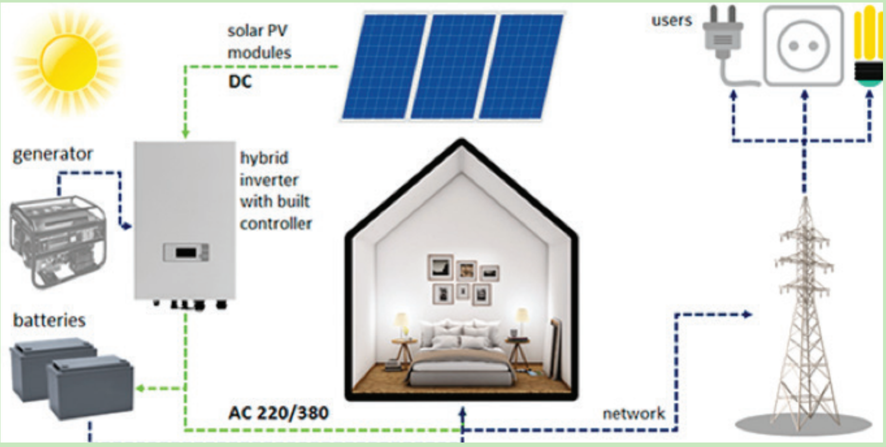
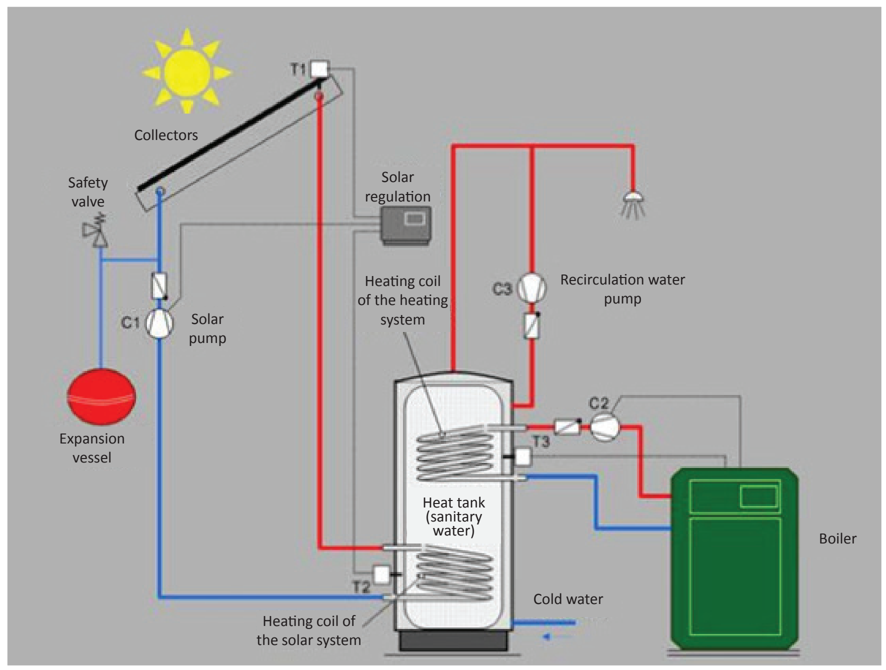


Figure 48
Photovoltaic system scheme [25]

SOLAR THERMAL COLLECTORS

Solar collectors convert solar energy into thermal energy of water (or other working substances). Water heating systems can be open, in which the water to be heated passes directly through the collector on the roof, or closed, in which the collectors are filled with a working substance. In addition to solar collectors, solar thermal systems consist of a whole series of elements: hot water tanks, boilers, pumps and accompanying equipment such as regulation systems, safety valves, etc. Solar thermal systems are most often used for heating hot water and as support for space heating. Since the time profile of the need for hot water and the available resource of solar radiation do not match, the hot water is constantly heated by the working fluid, and the hot water heated in this way is stored in the hot water tank. The most commonly used types of collectors are plate and vacuum collectors.

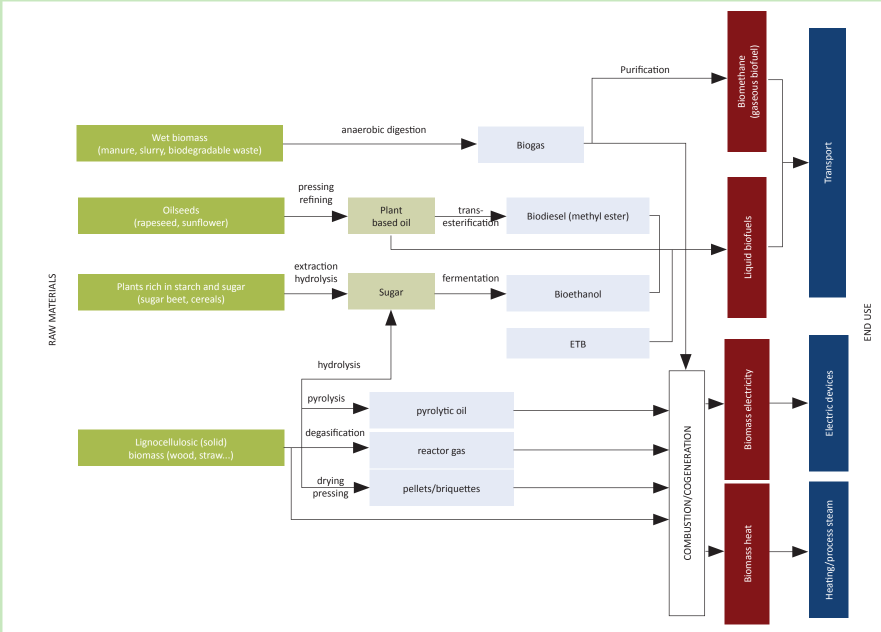
Figure 49
Scheme of application of solar collectors in the household [26]



BIOMASS

Biomass is the biodegradable part of products, waste and residues of agricultural production (plant and animal origin), forestry and related industries. Biomass energy comes in solid, liquid (e.g. biodiesel, bioethanol, biomethanol) and gaseous (e.g. biogas, biomass gasification gas and landfill gas) forms. Biomass can be used for direct conversion of biomass into electricity and heat or conversion into fuels. Biomass is a renewable source of energy, and in general it can be divided into woody and non-woody mass and animal waste, within which the following can be distinguished: woody biomass (residues from forestry, waste wood), woody grown biomass (fast-growing trees), non-woody grown biomass (fast-growing algae and grasses), residues and waste from agriculture, animal waste and residues, urban and industrial waste.

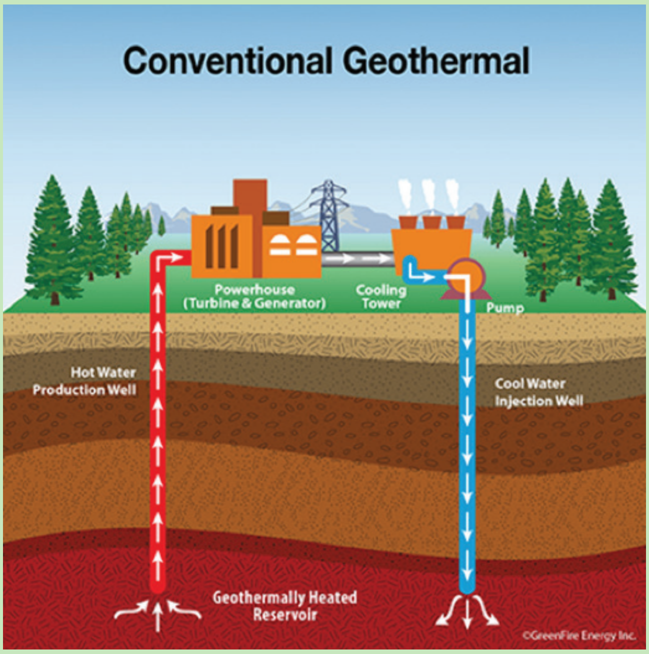
Figure 50
Scheme of possible biomass conversion steps [27]



GEOTHERMAL ENERGY

Geothermal energy is the Earth's thermal energy that is suitable for direct use or for conversion into electricity. The basic geothermal resource is represented by geothermal fluids located in underground reservoirs, which can be brought to the surface and used. Underground deposits of thermal waters occur at a wide range of depths – from shallow/surface to several kilometers deep. The direct use of geothermal energy is the use of heat from low-temperature resources (water temperature below 90 °C) for heating in industrial processes, in agriculture for heating greenhouses, in aquaculture for heating ponds, for melting

Figure 51
Scheme of a conventional geothermal power plant system [28]



snow on pavements, in balneology (spa) and in heating, for space heating and cooling. High-temperature and medium-temperature resources can be used to generate electricity. The operation of geothermal power plants is based on converting the thermal energy of the geothermal fluid into the kinetic energy of rotating the turbine, and then into electrical energy. Geothermal power plants work on three basic principles: dry steam, steam separation and binary cycle.

HEAT PUMPS

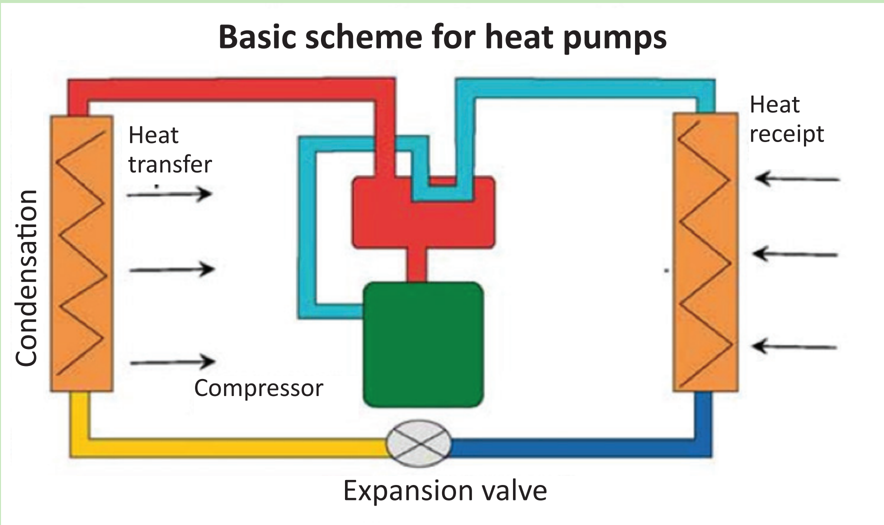
A heat pump enables the transfer of (thermal) energy from the system (heat reservoir) of a lower temperature level by using additional energy (work) using a counter-clockwise circular process of a suitable working medium. Because of this property, heat pumps are very suitable as sources of thermal (and cooling) effect in heating systems, preparation of domestic hot water, ventilation and air conditioning. Heat reservoirs of different temperature levels are: heat source (space or medium of lower temperature level from which heat is removed) and heat sink (space or medium of higher temperature level to which heat is supplied). Regarding the source of additional energy, heat pumps can be with the ground as a heat source, with water and air.

Heat pumps with the ground as a heat source refer to the thermal energy of the surface or underground layers of the Earth, i.e. geothermal energy. The basic feature of the soil as a source is the ability to store thermal energy all year round, which enables its utilization throughout the year.

Heat pumps with water as a heat source refer to the thermal energy of surface (stream, river, lake, sea), underground or waste water. The basic characteristics of water as a heat source is a relatively constant temperature throughout the year.

Heat pumps with air as a heat source refer to the thermal en-

▶ Figure 52
The basic scheme of the heat pump [29]

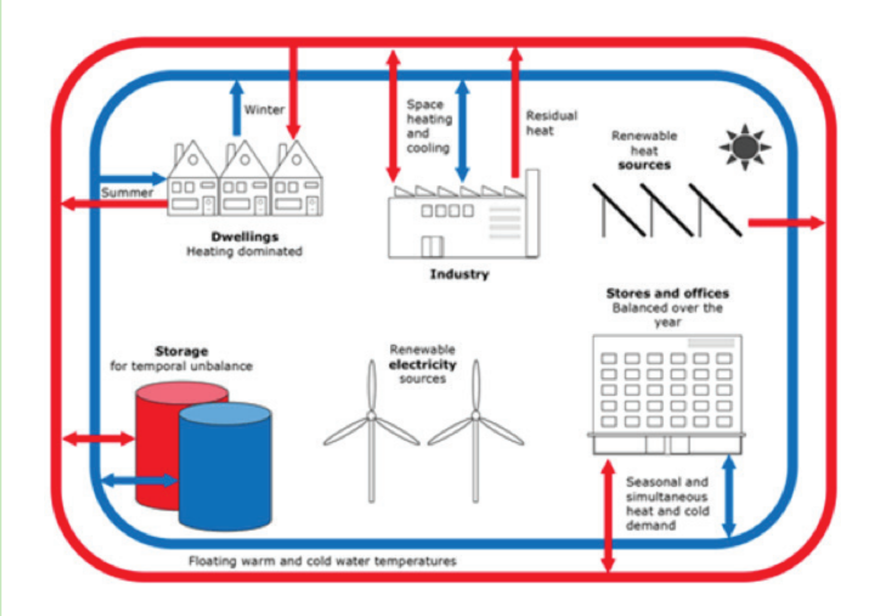


ergy of external or waste, spent or polluted air from the ventilation and air conditioning system or various processes. The basic characteristic of air as a heat source is the discrepancy between the times when the outside temperatures are the highest and when the heat needs for heating are the highest.

CENTRALISED HEATING SYSTEM (CTS)

A centralised heating system is a system of distribution of thermal energy that is produced in a central location, and is used to meet the thermal energy needs of commercial users, as well as private residential buildings in a remote location. Consumers can use the produced heat for space heating or for heating domestic hot water. Thermal energy is most often produced in central cogeneration plants. In addition to cogeneration plants, heat for central heating systems is also produced in the heating plants themselves. Thermal energy, after it has been produced, is taken to consumers through insulated steam pipes or hot pipes. The central heating system consists of incoming and outgoing water. Pipes are usually located below the surface of the Earth, but there are also above-ground versions. Inside the system, heat tanks can be installed, which have the role of compensating the peak consumption of thermal energy. The most common media used to transfer heat energy are water, hot water under pressure and steam. The advantage of steam is that in addition to satisfying heating needs, it can also be used in industrial processes due to its high temperature. The disadvantage of steam is higher heat losses due to its high temperature. It is possible to integrate some of the renewable energy sources such as biomass energy, solar, geothermal and electric energy into district heating systems. Traditionally, the largest share is occupied by energy from biomass, and in geologically suitable areas, geothermal energy also plays a large role. Furthermore, solar thermal systems and heat pumps are integrated into district heating systems. The principle of operation of solar thermal systems in district heating does not differ significantly from solar thermal systems in households or industry. However, solar thermal systems in district heating are characterised by a higher temperature regime and a larger installed capacity, which is achieved by installing a larger number of collectors. Furthermore, the capacity of the thermal storage tank is also significantly higher, especially in systems with a high proportion of solar thermal energy, which require seasonal storage of thermal energy.

▶ Figure 53
Circular view of the fifth generation CTS system [30]

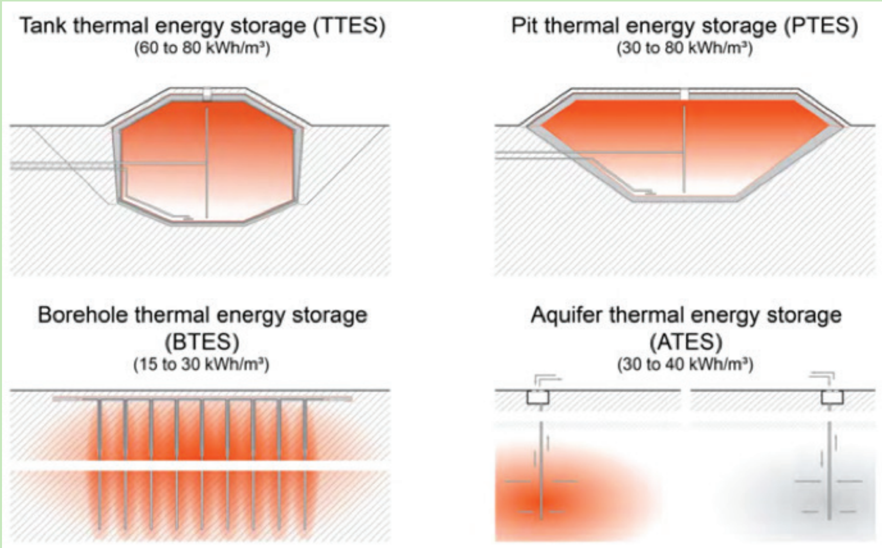


SEASONAL HEAT STORAGE TANKS

Seasonal heat storage tanks are used to store excess heat from industrial plants, power plants and geothermal plants, as well as heat generated during waste incineration, as an aid in the optimisation of cogeneration plants, as a storage tank for systems with heat pumps and as a heat storage tank for systems with different heat sources. They are divided into four types of containers for temperatures below 95 °C:

- thermal steel tank
- heat tank in the form of an insulated pit
- heat tank in the form of a borehole
- heat tank in the form of an aquifer.

▶ Figure 54
Four types of large seasonal heat storage technologies [31]



HYDROGEN

Hydrogen is a chemical element that we use in the energy sector as a propellant in engines to obtain mechanical energy, in fuel cells or by combining with oxygen to obtain electrical energy or as an energy reservoir to regulate the demand for electricity consumption in energy systems that use sources that do not have a constant supply of energy. Since there is very little elemental hydrogen in nature, it is necessary to produce it. It can be produced from fossil fuels, by the decomposition of water and hydrocarbons or by the decomposition of hydrocarbons into hydrogen and carbon. One of the environmentally acceptable ways is to obtain hydrogen by electrolysis of water, provided that the electricity for electrolysis is obtained from RES, which does not create carbon dioxide. A typical hydrogen storage system consists of an electrolyser, a hydrogen storage tank and a fuel cell. An electrolyser is an electrochemical converter that splits water by passing current into hydrogen and oxygen. It is an endothermic process, i.e. heat is needed during reactions. Hydrogen is stored under pressure in gas cylinders or tanks, and this can be done practically indefinitely. To generate electricity, both gases flow into a fuel cell where an electrochemical reaction reverses the process of splitting water: the reaction of hydrogen and oxygen produces water, heat is released and electricity is produced. For economic

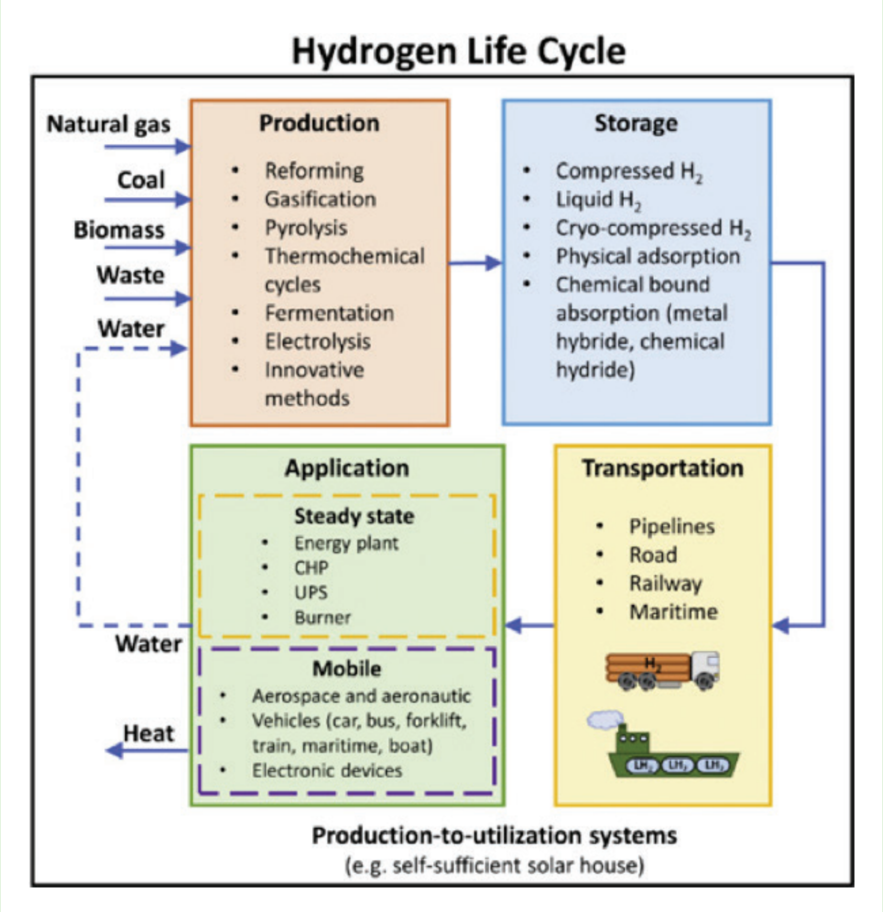


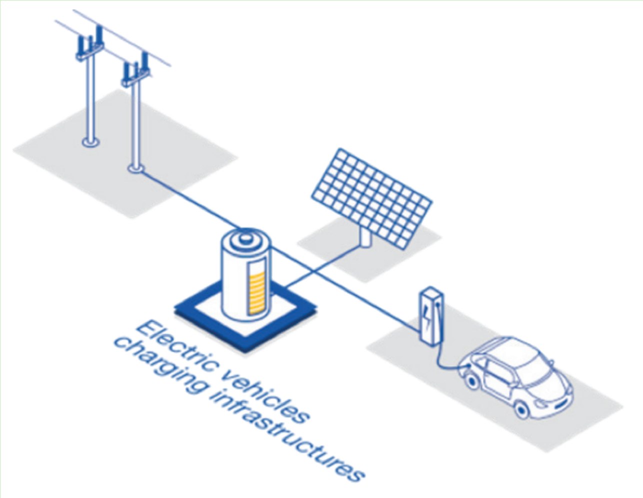
Figure 55
Life cycle of hydrogen [32]

and practical reasons, oxygen is not stored, but is released into the atmosphere during electrolysis and extracted from the air to produce electricity. There are different approaches to storing hydrogen, either as a gas under high pressure, in a liquid state at very low temperatures, adsorbed on metal hydrides or chemically bound in complex hydrides. For stationary applications, gaseous stored hydrogen under pressure is the most common choice. In addition to fuel cells, electricity can be produced in gas engines, gas turbines, and combined gas and steam turbine cycles.

ELECTROCHEMICAL ELECTRICAL ENERGY STORAGE SYSTEMS – BATTERIES

Electrochemical electrical energy storage systems can be divided into secondary flow batteries. Secondary batteries enable the conversion of electrical energy into chemical energy, storage and conversion back into electrical energy. Batteries consist of three basic parts: negative electrode, positive electrode and electrolyte. The negative electrode gives electrons to the external load, and the positive electrode receives electrons from the load. The electrolyte provides a path for charge transfer between the two electrodes. Chemical reactions between each electrode and the electrolyte remove electrons from the positive electrode and deposit them on the negative electrode. It describes the overall chemical reaction that constitutes the charging and discharging of a battery. The most widely used batteries are lead-acid, nickel-cadmium and nickel-metal hybrid, lithium-ion, metal air, sodium-sulfur and sodium-nickel-chloride. Flow batteries store and release electricity using a reversible electrochemical reaction in two liquid electrolytes. An electrochemical cell has two compartments, one for each electrolyte, physically separated by an ion exchange membrane. Electrolytes enter and leave the cell through separate dividers and undergo a chemical reaction inside the cell, with the exchange of ions or protons through the membrane and the exchange of electrons through the external electrical circuit. Chemical energy in electrolytes is converted into electrical energy and vice versa during charging. The most famous flow batteries are the redox flow battery and the hybrid flow battery. Batteries are most often used in a stationary version, connected to the network, or in the form of mobile batteries, e.g. in electric vehicles, thus providing additional storage capacities and system flexibility.

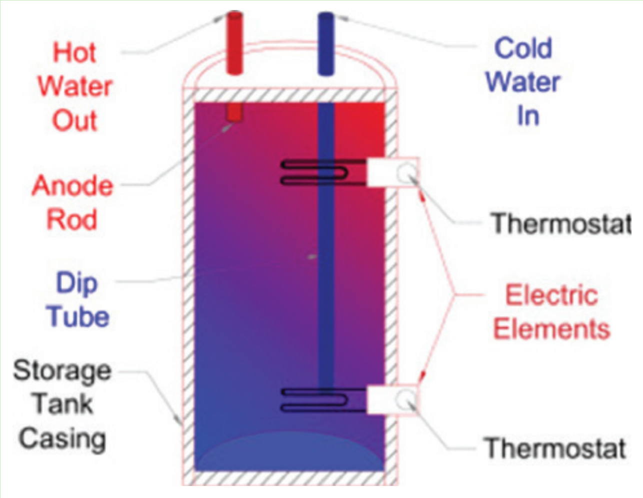
▶ Figure 56
View of the system with a stationary tank and an electric vehicle [33]



ELECTRICALLY RESISTANT HEATERS

Electric resistance heaters are devices that use electricity to produce thermal energy. In them, current flows through the heating element, which, due to its high ohmic resistance, produces heat according to Joule's law. Typical electric resistance heaters have an efficiency of 100%, this means that for every 1 W that enters the heating element, 1 J of heat is obtained.

▶ Figure 57
Scheme of electric resistance heater for heating hot water [34]



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