Multi-objective optimization of district heating and cooling systems for a one-year time horizon

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ABSTRACT

Besides lowering supply temperatures, the concept of fourth generation of district heating (4DH) also includes integration of heating, cooling and power sector. Due to their high interconnectivity, number of involved technologies and relatively long, but at the same time detailed temporal scale, optimization of such systems presents a challenging task. So far, only hourly district heating multi-objective optimization for a whole year period has been carried out, where detailed district heating and cooling multi-objective optimization has been reserved for small scale utilization and short temporal scale, usually covering specific days or weeks. The main objective of this paper was to develop an hourly based multi-objective optimization district heating and cooling model which is capable of defining supply capacities, including thermal storage size, and their operation for a whole year period. The objective functions are minimization of a total system cost, which includes discounted investment and operational costs, and minimization of environmental impact in terms of carbon dioxide emissions. By using multi-objective optimization, this research shows that for equal level of carbon dioxide emissions, combined district heating and cooling systems have lower total discounted cost when compared to district heating and cooling systems which operate separately.

KEYWORDS

District heating and cooling; multi-objective optimization; linear programming; thermal storage; Pareto front

1. Introduction

European Union (EU) has recognized the importance of district heating and cooling (DHC) systems by including them in a proposal of the Strategy on Heating and cooling [1]. They can reduce greenhouse gasses emissions and improve energy efficiency by using waste heat and low-temperature renewable energy sources (RES). The definition of an efficient DHC system has been shown in the EU Directive on energy efficiency [2]. They will also have important role in the future energy systems with a high share of intermittent RES where the excess of electrical energy could be transformed into thermal, by using efficient technologies, such as electrical heaters or heat pumps. In the literature, future DHC systems belong to 4th generation of district heating and cooling [3]. That doesn't just mean the improvement by reduction of a supply temperatures and better building's insulation. The emphasis is placed on integration of electricity, thermal and gas grids and usage of smart energy systems. B.V. Mathiesen et al

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shown the importance of integrating different energy sectors in order to develop smart system capable of introducing higher shares of renewable energy sources while at the same time maintaining system’s operability and economical feasibility [4]. In order to increase share of district heating, European countries have to increase flexibility of energy systems and make them part of the smart city, provide additional contribution to renewable energy sources integration and enable prosumers’ participation [5]. Similar conclusions have been obtained in [6], where final end-users needs have been taken into account through extensive questionnairey and interviews. There are numerous papers on how to calculate expansion potential of district heating system. In [7], comparison between results obtained by using consumer-economy and socio-economy has been presented.

District heating systems could be complex due to the great interconnection of a large number of energy and masses streams and optimizing such a system represents a challenge. Because of that, quasi-optimal solutions have been found by performing scenario analyses. Although, optimization is often used in order to choose the most suitable solution of the energy system, Lund et al. [8] provide theoretical positions for energy system modelling. In the mentioned paper, simulation and optimization approaches have been shown, including their strengths and weaknesses. In [9], scenario analysis in combination with optimization process has been carried out in order to reduce heat production costs. Work presented in [10] shows the optimal share of CHP with respect to the DHW share. In paper [11], the optimal solar share has been found. In order to start the optimization procedure, the objective function has to be defined. In most cases, it is related to a cost, such as investment or operational, or to an environmental impact of the system, such as equivalent CO_2 emissions [12]. The simplest case is a single objective optimization, which is often related to economic feasibility of a system [13]. For a multi-objective approach, at least two objective functions should be defined, which are usually total cost and environmental impact of the system [14]. In this case, a solution of optimization isn’t a single value, but a whole set of them which lie at the same front, called the Pareto front. In the case of the multi-objective optimization with three objective functions, all solutions are a part of the so-called Pareto surface [15]. It is important to mention that obtained Pareto solutions are all treated equally, i.e. there is no preference among them. In order to choose the most suitable one, decision making method is needed.

There are many possible approaches on how to handle the optimization procedure. The most common one is linear programming (LP), or mixed integer linear programming (MILP), where some of the optimization parameters are continuous or in the form of integers, such as binary variables, e.g. when deciding if the power plant should work or not [16]. If there is a need for a more detailed description of the system which includes nonlinearity, mixed integer non-linear programming (MINLP) is used [17]. In some cases, even more complex approach could be used, as shown in [18], where MILP in combination with stochastic methods is proposed. When dealing with multi-objective optimization, the genetic algorithms (GA) approach is mostly used [14]. Since all Pareto solutions are considered equal, the decision making process should be carried out in order to define the most suited one. Some authors propose the system’s reliability as the crucial parameter in obtaining the final solution of multi-objective optimization [19], while other propose linear programming technique for multidimensional analysis of preference (LINMAP), which is looking for ideal non dimensional objective values equal to unity [20].

One of the major issues in optimizing DH systems is the needed temporal scale. In order to capture the seasonal characteristics, the whole year should be studied on a one-hour scale to obtain the specific system’s technologies dynamics. In addition to this, 4DH is a part of the energy system that is connected to the one-hour scale electricity market. Furthermore, electricity markets are decreasing time step to a 15-minute level, which will have to be followed by even more detailed temporal scale used in energy system optimization. Sometimes, optimization doesn't have a temporal scale as shown in [21]. In order to accelerate optimization procedure, only specific days in the year could be studied, as shown in [22]. Obvious approach is a one-hour based optimization with the one-year horizon [23]. The most detailed temporal scale for single objective optimization of district heating systems found so far is 15-minute for a whole year, presented in [14]. Since 8760 hour optimization is a challenging task itself, the long term optimization of DHC systems hasn't been carried out so far. In future systems, different energy prices, heat demand and prosumers share are expected. Single objective optimization solution shift has been analysed for electricity price variations and heat demand reduction [24] while work presented in [25] shows that different heat price models could be used in the future in order to stimulate demand response. Physical model of the district heating system is rarely taken into account. Pirouti et al. [26] used optimization approach in order to minimize annual total energy consumption and costs while also considering different district heating network temperature variations and pressure losses. In [27] detailed model of cogeneration unit was studied in order to optimize repowering coal-fire district heating sources by a gas turbine.

Multi-objective optimization of combined heating and cooling system if often carried out on a micro-level scale and includes only system operation optimization. In [28], genetic algorithm was used in order to define strategy for system operation which consists of power plant, internal combustion engine, biomass boiler and electric and absorption chiller. Optimal control strategy of complex tri-generation plant was carried in [29], but for a single working day. The objective function was minimization of total energy and maintenance cost. Genetic algorithm was also applied in [15] where sizing of a small-scale combined cooling heating and power system was carried out. Stochastic methods could also be used for combined cooling heating and power system optimization as demonstrated in [19]. Mixed integer non-linear model was developed in [17] in order to optimize operation strategy under various load conditions. Optimization of the DHC systems often lacks crucial technologies proposed in the 4DH concept [30] or are investigated on the micro scale [19].

In this paper, multi-objective optimization model of combined district heating and cooling system is carried out. The time frame is a whole year with time-step equal to one hour. It is capable of optimizing supply capacity, including thermal storage size, and operation. Possible technologies include natural gas or biomass powered heat only boiler and cogeneration, absorption and compression heat pumps, electrical heater, solar thermal collectors and thermal storage. Objective function is minimization of overall operation and discounted investment cost of the system, while at the same time minimizing environmental impact of the system in terms of carbon dioxide (CO_2) emissions. Multi-objective optimization of this detailed time-scale for combined district heating and cooling systems which includes broad range of possible technologies hasn't been done so far. Furthermore, this research evaluated environmental and economic benefits of combined district heating and cooling systems in relation with separated operation. The model has been formulated with free and open-source programming language called Julia while Cbc was used as linear programming solver [31].

This paper is divided in several chapters. Chapter 2 shows methods used in order to deal with multi-objective optimization, including district heating and cooling model. Chapter 0 presents numerical case study in detail and input data used to demonstrate proposed approach. Chapter 0 displays the obtained results while Chapter 5 sums the most important outcomes of this research in the brief conclusion.

2. Method

In this paper, multi-objective optimization was used since energy planning decision making process often includes compromises. In this case, minimization of total cost and CO_2 emissions of the system. In order to deal with multi-objective optimization, district heating and cooling model was written in the LP form. The main reason for this is detailed time scale (one hour time step) and a time horizon equal to one year. In addition to this, numerous optimization runs were needed to acquire Pareto front. For these set of conditions, LP can simultaneously guarantee speed and needed precision. Furthermore, weighted sum in combination with epsilon constrained method has been used in order to reach Pareto front. Weighted sum method is appropriate if the single solution wants to be reached, such as the least-cost, the most environmentally friendly or their combination. However, if one wants to acquire the whole trend of solutions, as in this paper, epsilon constrained method is needed.

This chapter is divided in several subchapters. Firstly, multi objective optimization approach is shown in the Subchapter 2.1, Subchapter 2.2 presents district heating and cooling model, while Subchapter 0 shows programming language and tools used in this research.

2.1. Multi-objective optimization

The developed multi-objective optimization model of district heating and cooling system is defined with two objective functions: minimization of total system cost and minimization of environmental impact expressed through CO_2 emissions as shown in Equation 1.

$$\min(f_{econ}, f_{ecol}) \tag{1}$$

Since these two goals are often in contradiction, i.e. the first one could only be decreased if the second increases and vice versa, the final solution of the optimization will be set of points which will lie on the curve called Pareto front which present the compromise. Economical objective function could be calculated by using Equation 2, while environmental objective function is represented by Equation 3.

$$f_{econ} = \sum_i C_{investment,i} + C_{fuel,i} + C_{variable,i} + C_{other,i} - Income_i \tag{2}$$

Where $C_{investment,i}$ represents discounted investment cost of technology i, $C_{fuel,i}$ are fuel costs for each technology, $C_{variable,i}$ are variable costs, $C_{other,i}$ are other costs, and finally $Income_i$ is additional income due to the electrical energy produced in cogeneration units sold on the electricity market. Each technology has different specific investment, fuel and variable costs. In this approach, investment cost has to be discounted in order to take into account different lifetimes of used technologies. Furthermore, such approach is needed because optimization is carried out for a time horizon equal to one year where economical objective function represents yearly discounted cost. Other costs include additional expenses which exist only for some technologies. For example, additional fixed monthly cost paid to the grid operator for power capacity when using power-to-heat technologies. It is important to mention that investment and operational cost of the district heating and cooling network hasn’t been taken into account since heating and cooling demand are put as a boundary condition, i.e. treated as a constant value which could added to the final solution.

$$f_{ecol} = \sum_{t=1}^{t=8760} \sum_{i} e_{CO_2,i} \cdot Q_{i,t} / \eta_i \tag{3}$$

Total CO$_2$ emissions of the system can be calculated by using Equation (3), where $e_{CO_2,i}$ is specific carbon dioxide emissions for each technology, i.e. fuel, $Q_{i,t}$ is defined as thermal energy production for time step t and technology i, while η_i represents efficiency of technology i.

In this paper weighted sum coefficient method was used in order to obtain solution of the multi-objective optimization. This method enables translation of objective functions into single, weighted function by assigning weighted coefficients, as shown in Equation (4). It is important to mention that sum of weighted coefficients should be equal to unity, Equation (5).

$$F_{weighted} = \left(\frac{\omega_{econ}}{f_{econ_{\omega_{econ}=1}}}\right) \cdot f_{econ} + \left(\frac{\omega_{ecol}}{f_{ecol_{\omega_{ecol}=1}}}\right) \cdot f_{ecol} \tag{4}$$

$$\omega_{econ} + \omega_{ecol} = 1 \tag{5}$$

Since economical and environmental objective functions have different order of magnitude, normalization has to be carried out, as shown in Equation (4). Combining weighting coefficients, ω_{econ} and ω_{ecol}, all possible solutions could be obtained thus creating the Pareto front. However, due to the nature of this method, by using relatively high step, e.g. equal to 0.1, some solutions couldn't be obtained. In order to accelerate the process of acquiring Pareto front, epsilon constraint method was used. After acquiring the most optimal economical and the most optimal environmental solution, extremes of the Pareto front are obtained. By using epsilon constraint method, the constraint is put on one of the objective functions, while minimizing other one, thus obtaining more detailed Pareto front. Equation (6) presents epsilon constraint method used in this paper. The constraint ε was put on environmental objective function, while minimizing economical goal. By increasing the constraint, objective function is moving from one end of the Pareto front to the other. With this approach, multi-objective optimization problem has been translated to single-objective optimization with additional set of constraints.

$$\min(f_{econ}) \ for \ f_{ecol} = \varepsilon \tag{6}$$

2.2. District heating and cooling model

In this paper, in order to optimize hourly operation of the district heating and cooling system on the annual level, simplified model has been develop. It is based on system's energy balances with addition of several technology constraints. In the district heating (DH) model, several technologies' capacities, including their operation, are optimized. Possible technologies utilized in this model are following: natural gas and biomass boiler and cogeneration, electrical heater, air-source compression heat pump, solar thermal collectors and thermal storage. Their operation is defined by set of constraints shown below.

$$\begin{aligned} Q_{HOB,gas,DH,t} + Q_{HOB,biomass,DH,t} + Q_{EH,t} + Q_{HP,DH,t} + Q_{CHP,DH,gas,t} \\ + Q_{CHP,DH,biomass,t} + Q_{ST,t} - TES_{DH,in-out,t} = DEM_{DH,t} \end{aligned} \tag{7}$$

$$0 \leq Q_{i,t} \leq P_i \tag{8}$$

$$-r_{up-down,i} \cdot P_i \leq Q_{i,t} - Q_{i,t-1} \leq r_{up-down,i} \cdot P_i \tag{9}$$

Equation (7) indicates that district heating demand $DEM_{DH,t}$ should be satisfied with thermal energy production from optimal combination of technologies $Q_{i,t}$ including thermal storage charge and discharge $TES_{DH,in-out,t}$, in each hour. Thermal energy supply is coming from supply capacities. Technology operation $Q_{i,t}$ is optimized for each technology and every time step. From Equation (8) it can be seen that technology load, can't be larger than optimal technology capacity P_i and lower than zero. Thermal storage charge and discharge $TES_{DH,in-out,t}$ can have negative values: negative values during discharging and positive values during thermal storage charging. In order to obtain more realistic technology operation, ramp-up and ramp-down limits, $r_{up-down,i}$ are introduced for each technology, as shown in Equation (9). Thermal storage operation is defined with additional set of constraints.

$$SOC_{t=1} = SOC_{t=8760} = SOC_{start-end} \cdot TES_{size} \tag{10}$$

$$SOC_t = SOC_{t-1} + TES_{in-out,t} \tag{11}$$

Where SOC represents thermal storage state of charge in time step t, while TES_{size} represents optimal thermal storage size. Cooling and heating thermal storage are modelled by using similar set of constraints as shown in Equations (10) and (11). It could be seen from Equations (10) and (11) that thermal storage losses have been neglected. According to [32], thermal losses of seasonal thermal storage can reach up to 100% when operating in correct conditions. One of the main reasons for this is extremely low surface-to-volume ratio. Thermal losses of smaller thermal storages such as steel tanks are larger than for the seasonal one, accounting up to 5% for the storage cycle of one week [32]. Thermal losses could be reduced if additional insulation is installed. Although neglecting thermal loses doesn't cause great errors in terms of total discounted cost and environmental impact of the system, especially in case of seasonal thermal storage, future work should include losses calculation. This will make a model more complex but also more realistic in terms of storage capacity and operation optimization.

Solar thermal collectors' production have been modelled by using method described in detail in [20]. The simplified model is based on solar collector efficiency European standard EN12975 standard described in [33]. Solar collector efficiency could be obtained by using Equation (12) [33]:

$$\eta_{c,t} = \eta_0 - a_1 \frac{\left(T_m - T_{a,t}\right)}{G_t} - a_2 \frac{\left(T_m - T_{a,t}\right)^2}{G_t} \tag{12}$$

Where $\eta_{c,t}$ represents solar collector efficiency in time step t. It is dynamic variable because depends on hourly meteorological data such as global solar irradiation G_t and air temperature $T_{a,t}$. Meteorological data could be acquired by using numerous open-source databases such as PVGIS [34]. Other parameters in equation are taken as constants: maximum efficiency if there is no heat loss, also known as optical efficiency η_0, first order heat loss coefficient a_1, second order heat loss coefficient a_2 and T_m which represents mean solar thermal collector temperature. The last one is dynamic parameter, but since detailed physical model is needed to acquire correct value, this variable for purpose of this research was also taken as a constant. These parameters could be found in solar thermal collector factsheets.

Publicly available solar thermal collectors' specification database is available in [35]. For purposes of this research flat-plate collector data has been used. Specific solar thermal production $P_{solar,specific,t}$ could be calculated by using Equation (13):

$$P_{solar,specific,t} = \eta_{c,t} \cdot G_t \tag{13}$$

Optimization variable related to solar thermal collectors is the total collector area A_{ST}, while their operation is predefined by specific solar thermal production, as shown in Equation (14).

$$Q_{ST,t} = A_{ST} \cdot P_{solar,specific,t} \tag{14}$$

District cooling (DC) system is modelled with similar set of constraints, only difference is that other technologies are utilized: absorption heat pump driven by heat only boiler or cogeneration's thermal energy and compression heat pump, as shown in Equation (15).

$$Q_{HP,DC,t} + Q_{HP,abs,t} - TES_{in-out,DC,t} = DEM_{DC,t} \tag{15}$$

In this equation, again, supply units operation, $Q_{i,t}$, can have only positive values, since they represent cooling energy production, while $DEM_{DC,t}$ is cooling energy demand. As visible from Equation (15), thermal storage also exists. It is modelled in the same manner as the storage in the district heating model, as shown in Equations (10) and (11). Cooling thermal storage charge and discharge in this case can also achieve negative or positive values, depending on thermal energy flow. If storage discharges, $TES_{in-out,DC,t}$ is negative and if it is charging, than $TES_{in-out,DC,t}$ has positive values.

Energy balance of the absorption heat pump is represented by Equation (16).

$$\begin{aligned} &Q_{HP,absorption,t} \\ &= (Q_{HOB,DC,gas,t} + Q_{HOB,DC,biomass,t} + Q_{CHP,DC,gas,t} \\ &+ Q_{CHP,DC,biomass,t}) \cdot \eta_{HP,abs} \end{aligned} \tag{16}$$

Thermal energy from heat supply units is used to generate cooling energy through absorption heat pump which efficiency is defined with $\eta_{HP,abs}$. According to [36], absorption heat pumps' efficiency mainly depends on a temperature of a heat source. Because of this, only high temperature technologies, such as heat-only boiler and cogeneration are chosen to operate in combination with an absorption heat pump.

District heating and cooling systems could be connected through absorption heat pump which has possibility of utilizing excess of thermal energy during summer season from heat-only boilers and cogeneration units. In that case thermal energy produced in heat-only boilers and cogeneration units could be simultaneously used in district cooling and district heating as shown in Equations (17-20).

$$Q_{HOB,biomass,t} = Q_{HOB,DH,biomass,t} + Q_{HOB,DC,biomass,t} \tag{17}$$

$$Q_{HOB,gas,t} = Q_{HOB,DH,gas,t} + Q_{HOB,DC,gas,t} \tag{18}$$

$$Q_{CHP,biomass,t} = Q_{CHP,DH,biomass,t} + Q_{CHP,DC,biomass,t} \tag{19}$$

$$Q_{CHP,gas,t} = Q_{CHP,DH,gas,t} + Q_{CHP,DC,gas,t} \tag{20}$$

Where $Q_{i,DH,t}$ represents thermal energy coming from technology i to be used in district heating in a time step t. In a same manner, $Q_{i,DC,t}$ is thermal energy to be used in district cooling through absorption heat pump. These optimization variables exist only in the model where district heating and cooling systems are operating as a part of a single system.

2.3. Programming language and tools

Since all optimization variables are continuous, the optimization problem has been modelled by using linear programming. The model was written by using Julia programming language [31]. It is free and open-source language developed in order to achieve better performance in terms of speed of solving and building the model. In order to easily built the optimization model, JuMP package has been used [37]. It is Julia add-on used for mathematical programming. Furthermore, it also has built-in various free and open source optimization solvers. For the purposes of this research coin-or branch-and-cut linear programming solver has been used, called Cbc [38].

3. Case study

In order to validate the model, numerical test case has been performed, where Croatian city of Velika Gorica has been chosen as the case study. Useful heating and cooling demand on yearly level has been mapped. In order to obtain hourly distribution of heating and cooling demand, heating and cooling degree-hour method has been used. District heating demand also includes thermal energy for domestic hot water production. Velika Gorica currently has several smaller district heating systems which connect small number of building blocks, while no district cooling has been implemented so far.

In this paper two scenarios have been developed. In the first scenario district heating and cooling systems operate separately, i.e. there is no interconnection between them. In the second scenario connection between them has been introduced. In the first scenario, i.e. during separate operation, there is no connection between district heating and cooling networks, which means that thermal energy produced in heating network can’t be used in district cooling and vice versa. Interconnection between district heating and cooling systems means linking of thermal supply capacities, which implies that heat could be simultaneously used in district heating and cooling network. Connection between all possible technologies in Scenario 2 can be seen in Figure 1. It could be noticed that thermal energy from biomass and natural gas heat-only boilers and cogeneration units could be directly used for heating (red line in the figure) or for cooling energy production through absorption heat pump unit (orange line in the figure). This interconnection should increase overall flexibility of the system thus having great impact on the solution of the multi-objective optimization in comparison with the first scenario.

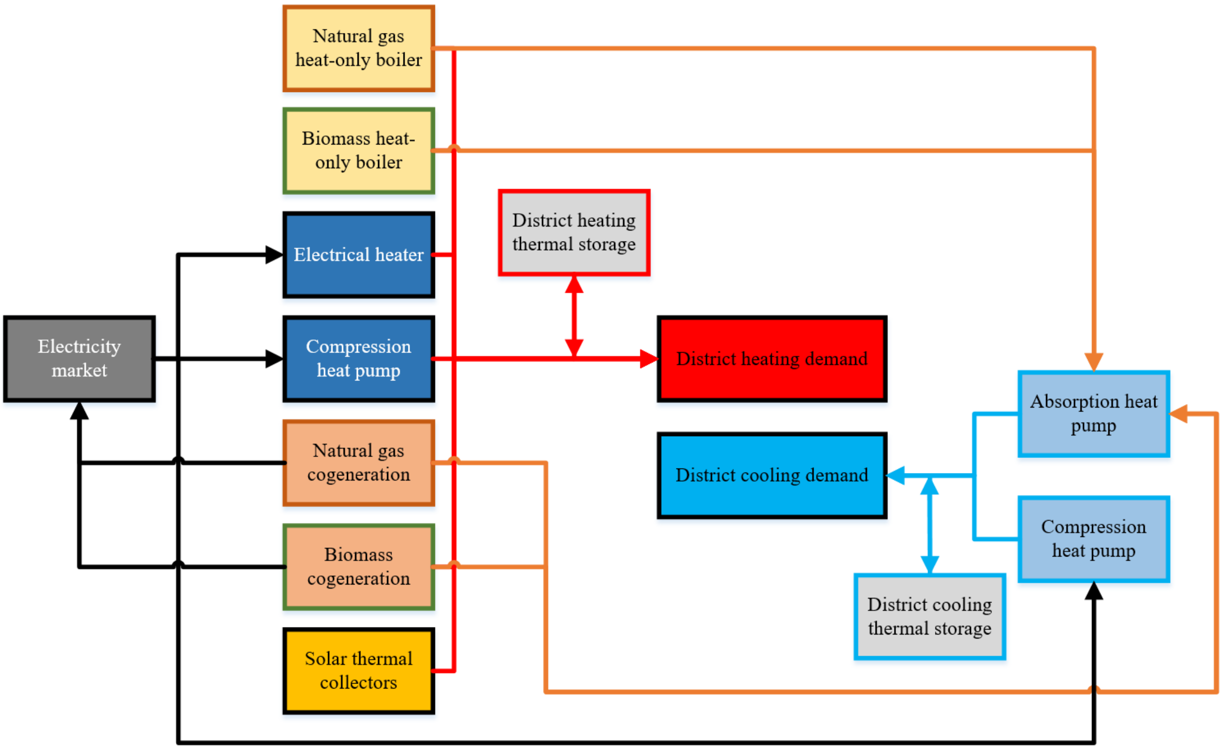


Figure 1 Scheme of interconnection between district heating and cooling in Scenario 2

Table 1 shows technology input data used for multi-objective optimization. Most of the data is publicly available through various technology databases, such as [32]. Characteristics of district heating and cooling demand, in terms of total and peak demand, are shown in

Table 2.

Table 1 Input data for multi-objective optimization

Technology	**Investment cost [€/MW] / [€/m^2] /[€/MWh]**	**Fuel cost [€/MWh]**	**Variable cost [€/MWh]**	**Emission factor [TCO_2/MWh]**
Natural gas boiler	100.000	20	3	0,22
Biomass boiler	800.000	15	5,4	0,04
Electrical heater	107.500	Electricity market	0,5	0,137
Heat pump, heating	680.000	Electricity market	0,5	0,137
Cogeneration natural gas	1.700.000	20	3,9	0,22
Cogeneration biomass	3.000.000	15	5	0,04
Solar thermal	300 €/m^2	0	0,5	0
Thermal storage district heating	500 €/MWh	0	0	0
Heat pump cooling	680.000	Electricity market	0,5	0,137
Absorption heat pump	400.000	0	3,5	0
Thermal storage district cooling	3.000	0	0	0

Table 2 District heating and cooling demand

System	**Total demand [MWh]**	**Peak demand [MW]**
District heating	43.767	14,98
District cooling	13.262	8,1

4. Results and discussion

Multi-objective optimization results for district heating system in Scenario 1 is shown in Figure 2. Figure 2a shows Pareto front putting into correlation economical and environmental objective function. Figure 2b shows optimal configurations which was obtained for specific points on the Pareto front. The capacities on the left side of the diagram represent solutions where economical objective function has advantage compared to environmental objective minimization, i.e. natural gas is frequently used. Right side of the diagram involves technologies for which environmental impact is minimized, such as solar thermal collectors and biomass heat-only boiler. It is important to notice that usage of heat pumps also emits carbon dioxide emissions due to the electricity sector emission factor defined on the national level. This is major drawback of the proposed model, since it doesn’t take into account future decarbonisation of the power sector. The model proposes optimal configuration of the supply system for a given set of starting condition: heat demand, system prices, emission factors, etc. Although used Croatian power sector emission factor is lower than European average, heat pump couldn’t be found in the most environmentally friendly solutions in Figure 2a. Figure 2c shows respective optimized thermal storage capacity for capacity solutions determined by optimization. It can be noticed that economically optimal solution has total discounted cost equal to 1.200.000 € and emissions equal to 10.600 tonnes of CO_2 per year. Total heat demand is covered with 11,17 MW natural gas heat-only boiler and thermal storage with capacity equal to 145 MWh. Reduction of environmental impact gradually increases total discounted cost of the system up to the 1.687.000 € where heat demand is covered with more environmentally friendly technologies such as biomass boiler, heat pump and solar thermal. District heating system emits around 2.250 tonnes of CO_2 per year for this configuration. After this point, further CO_2 reduction is possible only with large addition of solar thermal collectors in the system. The environmental impact slightly decreases at the expense of large increase of total discounted cost of the system. Linear addition of the solar thermal collectors in Figure 2b is followed by linear increase of seasonal thermal storage, as shown in Figure 2c, which is the cause of the high investment cost. The system could operate with almost zero emissions, but it would require unrealistic seasonal thermal storage capacity. Cogeneration and electrical heater aren’t part of any optimal configuration, as seen in Figure 2b. Main reason why cogeneration units aren’t part of any Pareto solution are low electricity market prices and inexistence of feed-in tariff or premiums. Electrical heaters aren’t used due to low efficiency when compared to heat pumps, and high fixed cost related to power capacity which is payed monthly to the grid operator. Lower efficiency also implies higher CO_2 emissions in relation to heat pumps.

Figure 3 shows optimization results for district cooling system in Scenario 1 in the similar manner. Figure 3a shows Pareto front for district cooling optimization. Optimal capacities which satisfy objective functions are shown in Figure 3b. The least-cost solution has configuration: 3 MW absorption heat pump, 2 MW natural gas heat-only boiler and 0,7 MW compression heat pump. Interesting solution is obtained with 600 tonnes of CO_2 emissions per year where compression heat pump reaches peak equal to 3,7 MW. Again, cogeneration has never been chosen for optimal configuration due to low electricity market prices. Furthermore, they don’t receive any additional subsidies such as feed-in premium of feed-in tariffs.

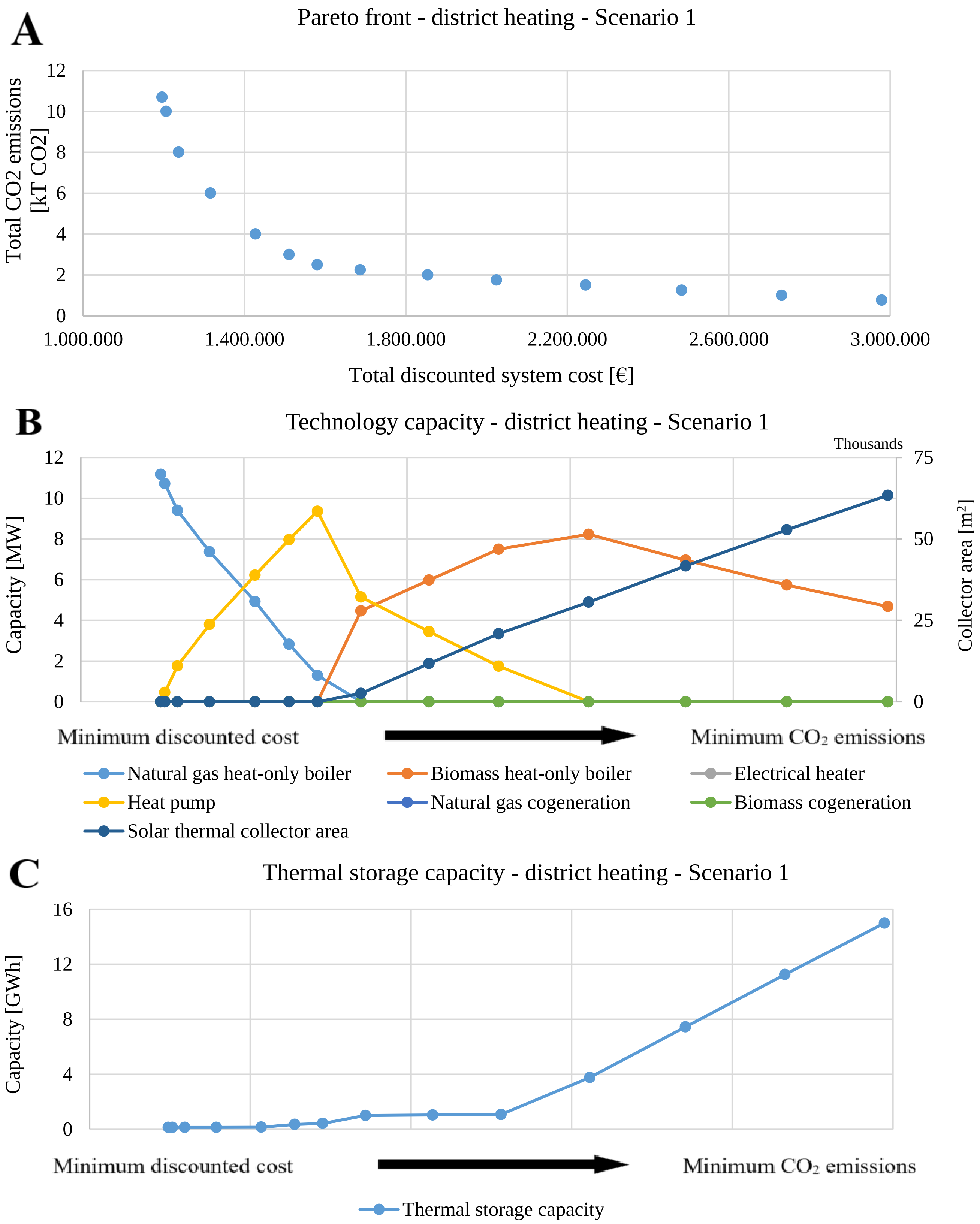


Figure 2 Multi-objective optimization results of district heating system: Pareto front (a), supply capacities (b), thermal storage size (c)

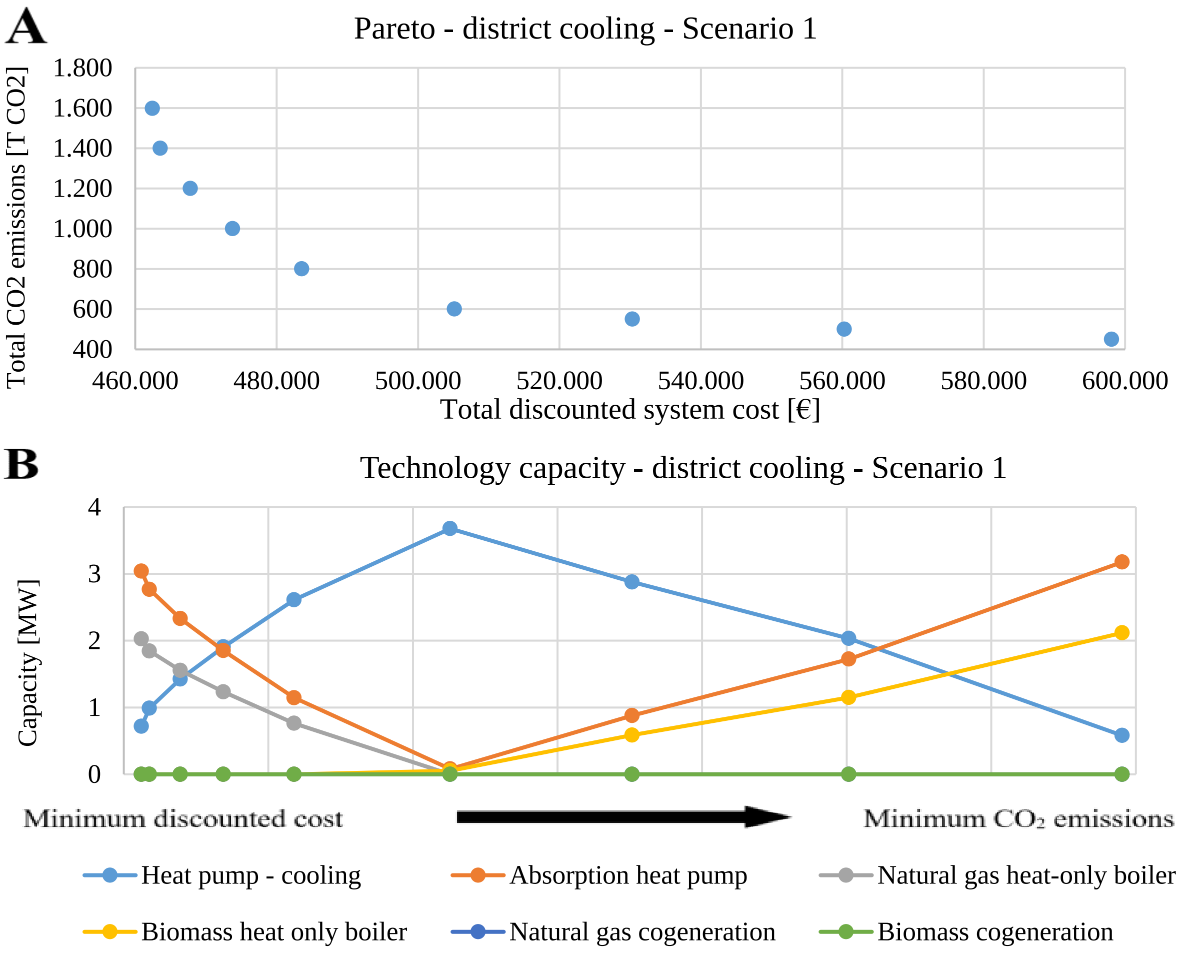
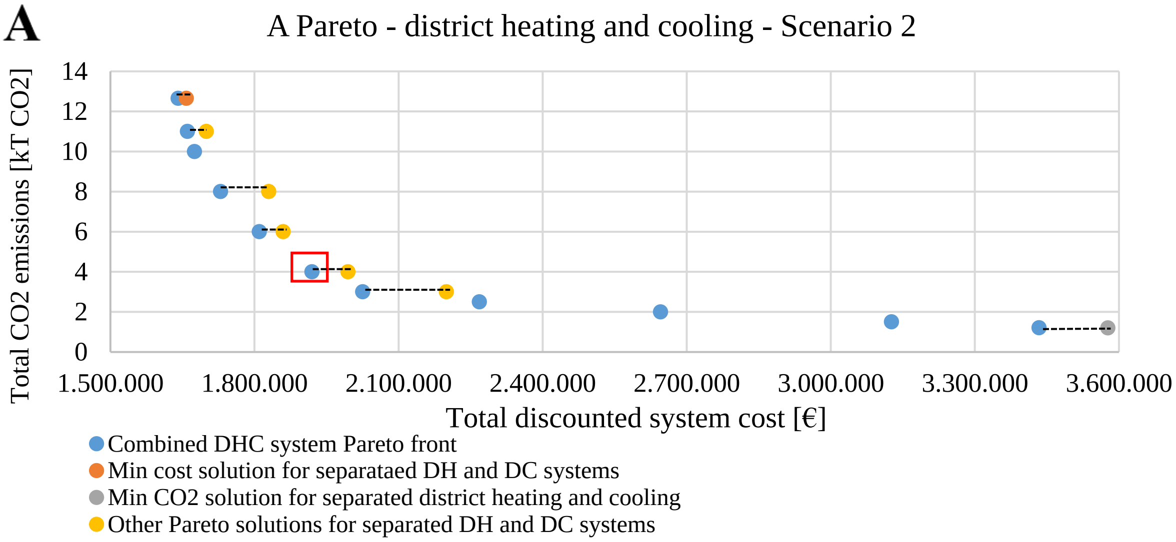


Figure 3 Multi-objective optimization results of district heating system: Pareto front (a), supply capacities with relation to optimal cost (b)

Results of the Scenario 2, where district heating and cooling systems are combined, are shown in Figure 4. Besides presenting the results of the Scenario 2, Figure 4a shows comparison between Pareto front where district heating and cooling systems are combined and specific Pareto points for Scenario 1 where district heating and cooling systems are operating separately. Firstly, solutions with least-cost and lowest environmental impact are explained in detail. It can be seen that least-cost solutions are almost equal total with value of 1.600.000 €. Nevertheless it is worth mentioning that Scenario 2 can provide configuration with lower discounted cost for the same level of carbon dioxide emissions. The solution with lowest environmental impact is again in favour of Scenario 2, where 200.000 € of discounted cost could be saved by configuration which combines district heating and cooling systems. If other Pareto solutions are observed in the assumed economically feasible region, i.e. up to the total discount cost approximately equal to 2.000.000 €, it can be seen that combined district heating and cooling systems have smaller discounted total cost for the same total yearly CO_2 emissions due to the interconnection through absorption heat pump which utilizes heat from heat-only boilers. Optimal supply capacities are shown in Figure 4b. Again, cogeneration units haven’t been chosen as a part of optimal system’s configuration. The reason for this is relatively low electricity market price and no subsidies available for biomass cogeneration. Reason why electrical heaters aren’t part of the solution, although they have lowest specific investment price, is extra cost related to the electrical power capacity which is payed annually.

As already mentioned, developed model is capable of simultaneously optimizing capacity and operation of supply capacities. In Figure 5, hourly operation of heating and cooling technologies is shown for Scenario 2 and configuration marked with red square in Figure 4. Figure 5a, shows operation of heating supply technologies. Total heat demand is covered with 4,2 MW natural gas heat-only boiler, 4,8 MW compression heat pump, 2,11 MW biomass heat-only boiler integrated with 175 MWh thermal storage. Operation of district heating thermal storage is shown in Figure 5b. Natural gas operates only during winter season as the peak boiler, while the heat pump operates through the whole year covering base load in the combination with thermal storage. Biomass boiler also operates through the whole year, but during summer period share of the heat is used in the absorption heat pumps to cover part of the cooling load. Figure 5c shows optimal operation of district cooling system. Cooling compression heat pumps cover the base cooling demand which consists of tertiary sector buildings and other facilities which have constant cooling load. Figure 5d displays optimal operation of district cooling thermal storage.

A



B

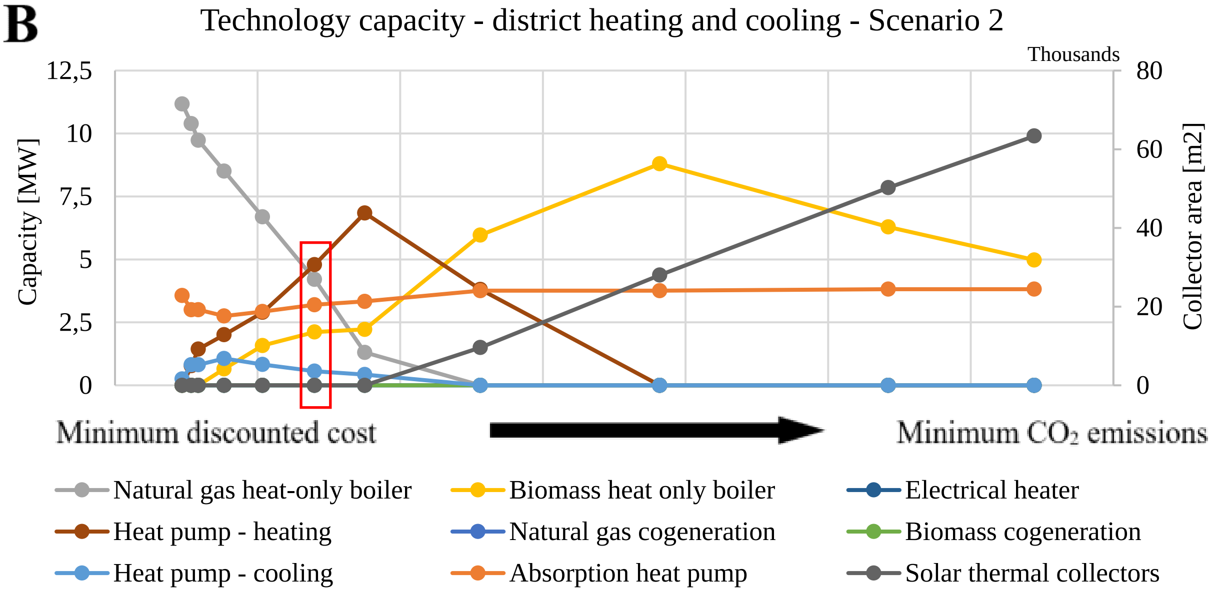
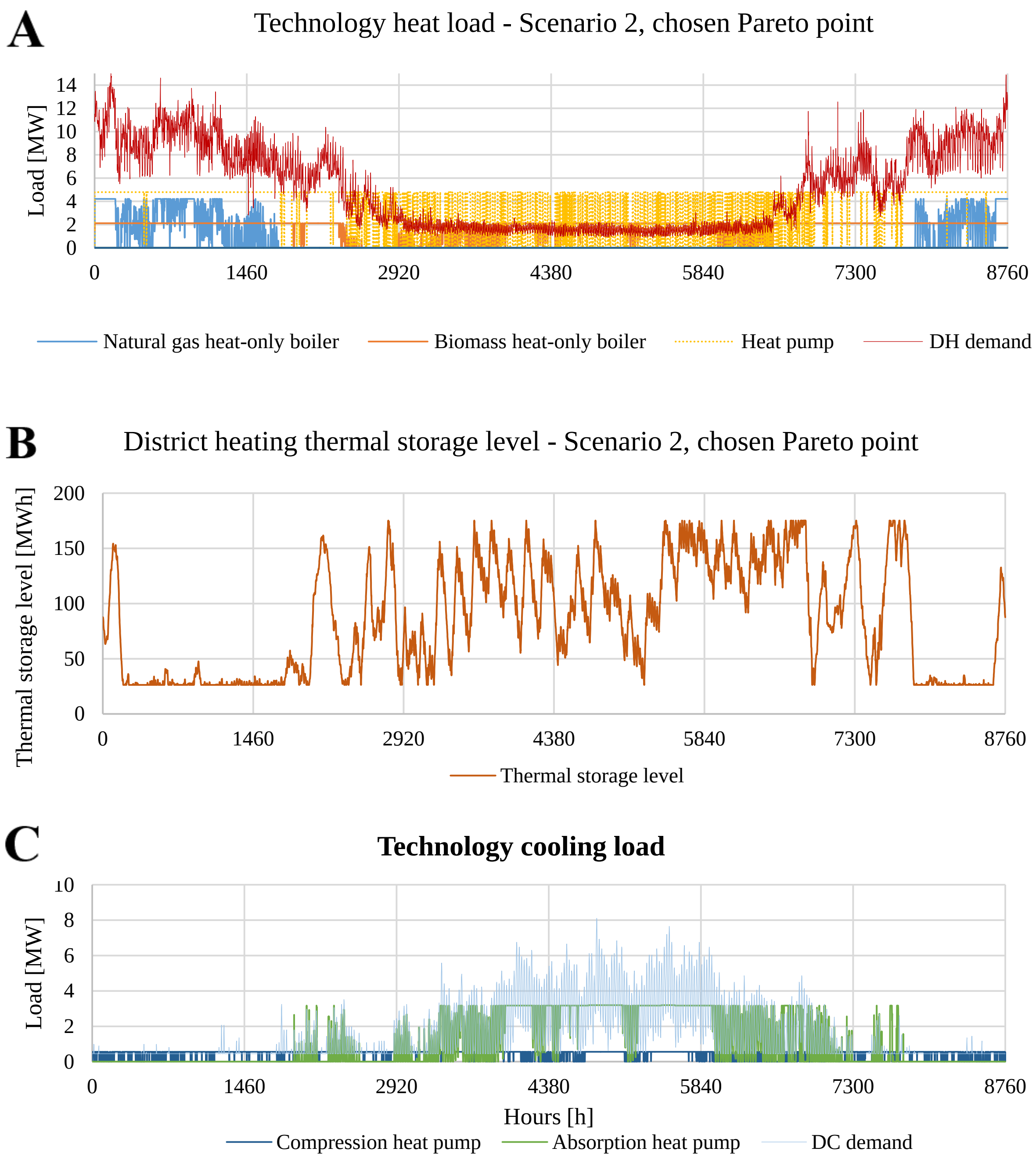


Figure 4. Multi-objective optimization results of district heating system: Pareto front comparison for separated and combined DHC systems (a), supply capacities (b),



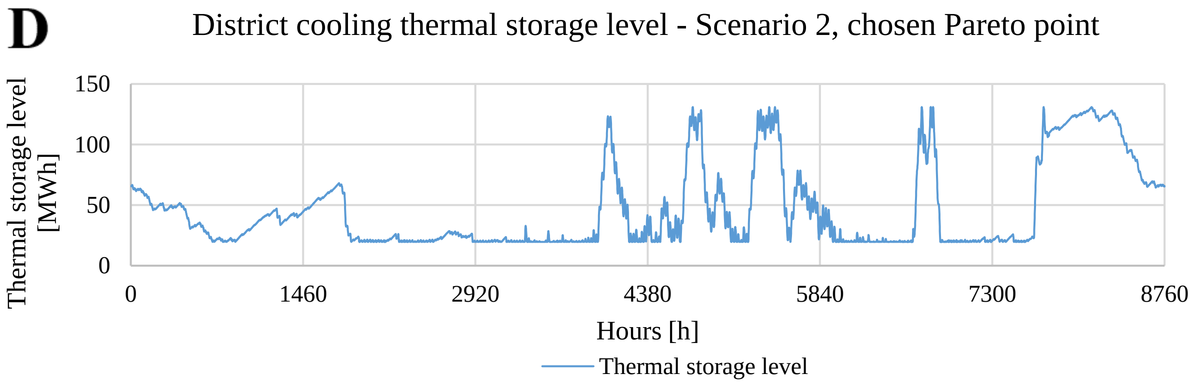


Figure 5 Optimized hourly operation combined systems: district heating (a), heating thermal storage (b), district cooling (c) and cooling thermal storage (d)

5. Conclusion

In this paper, multi-objective optimization model of district heating and cooling system has been developed in order to analyse benefits of integrated district heating and cooling systems. In order to obtain Pareto front, weighted sum and epsilon constrain methods were used. The model is able to define the compromise between total discounted cost and environmental impact of the system in terms of tonnes of CO_2 emissions. Since the model is hourly based for a whole year period, it is capable of optimizing supply capacities and hourly operation of optimal technology configuration, including thermal storage. This is novel approach of analysing district heating and cooling systems since multi-objective optimization on this level of temporal resolution and with this broad scope of possible technologies to be utilized hasn't been done so far, according to the authors' knowledge. The model was written in free and open-source programming language called Julia, while Cbc was used as the linear programming solver. The model was tested on the case study of Velika Gorica, where mapped yearly heating and cooling demands were combined with degree-hour method in order to create hourly demand distributions. Two scenarios were analysed: the first one where district heating and cooling systems operate separately and the second one where mentioned two systems operate simultaneously through utilization of absorption heat pumps. The obtained results of multi-objective optimization show that combined district heating and cooling systems can operate with the same yearly CO_2 emissions as when they operate separately, but with lower total discounted cost. In addition to this, the hourly multi-objective optimization model developed in this paper defined of technology configurations trends, including their operation, should be used in order to satisfy economical and environmental goals of the district heating and cooling system. Developed model and provided results shown in this paper could be utilized for energy policy making decisions when considering district heating and cooling systems. However, provided model can be used in order to define supply capacities and thermal storage size for more detailed technical and economic feasibility study. Furthermore, model includes real-life constraints, such as ramp-up and ramp-down speed in order to bring the model closer to real-life engineering applications.

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