Evaluation of District Heating with Regard to Individual Systems – Importance of Carbon and Cost Allocation in Cogeneration Units

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Abstract

Although, district heating has high share in the heating sector of Northern Europe, Central-Eastern European countries often do not utilize full potential for further thermal network expansion. The main reasons for this are relatively low energy market prices, such as natural gas for households, which diminish economic feasibility of the proposed projects. Even though there are numerous optimization methods which can optimize district heating system, they rarely provide cost comparison with individual heating solutions. This paper presents a novel method of evaluating district heating with respect to individual systems by using multi-objective optimization approach coupled with cost and carbon allocations in cogeneration units. Objective functions are defined as minimization of total discounted cost, including environmental impact, and maximization of exergy efficiency. To deal with multi-objective optimization, epsilon-constraint method has been used. The main outcome of this research are energy market prices for which district heating systems have lower environmental impact and exergy destruction than individual natural gas-based heating solutions, while at the same time being economically feasible. Finally, the paper demonstrates that cogeneration-based district heating systems are superior to individual heating, even for low households' natural gas prices.

Keywords*:* district heating, energy planning, cogeneration, multi-objective optimization, CHP allocation

Abbreviations

CHP	cogeneration
DH	district heating
EH	electrcial heater
HOB	heat-only boiler
HP	heat pump
RES	renewable energy sources
ST	solar thermal

Chemical formulas

CO_2	carbon dioxide

Variables and parameters

A_{ST}	area of solar thermal collectors [m^2]
a_1	first order heat loss coefficient [W/K]
a_2	second order heat loss coefficient [W/K^2]
b	binary variable, technology selection [-]
C	cost [EUR]
$Cost_{CHP}$	total cost of CHP unit [EUR]
$Cost^*_{CHP}$	cost of CHP unit allocated to heat [EUR]
$CO_{2_{CHP}}$	Total carbon emisssions of CHP unit [tonnes of CO_2]
$CO^*_{2_{CHP}}$	Carbon emisssions of CHP unit alocated to heat [tonnes of CO_2]
DEM	district heating demand [MW]
e_{Exe}	exergy factor of the fuel [-]
e_{CO_2}	Speficic carbon emissions of a fuel [tonnes of CO_2/MWh]
E	electrical energy production in CHP unit [MWh]
Ex_{in}	exergy input [MWh]
Ex_{out}	exergy output [MWh]
f_{eco}	ecological objective function [tonnes of CO_2]
f_{econ}	economical objective function (EUR)
f_{exe}	exergetic objective function [-]
$f_{Lorentz}$	Lorentz factor of the heat pump [-]
G	global solar radiation [W/m^2]
P	supply capacity [MW]
Q	thermal energy [MWh]
$r_{up-down}$	ramping limit of technology [h^{-1}]
SOC	state-of-charge [MWh]
T	temperature [°C]
TES	thermal storage
TES_{in-out}	thermal storage charge and discharge [MW]

Greek letters

β_{CHP}	power-loss factor of CHP unit [-]
η	technology efficiency [-]
η_0	optical efficiency of solar thermal collector [-]

ε_{eco}	epsilon constraint for ecological objective function [tonnes of CO_2]
ε_{exe}	epsilon constraint for exergetic objective function [-]
σ_{CHP}	power-to-heat factor of CHP unit [-]

Subscripts

eco	ecological
econ	economical
exe	exergetic
fix	fixed
i	technology type
inv	investment
t	time
var	variable

1. Introduction

District heating (DH) systems will be crucial component in future energy systems with high share of renewable energy sources [1], [2] by utilizing power-to-heat technologies [3] to store excess of electricity as thermal energy [4] in various thermal storage types [5]. In the literature, four generations of district heating systems are defined, each one with lower temperatures and higher thermal network efficiencies than the previous one [6]. Lower temperatures can offer additional possibilities of numerous available heat sources, such as data centres [7], [8], metro stations and other [9]. Ommen et al. have analysed different configurations of booster heat pumps in ultra-low temperature systems [10]. This technical challenge has also been interest of Elmegaard et al. in [11]. In other paper, authors have analysed how temperature reduction in DH supply will affect Danish energy system [12]. All authors agree how heat pumps will play crucial part in these systems, due to their increased efficiency in low temperature systems. However, this will also mainly depend on their positioning in the energy system, as shown in [13]. Buffa et al. have provided the extensive list of already existing ultra-low and neutral temperature DH systems, calling them the 5^{th} generation [14].

Although district heating systems are recognized as economically feasible option of heating in urban areas, their current potential is still left untapped [15]. Additionally, most of the current DH networks still have relatively high supply temperatures [16]. These systems are here to stay until most of the building stock is refurbished and prepared for lower supply temperatures. Besides high temperatures in the district heating, current systems still have high share of natural gas which is not always efficiently utilized through cogeneration (CHP) units. The importance of CHP in the coupled heating and power sector is analysed in [17]. Dominković et al. have studied the impact of natural gas CHP in thermal network expansion [18]. In paper [19], repowering of coal power plant to cogeneration units for district heating system has been analysed. Soltero et al. evaluated the potential of natural gas based cogeneration in order to decarbonize economy of the Spanish continental area [20]. Sun et al. have studied the integration of natural gas based DH system with geothermal renewable energy source [21]. The issue of exergy destruction in natural gas heat-only boiler has been studied in [22], with the combustion chamber being the highest source of irreversibility.

One of the main competitors of district heating in urban areas is still natural gas due to its relatively small price for households in numerous EU countries [23]. Attractiveness of district heating in these countries is reduced due to marginal financial feasibility, while usage of natural gas heat-only boilers is still expanding. Comparison of district heating with individual heating systems has been carried out for some specific cases. Authors are usually focusing on low-energy buildings and low temperature district heating systems. Paper [24] calculated carbon dioxide (CO_2) abatement cost for different district heating technologies which are substituting natural gas individual heating system. Utilization of natural gas and biomass district heating system have negative abatement cost for great range of the CO_2 emissions reduction. Yoon et al. have investigated opinion of final users on different heating options while focusing on district heating and individual boilers. They have concluded that higher-income and more educated consumers prefer district heating while other consumers who currently use power-to-heat appliances prefer individual heating options. The study was carried out for South Korea [25]. Similar survey has been carried out in [26]. Brum et al. analysed benefits of centralized systems providing space heating and domestic hot water for low energy buildings in Northern

California. From the results acquired, the most efficient technology is a district heating ground based heat pump [27]. Hansen et al. analysed the feasibility of district heating in a case of low energy buildings, while focusing on heating demand density. They have compared district heating and individual heating solutions. The paper concludes that percentage of connected customers is crucial factor for the feasibility of the district heating system [28]. Paper [29] provides an overview of the costs and benefits of preparing the existing Danish building stocks for low temperature district heating. From an energy system perspective, simple payback periods are equal to 1.2-4.3 years. The study concludes that it is economically feasible to invest in a system control which will enable lower district heating return temperatures.

One of the biggest challenges in planning of CHP based district heating systems is cost and carbon allocation between heat and electricity production. This issue is crucial for policy makers, energy planners and researchers which are dealing with heating and power sector coupling and district heating system expansion. Numerous methods have already been proposed. Noussan provides detailed overview of different allocation methods in cogeneration units. Paper also analyses allocation methods in different case studies. Obtained results vary greatly depending on the chosen method and different defined boundary conditions [30]. Tereschenko and Nord also provide different methods for the allocation of CO_2 emissions in cogeneration power plant [31]. Six different methods are explained in detail and used to calculate heat allocation factor while using district heating system as the case study. Gao et al. provided exergy and exergoeconomics analysis of the coal-fired cogeneration power plant [32]. By using these results, they have proposed CO_2 allocation factor for heat and electricity part of the cogeneration unit. Obtained results show how 22%-61%, depending on the method, of the CO_2 emissions produced in the unit should be allocated to heat. This results in heat carbon factors equal to 78-210 g/kWh. Pina et al. tackled the issue of allocating economic cost in trigeneration systems which include thermal energy systems. Hourly unit costs of the internal flows and final products were obtained for a day of the year [33]. Wang et al. proposed systematic method (ECAEL) for defining additional allocation equations and calculating the exergy cost of flows in thermal system [34]. The costs of all flows are calculated by solving the exergy consumption and allocation equations with design conditions. The proposed method provides an option to complete the thermoeconomic analysis of multi-product systems. Gao et al [35] carried out CO2 allocation in coal CHP unit based on exergoeconomic modelling. The results show that carbon emissions allocated to heat and electricity are similar, around 950 g/kWh. Paper [36] compares five allocation techniques usually applied in life-cycle analysis studies with three thermoeconomic allocation techniques for different pollutants (CO_2, NOx and SOx) and resources (fuel consumption) in cogeneration systems. Dos Santos et [37] showed how the thermoeconomic models can be adapted to allocate the overall CO_2 emission of four different cogeneration systems to the electricity and heat. They have also determined specific CO_2 emissions (in g/kWh) for each product. Furthermore, other papers provide allocation methods for other industrial processes, such as for syngas and ammonia production plant [38].

One of the most interesting allocation methods is power-loss, or sometimes called Dresden, method. It is based on translating electricity production reduction, due to the heat production, to carbon emissions and operational cost of a CHP unit. As such, it is in line with the idea that the thermal energy coming from CHP units is mostly excess, or waste heat, which would be unexploited if not used in district heating systems. This method has been presented in numerous reports [39], [40], [41] and research papers [30], [42], [31], [43]. Cost and carbon allocation approach shown in this paper is also based on this method, as explained in Section 2.

District heating systems are often analysed by means of multi-objective optimization approach. In paper [44], genetic algorithm has been used to obtain the Pareto solutions. Ameri et al. have used multi-objective optimization to integrate district heating and cooling [45]. Franco et al. [46] analysed optimal share of cogeneration in the technology mix while considering second law of thermodynamics. Issue of exergy losses minimization is incorporated in many other papers. Di Somma et al. have developed mixed integer linear programming model to maximize exergy efficiency [47]. Their model has been upgraded and presented in [48]. In paper [49], different DH operation strategies have been analysed by taking into account network temperatures and network losses. Mikulandrić et al. examined performance of hybrid district heating system [50]. Huang et al carried out economic analysis of DH systems combined with solar thermal collectors. They used levelized cost of heat as the objective function, while examining different boundary conditions [51]. Pavičević et al develop the method for operation and capacity optimization of DH supply system, however CHP units have not been considered in the model [52]. In paper [53], multi-objective optimization of integrated district heating and cooling systems has been carried out by using LP approach. Cogeneration units have been included as an option. However, CHP allocation has not been proposed and efficiency of optimal solutions has not been calculated. Although Leśko et al proposed detailed optimization of CHP unit operation, integrated with thermal storage, neither cost nor carbon allocation has been carried out in cogeneration system [54]. Furthermore, the modelling covers only single day, i.e. 24 hours. Similar modelling has been carried out by Kazagić et al in [55]. However, they used commercially available tool called energyPRO. Jie et al developed district heating model [56] based on cogeneration, while also taking into account final customers, i.e. existing buildings. They have optimized insulation thickness to obtain minimum annual total cost. Morvaj et al [57] carried out multi-objective optimization of DH system sizing and operation. Objective functions are minimization of total cost and carbon emissions. Epsilon constraint method was also used to deal with multi-objective optimization. Although cogeneration units were considered, no CHP allocation has been implemented. Finally, no comparison with individual solutions has been carried out. Paper [58] deals with optimisation of marginal extension of existing DH system. The model is capable of optimising DH operation and selecting between different CHP units and sizes. The objective function is cost savings maximization or CO_2 emissions minimisation. The method also includes CHP carbon allocation based on the boiler displacement method used in UK industry for energy reporting. However, only CHP carbon factor for electricity is calculated, while cost allocation has not been carried out. Obtained results have not been compared with individual solutions.

According to the carried-out literature review, multi-objective optimization of district heating systems is rarely carried out in combination with cost and carbon allocation in cogeneration units. Secondly, carbon allocation is usually used to provide analysis of already existing district heating systems or to carry out simple calculation carried out on yearly level. Thirdly, carbon allocation is rarely used together with cost allocation in CHP units, while analysis of allocation for integrated district heating and cooling systems has not been carried out so far on this level of detail. Finally, most of the papers dealing with multi-objective optimization of district heating systems do not compare obtained results with individual heating solutions, such as natural gas. In other words, their economic feasibility and environmental impact are not brought into question.

While considering carried out literature review and gap analysis of the existing papers dealing with multi-objective optimization of district heating systems, scientific contribution of this paper is defined as following:

- Development of the mixed-integer linear programming, hourly based, multi-objective optimization model capable of optimizing supply capacities and system operation for a whole year, while minimizing total cost, carbon emissions and maximizing exergy efficiency of the system;
- Analysis of the Pareto shift caused by carbon and cost allocation based on the power-loss in cogeneration units;
- Systematic comparison of the district and individual heating systems with respect to cost and carbon allocation methods in cogeneration units;
- Analysis of the impact of allocation methods on integrated district heating and cooling systems.

This paper is divided into several sections. Section 2 provides overview of the district heating optimization model, cost and carbon allocation in CHP unit and multi-objective optimization approach. Section 3 displays input data needed to run the model, while Section 4 shows the obtained results and discusses them in detail. Section 5 summarizes the main outputs and concludes the paper. Finally, Appendix shows different hourly input data, displays overview of the district heating system and provides analysis of renewable energy sources share in energy and exergy output.

2. Method

In this section method used in this paper is presented. In Section 2.1, district heating model is shown in detail, while Section 2.2 shows P-Q (power-heat) diagrams approach used for CHP modelling. Section 2.3 displays carbon and cost allocation used in cogeneration units. Section 2.4 defines objective functions used in the optimization approach, while Section 2.5 shows how multi-objective optimization was treated in the paper.

The method developed for the purpose of this paper is based on the model previously developed by the authors [59].

2.1. District heating model

In this section, district heating model is presented in detail. The model involves several technologies such as heat-only boilers, cogeneration units, heat pumps, electrical heaters, solar thermal collectors, including short-term and seasonal thermal storage. Optimization variables are technology capacities P_i, thermal storage capacities TES_{size} and hourly system operation of each supply unit $Q_{i,t}$, including thermal storage charging and discharging $TES_{in-out,t}$. In other words, P_i represents maximum possible load of technology i, i.e. installed nameplate capacity. Hourly load of technology $Q_{i,t}$ represents thermal energy dispatched from the supply unit to the thermal network in a single hour. Its value cannot be higher than installed capacity P_i. Thermal storage units are treated in similar manner. Maximum state-of-charge is equal to TES_{size}, it represents the size of thermal storage expressed in energy equivalent. Thermal storage charging and discharging on hourly level, is represented with variable $TES_{in-out,t}$. It has negative value in case of discharging and positive value when thermal storage is being charged.

As said, proposed model has a time step of one hour, while time horizon is equal to a whole year. Such lengthy time horizon is needed to carry out sizing of the system without using time slices, as done in other papers. Equation (1) presents basic constraint which implies that heating demand DEM_t should be satisfied in every hour of the year by using various supply capacities and storage. Furthermore, it should be noticed that there are two thermal storage units, as shown in Figure 5A of Appendix. Thermal storage 1 serves as a buffer and can be charged with all technologies, except solar thermal. Thermal storage 2 can be charged only with solar thermal collectors and can also serve as a seasonal storage.

$$\begin{aligned} DEM_t = Q_{HOB,gas,t} + Q_{HOB,biomass,t} + Q_{EH,t} + Q_{HP,t} + Q_{CHP,gas,t} \\ + Q_{CHP,biomass,t} - TES_{1,in-out,t} - TES_{2,in-out,t} \end{aligned} \tag{1}$$

Hourly operation of each supply unit is constrained by using Equation (2), i.e. hourly production of the unit cannot be higher than its installed peak capacity.

$$0 \leq Q_{i,t} \leq P_i \tag{2}$$

Since the technology used in the model include natural gas combi-cogeneration and other large units, minimum possible installed capacity is defined. In order to model such constraint, Equation (3) is used, where b_i is binary variable which describes selection of the technology i, while $P_{min,i}$ is predefined minimum possible capacity of technology i.

$$b_i \cdot P_{min,i} \leq P_i \leq b_i \cdot P_{max,i},\ b_i = \{b_i \in \mathbb{Z} | 0 \leq b_i \leq 1\} \tag{3}$$

In order to acquire more realistic operation supply units, ramping limits are integrated in the model by using Equation (4), where $r_{up-down,i}$ is ramping limit expressed as share of the peak capacity of the technology.

$$-r_{up-down,i} \cdot P_i \leq Q_{i,t} - Q_{i,t-1} \leq r_{up-down,i} \cdot P_i \tag{4}$$

Short-term and seasonal storages are modelled similarly by using Equations (5)-(9). SOC_t is state-of-charge in a time step t, while TES_{loss} is hourly self-discharge of the storage, i.e. hourly thermal loss.

$$SOC_{1,t=1} = SOC_{1,t=8760} = SOC_{1,start-end} \cdot TES_{1,size} \tag{5}$$

$$SOC_{1,t} = SOC_{1,t-1} + TES_{1,in-out,t} - SOC_{1,t} \cdot TES_{1,loss} \tag{6}$$

$$SOC_{2,t=1} = SOC_{2,t=8760} = SOC_{2,start-end} \cdot TES_{2,size} \tag{7}$$

$$SOC_{2,t} = SOC_{2,t-1} + TES_{2,in-out,t} - SOC_{2,t} \cdot TES_{loss} + Q_{ST,t} \tag{8}$$

Operation of the solar thermal collectors is acquired by using Equation (9), where A_{ST} is area of the solar field. This is also the only optimization variable related to the solar thermal collectors, since their operation is constrained, as shown in Equation (9). $P_{solar,specific,t}$ is specific solar thermal output which could be calculated by using Equation (10), $\eta_{c,t}$ is solar thermal collector efficiency which is calculated as explained below.

$$Q_{ST,t} = A_{ST} \cdot P_{solar,specific,t} \tag{9}$$

$$P_{solar,specific,t} = \eta_{c,t} \cdot G_t \qquad 10)$$

Besides optimization variables, there are various exogeneous variables which are calculated by using meteorological data and district heating network temperatures. Equation (11) shows calculation of the solar thermal collector efficiency by using predefined solar thermal collector parameters η_0, a_1 and a_2. The first parameter, η_0, is called optical efficiency, a_1 is first order thermal loss coefficient and a_2 is second order thermal loss coefficient. $T_{ref,t}$ is hourly outside temperature, G_t is hourly global solar radiation, while $T_{m,t}$ is mean collector fluid temperature. For the purposes of this paper it is equal to mean value of district heating supply and return temperature in respective time step t, already proposed in [60]. Its calculation has been simplified to secure linearity of the model.

$$\eta_{c,t} = \eta_0 - a_1 \frac{\left(T_{m,t} - T_{ref,t}\right)}{G_t} - a_2 \frac{\left(T_{m,t} - T_{ref,t}\right)^2}{G_t} \tag{11}$$

Coefficient of performance of the heat pump (COP) could be calculated by using Equation (12), where f_{Lorenz} presents the ratio between real and ideal heat pump efficiency.

$$\eta_{HP,t} = f_{Lorenz} \cdot \left(\frac{T_{DH,t}}{T_{DH,t} - T_{ref,t}}\right) \tag{12}$$

Illustration of proposed DH system is shown in Figure A5 in Appendix. It shows correlations between all technologies and related optimization variables.

2.2. CHP modelling

To understand allocation methods used in this paper, the CHP modelling approach should firstly be introduced. Cogeneration units used in this paper are steam extraction plants which could operate in three regimes: back-pressure, condensation and steam extraction mode. Possible combinations of CHP's heat and power outputs can be illustrated by using so called P-Q (power-heat) diagram, as shown in Figure 1. However, real P-Q diagrams are more complex since they include minimum technical power and heat outputs, the illustrated lines are not straight, heat capacity is sometimes constrained, etc. For the purpose of this paper, and to secure linearity of the model, technical minimum of the CHP units is neglected. This approach is interesting since complex operation of cogeneration units can be modelled by using two lines – back-pressure and extraction line. The slope of the back-pressure line is called power-to-heat factor and is labelled with σ_{CHP_i}. The slope of the extraction line is called power-loss factor and is marked with β_{CHP_i}. They depend on the numerous parameters, such as cogeneration unit type, extraction temperature, i.e. district heating supply temperature, etc. [61]. Heat ($Q_{CHP_i,t}$) and power ($E_{CHP_i,t}$) cogeneration outputs are correlated according to the Equations (13)-(15). In other words, operating point of the CHP unit could only be inside the region bounded with back-pressure and extraction line. The CHP unit could also operate in the condensation mode. In that case, heat output is equal to zero, i.e. operating point is on the y-axis. However, in that case total efficiency would be the lowest, since it could be assumed that fuel input is constant on the extraction line. CHP modelling based on using P-Q diagrams is fully explained in papers [61] and [62].

$$E_{CHP_i,t} \geq \sigma_{CHP_i} \cdot Q_{CHP_i,t} \tag{13}$$

$$E_{CHP_i,t} \leq P_{el,CHP,i} - \beta_{CHP_i} \cdot Q_{CHP_i,t} \tag{14}$$

$$E_{CHP_i,t} \leq P_{el,CHP,i} \tag{15}$$

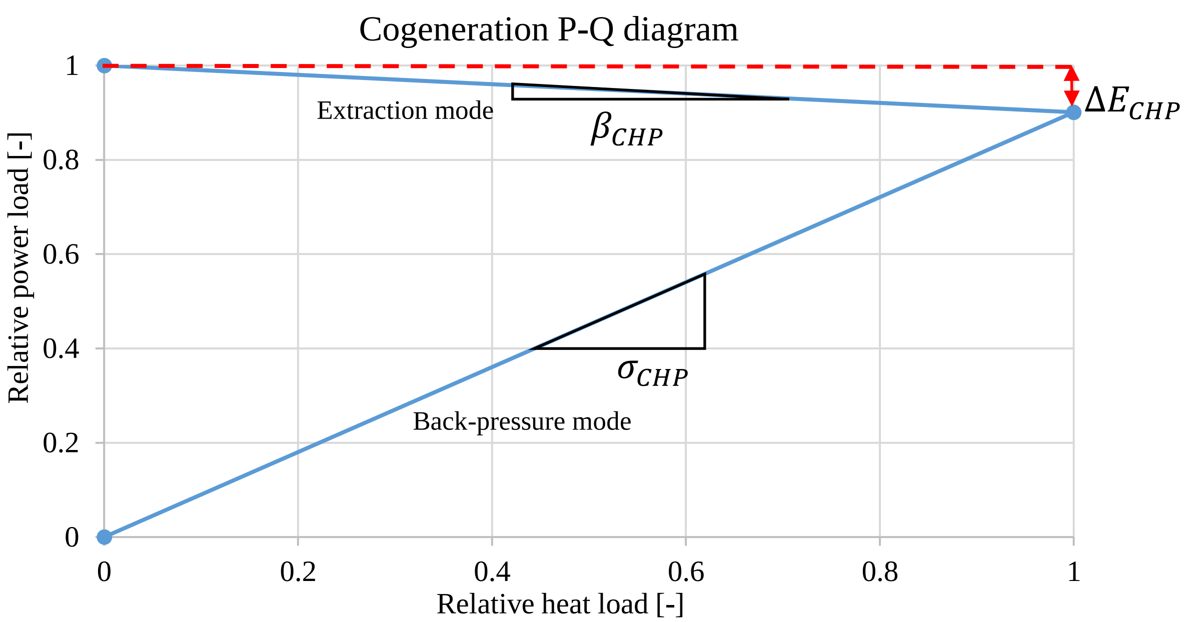

Figure 1 Illustration of cogeneration plant P-Q diagram

2.3. CHP allocation methods

There are various allocation methods proposed by numerous researchers. Allocation method used in this paper is based on the idea that heat output should be treated as a power-loss of the cogeneration unit. Due to this, the method is called power-loss method, or sometimes referred to as Dresden method. It is illustrated in the Figure 1 by using a dashed red line. Power loss due to the heat production in a CHP unit, i.e. $\Delta E_{CHP_i,t}$, could be calculated by using Equation (16). It presents loss of electrical energy production at the expense of thermal energy production in cogeneration units.

$$\Delta E_{CHP_i,t} = \beta_{CHP_i} \cdot Q_{CHP_i,t} \tag{16}$$

Power loss could thus be translated into cost and carbon emissions due to the heat production in a CHP unit. Following subsections explain in detail such approach.

2.3.1. Cost allocation

As already mentioned, cost of CHP unit could be allocated to heat and electricity. Equation (17) shows cost of CHP with no allocation between heat and electricity, $Cost_{CHP_i}$. Cost of the fuel is represented with $c_{fuel,i}$, c_{CO2} represents CO_2 cost, in terms of EUR/ton of CO_2, e_{CO2_i} are specific carbon emissions of the fuel i.e. technology, $c_{var_{CHP_i}}$ are variable operation and maintenance costs of CHP unit, $c_{el,t}$ are power market prices, c_{inv,CHP_i} is specific investment cost of the CHP unit and $c_{fix_{CHP,i}}$ are specific fixed operation and maintenance costs, while CRF_{CHP_i} is capital recovery factor used to discount investment cost. Finally, η_{el,CHP_i} represents electrical efficiency of the CHP unit. It can be noticed how the total cost of CHP is assigned to heat production. The first part of the equation of the right side consists of fuel, variable cost and carbon tax in case of natural gas utilization, second part represents income in terms of electricity production, while the third part is investment and fixed cost of the CHP unit. Allocated cost of CHP $Cost^*_{CHP}$ can be calculated by using Equation (18). In this case operational cost is equal to the electricity market loss due to the heat production, while investment cost is calculated by using c_{conv,CHP_i}, specific investment needed for CHP conversion [61]. This is cost which is needed to upgrade condensation power plant to cogeneration unit. In this case this is theoretical value since it only indicates the share of a CHP investment allocated to heat.

$$\begin{aligned} Cost_{CHP_i} = \sum_i \sum_{t=1}^{t=8760} & (E_{CHP_i,t} + \Delta E_{CHP_i,t}) \cdot \left(\frac{c_{fuel,i} + e_{CO2_i} \cdot c_{CO2}}{\eta_{el,CHP_i}} + c_{var_{CHP_i}} \right) \\ & - E_{CHP,i,t} \cdot c_{el,t} + P_{el,CHP_i} \cdot \left(c_{inv,CHP_i} \cdot CRF_{CHP_i} + c_{fix_{CHP,i}} \right) \end{aligned} \tag{17}$$

$$Cost^*_{CHP} = \sum_i \sum_{t=1}^{t=8760} \Delta E_{CHP_i,t} \cdot c_{el,t} + P_{el,CHP_i} \cdot c_{conv,CHP_i} \cdot CRF_{CHP_i} \tag{18}$$

2.3.2. Carbon allocation

Like cost, carbon allocation in CHP units is also based on power-loss due to the heat production. Total carbon emissions in a CHP unit $CO_{2_{CHP_i}}$ could be calculated by using Equation (19). It can be noticed once again, how all emissions are associated to heat production, i.e. to district heating system. However, power-loss could be recalculated to carbon emissions. In other words, CO_2 emissions due to the heat production $CO^*_{2_{CHP_i}}$ are equal to the lost power which should be produced in a power plant with the same electrical efficiency unit by using the same fuel. This is also shown in Equation (20).

$$CO_{2_{CHP_i}} = \sum_i \sum_{t=1}^{t=8760} \frac{E_{CHP_i,t} + \Delta E_{CHP_i,t}}{\eta_{el,CHP_i}} \cdot e_{CO2_i} \tag{19}$$

$$CO^*_{2_{CHP_i}} = \sum_i \sum_{t=1}^{t=8760} \frac{\Delta E_{CHP_i,t}}{\eta_{el,CHP_i}} \cdot e_{CO2_i} \tag{20}$$

2.4. Objective functions

Since this paper uses multi-objective optimization approach, more than one objective function must be identified. In this research, three objective functions are defined – minimization of discounted cost, minimization of carbon emissions and maximization of exergy efficiency. Equations (21) show economic objective functions where cost allocation is not implemented, while Equation (22) shows objective function with inclusion of CHP cost allocation.

$$f_{econ} = \sum_i \sum_{t=1}^{t=8760} Q_{i,t} \cdot \left(\frac{c_{fuel,i} + e_{CO2_i} \cdot c_{CO2}}{\eta_i} + c_{var_i}\right) + P_i \cdot (c_{inv,i} \cdot CRF_i + c_{fix,i}) + Cost_{CHP_i} \tag{21}$$

$$f^*_{econ} = \sum_i \sum_{t=1}^{t=8760} Q_{i,t} \cdot \left(\frac{c_{fuel,i} + e_{CO2_i} \cdot c_{CO2}}{\eta_i} + c_{var_i}\right) + P_i \cdot (c_{inv,i} \cdot CRF_i + c_{fix,i}) + Cost^*_{CHP_i} \tag{22}$$

In the similar manner, Equations (23) and (24) show ecological objective function with and without CHP carbon allocation.

$$f_{eco} = \sum_i \sum_{t=1}^{t=8760} \frac{Q_{i,t}}{\eta_i} \cdot e_{CO2_i} + CO_{2_{CHP_i}} \tag{23}$$

$$f^*_{eco} = \sum_i \sum_{t=1}^{t=8760} \frac{Q_{i,t}}{\eta_i} \cdot e_{CO2_i} + CO^*_{2_{CHP_i}} \tag{24}$$

Since exergy efficiency of the system does not depend on the allocation methods in the CHP units, it is calculated as follows. By using Equation (25), exergy input $Ex_{in,i,t}$ could be calculated, while Equation (26) shows how to obtain exergy output $Ex_{out,i,t}$. Finally, exergy efficiency of the system could be calculated by using Equation (27). It is important to notice how this is non-linear equation since exergy input and output contain optimization variables. To deal with this challenge, epsilon constraint method has been used as shown in the following section.

$$Ex_{in,i,t} = \frac{Q_{i,t}}{\eta_i} \cdot e_{Exe,i} \tag{25}$$

$$Ex_{out,i,t} = Q_{i,t} \cdot \left(1 - \frac{T_{ref_t}}{T_{DHN_t}}\right) + E_{CHP,i,t} \tag{26}$$

$$\eta_{exe} = \frac{\sum_{t=1}^{t=8760} \sum_i Ex_{out,i,t}}{\sum_{t=1}^{t=8760} \sum_i Ex_{in,i,t}} \tag{27}$$

It can be noticed that exergy efficiency of the district heating system includes only energy transformation at the location of supply technology i.e. at the boundary with the thermal network. In other words, exergy destruction of the thermal network, building substation and building distribution are not integrated in the objective function. Nevertheless, Section 4.2 shows the impact of exergy destruction in the thermal network and comparison with natural gas-based individual boilers.

2.5. Multi-objective optimization approach

In this paper, multi-objective optimization is handled by using epsilon-constraint method. The main advantage of this approach is that translates multi-objective optimization problem into single objective optimization with additional sets of constraints, called "epsilon constraints" ε_{eco} and ε_{exe}, as shown in Equation (28) [63]. In order to start the procedure, the borders of Pareto front have to be known in order to ensure that assigned epsilon constraints are eligible. In other words, the least-cost, the most environmentally friendly and the solution with the highest exergy efficiency must be known.

$$\min\left(f_{econ}\right) \text{ for } f_{eco} \leq \varepsilon_{eco},\ f_{exe} = \varepsilon_{exe} \tag{28}$$

The main drawback of this method is large computational time, since it acquires great number of optimization runs in order to visualize a whole Pareto set, especially in a case of three objective functions.

3. Case study and input data

The developed method was tested on the numerical case study which includes following data: hourly demand, hourly district heating network temperatures and hourly meteorological data. Mentioned distributions are shown in Appendix. Case study is located in Northern Croatia, with continental climate. Minimum temperature reaches -10°C during winter season, while the highest summer temperature reaches more than 35°C, as shown in Figure A1. District heating supply temperature is in direct correlation with outside temperature, as shown in Figure A2. Maximum supply temperature reaches around 115°C. District heating system in this case study covers both space heating and domestic hot water demand, i.e. operates through a whole year as shown in Figure A3. Peak load is around 450 MW, achieved during winter season, while total thermal demand is equal to 808 GWh. In this section, technology input data is displayed, together with district heating network cost. Finally, programming language and optimization solver is presented.

3.1. Technology data

Table 1 shows various technology characteristics, including prices per technology. It also includes thermal storage characteristics such as daily losses. Technology characteristics are based on the information provided by the Danish Energy Agency database for energy plants [64]. Power-to-heat and power-loss factor of cogeneration units are defined by using EC Joint Research Centre (JRC) report [65] and paper [61].

Table 1 Technology data [64], [65]

Technology	Investment cost [€/MW] / [€/m^2] /[€/MWh]	Variable cost [€/MWh]	Fixed cost [€/MW] / [€/m^2] /[€/MWh]	Efficiency/ storage self-discharge [-]	Ramp-up/down [-]	Technical lifetime [years]	Power-to-heat ratio [-]	Power-loss factor [-]
Natural gas boiler	60,000	1,1	2,000	0.89	0.9	25	-	-
Biomass boiler	300,000	1,0	32,000	0.8	0.6	25	-	-
Electrical heater	150,000	0.8	1,100	0.98	0.95	20	-	-
Heat pump	700,000	3.3	2,000	Hourly distribution (avg.2.3)	0.95	25	-	-
Cogeneration (combined cycle) natural gas	1,200,000 (electrical power)	5.5	20,000	0.55 (electrical)	0.6	25	1.17	0.13
Cogeneration biomass	3,000,000 (electrical power)	3.8	45,000	0.45	0.5	25	0.377	0.334
Solar thermal	190 €/m^2	0.2	0.04 €/m^2	Hourly distribution	-	25	-	-
Short term thermal storage	4,500	-	8.6 €/MWh	0.5 %/day	-	40	-	-
Seasonal thermal storage	900	-	3 €/MWh	0.05 %/day	-	20	-	-

Table 2 shows other data related to district heating system optimization such as fuel prices, electricity market prices and electricity network costs. As already mentioned, the model includes carbon tax for natural gas technologies. For the purpose of this paper it is equal to 25 EUR/ton of CO_2. To calculate emissions for respective technologies, emission factors for fuels are defined. It is important to mention that both biomass and electricity have carbon factors, however they are not part of the carbon taxing system. Exergy factors are used to calculate exergy input of the fuel. Finally, CHP conversion cost is used to allocate investment cost between heat and electricity.

Table 3 shows data which data are used for calculation of levelized cost of heat (LCOH) and carbon factor of the natural gas based individual heating, while Table 4 displays cost data for district heating network connection.

Table 2 Other district heating input data [64]

Natural gas price [EUR/MWh]	30
Biomass price [EUR/MWh]	20
Electrical energy price [EUR/MWh]	hourly distribution
Electricity network price [EUR/MWh]	30
CO_2 price [EUR/ton]	25
Natural gas CO_2 factor [tonnes of CO_2/MWh]	0.22
Biomass CO_2 factor [tonnes of CO_2/MWh]	0.042
Electricity CO_2 factor [tonnes of CO_2/MWh]	0.234
Exergy factor biomass [-]	1.2
Exergy factor natural gas [-]	1.04
Cogeneration plant conversion cost [EUR/MW]	300,000

Table 3 Input data for individual gas boilers [64]

Natural gas price for individual customers [EUR/MWh]	30
Natural gas CO_2 factor [ton of CO_2/MWh]	0.22
Natural gas boiler efficiency, individual [-]	0.95
Natural gas price boiler, investment cost	320,000
Lifetime [years]	20

Table 4 Cost data for district heating network connection with a building [64]

District heating network connection pipe investment cost [EUR/MW]	250,000
Lifetime of network connection pipe [years]	50
Building substation investment cost [EUR/MW]	220,000
Lifetime of a substation [years]	25

3.2. District heating network cost calculation

Calculation of district heating network investment cost has been modelled by using information gathered in the Horizon2020 project called STRATEGO. In report [66], relation between heating demand density and thermal network investment cost is presented. This correlation is shown in Figure 2, including the corresponding equation. For higher demand densities, lower specific investment cost is needed. In other words, economic feasibility of a district heating system greatly depends on the heating demand density in a specific area.

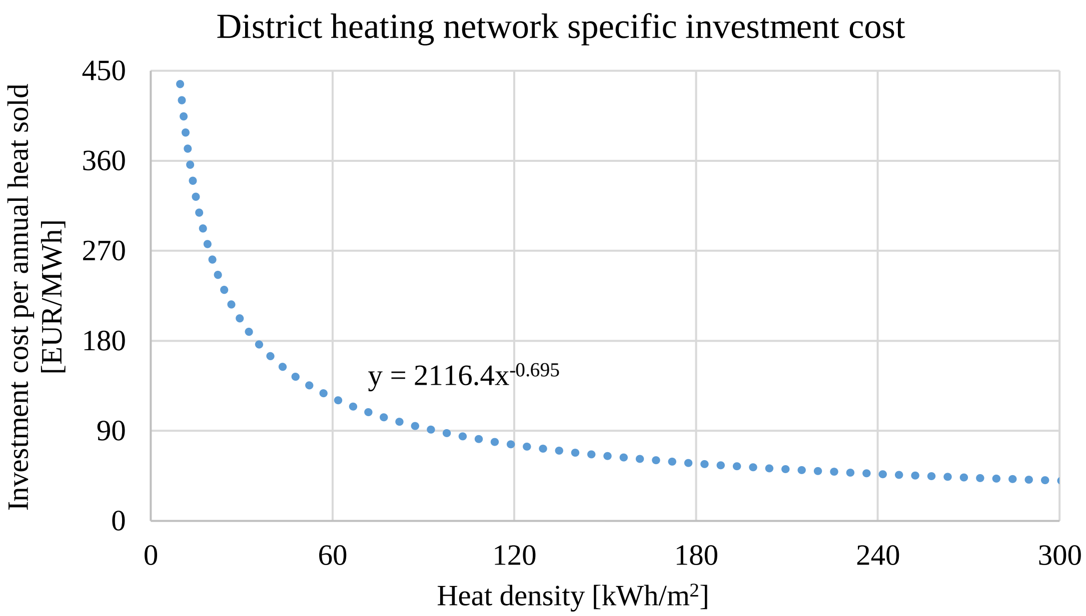

Figure 2 District heating network specific investment cost as a function of heat density [66]

3.3. Programming language and optimization solver

The proposed multi-objective optimization model is written by using free and open-source Julia programming language [67]. The language has been developed for the purpose of increasing computational speed. Julia package, called JuMP [68] is needed in order to create and run optimization model. The optimization problem was solved by using Gurobi [69]. Optimization runs were carried out by using PC workstation with Intel Xeon CPU E5-2623 processor. Single optimization run, i.e. per single set of epsilon constraints, lasted 60 minutes in average.

4. Results and discussion

The results obtained in this paper and related discussions are represented through five sections. Section 4.1 shows Pareto solutions supply technologies, including CHP share with respect to different CHP allocations. In Section 4.2, the acquired results have been compared with individual heating solutions, while focusing on exergy efficiency. In Section 4.3, obtained results are shifted due to the addition of district heating network cost and then compared with natural gas individual heating. Section 4.4 shows the impact of district heating and cooling integration.

Economical objective function is translated to levelized cost of heat (LCOH). It is done by dividing economical objective function value with total heating demand. In the similar manner, environmental objective function is reduced to specific CO_2 emissions, sometimes referred to as a carbon factor. It should be mentioned that in Section 4.4, where district cooling integration is analysed, levelized cost of thermal energy (LCOTE) is used as economical parameter. In this case, economical objective function is divided by total heating and cooling demand.

Finally, it should be mentioned that additional analysis has been carried out, in which share of renewable energy sources in energy and exergy output has been obtained. The results of this analysis are shown in Appendix.

4.1. The impact of different CHP allocations on district heating parameters

In this section, the impact of different CHP allocations on district heating parameters are shown. The focus is put on specific CO_2 emissions, levelized cost of heat and exergy efficiency of the system. Furthermore, optimal technology mix and overall CHP share of selected Pareto solutions is displayed. Each figure shown below consists of six Pareto fronts, constructed for six different exergy efficiency constraints. It should be mentioned how the solutions with the lowest CO_2 emissions, and consequently with the highest cost, are not shown in the diagrams since they are out of scale. It is crucial to mention that exergy efficiency calculation presented in this section includes exergy destruction related to energy transformation on the supply technology level, i.e. exergy destruction of the thermal network has not been considered. Exergy losses of the network are considered and analysed in Section 4.2.

4.1.1. No CHP allocation

The results acquired if no CHP allocation is implemented is shown in Figure 3, where x-axis shows specific CO_2 emissions of the system, while y-axis shows LCOH of the system. For specific points on the diagram, pie charts are developed, indicating technology share in a thermal energy production. The number next to the pie chart indicates CHP share in the technology mix. It should be mentioned that in these results, thermal network cost is not included. For the sake of clarity, third objective function, i.e. exergy efficiency is not plotted on the third axis, but as a parameter. Six Pareto fronts are constructed – five with constrained exergy efficiency, starting with 0.2 and reaching 0.5, and one Pareto front with no constraints put on exergy efficiency. The Pareto front with no constraint put on exergy efficiency reaches the lowest LCOH and CO_2 emissions, i.e. less than 50 EUR/MWh and 0.12 tCO_2/MWh, respectively. These solutions utilize only natural gas and biomass boilers, while CHP share is equal to zero. Similar, but nonetheless higher, system parameters are obtained for Pareto solution with exergy efficiency equal to 0.2. However, to obtain such exergy efficiency, heat pump must be integrated. For Pareto fronts with exergy efficiency higher than 0.2, CHP share is increased – solutions with lower LCOH and higher emissions utilize natural gas CHP, while solutions with higher cost and lower emissions uses biomass CHP and heat pump. The Pareto front with exergy efficiency equal to 0.5, reaches CO_2 factor of 0.52 tCO_2/MWh, with LCOH in the range of 55-80 EUR/MWH.

It should be noticed how specific trend emerges – solutions with higher CHP share have higher CO_2 emissions and higher system costs. This is also emphasized with the arrow shown in Figure 3. The main reason behind this is allocation in which all carbon emissions and investment, including operational, costs are assigned to heat production. However, heat produced in cogeneration units should be considered as excess, or sometimes called waste, heat and treated as such during system optimization. In the following subsections, we will show how this trend could be influenced by using CHP carbon and cost allocation methods.

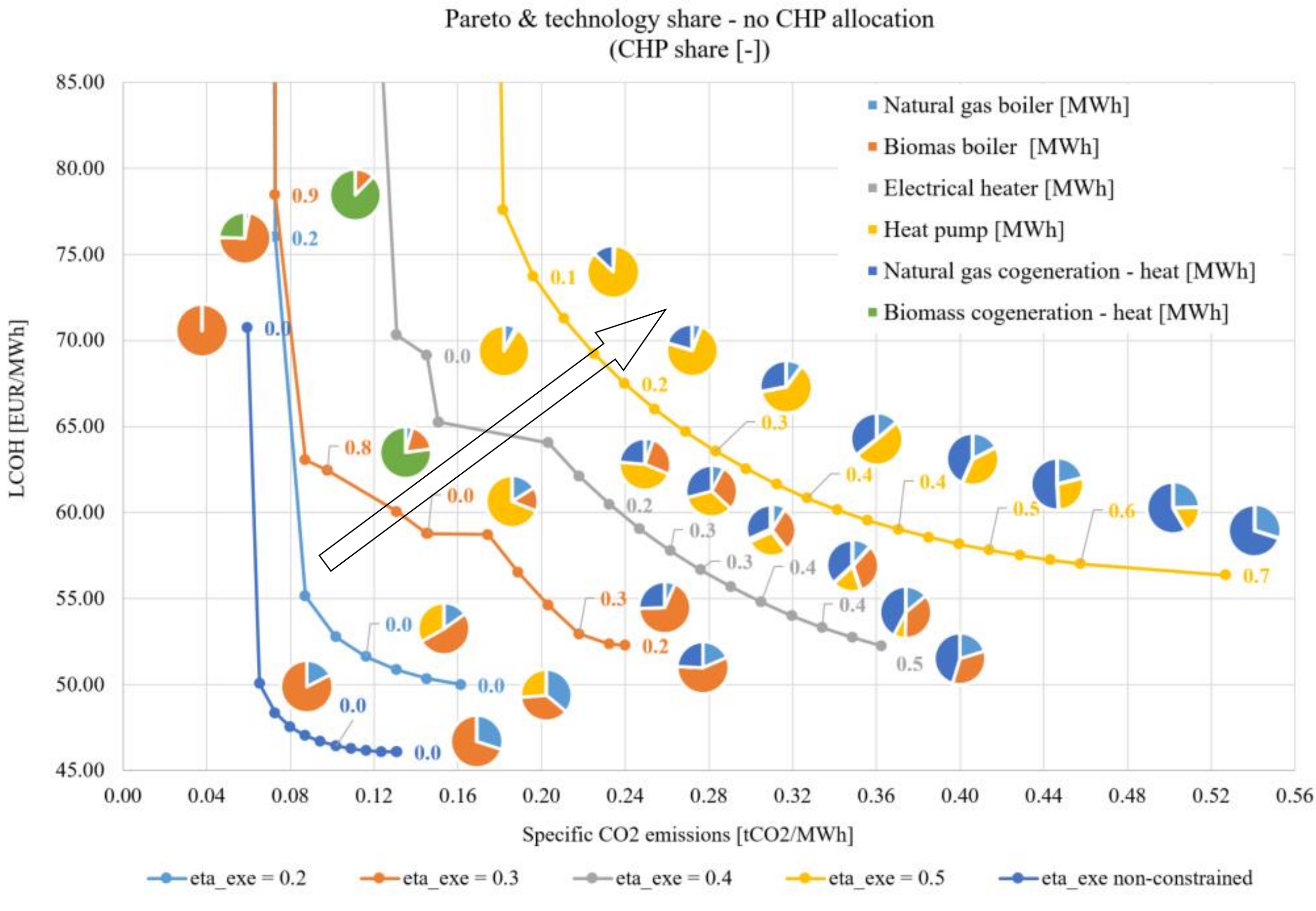

Figure 3 Pareto solutions, technologies and CHP share for no CHP allocations implemented

4.1.2. Cost CHP allocation

Figure 4 shows Pareto results obtained if CHP cost allocation is considered. In this case, the solution with the lowest exergy efficiency, equal to 0.2, reaches highest LCOH (around 40 EUR/MWh) and the lowest carbon emissions (less than 0.1 tCO_2/MWh), while the CHP share is kept relatively low, equal to 0.3. With the increase of exergy efficiency, CHP share is also increased, as already seen in the case when no allocation methods in CHP units are introduced. However, in this case increase of exergy efficiency results in lower LCOH of the system, reaching around 20 EUR/MWh. This is almost 50% lower than in the first case with no allocation in CHP units. However, the results with the highest share of CHP and high exergy efficiency have the highest carbon factor equal to 0.7 tCO_2/MWh. Thus, the following can be concluded: if cost allocation method is implemented, increase of CHP share results in LCOH reduction and carbon factor increase. In other words, exergy efficiency increase shifts Pareto solutions to the region of high carbon emissions and lower total costs. Once again, this is also emphasized with the arrow shown in Figure 4. It should be mentioned how Pareto front with no constraint put on exergy efficiency is relatively flat, i.e. LCOH reaches values between 25 and 20 EUR/MWh, while carbon factor is in range of 0.1-0.7 tonnes of CO_2/MWh. The highest CO_2 emissions are obtained for natural gas CHP dominated system, while the lowest emissions are reached for biomass-based system.

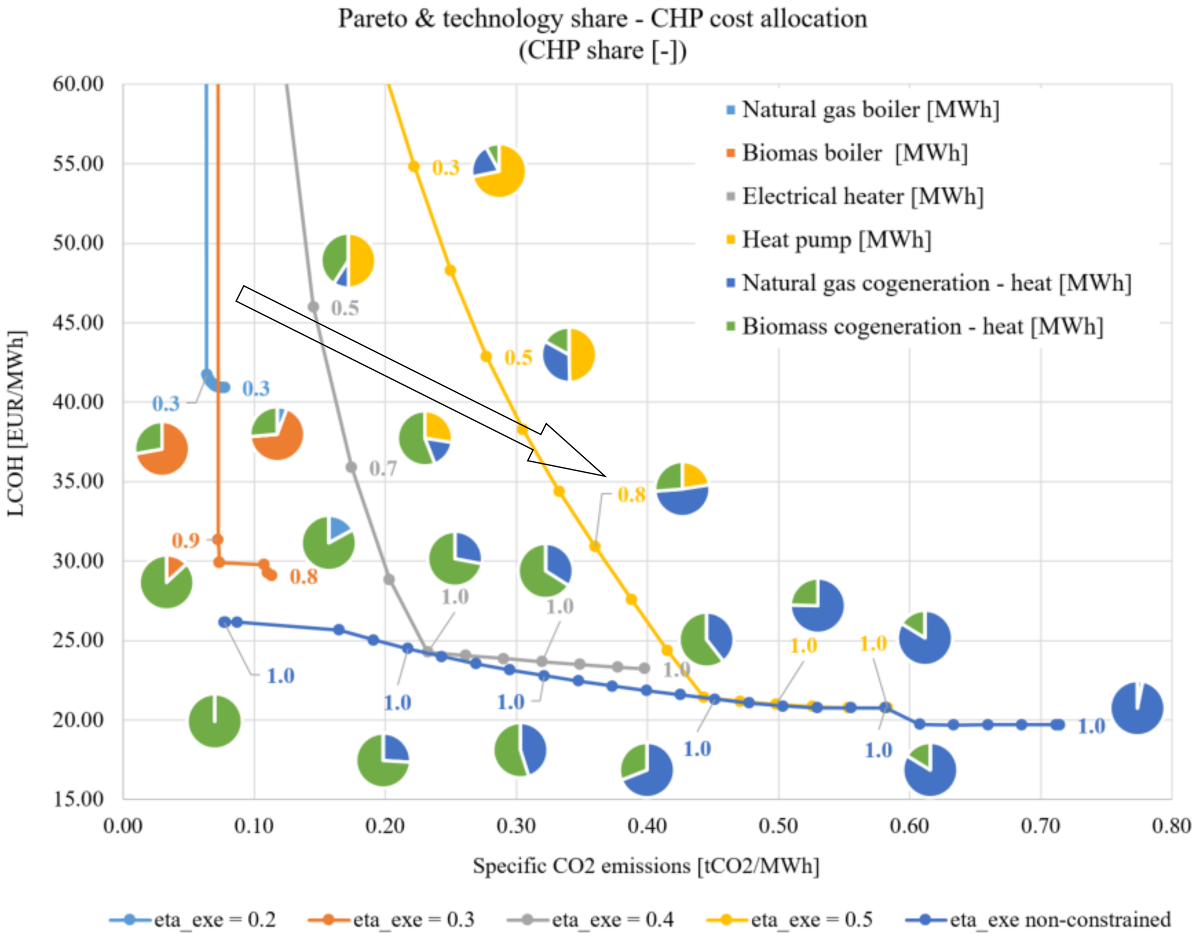

Figure 4 Pareto solutions, technologies and CHP share for cost CHP allocation implemented

4.1.3. Carbon CHP allocation

Pareto solutions with implemented cogeneration carbon allocation is shown in Figure 5. Firstly, it should be noticed that the highest carbon factor of the system is equal to 0.16 tonnes of CO2/MWh, which is relatively low when compared with the first two cases where the highest value reached 0.5 and 0.7 tCO_2/MWh respectively . Solutions with the lowest CO_2 emissions are based on biomass CHP, while natural gas cogeneration causes larger emissions and higher exergy efficiency. Heat pump is rarely part of the optimal solution, only visible for exergy efficiency equal to 0.2. Although all Pareto fronts have different exergy efficiencies, they are all clustered together, i.e. there is no specific shift of the Pareto solution. However, increase of exergy efficiency (and CHP share) tends to move all Pareto solutions, except those with exergy efficiency equal to 0.5, to the region of lower CO_2 emissions. This is also emphasized with an arrow illustrated in the Figure 4. In other words, carbon allocation allows utilization of CHP in different technology mixes which result in similar carbon emission factor and LCOH values.

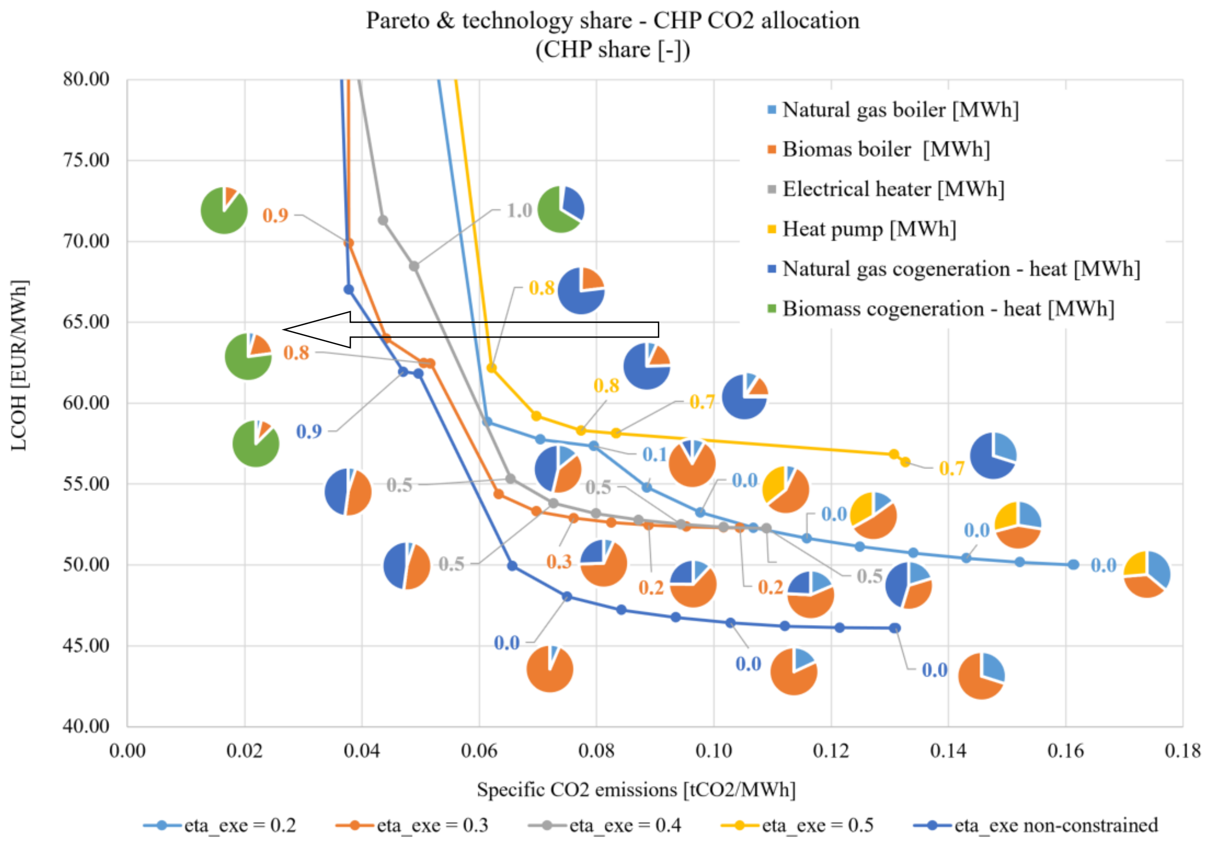

Figure 5 Pareto solutions, technologies and CHP share for carbon CHP allocation implemented

4.1.4. Carbon and cost CHP allocation

Figure 6 shows optimization results for implemented carbon and CHP allocation. It can be noticed how increase of exergy efficiency shifts Pareto solutions to the region of low LCOH and low carbon emissions. This is consequence of a large CHP share and allocation in cogeneration units put both on carbon emissions and cost. This is also displayed with the arrow shown in Figure 6. The largest shift is visible between exergy efficiency increase from 0.2 to 0.3 When exergy efficiency exceeds value of 0.3, all Pareto results have CHP share equal to unity. In these cases, share between natural gas and biomass CHP depends on the position at the Pareto front. It should be mentioned that Pareto front with no constraints put on exergy efficiency coincides with some parts of other Pareto fronts. Simultaneous cost and carbon allocations give the lowest maximum carbon factor with the value equal to 0.08 tonnes of tCO_2/MWh. Values of LCOH are relatively low when compared with previous scenarios since in the most cases stay well below 35 EUR/MWh.

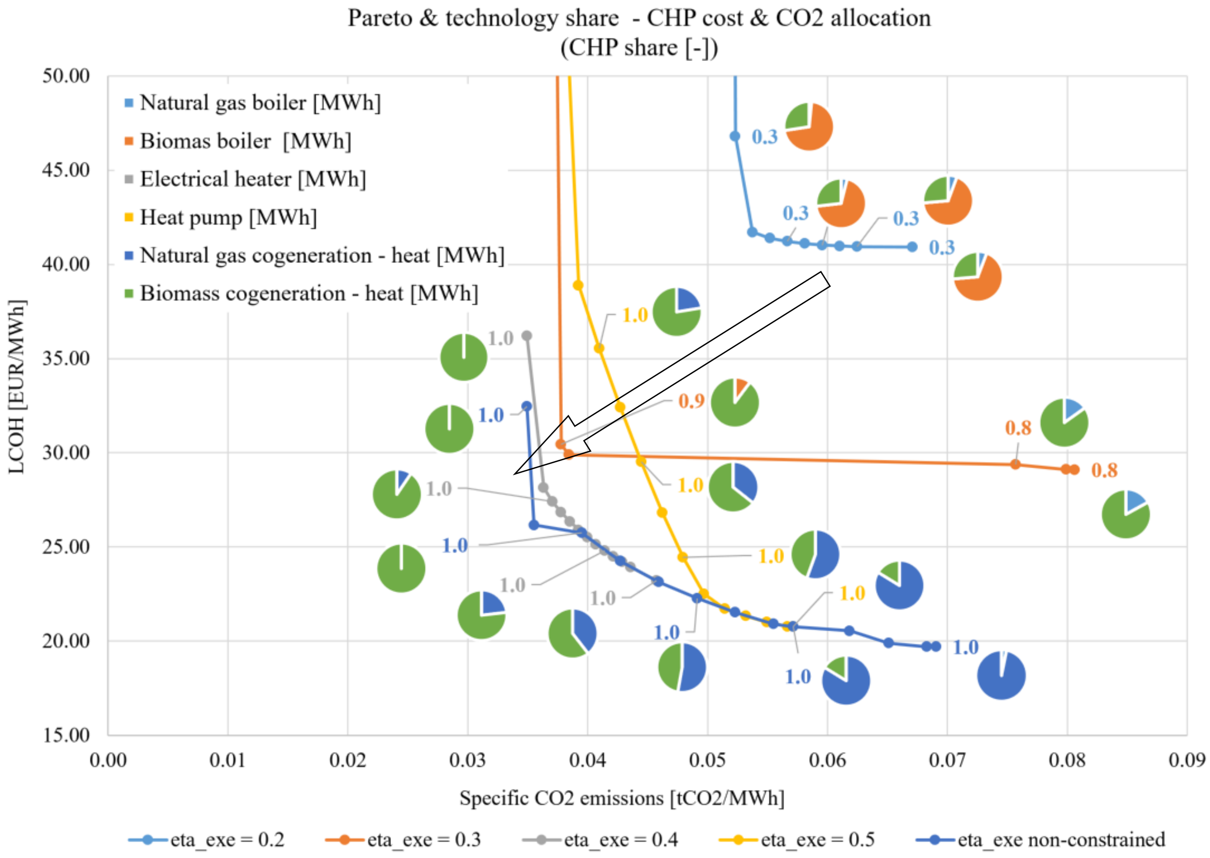

Figure 6 Pareto solutions, technologies and CHP share for cost and carbon CHP allocations implemented

4.2. Comparison with individual heating solutions focusing on exergy efficiency

Figure 7 presents exergy efficiency comparison of a whole DH system (includes supply technology and a thermal network) and individual natural gas boilers. X-axis presents exergy efficiency of the system which consists of supply technologies only (no exergy loss of the thermal network included). This exergy efficiency was obtained during multi-objective optimization and the results were already presented in Section 4.1. Y-axis presents exergy efficiency of the system calculated when exergy losses of the network are included. Exergy losses of the thermal network were obtained by using thermal loss of the network, district heating supply temperatures and temperature of the building substation. Black dotted line presents case for which exergy losses of the thermal network are neglected. The distance between blue dot (exergy efficiency of DH system) and a black dotted line corresponds to the share of exergy losses which are attributed to the thermal network. This is also marked with orange arrow in Figure 7a. Red full line represents exergy efficiency of the natural gas-based individual boiler. District heating systems should have exergy efficiency higher than natural gas-based individual boilers to be superior to individual natural gas-based heating.

Although exergy efficiency of the supply system (x-axis) is equal for many configurations, such as in Figure 7a and Figure 7b, the exergy efficiency of a whole system (which includes exergy destruction of thermal network) varies greatly. It should be mentioned that this difference mainly depends on the amount of electricity production, i.e. on the CHP share of the system. Although most of the configurations have exergy efficiency of a whole system higher than individual natural gas-based boilers, some solutions do not. They are marked with red circles in Figure 7. These systems are based on heat-only boiler technologies. Although these systems could be economically more feasible and environmentally more friendly than individual solutions, as shown in Section 4.3, they should also be avoided since their exergy efficiency of a whole system is relatively low. In other words, replacement of individual natural gas boilers should not be done by using heat-only boilers, but CHP technologies or heat pumps combined with convenient heat source.

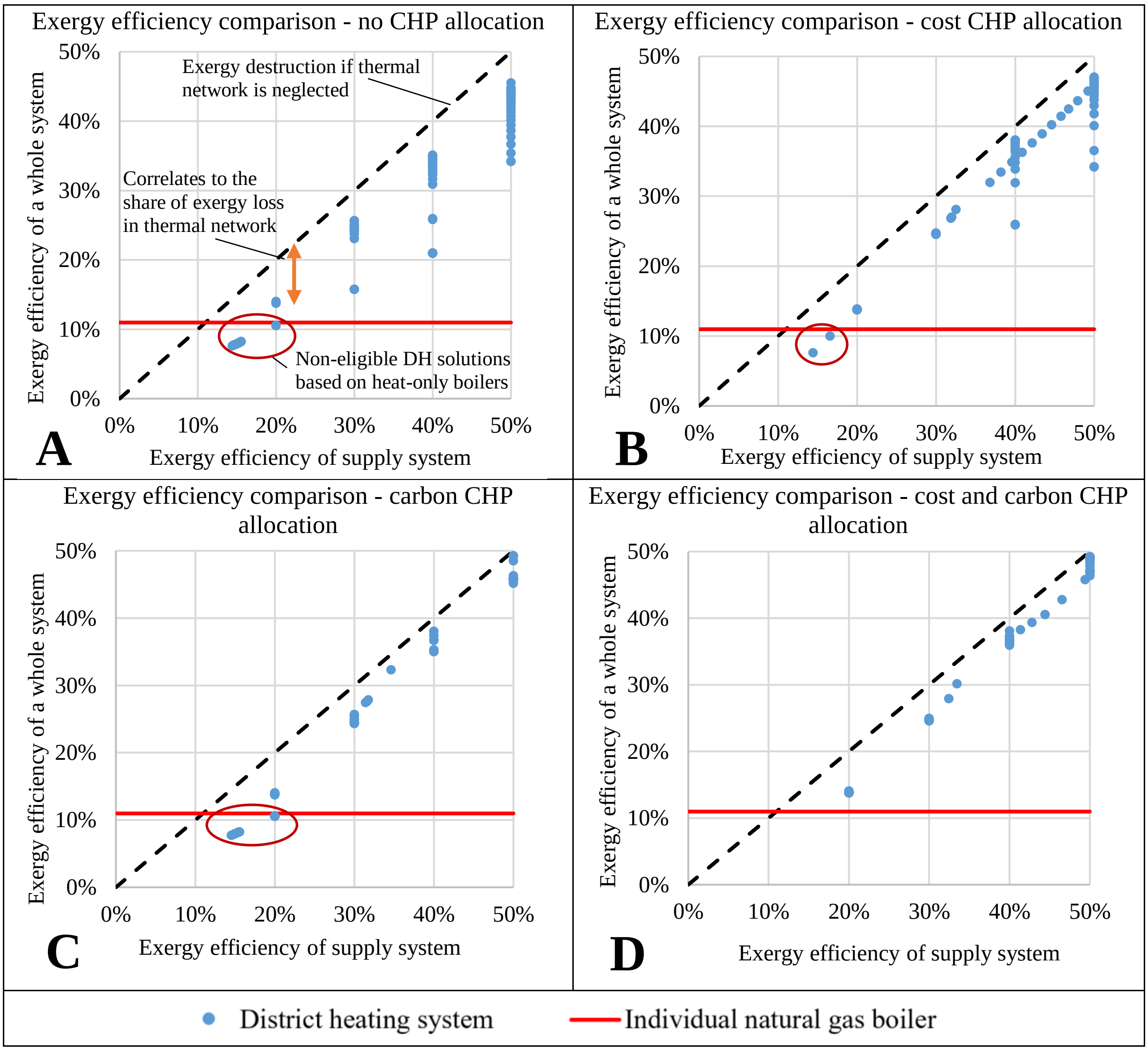

Figure 7 Exergy efficiency comparison between district heating system and individual natural gas-based system (exergy efficiency of the thermal network included): a) no CHP allocation, b) cost CHP allocation, c) carbon CHP allocation, d) cost and carbon allocation

4.3. Comparison with individual heating solutions focusing on cost and carbon emissions

In this section, obtained results are compared with the individual solution based on natural gas, i.e. the case in which predefined demand is covered with individual natural gas boilers. To do so, additional costs should be added to the results obtained by the multi-objective optimization. They are equal to the discounted investment cost of district heating network, individual heating substation and connection pipe between a building and a district heating network. As shown in Section 0, district heating network cost depends on heating demand density. In the following sections, two cases of heating demand densities are used, the first one equal to 50 kWh/m^2 and a second one equal to 200 kWh/m^2. The former represents relatively low, while latter represents relatively high heating demand density. Finally, it is important to notice that discounted costs of installation of natural gas boiler at a building level and installation of district heating substation at building level have similar value, according to the technology database [64].

Since natural gas price for households has crucial impact on the final comparison of results, three natural gas prices have been taken into account: Croatian, Swedish and EU-average, equal to 35, 55 and 95 EUR/MWh respectively [23]. These prices do not include VAT taxes.

4.3.1. No CHP allocation

In this section, multi-objective optimization results with no CHP allocations implemented, which include other district heating network related costs, are compared with individual natural gas boiler solution. The result is shown in Figure 8 and are explained in detail below. Firstly, network cost addition is presented on the example of Pareto front with exergy efficiency equal to 0.5. Three fronts are visible (full, dashed and dotted line). The first one (full) represents the Pareto front with no district heating network cost added, i.e. LCOH is equal to the supply system costs. Second Pareto front (dashed line) represents the solutions which include other district network costs for high heating demand which is equal to 200 kWh/m^2. Similarly, the third Pareto front (dotted line) represents the solutions which include other district heating network cost for low heating demand density, equal to 50 kWh/m^2. Natural gas based individual solutions are illustrated as follows. Carbon factor of individual systems is equal to 0.23 tonnes of tCO_2/MWh, which is represented with vertical dotted black line on the diagram. This means that all solutions left of this line have lower emissions, which is also indicated with horizontal green arrow. Similar illustration can be made for LCOH of individual natural gas boilers. Three black dotted horizontal lines are visible. Each one represents different LCOH obtained for different natural gas prices for households: Croatia, Sweden and EU average. Resulting LCOH of individual natural gas boiler heating system is equal to 54 EUR/MWh for Croatia, 75 EUR/MWh for EU average and 117 EUR/MWh for Sweden. All Pareto solutions which are below these boundaries are better, in economic terms, than natural gas based individual heating in respecting countries. This is also displayed with vertical green arrow. If district heating Pareto solution is inside “the box”, then it can be declared superior, both in carbon emissions and economic terms, to individual heating based on natural gas. According to the results shown in Figure 8 no Pareto results are located inside “the box” for Croatian price conditions. However, for natural gas prices higher than EU average, great part of the Pareto solutions is superior to the individual natural gas-based heating. Furthermore, it should be mentioned that numerous solutions have lower carbon factor than natural gas individual heating. Nevertheless, it is important to notice how great part of the Pareto solutions with the exergy efficiency higher than 0.4 has higher carbon factor than individual heating.

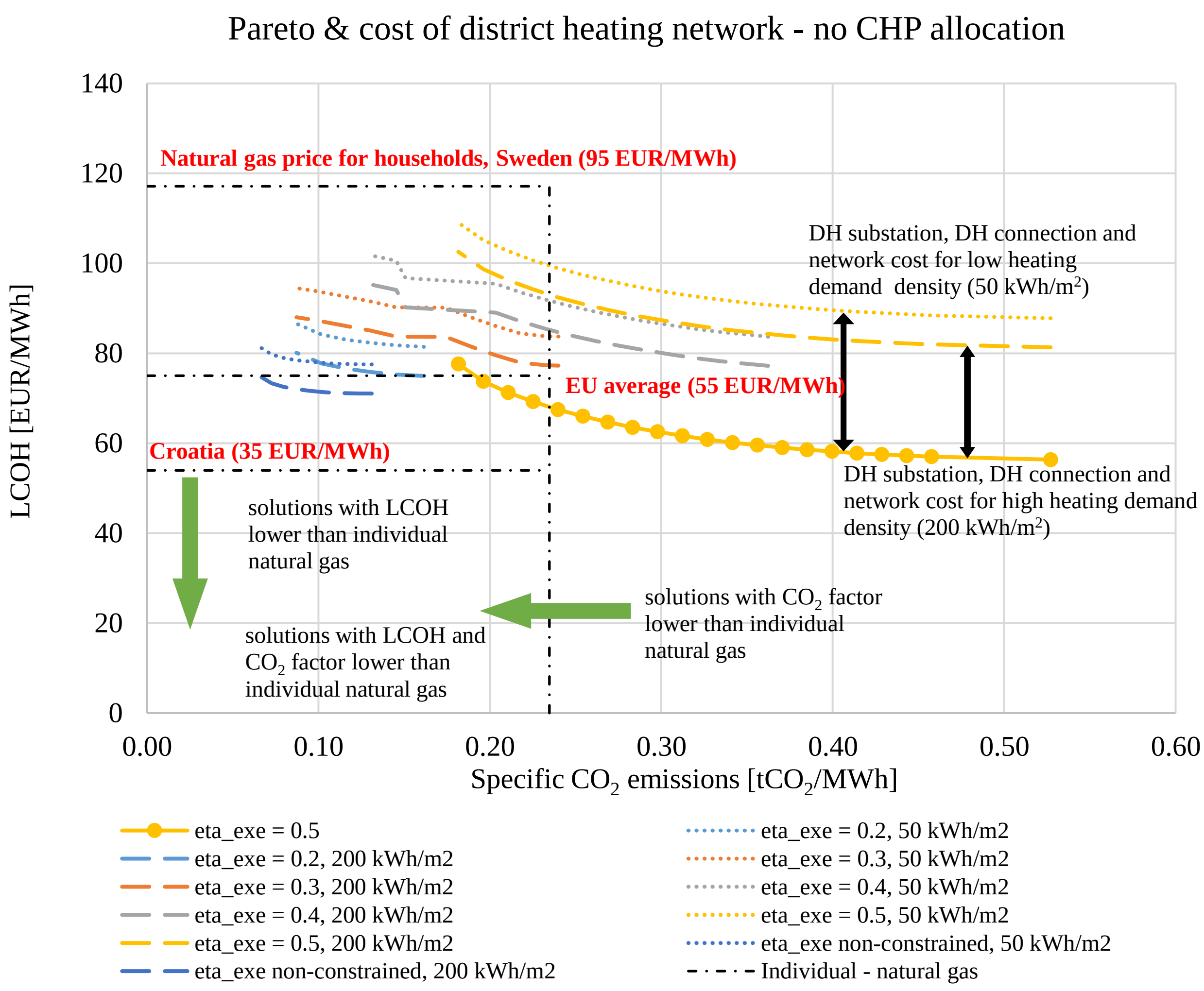

Figure 8 Pareto solutions, including network cost, and comparison with individual natural gas heating for no CHP allocation implemented

From the acquired results, one can conclude that individual natural gas boilers are better solution than cogeneration-based district heating. However, this conclusion heavily depends on the allocation methods used in the cogeneration units. Following sections will demonstrate how CHP based district heating systems are superior to individual natural gas-based heating systems, even for low natural gas price conditions such as in Croatia.

4.3.2. CHP cost allocation

Figure 9 shows comparison of Pareto results with implemented CHP cost and individual heating based on natural gas boilers. All Pareto solutions with exergy efficiency equal or lower than 0.3 are better than individual heating, for EU average natural gas price conditions. It should be noticed how only high demand density solutions with to no constraint put on exergy efficiency are economically better than individual systems for Croatian pricing conditions. As previously shown, this allocation causes great increase of carbon emission factor of the system. Great part of solutions with exergy efficiency higher than 0.4 have carbon emission factor higher than individual heating systems. For results with the highest exergy efficiency, only the most environmentally friendly solutions are superior to individual heating systems, but for pricing conditions which are higher than the EU average.

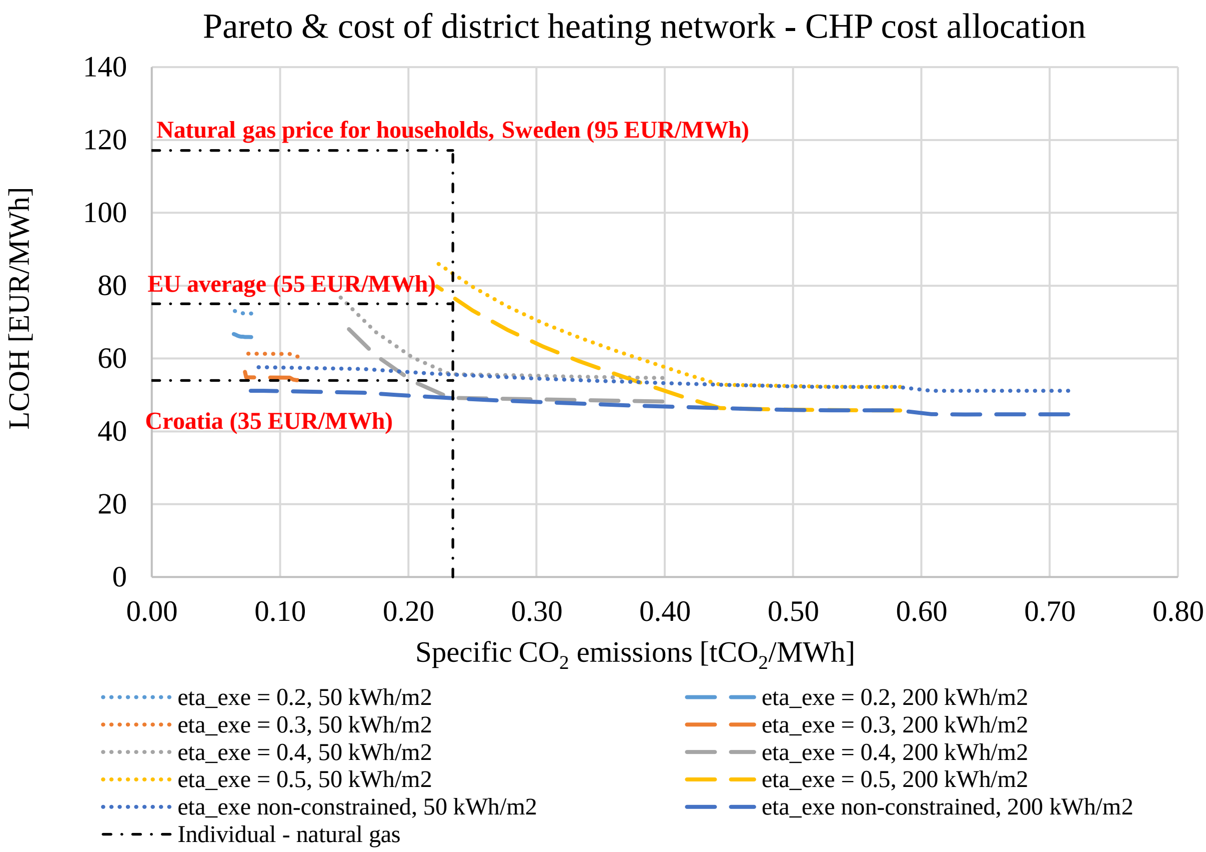

Figure 9 Pareto solutions, including network cost, and comparison with individual natural gas heating for CHP cost allocation implemented

4.3.3. CHP carbon allocation

Comparison of Pareto solutions with implemented CHP carbon allocation and individual heating is shown in Figure 10. All Pareto results have lower carbon factor than individual heating solution based on natural gas. However, all of them also have higher LCOH than individual heating for Croatian and EU average natural gas pricing conditions. Of course, the reason behind this is relatively low natural gas price for individual customers which is equal to 35 EUR/MWh. It should be noticed how all solutions are clustered in the region of carbon emission factor which is around 50% lower than the one for individual heating solutions. To proclaim district heating option economically better than individual heating, natural gas price for households should be higher than 55 EUR/MWh. Finally, it should be noticed that all solutions have relatively similar LCOH values which are in range 80-100 EUR/MWh.

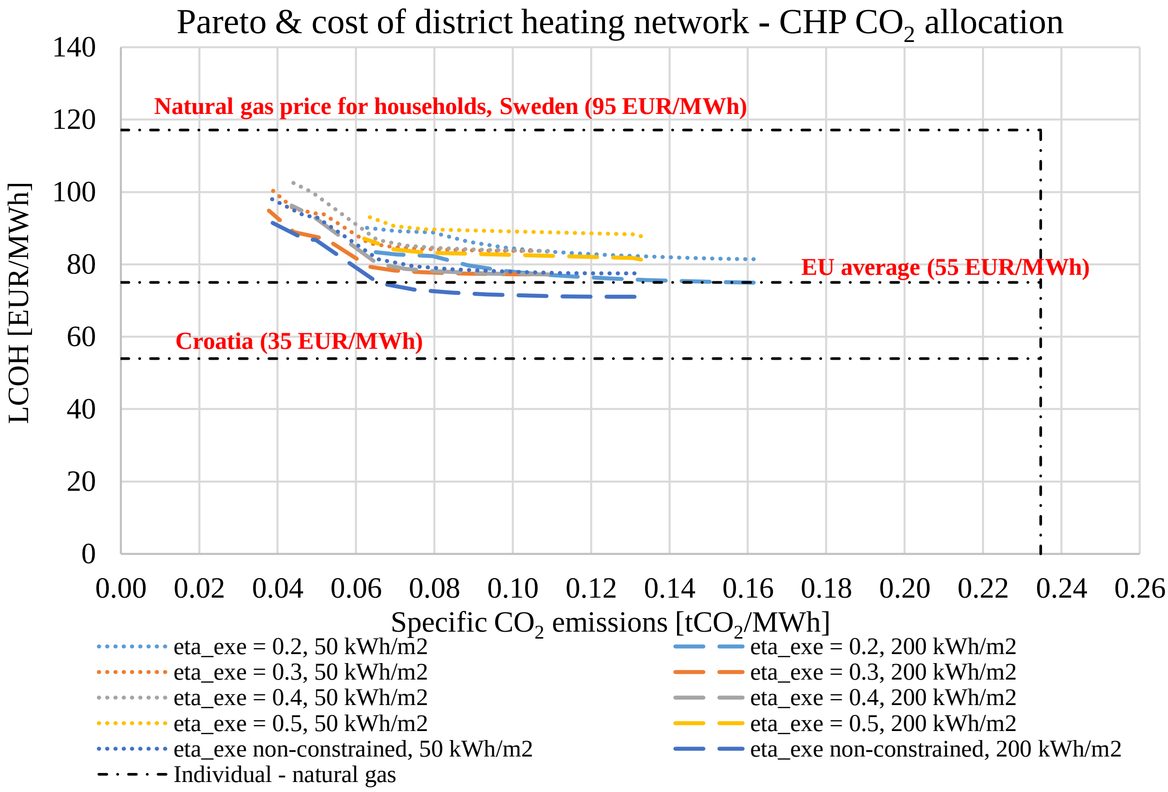

Figure 10 Pareto solutions, including network cost, and comparison with individual natural gas heating for CHP carbon allocation implemented

4.3.4. CHP cost and carbon allocation

Figure 11 shows comparison of Pareto results, for which both allocations are implemented, and individual heating solutions based on natural gas. It is crucial to notice how most of the Pareto solutions are superior to natural gas based individual heating, even for Croatian natural gas pricing conditions. Heating demand density has little-to-no impact. Interestingly, the only Pareto front outside of the box for Croatian conditions, is the one with the exergy efficiency equal to 0.2. On the other hand, all solutions have system LCOH lower than individual heating solutions for EU average natural gas prices. Levelized cost is in range of 45-75 EUR/MWh. In other words, high exergy efficient district heating systems are less expensive option than individual natural gas boilers in the most of EU countries. Finally, it should be noticed how carbon factor for all solutions is almost five times lower than the natural gas based individual heating. Carbon factor of district heating systems is in range 0.04-0.09 tCO_2/MWh.

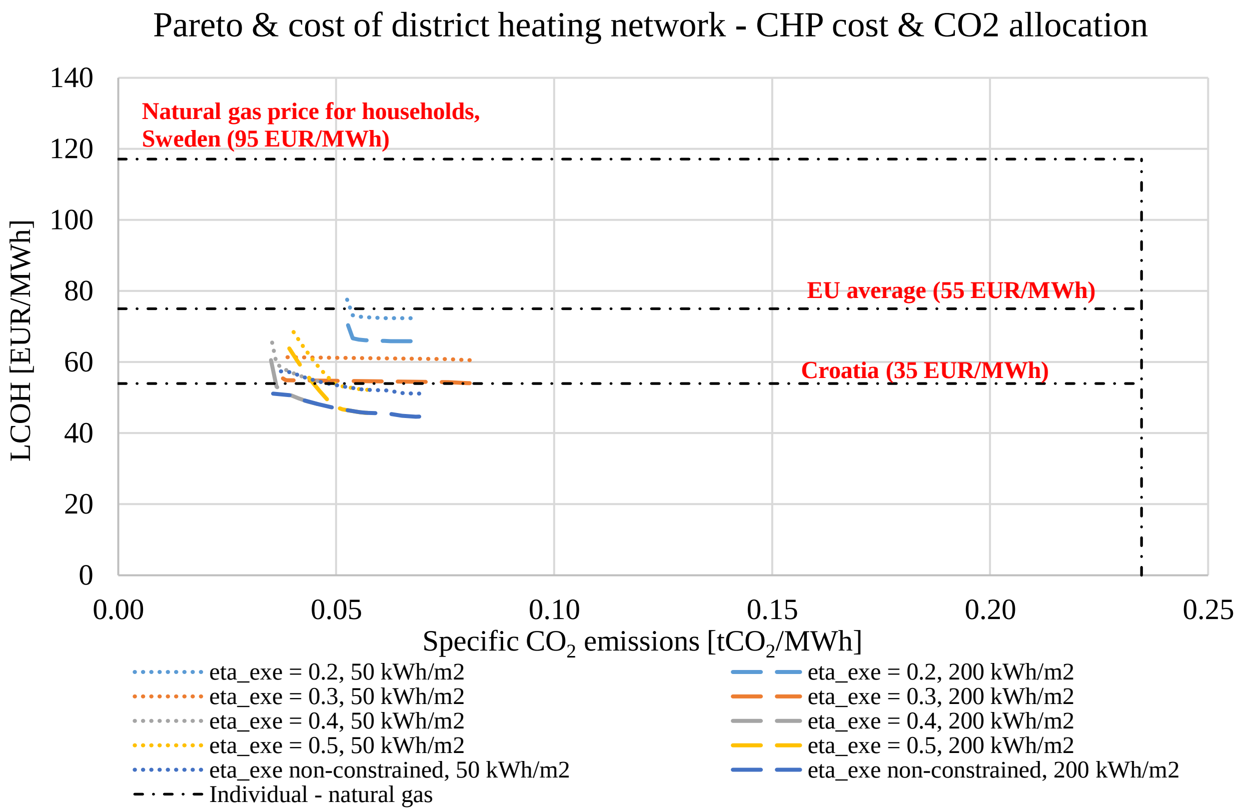

Figure 11 Pareto solutions, including network cost, and comparison with individual natural gas heating for CHP cost and carbon allocation implemented

4.4. District cooling integration

In this section, the impact of integrating of district cooling is analysed. It is connected to district heating by adding absorption heat pump which is utilizing high-temperature heat from heat-only boilers and cogeneration units. It should be mentioned that both absorption heat pump and cooling storage size, including hourly operation on hourly level, are optimization variables. Similar to Section 4.1, four scenarios are developed depending on the allocation used in the CHP units. It should be mentioned that economical objective function is represented by using parameter called levelized cost of thermal energy (LCOTE). It is similar to LCOH, but this time both heating and cooling demand are taken into account.

4.4.1. No CHP allocation

Figure 12 shows the results obtained by integrating district cooling with no CHP allocation used in the CHP units. This figure will also serve as an opportunity to familiarize the reader with the presentation of the results. Once again, Pareto front are plotted for different exergy efficiency values. X-axis represent a carbon factor of the system, while y-axis includes economic parameter called levelized cost of the thermal energy (LCOTE). Pareto fronts with full lines represent the results which include only district heating systems. These Pareto fronts have already been shown in Section 4.1. Dashed Pareto fronts show the results obtained once district cooling is integrated. The difference between the full and dashed Pareto fronts, corresponds to the specific cost difference between the two systems, as illustrated with black arrow in Figure 12. It can be noticed how this difference is relatively low, around 5 EUR/MWh for high carbon emissions. For low exergy efficiency values, integrated district heating and cooling systems even have LCOTE lower than the systems with only district heating option. For high exergy efficiency systems, in the region of low carbon emissions, the difference greatly rises. However, it can be concluded that the cost of the integrated system is kept relatively similar to the DH-only systems. In other words, whenever possible, district cooling should be made available. Nevertheless, it should be mentioned that introduction of district cooling in the buildings is challenging issue due to the distributions systems which should be taken into account. Unfortunately, this analysis is out of the scope of this paper and was not considered.

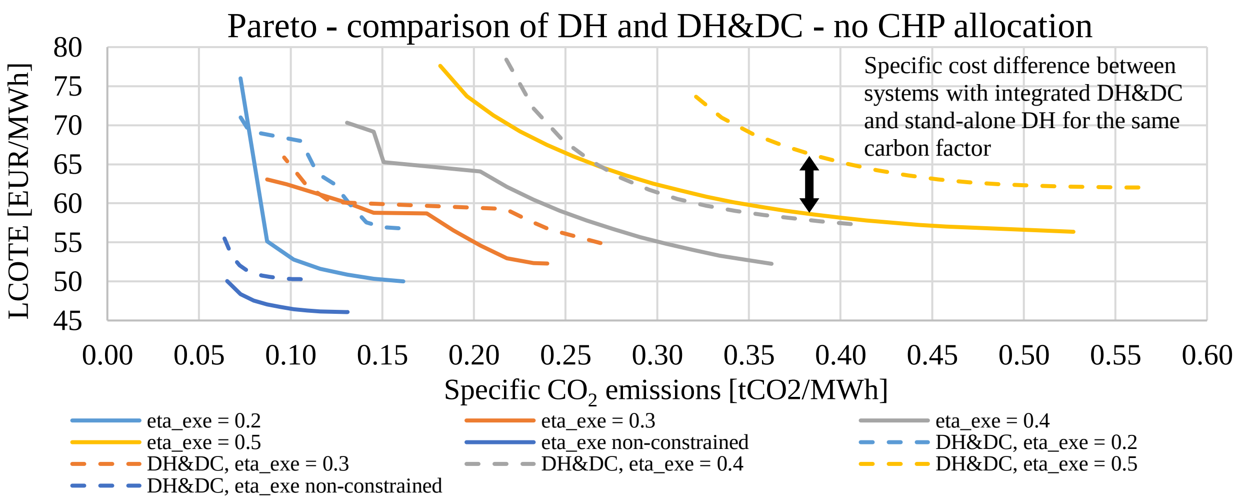

Figure 12 Pareto front comparison for systems with integrated district heating and cooling and a stand-alone district heating system – no CHP allocation implemented

4.4.2. CHP cost allocation

Figure 13 shows the impact of district cooling (DC) integration for CHP cost allocation. Once again, it can be noticed how the cost difference for DH-only and DH-DC integrated systems is relatively small, below 5 EUR/MWh. Low-exergy efficiency solutions have almost identical specific price of the system.

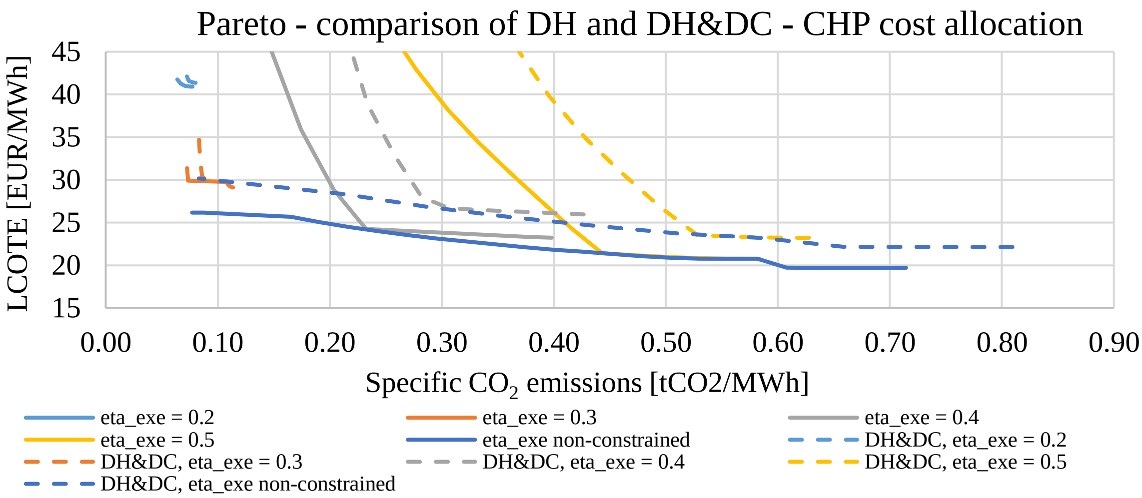

Figure 13 Pareto front comparison for systems with integrated district heating and cooling and a stand-alone district heating system –CHP cost allocation implemented

4.4.3. CHP carbon allocation

Figure 14 shows how district cooling integration behaves under CHP carbon allocation. Once again, the cost difference is relatively low, under 5 EUR/MWh. It should be noticed that full and dashed Pareto fronts are getting closer for low carbon factors. In other words, integration of district heating and cooling systems is more feasible for lower carbon emissions.

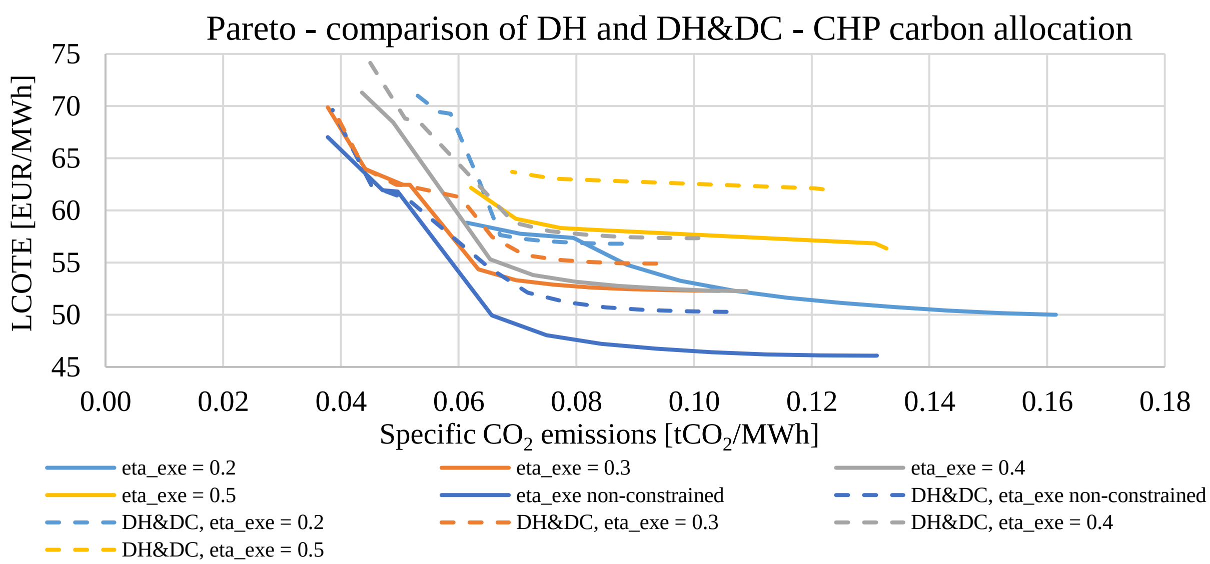

Figure 14 Pareto front comparison for systems with integrated district heating and cooling and a stand-alone district heating system –CHP carbon allocation implemented

4.4.4. CHP cost and carbon allocation

Finally, Figure 15 displays how does district cooling integration influences the results when both cost and carbon allocations are implemented. Cost of difference of 5 EUR/MWh is also kept here. For low exergy efficiencies, the difference is almost equal to zero.

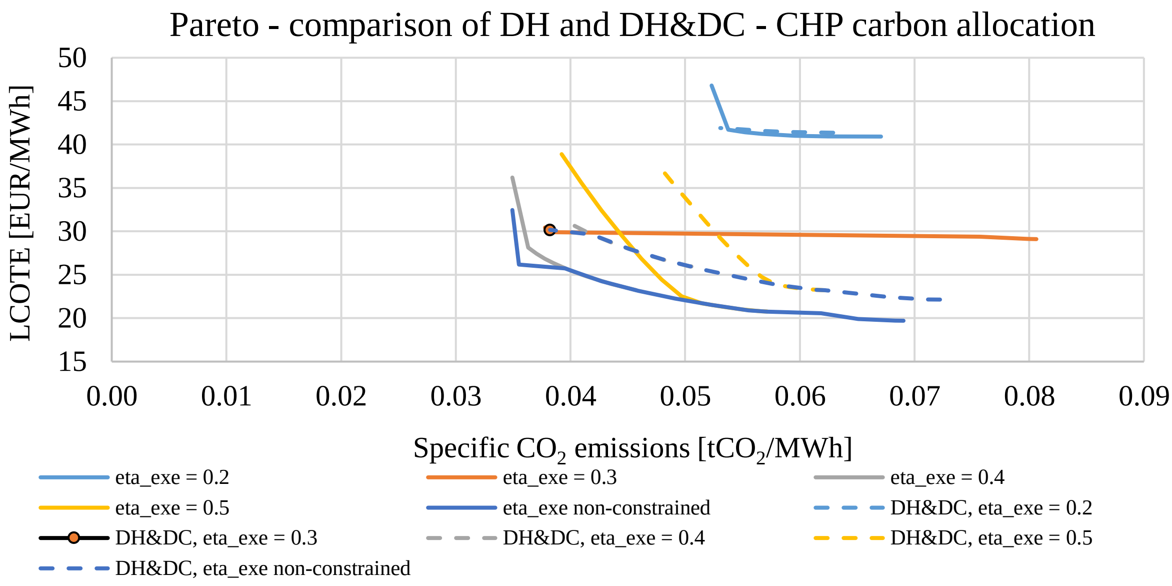

Figure 15 Pareto front comparison for systems with integrated district heating and cooling and a stand-alone district heating system – CHP cost and carbon allocation implemented

5. Conclusion

In this paper, multi objective optimization of district heating, coupled with cogeneration cost and carbon allocation, has been used to provide systematic comparison with individual natural gas-based solutions. The model considers minimization of total cost, carbon emissions and maximization of exergy efficiency. It can optimize supply capacities, including thermal storage, and hourly operation of the system for a whole year. The allocation method is based on translating power-loss, caused by the heat production, to CHP's operational cost and carbon emissions which are allocated to heat production. Obtained results show how increase of exergy efficiency of the system (followed by growth of CHP share) causes rise of system's levelized cost of heat (LCOH) and carbon factor if no allocation in CHP units is implemented. However, once cost and carbon emissions are allocated in CHP units, the results changed drastically. Cost allocation triggered 50% reduction of the system cost, when compared to the reference case, but carbon factor is increased by approximately 30%. Carbon allocation causes great reduction of carbon emissions with no noticeable increase of LCOH. Combined allocation caused simultaneous reduction of carbon factor and LCOH with exergy efficiency increase. These results have also been compared with individual heating based on natural gas. To declare district heating solution superior to the individual heating, it must have lower carbon factor and LCOH. With no implemented heat allocation methods, no district heating solutions are better than individual for low households' natural gas prices. With implemented cost allocation part of the Pareto solutions are superior to individual natural gas heating, however the solutions with the highest exergy efficiency are not. Implementation of carbon allocation positions all district heating solutions in the region with lower carbon factor, however all solutions have higher LCOH when compared to individual heating which utilizes cheap natural gas. Finally, combined cost and carbon allocation makes all district heating solutions, which include CHP, superior to individual systems. In addition to this, analysis of district cooling integration has been carried out. Obtained results show how for small increase of specific cost, cooling energy production could be included in a system.

Appendix

A1 Input data distributions

In this Section, hourly input data are shown. Figure A1 shows meteorological data for a case study – outside temperature and global solar radiation. District heating supply temperature regime is shown in Figure A2. It is assumed that it is in direct correlation with outside temperature. Maximum supply temperature is around 115°C, while minimum supply temperature is 80°C to supply thermal energy needed for domestic hot water production. District heating load is shown in Figure A3. Peak load of the system is around 450 MW. Furthermore, Figure A4 shows hourly power market prices which are used to calculate operational cost of power-to-heat and cogeneration technologies.

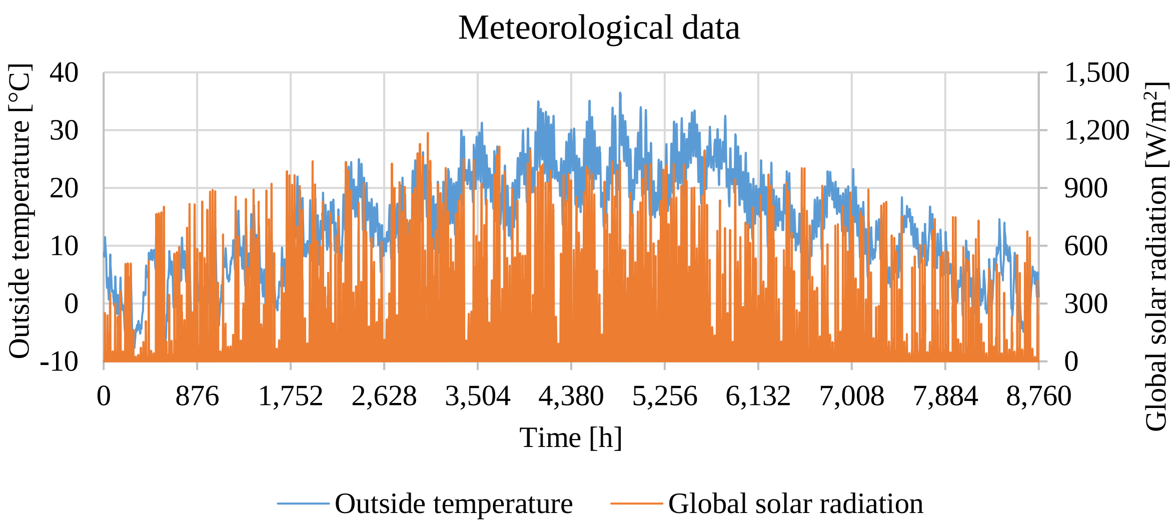

Figure A1 Meteorological data – outside temperature and global solar radiation

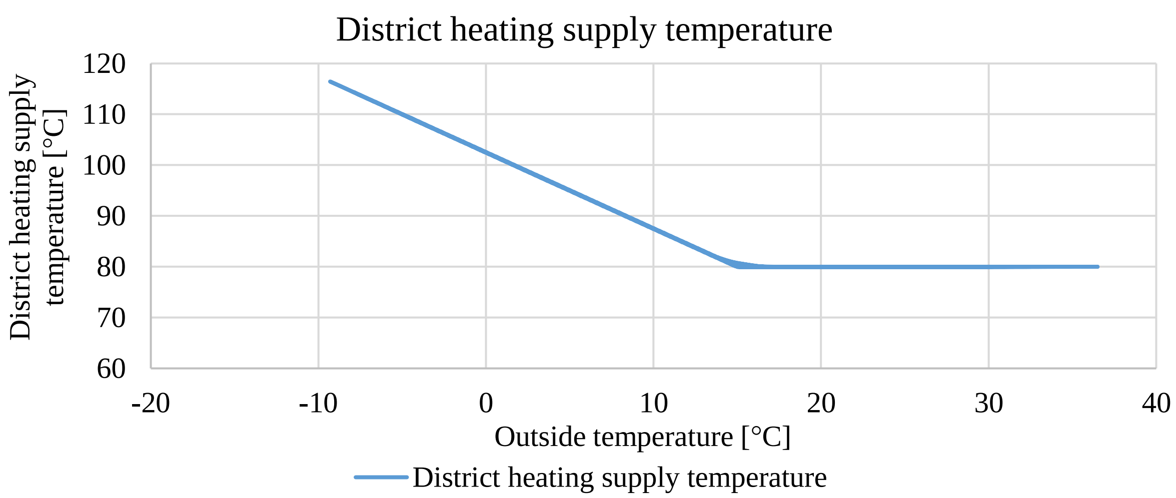

Figure A2 District heating supply network temperature

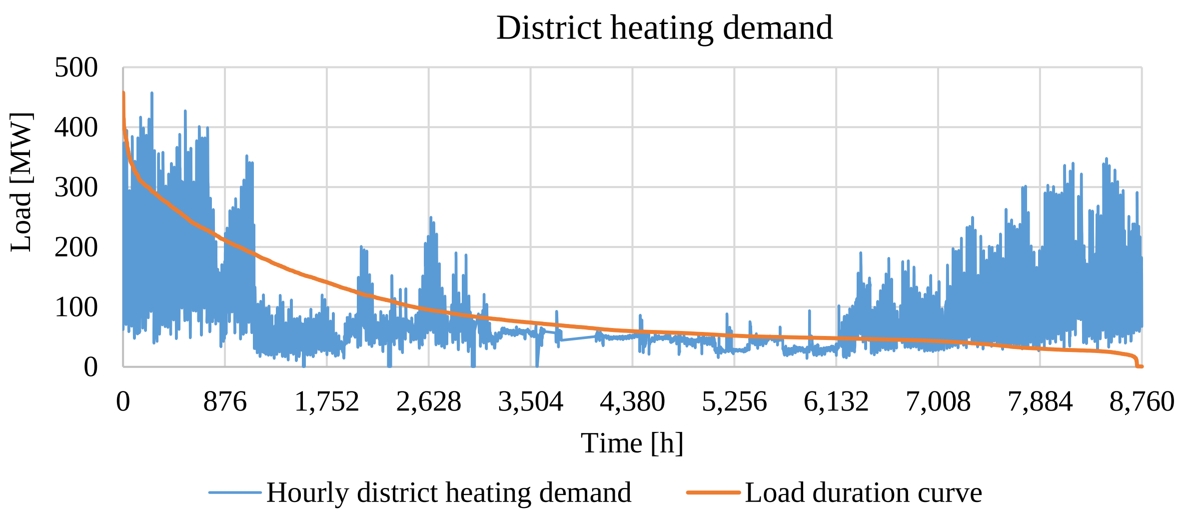

Figure A3 District heating demand – hourly demand and load duration curve

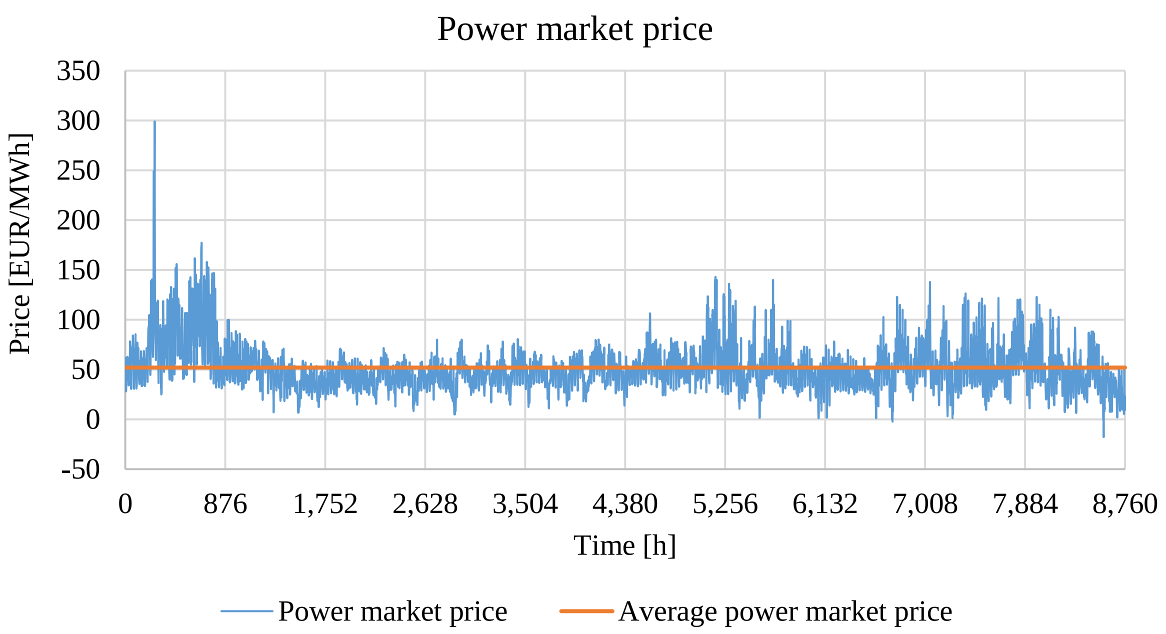

Figure A4 Hourly and average power market price

A2 District heating system overview

Figure A5 illustrates correlation between all technologies and related optimization variables. District heating supply units are supplying district heating demand and are connected to thermal storage units. It should be noticed that only solar thermal collectors are charging seasonal thermal storage. Power-to-heat and cogeneration units are also connected to the power market.

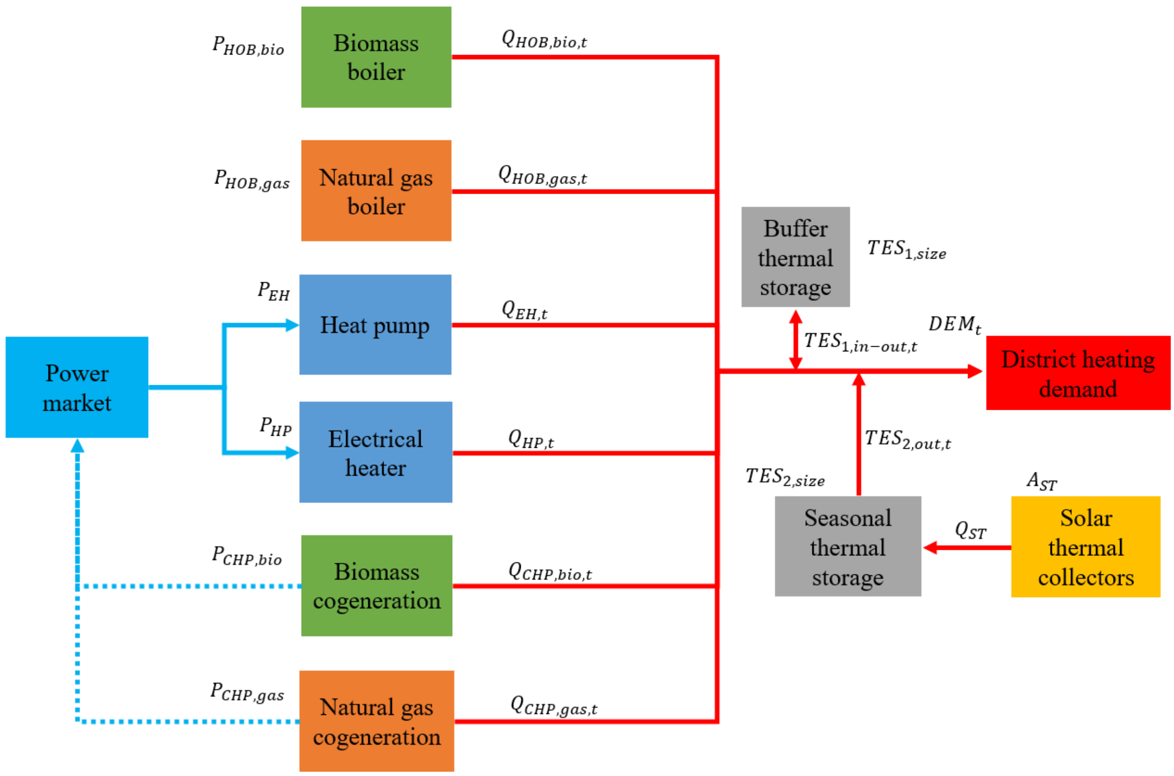

Figure A5 – District heating system overview

A3 Energy and exergy output RES share

This Section presents results of the analysis of energy and exergy output renewable energy sources share. In other words, the obtained results show how much of energy and exergy output is covered by renewable energy in district heating system. It should be mention that this analysis was carried out for different CHP allocation methods. Figure A6 shows the obtained results. In order to simplify visualization, only economic objective function (LCOH) is shown on x-axis, while exergy efficiency of a supply system is plotted as a parameter. Y-axis of diagram shows energy and exergy output RES share. For no CHP allocation, increase of LCOH rapidly increases RES share, as shown in Figure A6a. Furthermore, it should be noticed, that RES share falls down with exergy efficiency increase, due to usage of natural gas CHP. Similar results can be seen in Figure A6b where cost allocation in CHP units is implemented. Figure A6c shows the results with carbon allocation. It should be noticed that low exergy efficiency results have relatively high RES share, due to utilization of biomass. Finally, when both carbon and cost allocation is implemented, increase of exergy efficiency reduces RES share, as shown in Figure A6d.

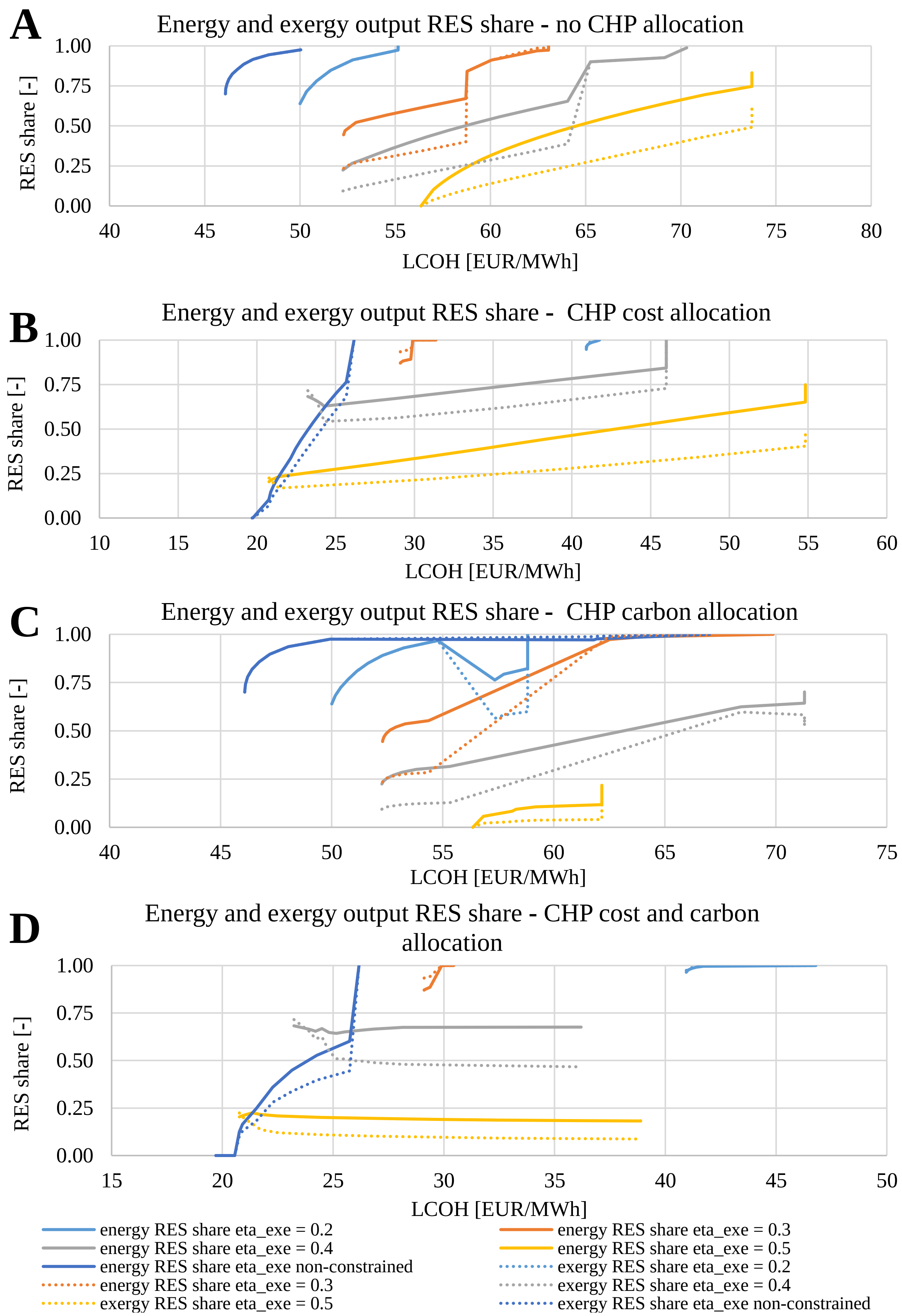

Figure A6 Energy and exergy output share of RES for different CHP allocation methods: A) no allocation, B) cost allocation, C) carbon allocation, D) cost and carbon allocation

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