Analysis of displacing natural gas boiler units in district heating systems by using multi-objective optimization and different taxing approaches

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Abstract:

District heating systems are proven to be effective way of increasing energy efficiency, reducing environmental impact and achieving higher exergy efficiency. In research papers, district heating multi-objective optimization usually takes into account minimization of the total discounted cost and environmental impact, while exergetic objective function is rarely introduced. Most of the times, economic and ecological objective functions are studied as a single objective optimization problem through internalization of the cost related to carbon dioxide emissions tax. This paper presents novel approach since additional tax, related to exergy destruction, has been introduced. The influence of these two taxing systems on a single and multi-objective optimization results of district heating system has been carried out. Two approaches have been proposed. In the first one, multi-objective optimization has been used where objective functions were defined as economic and ecological or exergetic. In the second approach, single-objective optimization has been used where cost function also includes both carbon and exergy destruction tax. It has been shown that inclusion of carbon tax causes convergence of Pareto fronts after specific exergy destruction has been reached. On the other hand, if all technologies are available, increase of exergy tax doesn't reduce carbon dioxide emissions. The most important outcome of this paper is analysis of the impact of exergy tax on natural gas consumption in heat-only boilers. Acquired results show that exergy, together with carbon tax, can effectively reduce natural gas consumption in heat-only boilers. If there are no back-pressure CHP technologies available, these taxing systems can completely push out its consumption. Finally, the analyses with carbon emissions in CHP units has also been carried out. Acquired results have shown that with increase of carbon tax, exergy efficiency of the system could be increased.

Keywords:

District heating, Exergy, Multi-objective optimization, Linear programming, Thermal storage, Internal cost, External cost

1. Introduction

District heating (DH) systems are proven to be more energy efficient and environmentally friendly than individual heating solutions [1]. Furthermore, they will have important role in future energy systems as described in [2], [3]. However, in order to reach their full potential, additional measures should be implemented in order to overcome social and legislation issues. One of the most important advantages is their capability of using low temperature renewable energy sources through heat pumps [4], waste heat [5] and simultaneous power and heat generation [6]. Due to these, DH systems potentially have higher exergy efficiency than individual heating solutions, which are often based on natural gas heat-only boilers. Lowering the thermal network supply temperature can significantly reduce exergy destruction of the system as shown by Li and Svendsen [7]. In [8], Rhein et al are even analysing topology for 5th generation of district heating systems for ambient range of 15-25°C. However, natural gas heat-only boilers are still frequently used even in district heating systems, especially when cogeneration units aren't economically feasible or are too big [9]. Terhan et al. provided detailed analysis of the natural gas fired boiler used in district heating system [10]. They have shown that exergy efficiency is more than 50% lower than energy efficiency. The main reason for this loss is exergy destruction in the combustion chamber due to the high adiabatic combustion temperatures. Natural gas is often seen as the fuel which could be utilized in the energy transition in order to phase-out coal consumption in cogeneration plants [11].

Exergy efficiency is rarely used in decision making process related to energy systems, but is often analysed in various technologies and systems. Exergy of the system could be studied through various related parameters, such as exergy efficiency, exergy destruction, exergy input of the system, etc. [12]. Bonati et al. have developed novel method for using exergy criterion for energy planning of 100% renewable energy systems [13]. They have used EnergyPLAN tool, which is based on energy system operation optimization, in combination with scenario analysis approach to obtain the final result. Siir Kilkis has developed a method based on rational exergy management model [14]. In the other paper, the method for near-zero exergy district has been developed [15]. In paper [16], authors have demonstrated how exergy efficiency based control strategy can be economically feasible and suitable for geothermal district heating systems. Obtained results show a short payback period of 3.8 years. Sciubba developed exergy-based ecological indicators and shown how exergy analysis of complex systems can be formulated in such a way to related irreversibility with unsustainability [17]. Birol and Şiir Kilkiş developed new exergy metrics for energy, environment and economy nexus used for acquiring optimum design model of nearly-zero exergy system [18]. The model has been developed for airport energy systems, while the case study was Schiphol.

Optimization of district heating systems has been carried in numerous research papers. The goal is often to minimize system's total cost [19],[20] or ecological impact in terms of carbon dioxide (CO_2) emissions [21]. In some cases, while minimizing overall costs, even pressure losses could be taken into account by studying different operational strategies [22]. Single objective optimization is the most often approach, usually handled by using linear or mixed integer linear programming [23] and genetic algorithms [24]. Opposite to single objective optimization, where final solution is single value, results of multi-objective optimization is a whole set of values lying on the so called Pareto front. In order to handle this problem, various techniques could be used, such as weighted sum method [23] or epsilon constraint method [25]. Exergy is also often included in the optimization problem as one of the objective functions, but is rarely used in the single objective optimization problems. Franco et al. [26], optimized exergy efficiency of the cogeneration plan which operates as the part of DH system. In paper [27], exergy efficiency of the organic Rankine cycle has been part of the optimization problem. M. Di Somma et al. in papers [28] and [29] have taken into account exergy efficiency during optimization of district energy system which takes into account electricity and heat production. It is important to mention that they didn't take into account carbon dioxide emissions, neither through carbon tax system or objective function.

Carbon taxing has already been successfully implemented in the legislation of the EU, under the name of Emissions Trading System (ETS) set up in 2005 [30]. It is based on the "cap and trade" principle, where the "cap" is defined as the total amount of greenhouse gasses which could emitted by installations covered by the system. However, the cap is reduced over time, which causes emissions reduction. Verbruggen et al. provided thorough explanation of the EU ETS system [31]. In the 2018, the ETS prices have started growing rapidly, from 8.5 EU/tonne, reaching more than 25 EUR/tonne in 2019 [32]. It is expected to go as high as 60 EUR/tonne by 2030. Soliman and Nasir provided analysis of EU emission trading system and made correlation between different energy prices [33] while Dutta has carried out modelling and forecasting of the volatility of the carbon emission market [34].

Exergy related taxing, or exergy cost approach, and exergoeconomic analysis aren't new concepts. It has already been proposed in various papers. Chaiyat et al. have developed novel levelized energy and exergy costing per life cycle assessment [35]. The method was applied to the system of combined heating and power generation in Thailand. Usón et al. carried out exergy assessment of a renewable based and hybrid trigeneration scheme for domestic water and energy supply [36]. They have used TRNSYS software combination together with exergy cost method in order to provide detailed analysis of exergy efficiency. Franco and Versace [37] proposed composite indicators' analysis which also included exergy loss. In [38] specific exergy cost (SPECO) method has been used in order to provide exergoeconomic analysis of a residential district heating system in Japan. Arat and Arslan have carried out exergoeceonomic analysis of the district heating system which utilizes geothermal heat pump [39]. They have simulated more than 4,500 design in order to find the optimal one. On the other hand, Meesenburg et al. have performed dynamic exergoeconomic analysis of the heat pump which could be used for ancillary services in the integrated energy systems [40]. Yang et al have evaluated domestic hot water supply through low temperature district heating systems by using exergetic and exonomic analysis [41]. Finally, exergoeconomic optimization could also be used in district cooling networks as shown in paper [42]. In paper [43], exergy lost is translated as the additional cost and added to the economic objective function. Although optimization model has been used, it doesn't take into account carbon dioxide emissions neither as the internalized cost or objective function. Exergy costing was also used in [44] in order to analyse energy savings in systems which utilize combined heating and cooling.

According to the author's knowledge and carried out literature review, no research papers have proposed using exergy tax in combination with multi-objective optimization in order to analyse shift of a Pareto front and phase-out of natural gas in heat-only boiler units. Furthermore, exergy taxing system used in this paper is novel since it only penalizes destroyed exergy which wasn't potentially utilized in a cogeneration unit.

The method and the model developed in this paper is based on the two previous papers published by the authors. In paper [45] multi-objective optimization model has been developed which takes into account total cost and carbon dioxide emissions. The model was upgraded in [46] and exergy destruction as the objective function has been added. The model is capable of optimizing supply capacities and thermal storage size, including hourly operation, of the district heating system. Since seasonality of the thermal demand is crucial issue, the time horizon of the optimization model is a whole year.

In this paper, novel exergy taxing system was introduced. It is based on penalizing exergy destruction in heat-only boilers which could be potentially used in cogeneration units. Together with existing, but slightly modified, carbon taxing system, analysis of impact on multi and single objective optimization of DH system has been carried out. Finally, this paper provides scientific contributions by answering following questions:

- How do exergy and carbon taxing systems shift solutions of the multi-objective optimization of a district heating system?
- How do these taxing systems influence exergy efficiency and carbon dioxide emissions of the least-cost solution of the district heating supply system?
- What is the impact of mentioned taxing systems on reduction of natural gas consumption in heat-only boiler of an optimal DH supply system?

The paper is divided in several sections. In Section 2 the method is presented. District heating model, together with multi-objective optimization approach, based on previous papers, and exergy destruction tax has been shown in detail. Section 3 displays case study which has been used as the numerical test for this paper. Input data, including hourly distributions have been briefly discussed. Section 4 shows and discuss obtained results in detail. Finally, Section 5 concludes the paper and outlines the main outcomes and findings of this research.

2. Method

The method described in this section is based on the previously published papers [45] and [46]. In the paper [45], district heating model has been established and multi-objective optimization problem has been explained in detail. Two objective functions have been defined: minimization of system's total discounted cost and minimization of system's total carbon dioxide emissions. In the paper [46], minimization of exergy destruction was introduced as the third objective function, which enables creation of 3D Pareto front. The novelty of this paper is introduction of the carbon and exergy destruction tax and analysis of their influence on the results of multi-objective and single-objective optimization problem.

2.1. District heating model

District heating system was modelled as a linear programming (LP) problem and contains various supply technologies: heat-only boiler, cogeneration, electrical heater, heat pump, solar thermal collectors and thermal storages, which include both buffer and seasonal. Two fuels could be used: fossil fuel, i.e. natural gas, and biomass, which is representative of a carbon neutral fuel. Power-to-heat technologies are using electrical energy bought at the electricity market. Cogeneration units are selling electricity on the same market but are also receiving incentives as a feed-in premium tariff. The model is capable of optimizing supply capacities, including thermal storage size, and operation of supply units on hourly level for a whole year. In order to provide more realistic operation, ramp-up and ramp-down limitations have been added. Optimization time step is equal to one hour, while the time horizon is equal to a whole year, i.e. 8760 hours. It should be mentioned how the choice of the time-step has influence on the results due to the several reasons. First of all, heating demand has recognizable hourly profile with two noticeable peak demand during the day. Increase of the time step would cause reduction of the heat demand amplitude and neglect necessity for fast ramping and usage of thermal storage. Secondly, power-to-heat and cogeneration technologies are participating on the power-market which is also on the hourly level. Nevertheless, it should be mentioned that time-step increase from one-hour to two-hour, wouldn't have pronounced effect as e.g. increase to 24-hour time step which would totally mitigate hourly variation of the heating demand on the daily level, thus influencing the optimized results. However, such analysis unfortunately hasn't been carried out in this paper.

Prior to the optimization, the model calculates efficiency of the heat pump and solar thermal collectors, including district heating network supply temperature, which are also hourly distributions. The model was written in the Julia programming language [47] by using JuMP package for mathematical optimization [48]. The model's optimization variables and constraints are explained below.

Equation (1) presents the most important constraint of the model – thermal energy demand DEM_t has to be covered in every time step t by numerous supply sources $Q_{i,t}$ or thermal storage discharge $TES_{i,t}$. Where i denotes a technology type which is used. $Q_{i,t}$ and $TES_{i,t}$ present optimal operation of the system, i.e. optimization variables.

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

The supply technology can operate inside defined limits, as shown in equation (2), where P_i is supply capacity of technology i. In this case it is also maximum possible power output. It is important to mention that supply capacity is also optimization variable.

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

In order to describe operation of the system in more detailed manner, ramping limits are introduced, as shown in equation (3), where $r_{up-down,i}$ represents ramping limit of technology i.

$$-r_{up-down,i} \cdot P_i \leq Q_{i,t} - Q_{i,t-1} \leq r_{up-down,i} \cdot P_i \tag{3}$$

Operation of thermal storage is described with equations (4) and (5), where SOC_t represents state-of-charge of thermal storage in a time step t and TES_{size} is thermal storage size. Together with thermal storage operation $TES_{in-out,t}$, TES_{size} is optimization variable which defines optimal thermal storage size (in MWh). In order to assure that state-of-charge is the same at the end and at the beginning of the time horizon, equation (4) is used, where $SOC_{start-end}$ represents the predefined state-of charge at the end and at the beginning of the time horizon. Equation (5) represents energy balance of the thermal storage, where TES_{loss} represents thermal losses of the thermal storage.

$$SOC_{t=1} = SOC_{t=8760} = SOC_{start-end} \cdot TES_{size} \tag{4}$$

$$SOC_t = SOC_{t-1} + TES_{in-out,t} - SOC_t \cdot TES_{loss} \tag{5}$$

Operation of solar thermal collectors, $Q_{ST,t}$ is described with equation (6), where A_{ST} is solar thermal collectors installed area and $P_{solar,specific,t}$ is specific solar thermal production calculated for which hour, explained below. It is important to notice that solar thermal supply operation is constrained, while A_{ST} is only optimization variable associated with solar thermal collectors.

$$Q_{ST,t} = A_{ST} \cdot P_{solar,specific,t} \tag{6}$$

Specific solar thermal production is described with equation (7), where $\eta_{c,t}$ is solar thermal collector thermal efficiency in a time step t, and G_t is global solar irradiation in a time step t. The last is acquired for optimal slope an azimuth angle by using publicly available databases [49].

$$P_{solar,specific,t} = \eta_{c,t} \cdot G_t \tag{7}$$

Solar thermal collector efficiency is calculated by using equation (8) [50], where η_0, a_1, a_2 and T_m, specified for each solar thermal collector by the manufacturer [51] and $T_{ref,t}$ is hourly outside air temperature for the given location obtained by using available databases [49], [52], [53].

$$\eta_{c,t} = \eta_0 - a_1 \frac{\left(T_m - T_{ref,t}\right)}{G_t} - a_2 \frac{\left(T_m - T_{ref,t}\right)^2}{G_t} \tag{8}$$

Heat pump is supply technology which has variable efficiency $\eta_{HP,t}$. It could be calculated by using equation (9), where $f_{Lorentz}$ is factor obtained from the literature [54] and $T_{DH,t}$ is hourly supply temperature of the district heating network obtained by using data from the literature [1].

$$\eta_{HP,t} = f_{Lorentz} \cdot \left(\frac{T_{DH,t}}{T_{DH,t} - T_{ref,t}}\right) \tag{9}$$

2.2. Objective functions

Multi-objective optimization model used in this paper has two objective functions: minimization of total cost and minimization of total carbon dioxide emissions or minimization of exergy destruction. Optimization variables are supply capacities and thermal storage size, including hourly operation of supply units and storage charge, i.e. discharge. Since all objective functions, including constraints, are linear and optimization variables are continuous, the problem is described with linear programming. In this paper, two approaches have been used. In the first approach multi-objective optimization has been used, while in the second approach single-objective, i.e. cost, optimization is proposed.

Equations (10) and (11) describe the first approach. Equation (10) presents multi-objective optimization problem in which economical (f_{econ}) and ecological (f_{ecol}) objective functions have to be minimized. Equation (11) also presents multi-objective optimization problem, but instead of minimizing environmental objective function, exergetic objective function is introduced. Equation (12) presents the second approach, where single-objective has been used. Since only economical objective function has to be minimized, this also represent cost optimization problem. All objective functions are explained in more detailed below.

$$\min(f_{econ}, f_{ecol}) \tag{10}$$

$$\min(f_{econ}, f_{exe}) \tag{11}$$

$$\min(f_{econ}) \tag{12}$$

Equation (13) presents economical objective function. It represents total cost of the district heating system. $C_{investment,i}$ is discounted investment cost of technology i, $C_{fuel,i,t}$ are fuel costs of technology i in a time step t, $C_{O\&M,i,t}$ are operation and maintenance cost of technology i in a time step t and $Income_{i,t}$ presents income due to the electricity sold from CHP units. The last two terms, Ex_{tax} and Eco_{tax} present exergetic and carbon tax, respectively. The exergetic tax Ex_{tax} is taken into account during multi-objective optimization problem of minimizing economical and environmental objective function. On the other hand, carbon tax Eco_{tax} is taken into account during multi-objective optimization of minimizing environmental and exergetic objective functions. Calculation of these taxes is explained in more detail in the Section 2.3.

$$f_{econ} = \sum_i C_{investment,i} + \sum_{t=1}^{t=8760} \sum_i \left(C_{fuel,i,t} + C_{O\&M,i,t} - Income_{i,t}\right) + Ex_{tax} + Eco_{tax} \tag{13}$$

Ecological objective function could be calculated by using equation (14). It represents sum of the total carbon dioxide emissions of the district heating system, where $e_{CO_2,i}$ is specific carbon emission factor of technology i, while η_i is efficiency of technology i.

$$f_{ecol} = \sum_{t=1}^{t=8760} \sum_i (e_{CO_2,i} \cdot Q_{i,t} / \eta_i) \tag{14}$$

Finally, exergetic objective function is defined as total exergy destruction of the district heating system. It could be calculated by using equation (15). Exergy destruction is difference between exergy input $Ex_{in,i,t}$ and exergy output $Ex_{out,i,t}$.

$$f_{exe} = \sum_{t=1}^{t=8760} \sum_i (Ex_{in,i,t} - Ex_{out,i,t}) \tag{15}$$

Exergy input is calculated by using exergy factor of the fuel, $e_{Exe,i}$, as shown in equation (16). Exergy output could be calculated by using Carnot factor, which is the term in the brackets shown in the equation (17).

$$Ex_{in,i,t} = \frac{Q_{i,t}}{\eta_i} \cdot e_{Exe,i} \tag{16}$$

$$Ex_{out,i,t} = Q_{i,t} \cdot \left(1 - \frac{T_{ref_t}}{T_{DHN_t}}\right) \tag{17}$$

Although, exergy efficiency isn't objective function, it could be calculated by using equation (18). It represents the ratio of exergy output and exergy input of the system

$$\eta_{exe} = \frac{\sum_{t=1}^{t=8760} \sum_i Ex_{out,i,t}}{\sum_{t=1}^{t=8760} \sum_i Ex_{in,i,t}} \tag{18}$$

2.3. Exergy destruction and carbon dioxide emission tax

As already mentioned, two approaches have been used in this paper. In the first one, exergy destruction or carbon dioxide emissions are treated as objective functions, together with the economical objective function. In the second approach, exergy destruction and carbon dioxide emissions are translated into taxes and added to the total cost, i.e. their costs have been internalized.

Carbon dioxide emissions tax system already exists and is part of the European Union Emission Trade System (EU ETS) [31], thus doesn't present novelty itself. The only difference in this paper is that units lower than 20 MW of thermal power are also part of the taxing system. Furthermore, it is important to remember that power-to-heat technologies are not part of the carbon taxing system. Carbon tax Eco_{tax} could be calculated by using equation (19), where C_{carbon} is carbon tax value expressed in currency unit per tonne of emitted CO_2.

$$Eco_{tax} = \sum_{t=1}^{t=8760} \sum_{i} (e_{CO_2,i} \cdot Q_{i,t} / \eta_i) \cdot C_{carbon} \tag{19}$$

Proposed exergy destruction tax could be calculated by using the equation (20).

$$Ex_{tax} = \sum_{i} \sum_{t=1}^{t=8760} Ex_{in,t,i} \cdot \left(\overline{\varepsilon_{DR,HOB,\iota}} - \overline{\varepsilon_{DR,\iota,CHP}}\right) \cdot C_{exergy} \tag{20}$$

Where Ex_{tax} is total exergy destruction tax of the system, expressed in a currency, $Ex_{in,t,i}$ is exergy input of technology which uses fuel i in a time step t, $\varepsilon_{DR,HOB,i}$ is a reference exergy destruction ratio for technology which uses fuel i in a time step t, while $\overline{\varepsilon_{DR,\iota,CHP}}$ is a reference exergy destruction ratio for fuel i which would be used in cogeneration unit, and finally C_{exergy} is specific exergy destruction cost expressed in unit of currency per unit of exergy destroyed. Exergy destruction ratio is defined as the ratio of exergy destruction and exergy input. It is important to notice that only natural gas and biomass heat-only boilers are included in the exergy taxing system, while power-to-heat technologies are not part of the exergy taxing system. Furthermore, it should be noticed only one part of the exergy destruction is being taxed, i.e. the difference between exergy destruction in a heat-only boiler and a cogeneration unit. In other words, if the model chooses to use a CHP technology instead of a heat-only boiler, the tax could be avoided. $\overline{\varepsilon_{DR,HOB,\iota}}$ and $\overline{\varepsilon_{DR,\iota,CHP}}$ are calculated prior to the optimization process for reference conditions, in order to secure linearity of the optimization model.

2.3. Multi-objective optimization

It is important to mention that the goal of this research isn't to obtain a single solution of the multi-objective optimization problem, but to acquire a whole trend of solutions, i.e. Pareto front. In order to deal with multi-objective optimization problem, epsilon constraint method has been used. The method is based on translating multi-objective optimization problem into single-objective optimization with additional set of constraints put on other objective functions [55]. These constraints are also called epsilon constraints. In order to acquire Pareto front, several optimizations should be run with different epsilon constraints, thus marching from one end of the Pareto front to the other. However, in order to successfully set epsilon constraint, the boundaries of the Pareto front should be acquired. This could be done by running single objective optimization, firstly with the first objective function, then with the other.

In this case, epsilon constraints were put on exergetic or ecological objective function while minimizing economical objective function, as shown in equations (19) and (20). It is important to notice that the level of detail of the constructed Pareto front depends on the number of optimization runs.

$$\min\,(f_{econ}) \ \text{ for } f_{ecol} = \varepsilon_{ecol} \tag{21}$$

$$\min\,(f_{econ}) \ \text{ for } f_{exe} = \varepsilon_{exe} \tag{22}$$

3. Case study

In this section input data and scenarios are presented. Input data includes various information needed in order to run the optimization model such as: meteorological and heat demand data, parameters related to district heating thermal network and finally, technology information regarding investment and O&M costs, efficiency, ramping limits, carbon emission factors, etc. It is important to mention that data are divided in: hourly data (8760 values), such as heating demand, and single value data, e.g. carbon emission or exergy factors. Furthermore, this section presents scenarios developed in detail. Three main scenarios have been proposed. Two scenarios are based on multi-objective optimization, while one scenario is single-objective optimization. Finally, for each mentioned scenarios, the authors have defined additional subscenarios in order to provide better analysis of the different taxing systems.

3.1. Input data

In order to validate the approach, numerical test has been carried out where City of Velika Gorica has been used as the case study. It is located in Zagreb County and has 14 smaller district heating systems usually connected to several buildings. The idea main idea of this paper is to connect few smaller district heating networks and replace existing supply units with the new ones. Definition of new supply capacities is carried out by using approach presented in the Section 2. Figure 1 shows all smaller district heating systems in Velika Gorica.

Figure 1 Group of smaller district heating systems

Heat demand data could be acquired by using publicly available data, such as national energy reports, Sustainable Energy Action Plans (SEAPs) or district heating service operators' data. For the purpose of this study, National Heating and Cooling Plan has been used in order to acquire heat demand of Velika Gorica district heating system [56], [57]. Heat demand is constituted of space heating and domestic hot water (DHW) demand. Since these reports usually do not make a difference between space and DHW demand, it is important to segregate it by using other public available data such as [58], which is unfortunately on the national level. For this reason it has been assumed that DHW share for the district heating system of Velika Gorica is equal to 15%. Hourly distribution of space heating demand has been created by using degree-hour method. The method is based on distributing total yearly heating demand on hourly level by using outside and inside-of-the-building temperature difference as the key input. For DHW demand, already known distribution has been used [54]. Figure 2 shows hourly distribution for a winter and a summer week. Seasonal effect related to thermal load is evident. During winter months, thermal load consists of space heating and domestic hot water demand. During summer period, only domestic hot water demand has to be covered by district heating system. Total district heating demand is equal to 32 GWh, with a peak demand equal to 19.7 MW.

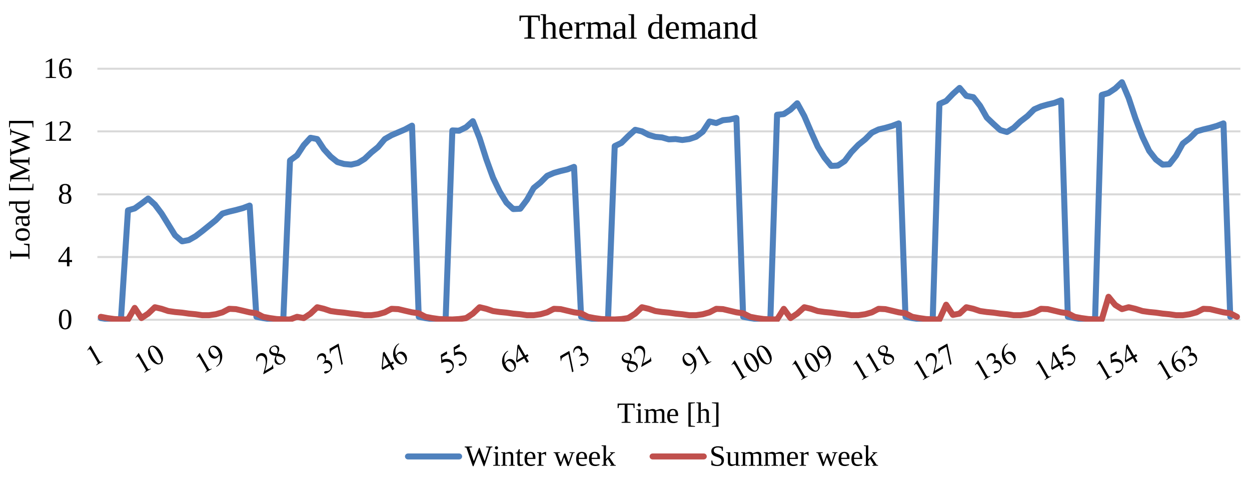


Figure 2 Thermal load for winter and summer week

Due to a relatively low specific space heating demand and a short thermal network, it has been assumed that a new district heating system operates as the third generation district system, i.e. with supply temperatures lower than 100°C [1], [57]. It is important to mention that DH supply temperature is mostly related to the outside air temperature. This correlation could be acquired by using available measurement data [1]. The exact information on district heating supply temperature could be obtained by contacting district heating system provider, but unfortunately, authors haven't received this information. Hourly distributions of meteorological data, i.e. outside temperature and global solar irradiation, which are needed inputs, were obtained by using Meteonorm [52]. Hourly power market prices are obtained from the Croatian power exchange called CROPEX [59]. Finally, all technology related data has been acquired by using publicly available databases [60] and [51]. Table 1 shows technology input data used for optimization.

In order to successfully calculate exergy destruction and exergy tax, exergy related data is needed, such as exergy factor and exergy destruction ratio. Exergy factor is defined as the ratio of exergy and energy of the fuel [28], [61]. In some cases, it can be higher than 1. As explained in the Section 2, reference exergy destruction ratio is calculated prior to the optimization in order to secure linearity of the model. Table 2 shows exergy related parameters for natural gas and biomass fuels, including exergy destruction ratio for heat-only boiler and cogeneration technologies.

Table 1 Technology data

Technology	**Investment cost [€/MW] / [€/m^2] /[€/MWh]**	**Fuel cost [€/MWh]**	**Variable cost [€/MWh]**	**Emission factor [TCO_2/MWh]**	**Efficiency/ storage loss [-]**	**Ramp-up/down [-]**	**Technical lifetime [years]**	**Power-to-heat ratio [-]**
Natural gas boiler	100,000	20	3	0.22	0.9	0.7	35	-
Biomass boiler	800,000	15	5.4	0.04	0.8	0.3	25	-
Electrical heater	107,500	Electricity market	0.5	0.234	0.98	0.95	20	-
Heat pump	680,000	Electricity market	0.5	0.234	Hourly distribution	0.95	20	-
Cogeneration natural gas	1,700,000	20	3.9	0.22	0.5 (thermal)	0.3	25	0.82
Cogeneration biomass	3,000,000	15	5	0.04	0.6 (thermal)	0.3	20	0.55

Solar thermal	300 €/m^2	0	0.5	0	Hourly distribution	-	25	-
Thermal storage, buffer	3,000 €/MWh	0	0	0	1% (loss)	-	25	-
Seasonal thermal storage	500 €/MWh	0	0	0	0.1% (loss)	-	25	-

Table 2 Exergy related input data for biomass and natural gas fuels

Technology/fuel	**Exergy factor**	**Exergy destruction ratio of heat-only boiler / CHP**
Biomass	1.2	0.87 / 0.63
Natural gas	1.04	0.83 / 0.51

3.2. Scenario analyses

For the purpose of this study, several scenarios have been developed. Generally, they could be split in two groups. The first group is based on multi-objective optimization approach, i.e. Pareto solution is obtained, where one of the objective functions is always economical one, i.e. total discounted cost of the system. Other objective function is minimization of carbon dioxide emissions or minimization of exergy destruction. The second group is based on single-objective optimization, where all objective functions are translated to the total system cost by using taxing approach explained in the section Method. The details of each scenario are shown in Table 3. As previously explained, every scenario consists of several subscenarios. Scenario 1 is multi-objective optimization problem where economical and exergetic objective function is minimized, while carbon tax is implemented. In Scenario 1a, all technologies are available, in Scenario 1b biomass CHP couldn’t be used, while in Scenario 1c solar thermal isn’t available. Scenario 2 is also based on multi-objective optimization, but this time economic and ecological objective functions are minimized, while exergy destruction is internalized by using exergy tax. In Scenario 2a all technologies are available, while in Scenario 2b no CHP technologies are available. Finally, Scenario 3 is single-objective optimization where total cost of the system is minimized. In this scenario, both carbon and exergy taxes are used. Similarly to Scenario 2, Scenario 3a can utilize all technologies, while Scenario 3b can’t use CHP technologies. In the Scenario 1 and Scenario 2, there is clear distinction between three objective functions. Each is different than the other (unique), since it takes into account different parameters of the district heating system. This is also visible from the acquired result, i.e. Pareto front – minimum can’t be acquired for both at the same time. However, in the Scenario 3, ecological and exergetic objective functions are translated into the cost, by using taxing systems. In this scenario the model searches for minimum cost, while exergy efficiency and carbon emissions are only calculated parameters.

Table 3 Scenario description

Scenario name	Tax		Objective function(s)			Technology availability
	Carbon	Exergy destruction	Economical	Ecological	Exergetic	
Scenario 1a	✓		✓		✓	All technologies available
Scenario 1b	✓		✓		✓	No biomass CHP
Scenario 1c	✓		✓		✓	No solar thermal
Scenario 2a		✓	✓	✓		All technologies available
Scenario 2b		✓	✓	✓		No CHP technologies available
Scenario 3a	✓	✓	✓			All technologies available
Scenario 3b	✓	✓	✓			No CHP technologies available

4. Results and discussion

In this section, scenario results are presented in detail. Section 4.1. shows Scenario 1 results which include Pareto shift due to the carbon tax increase, while Section 4.2. displays Scenario 2 results which consists of Pareto shift due to the exergy tax increase. Finally, Section 4.3. shows results of the single objective optimization when both carbon and exergy tax are introduced.

Results for Scenario 1 and Scenario are shown in the form of Pareto fronts since they present multi-objective optimization problem. It is important to notice that each point on the Pareto front contains various information such as: optimal capacities, hourly operation stem and exergy efficiency of the system. However, in this paper, the emphasis is put on the analysis of the objective functions: total discounted cost, carbon dioxide emissions and exergy destruction of the system. Scenario 3 presents single-objective optimization problem, thus Pareto front couldn't be constructed. The results present chosen system characteristics (exergy efficiency and CO_2 emissions) for the least-cost solution acquired by optimization.

The optimization was run for on Intel i7 laptop with 8 GB of RAM. Every optimization run lasted for around 25 minutes. Due to this, Pareto fronts are constructed with limited number of points.

4.1. Results of Scenario 1

Scenario 1 presents multi-objective optimization scenario in which two objective functions have been studied: total discounted cost and exergy destruction of the system, while carbon dioxide emissions are translated to internal cost by using carbon taxing system which was added to the first objective function. Five Pareto fronts were obtained, each for different carbon tax price. The tax was increased from 0 EUR/tonne up to the 80 EUR/tonne with the step equal to 20 EUR/tonne. In order to provide more detailed analysis, three subscenarios have been modelled. In Scenario 1a, all technologies are available, in Scenario 1b biomass CHP isn't available, while in Scenario 1c solar thermal couldn't be used.

Figure 3 shows Pareto shift for Scenario 1, i.e. every Pareto front has been constructed for different value of a carbon tax. Two objective functions are taken into account: minimization of exergy destruction and minimization of the total system cost. It can be noticed that, for every subscenario, Pareto fronts are converging to a single front. For the first subscenario, Figure 3a, Pareto fronts are converging to equal solution, at around 14,000 MWh. The lowest possible exergy destruction is equal to around 11,000 MWh. In the region of the Pareto front where cost objective function is dominant, cogeneration technology is used. Once approaching the region with the lowest exergy destruction, solar thermal is dominantly utilised, thus achieving extremely high cost of the system. For Scenario 1a, at the carbon tax equal to 40 EUR/tonne, biomass CHP is becoming part of the least-cost solution and is present through the most of Pareto front. This is the reason why these Pareto fronts have higher exergy destruction of the least cost solutions: biomass has higher exergy content per unit of energy than natural gas.

This is the main reason why it was decided that biomass CHP isn't available in Scenario 2b, shown in Figure 1b. Again, all Pareto front are converging to a single point, at around 14,000 MWh, just as in Scenario 1a. Since solar thermal is still available in this subscenario, the lowest exergy destruction is similar to subscenario 1a, around 11,000 MWh. For carbon tax, equal to 80 EUR/tonne, biomass boiler is part of the least-cost solution. This is the reason why this Pareto front has higher exergy destruction of the least-cost solution than other Pareto fronts. Since biomass CHP couldn't' be utilized in this subscenario, heat pump is starting to be part of the optimal solution much sooner, at around 1,400,000 EUR of the total discounted cost.

Finally, Scenario 1c, shown in Figure 3c, acquires similar results as other subscenarios but, since there is no solar thermal available, minimum exergy destruction acquired is relatively higher, around 14,000 MWh. Furthermore, all Pareto fronts are converging faster than in other two scenarios. The most expensive solution has lower cost than other two scenarios, due to the unavailability of solar thermal collectors. As in Scenario 1a, biomass CHP is used part of the least-cost solution for carbon tax higher than 20 EUR/tonne, which is the reason why these three Pareto front have higher exergy destruction in the region where cost function is dominant.

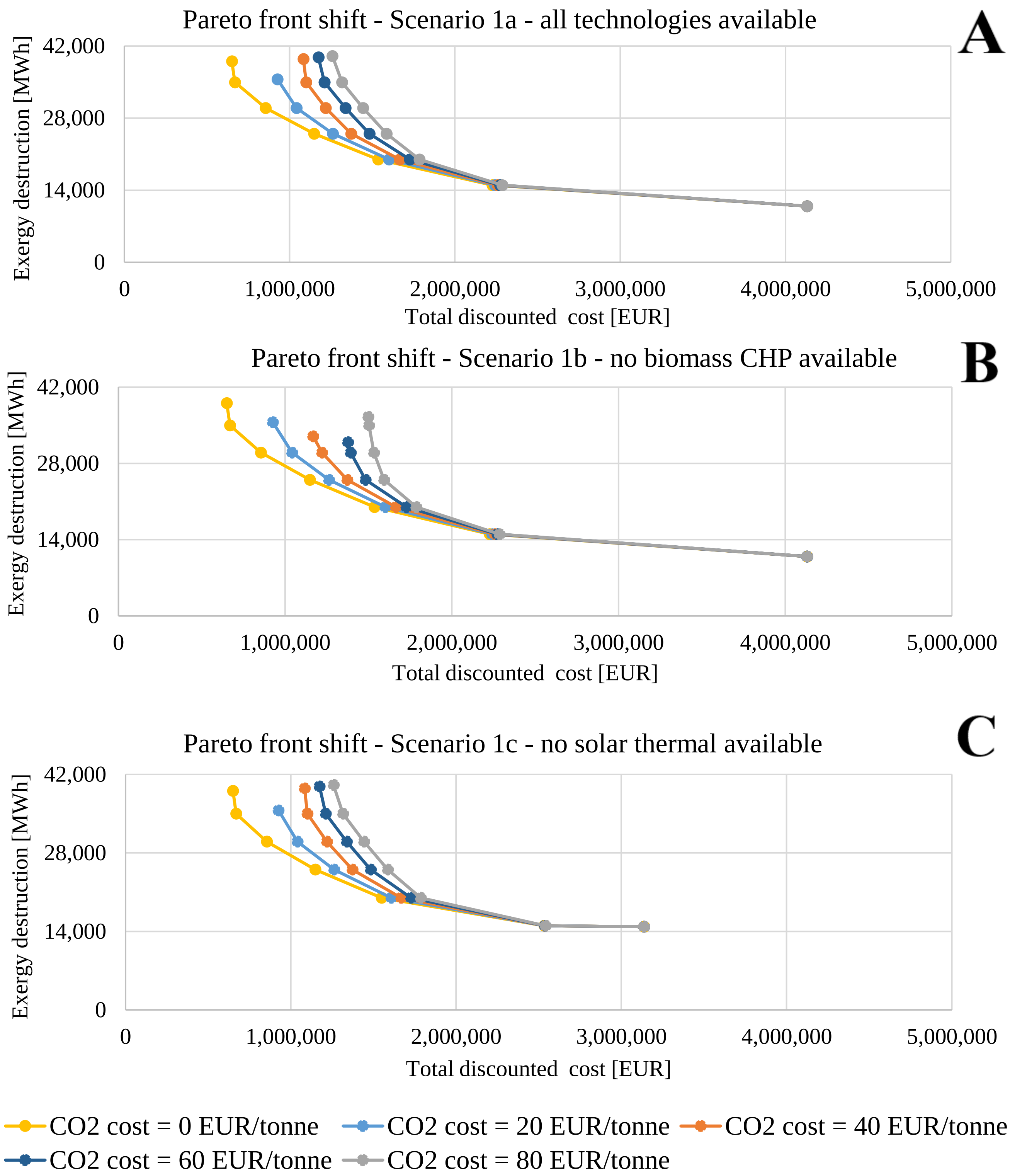


Figure 3 Pareto front shift due to the CO_2 tax increase: a) Scenario 1a - all technologies available, b) Scenario 1b - no biomass CHP available, c) Scenario 1c - no solar thermal available

4.2. Results of Scenario 2

Scenario 2 is also multi-objective optimization problem in which total discounted cost and carbon dioxide emissions are defined as objective functions. In this scenario exergy destruction is translated into the additional expense, by using previously explained exergy taxing system, and added to the cost objective function. Two subscenarios are developed. In Scenario 2a, all technologies are available, while in Scenario 2b no CHP technologies are available. For each of them, five Pareto fronts have been constructed by using epsilon constraint method. Figure 4 shows Pareto fronts for different exergy tax values, starting from zero and up to 400 EUR/MWh.

Figure 4a, shows results acquired for Scenario 2a, where all technologies are available. The least-cost solution obtains value of economical objective function around 700,000 EUR, while the CO_2 emissions reach up to 16,500 tonnes. The lowest possible CO_2 emissions is around 1,100 tonnes, obtained for every exergy tax value. It can be noticed that, when compared to Scenario 1 results, there is no convergence of Pareto fronts. They are becoming saturated with the increase of the exergy tax value. The most noticeable difference between is when the exergy tax is increased from 0 up to 100 EUR/MWh: the front is shifted to the region of higher total discounted cost and higher carbon dioxide emissions. The difference is relatively small in the region where economical objective function dominates. However, in the region where carbon dioxide emissions reach minimum values, the difference between Pareto fronts is substantial. This is due to the existence of biomass heat-only boiler with relatively high exergy destruction, i.e. high exergy tax. It is important to notice that carbon dioxide emissions of the least cost solution aren't decreasing with increase of exergy tax values. The main reason for this is following. Increase of exergy tax gives opportunity of increasing the size and load factor of CHP cogeneration units, since natural gas boiler operation is starting to be relatively expensive due to the exergy tax increase. Natural gas cogeneration has higher carbon dioxide emissions, per unit of covered heat demand, and overall carbon dioxide emissions of the system are increasing. It is important to mention that heat pump hasn't been used as the solution, since biomass cogeneration has lower carbon dioxide emission, due to the power sector emission factor. However, once exergy tax increases up to 300 EUR/MWh, electrical heaters are becoming peak demand technology, together with natural gas heat-only boiler. Biomass heat-only boiler are included only in the most expensive solutions, i.e. where carbon dioxide emissions reach minimum.

Scenario 2b, where CHP technologies aren't available, is shown in Figure 2b. When compared to Scenario 2a, obtained results differentiate to a great extent. Firstly, all Pareto front have lower values of carbon dioxide emissions. The reason of this is non-existence of CHP technologies. As explained before, CHP technologies emit more carbon dioxide per unit of thermal energy produced. Secondly, Pareto fronts are shifting to the region of lower carbon dioxide emissions with the increase of exergy tax value. Once reaching exergy tax value of 200 EUR/MWh, the least cost solutions don't differentiate much in terms of carbon dioxide emissions, i.e. saturation has been realized. However, the cost of the most environmentally friendly solution greatly depends on the exergy tax value. As in the Scenario 2a, the reason behind this is usage of biomass heat-only boiler with high exergy destruction. It is important to notice that the lowest CO_2 emissions are equal for Scenario 2a and Scenario 2b.

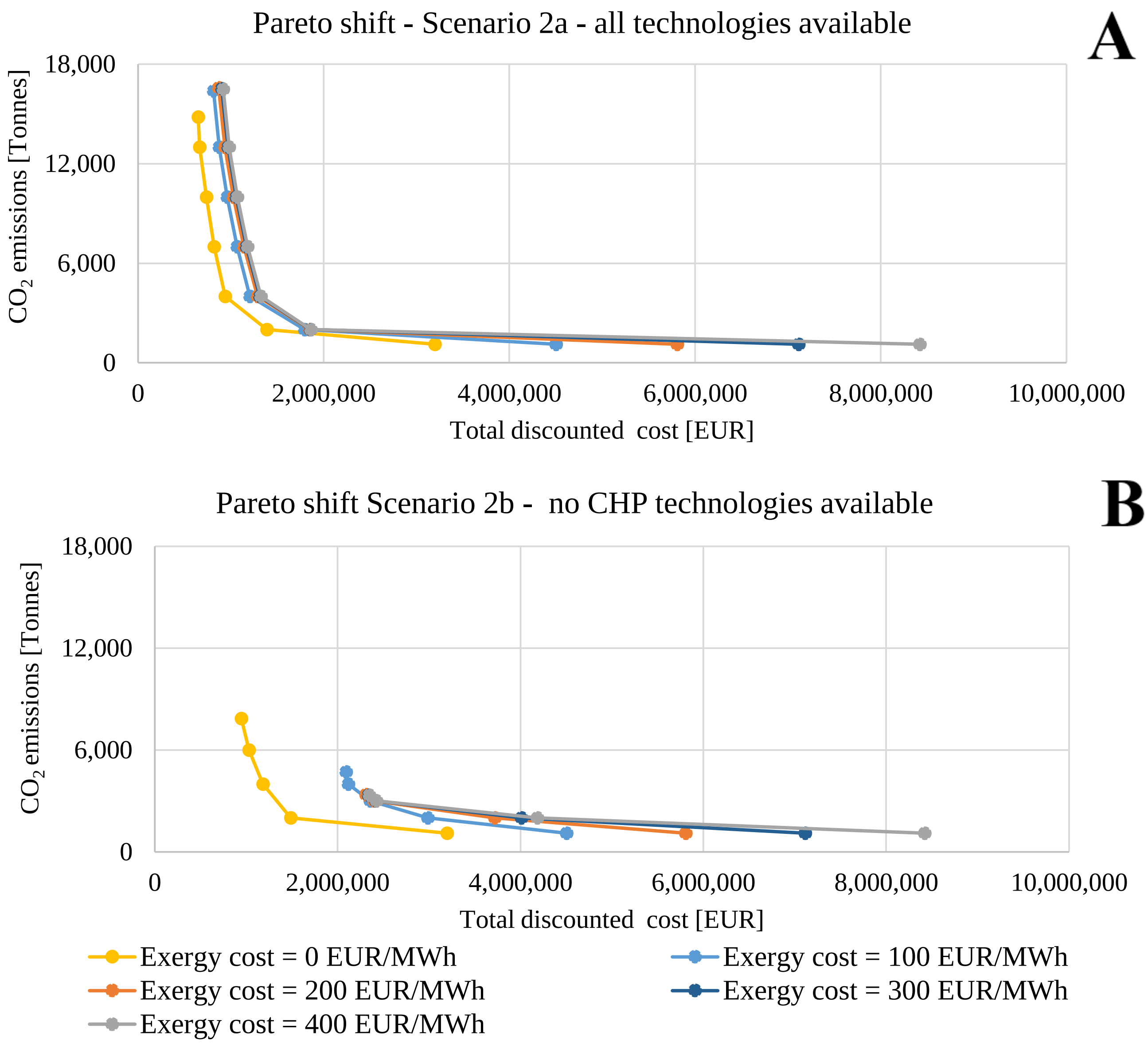


Figure 4 Pareto front shift due to the exergy tax increase: a) Scenario 2a - all technologies available, b) Scenario 2 - no CHP technologies available

4.3. Results of Scenario 3

Results of the Scenario 3 are shown in Figure 5. This scenario is based on a single-objective optimization where both exergy and carbon taxes are included in the economic objective function. Due to this, all obtained results present the least cost solution for the given taxing conditions. There are two parameters which could be followed: exergy efficiency and carbon dioxide emissions of the system. Furthermore, the sensitivity analysis of these parameters on the carbon and exergy tax value has been carried out and is explained in detail below. Two scenarios have been developed. In Scenario 3a all technologies are available, while in Scenario 3b CHP technologies aren't allowed to be utilised.

Figure 5a shows exergy efficiency of the Scenario 3a and the influence of exergy and carbon tax. In Scenario 3a, all technologies are available. It can be seen that 100 EUR/MWh of exergy tax is enough for the system to reach maximum exergy efficiency. Two groups of curves could be noticed: one has higher while the second one has lower exergy efficiency. The group with lower exergy efficiency has carbon tax. The reason for this is similar as preciously explained for Scenario 2a. Increase of carbon tax will gradually replace natural gas cogeneration with natural gas boiler and additionally introduce electrical heater as the peak demand unit, which additionally lowers exergy efficiency of the system.

It is important to remember that only boilers are included in the exergy tax system. Furthermore, it is worth mentioning that biomass heat-only boiler, heat pump and solar thermal weren't part of any solution. Biomass heat-only boiler has too high exergy destruction, thus biomass cogeneration is used, while heat pump and solar thermal have too high investment cost. Once carbon tax reaches 40 EUR/tonne, biomass cogeneration becomes part of every least-cost solution, regardless exergy tax value.

Figure 5b shows carbon dioxide emissions for Scenario 3a and the given tax system conditions. It can be noticed that exergy tax value has small influence on carbon dioxide emissions. However, the trend could be observed. If the carbon tax is lower or equal to 40 EUR/tonne, rise of exergy tax increases CO_2 emissions, while for carbon tax higher than 40 EUR/tonne, exergy tax increase reduces them. Furthermore, increase of the carbon tax to more than 20 EUR/tonne significantly reduces CO_2 emissions. The main reason for this is, as previously explained, inclusion of biomass cogeneration. It is important to mention that carbon tax is able to It is important to mention that carbon tax is able to greatly reduce carbon dioxide emissions even for exergy tax value equal to zero.

Figure 5c shows exergy efficiency of Scenario 3b for different taxing conditions. As previously mentioned, this scenario doesn't include cogeneration technologies, thus the results differ from Scenario 3a. For all values of carbon tax, from zero to 80 EUR/tonne, exergy efficiency of the system reaches plateau for value around 200 EUR/MWh. It is important to notice role of carbon tax in exergy efficiency increase. Plateau of maximum exergy efficiency will be reached for lower exergy tax value, if carbon tax is higher. For example, if carbon tax is 80 EUR/tonne, plateau is reached already at 100 EUR/MWh. Once exergy tax value reaches 200 EUR/MWh, exergy efficiency stays mostly the same for all taxing conditions. However, there is slight decrease in exergy efficiency for high exergy tax values, due to the inclusion of electrical heater. It is important to mention that heat pump is present in every solution, once exergy tax value of 200 EUR/MWh is reached. As in Scenario 3a, biomass heat-only boiler is rarely included in Scenario 3b solutions. It is only present for exergy tax value of 0 EUR/MWh and carbon tax higher or equal to 20 EUR/tonne.

Figure 5d shows carbon dioxide emissions for Scenario 3b. Similarly to Figure 5c, carbon dioxide emissions also reach plateau of minimum value once carbon tax value of 200 EUR/MWh is reached. As expected, the increase of carbon tax will boost reduction of carbon dioxide emissions for any associated exergy tax. Again, as in Figure 5b, increase of carbon tax has important role since it reduces carbon dioxide emissions of the system when there is no exergy tax.

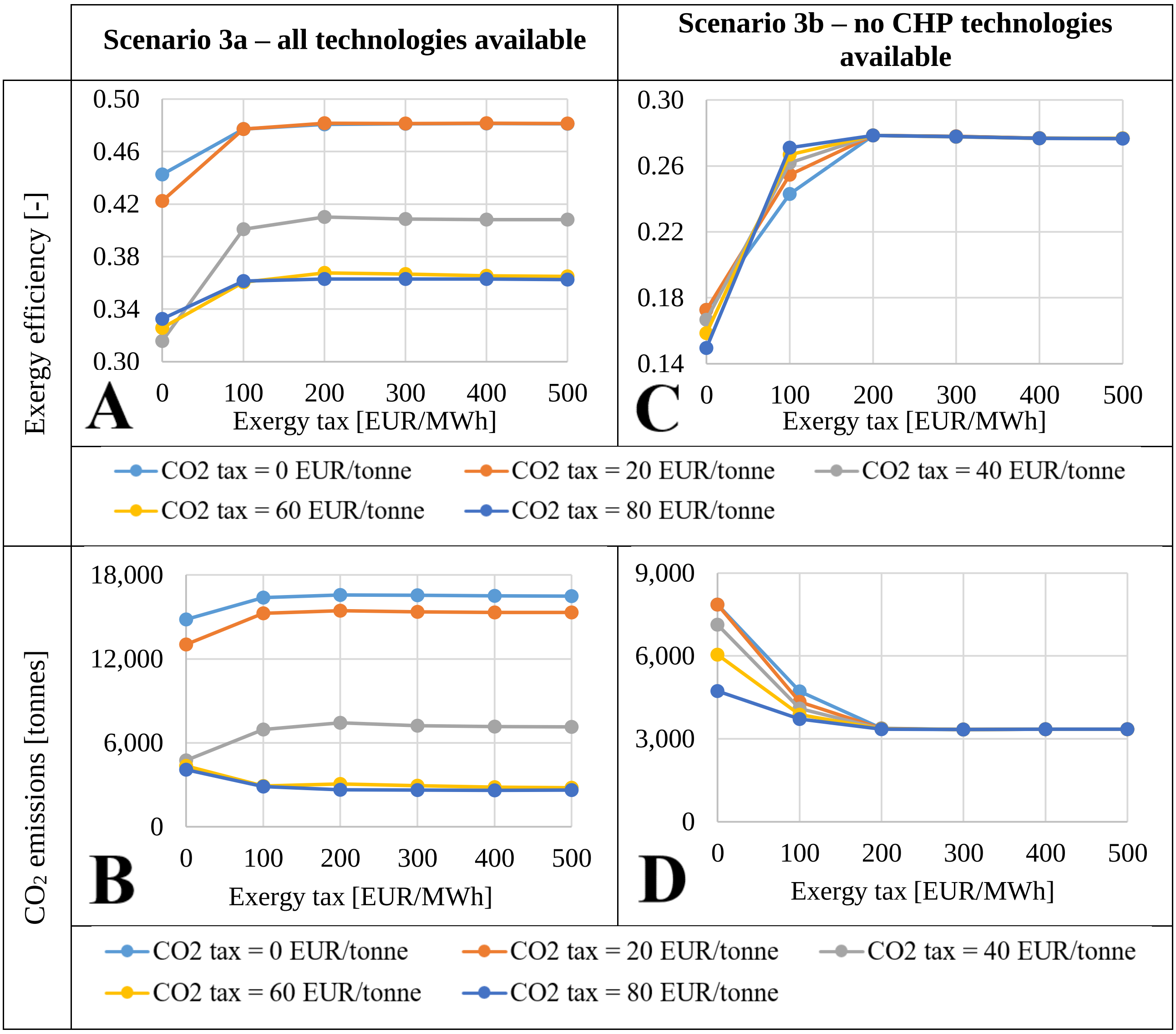
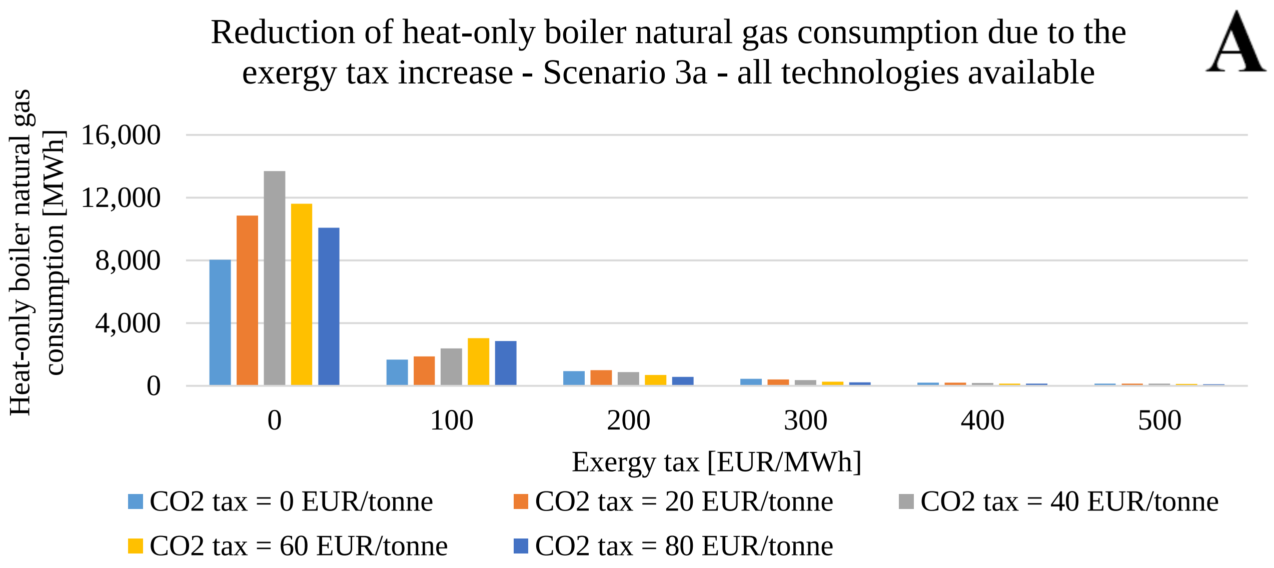


Figure 5 Exergy efficiency and CO_2 emissions of the least-cost solution for Scenario 3a and Scenario 3b

One of the important contributions of this paper is to analyse how different taxing systems can phase out natural gas consumption in heat-only boilers from the least-cost solution of the district heating system. Figure 6 shows consumption of natural gas in heat-only boilers for various taxing conditions. X-axis in Figure 6 represent different exergy tax values, while various colour bars represent different carbon tax values. First of all, it could be noticed that increase of exergy tax significantly reduces natural gas consumption in heat-only boilers, but even 500 EUR/MWh of exergy destroyed isn't enough to completely push it out. Figure 6a shows reduction of natural gas consumption in heat-only boilers for Scenario 3a. It can be noticed, similarly to Scenario 2a, that highest natural gas consumption isn't reached for carbo tax equal to zero. In this case, the highest consumption is reached for carbon tax equal to 40 EUR/MWh. Once this price is reached, biomass cogeneration becomes part of the least-cost solution. Such a trend isn't visible in Scenario 3b, as could be seen in Figure 6b. In this scenario, both exergy and carbon tax increase are resulting in natural gas consumption reduction.



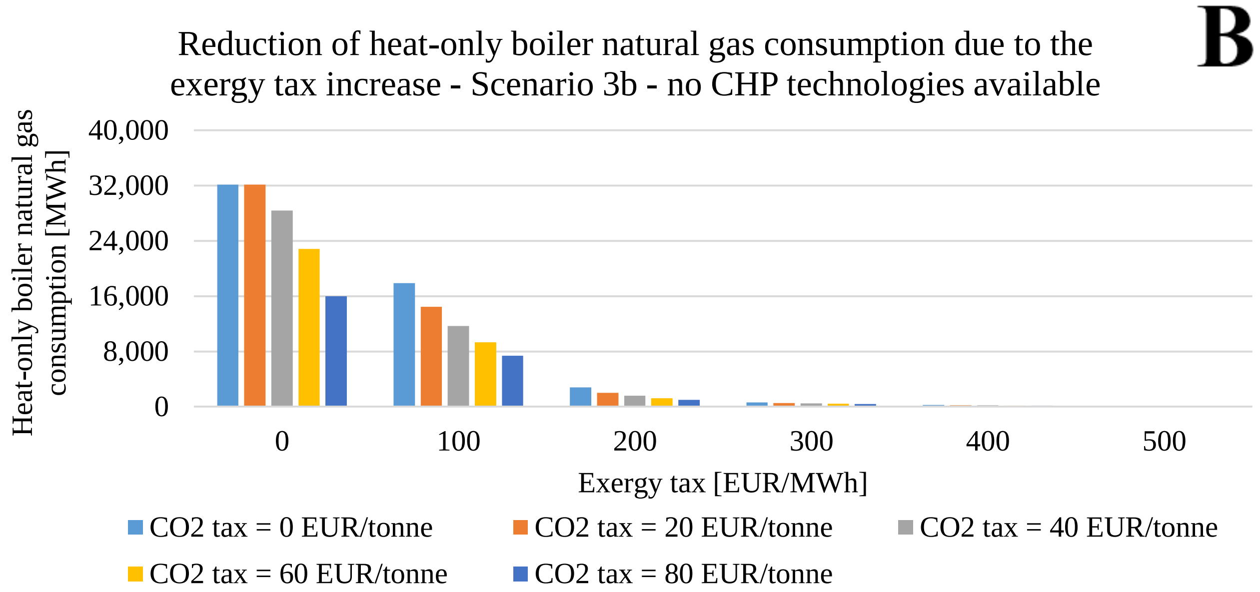


Figure 6 Influence of carbon and exergy tax cost on reduction of heat-only boiler natural gas consumption: a) Scenario 3a and b) Scenario 3b

In order to fully understand the impact of different taxing conditions on reduction of natural gas consumption in heat only boiler, it is crucial to analyse the total cost structure. Figure 7 shows cost distribution for different taxing conditions for Scenario 3a, i.e. when all technologies are available for utilization. The total cost of the system is divided into: discounted investment and running costs, total exergy tax and total carbon tax. First of all, it should be noticed that increase of carbon tax rises overall system cost from 600,000 EUR for carbon tax equal to 0 EUR/MWh up to 1,400,000 EUR for 80 EUR/tonne. Increase of exergy tax has smaller influence on the total system price. The highest impact is observed when increasing exergy tax value from 0 EUR/MWh to 100 EUR/MWh. Furthermore, the highest share of exergy tax in the overall system price is obtained for exergy tax value of 100 EUR/MWh and is around 8.5-10%. It is important to notice that this is relatively small when compared to carbon tax share which could be as high as 20% of the overall system cost. However, carbon tax itself can’t push-out consumption of natural gas in the heat-only boiler unit, thus exergy tax is needed. As the conclusion, it should be noticed that exergy tax, which presents small share of the total system cost, can effectively push-out the usage of natural gas in heat-only boiler unit of the optimal least-cost solution of the district heating system.

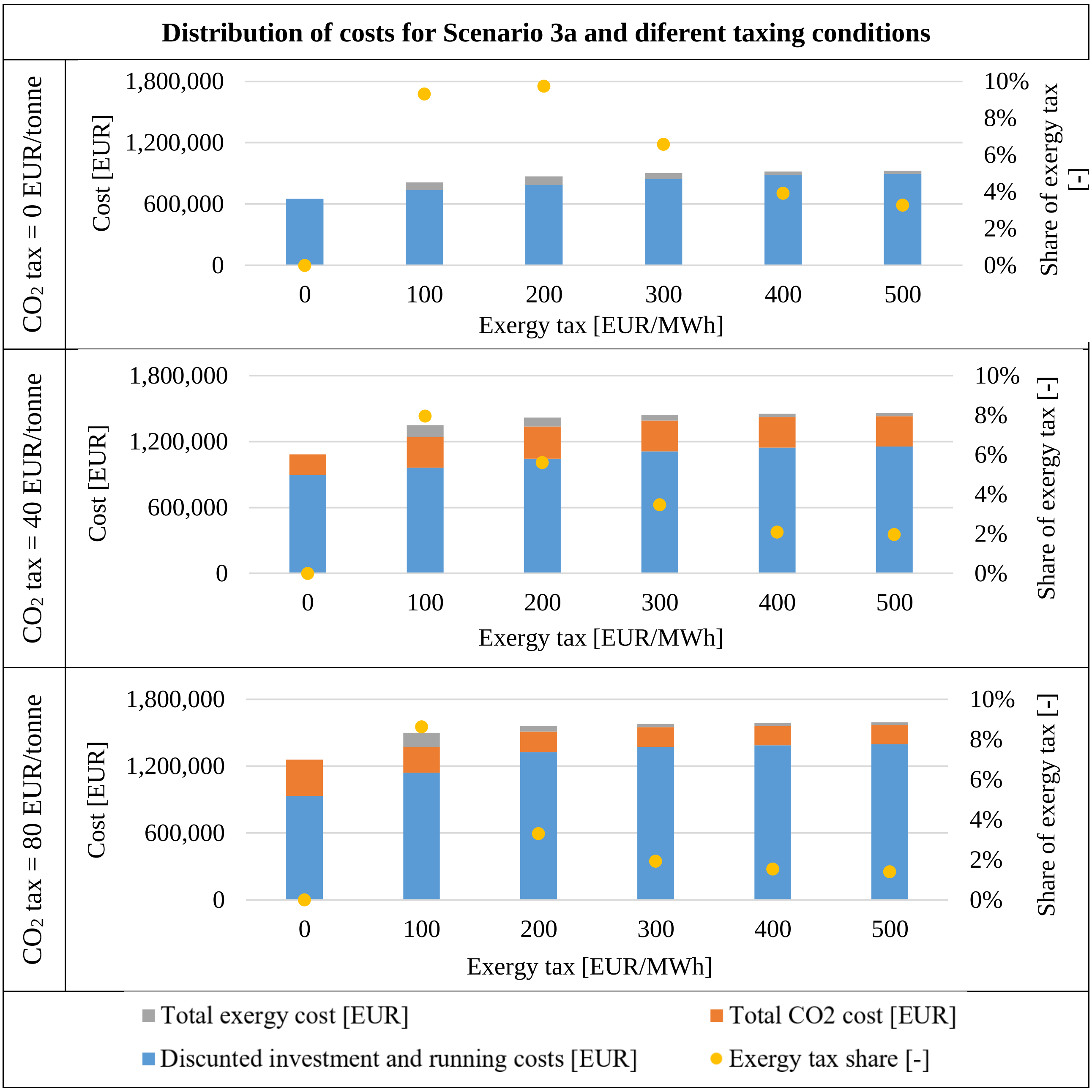


Figure 7 Cost distribution for Scenario 3a and different taxing conditions

4.4. Results of Scenario 3a with CO_2 allocation in cogeneration units

One of the major issues with the results obtained for Scenario 3a, shown in Figure 5, is following. It can be noticed that with the increase of carbon tax, exergy efficiency of the district heating is reduced. The main reason behind this is increased integration of heat-only boilers, which have higher exergy destruction rates and lower CO_2 emissions than cogeneration units. However, authors' opinion is that such approach is incomplete, since all the emissions emitted from CHP plant are allocated to district heating, i.e. thermal energy production. Heat produced in cogeneration units is mostly by-product of the electricity production process, sometimes called excess or waste heat. Due to this, CO_2 emissions from CHP units should be allocated between heat and power production. Numerous authors have already discussed the issue of CO_2 allocation in cogeneration plants. Rosen has provided overview of numerous allocation methods based on the energy output of a CHP unit [62]. One of the most noteworthy methods is the one based on power loss caused by heat recovery. In the other words, it states that CO_2 emissions linked to the district heating in CHP units should be proportional to the power loss due to the heat production. In the paper [63], it is listed as the Dresden method. According to study [64], specific emissions for generated heat in CHP units is around 150 kg/MWh (depending on the technology), i.e. five times lower than the specific emissions for electricity production in the same CHP unit. Similar results are obtained in study [65]. Finally, paper [66] provides allocating factors for numerous technologies and compares seven different allocation methods. By using the Dresden or power-loss method, heat allocation factor is around 0.1. This means that 90% of the CO_2 emissions from CHP unit should be allocated to electricity production, while only 10% of the overall emissions should be allocated to district heating, i.e. heat production.

The authors have re-run optimization for the Scenario 3a, while taking into account findings acquired in paper [66], i.e. allocating only 10% of the overall CHP emissions to the heat production. The results of Scenario 3a with CO_2 allocation in CHP units is shown in Figure 8. It can be noticed that, if taking into account CO_2 allocation in CHP units, inclusion of carbon tax increases exergy efficiency of the least-cost district heating system, while at the same time decreases total CO_2 emissions. These findings are in contradiction with results shown in Figure 5, which shows that carbon tax increase decreases exergy efficiency of the least-cost district heating system.

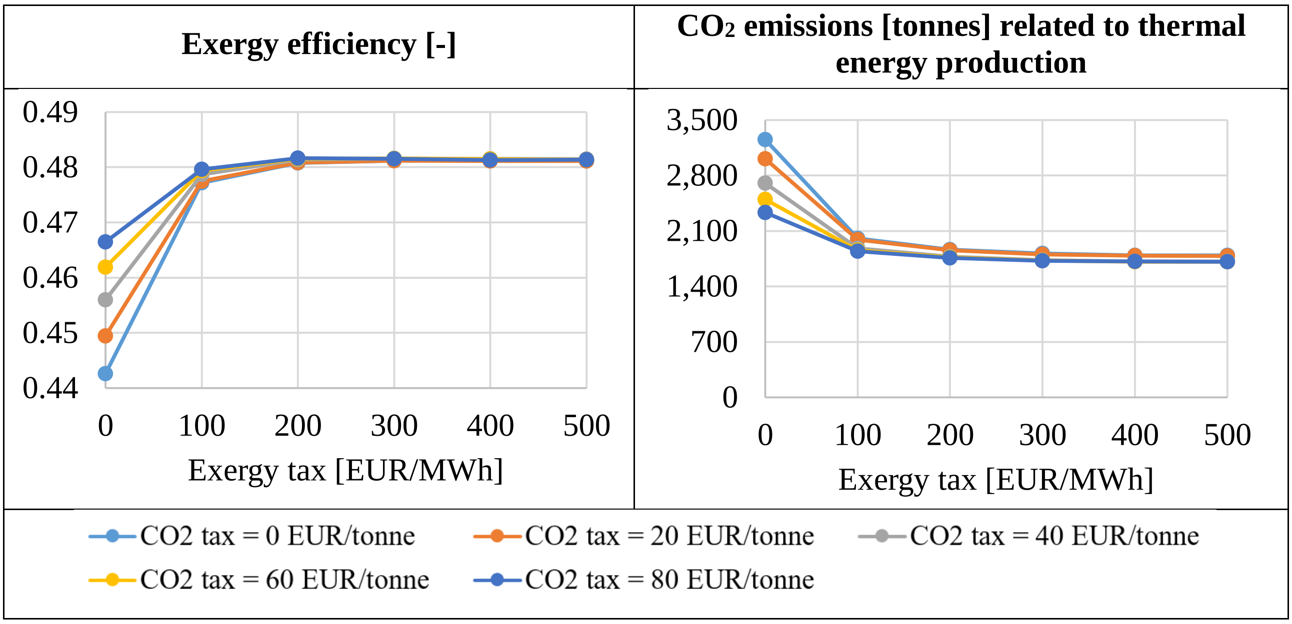


Figure 8 Exergy efficiency and CO2 emissions of the least-cost solution for Scenario 3a with CO_2 allocation in CHP units

4.5. Discussion

The method developed for the purpose of this paper is based on multi-objective optimization of district heating system's supply capacities and hourly operation. Due to this, it is challenging to verify accuracy of the model by using existing data, since the reference case doesn't exist. This issue is discussed in the text below. As explained by Lund et al in [67], there are two approaches in energy planning: simulation and optimization. Both could be used for system capacity definition and operation analysis. While simulation approach depends on the scenarios developed by the decision maker, optimization provides the solution of the problem by considering various constraints and various input data such as cost database. For this reason, supply capacities of the complex system obtained by optimization are unique solution which could be hardly obtained by using scenario analysis approach. This issue becomes even more complicated when discussing verification of multi-objective optimization since real life decisions are usually based only on economic benefits, i.e. total cost. Furthermore, this method involves exergy taxing, the approach which hasn't been introduced in real life systems, according to the authors knowledge. Nevertheless, it should be mentioned that hourly operation of the system acquired with optimization procedure could be verified. In this case, exergy taxing should be put to zero and compare obtained operation with real life data. However, it should be mentioned that focus of this paper isn't put on the development of dispatch and unit-commitment district heating model, but on the overall system planning which includes simultaneous optimization of capacities and operation of the system.

Other papers have also tackled the issue of exergy in heating systems by using multi-objective optimization. Paper [28] uses mixed-integer linear programming in order to optimize operation of the distributed energy system with predefined technology capacities. Besides this, the crucial difference is that exergy efficiency, i.e. exergy input, has been used as one of the objective functions, while carbon tax and CO_2 emissions haven't been taken into account. The acquired points of the Pareto front are relatively undistributed since weighted sum method has been used in order to tackle multi-objective optimization. Results show that natural gas and biomass boiler isn't utilized at all when putting the weight to exergy-related objective function. This model has been upgraded in paper [29] in order to include capacity optimization and number of units per technology. Once again, Pareto front has been constructed by using weighted sum method. For the least-cost solution, the system uses natural gas cogeneration in combination with natural gas boiler and heat pump. The least cost results obtained in this paper do not utilize heat pump. The reason behind this could be constant efficiency of the heat pump (COP) assumed by authors in paper [29]. On the other hand, the optimal solution from the exegetic point of does not use natural gas boiler at all, similarly to the results obtained in this study. Finally, the natural gas phase out results from this paper could be compared with outputs from authors' previously published paper [46]. Natural gas consumption reduction strictly follows increase of exergy tax increase, while in paper [46], it is obtained with constraining exergy destruction. Around 200 EUR/MWh of exergy tax is needed in order to obtain natural gas consumption reduction achieved in paper [46]. Furthermore, the most suitable solution defined in paper [46] does not include cogeneration units, while having CO_2 emissions around 4,000 tonnes with exergy efficiency of 30%. This paper has shown that if taking into account CO_2 allocation in CHP units, exergy efficiency of the system could still be kept high at 45%, while producing lower amount of CO_2 emissions thanks to utilization of CHP units. Paper [45] dealt with multi-objective optimization of district heating systems taking into account economic and ecological objective functions, but it didn't involve any taxing methods. This paper shows how these results could be shifted by using exergy taxing methods, thus reducing CO_2 emissions.

Finally, it should be mention how this method could be used for energy planning and could present the first step in decision making. The acquired results could serve as the input for more complex analysis of the district heating system based on more realistic model of operation, i.e. unit commitment and dispatching which involves additional physical constraints. Additionally, the method could be used for policy discussion for natural gas phase-out in order to show crucial drawbacks of this fuel for heating purposes, i.e. exergy destruction.

5. Conclusion

In this paper, the influence of carbon and exergy destruction tax on the results of multi-objective optimization of district heating system has been analysed. The district heating supply model includes various technologies, such as heat-only boiler, cogeneration, solar thermal and power-to-heat units, including thermal storage. The model is capable of optimizing their capacities and hourly operation for a whole year. Objective functions are defined as minimization of total discounted cost, minimization of carbon dioxide emissions and minimization of exergy destruction. In order to carry out the analysis, two approaches has been used through three scenarios. In the first two scenarios, multi-objective optimization has been used, while in the third scenario, single-objective optimization was introduced. Scenario 1 includes economical and exergetic objective functions, while the influence of the carbon tax on the Pareto front shift was analysed. It was shown that fronts are converging to a single one no matter the carbon tax value. In Scenario 2, ecological objective function was used together with economical and the influence of exergy destruction tax was analysed. It has been shown that, if all technologies are available, introduction of exergy tax doesn’t decrease carbon dioxide emissions. However, due to the additional costs, Pareto frontiers are shifting to the region of higher total cost. On the other hand, if there are no CHP technologies available, increase of exergy tax reduces carbon dioxide emissions. In Scenario 3, single objective optimizing has been carried out in order to acquire the least cost solution, while carbon and exergy tax have both been added to the cost function. It has been concluded that exergy tax of 150 EUR/MWh is enough in order to reach maximum exergy efficiency. If all technologies are available, exergy tax has small influence on the carbon dioxide emissions. On the other hand, if no CHP technologies are available, exergy tax of 200 EUR/MWh is enough to reach minimum carbon dioxide emissions. The main outcome of this paper is the analysis of exergy tax impact on natural gas consumption in heat-only boilers. It has shown that inclusion of exergy tax can significantly reduce natural gas consumption. However even for the value of 500 EUR/MWh, the least cost solution includes natural gas as one of the supply units in order to cover the peak demand if all technologies are available. The cost structure shown that share of exergy tax is relatively small, lower than 10% while carbon tax share can go up to 20% of the total system cost. However, carbon tax itself isn’t enough to push out utilization of natural gas in the heat-only boiler unit.

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