Hourly optimization and sizing of district heating systems considering building refurbishment – Case study for the city of Zagreb

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Abstract

District heating plays a crucial role in future energy systems due to its beneficial impacts on the overall flexibility and efficiency of the energy system as a whole. In order to fully utilize its benefits, the sizing and operation of said systems needs to be optimized. This is a computationally difficult task due to a large number of parameters that need to be considered and calculated. Another issue is a need for long optimization horizons of at least one year, in order to capture seasonal, and a small time step of one hour or less, to capture intraday variations. The goal of this work has been the development and demonstration of an optimization model capable of handling both the sizing and the operation of a district heating system based on a heat only boiler, solar thermal collectors, electric heaters, heat pumps and thermal energy storage units while considering building refurbishment. The model has been implemented on nine scenarios. The results of the analysis have demonstrated the economic and environmental benefits of the utilization of highly efficient and renewable energy sources in the proposed system.

Key words: District heating; MILP optimization, Thermal energy storage: Unit commitment problem; Energy planning

1. Introduction

Worldwide demand for energy is continuously increasing. At the same time, RES (renewable energy sources) such as solar, wind and biofuels are becoming more competitive and available due to technological advancements, access to an open market and a shift in EU (European Union) directives and national legislations. Their penetration in the global final energy consumption summed up to 19,1% in 2013 [1]. In order to mitigate climate change, increase energy security and ensure competitive energy prices in the region, the EU has adopted the 2020 climate & energy package that sets three key targets until the year 2020, a reduction of GHG (greenhouse gas) emissions by 20% from 1990 levels, an increase of the RES share in the EU energy mix to 20% and an energy efficiency increase by 20% [2]. The 2030 Energy strategy has set even more ambitious goals with a planned cut in GHG emissions of 40% compared to 1990 levels, a share of renewable energy consumption of at least 27% and at least 27% energy savings compared to a business-as-usual scenario [3].

The utilization of highly efficient CHP (combined heat and power) units trough DHC (district heating and cooling) that maximize the utilization of waste heat and locally available RES like solar, renewable biomass, biogas and geothermal can greatly increase energy efficiency and reduce the CO_2 emissions of the energy system. The utilization of power-to-heat technologies like HPs (heat pump) in conjunction with thermal energy storage (TES) can also help to increase the potential for the utilization of intermittent RES like wind and solar and achieving a positive synergy between the heat and power sectors. According to [4], DH (district heating) has an important role in the task of increasing energy efficiency and thus enabling a reduction in the utilization of fossil and other non-renewable energy as a source to meet future demands. The term "Fourth generation DH systems" has been coined for DH systems capable of tackling the issues modern energy systems will face and are currently facing. Future DH systems will have to be able to fulfil several roles in order to achieve this, meaning that they will have to be able to supply existing, refurbished and new buildings with low temperature heating, minimize energy losses in the distribution system, use low-temperature waste heat and integrate RES as well as being an integral part of smart energy systems linking the power and heat sectors [4]. Papers such as [5] have already shown that energy systems such as the Danish one could integrate upwards of 50% DH and have highlighted its impact on the overall energy system if large scale HPs and TES would be integrated into it. The analysis conducted in this work focuses, aside from the technical potentials and environmental impacts, on the economic effect such systems have on the end users. Similar analyses on a larger scale have been conducted for other countries such as China [6], Sweden [7], UK [8], Italy [9], Spain [10] and France [11], among others. Other research has also demonstrated the positive impact of energy efficiency measures related to DH such as the reduction of the supply temperature [12] and the utilization of smart grids [13], low temperature renewable heat [14] and hybrid DH systems [15]. The authors of [16] have conducted a comparative analysis of representative Danish and Croatian DH systems that has shown a great potential for the improvement of the systems in South-East Europe (SEE) from an energy efficiency perspective. Pukšec and Mathiesen [17] have also demonstrated this potential using their NeD (National energy demand) model which has proven that an energy consumption reduction of 40% in Croatia can be achieved by the year 2050. The research in [18] has also shown the potential impact DH expansion can have in a Croatian city. The inclusion of DH in future sustainable cities allows for the wide use of CHP together with the utilisation of heat from waste-to-energy and various industrial surplus heat sources as well as the inclusion of geothermal and solar thermal (ST) heat [19]. The authors of [20] have provided a solution for the utilization of excess heat production in trigeneration through the implementation of TES. The importance of TES in a future sustainable energy system in Croatia was assessed in [21]. The research conducted in [22] has shown that integration of HPs as a centralized heat production unit in a DH system is possible when combined with a heat exchanger or a combination of a DH system based on centralized HPs and a small booster HP using DH water as low-temperature source for DHW (domestic hot water) production. Authors from [23] have shown that it is indeed possible to utilize an in-house circuit of the building heating system as a heat source for HP. A recent study has emphasized the importance of taking both the socio-economic and consumer-economic approaches into account when expanding existing and building new DH systems [24].

In order to optimize the benefits of a DH system on the overall energy sector, the individual components have to be properly sized and their operation planned. This can become a computationally demanding task. Buoro and Pinamonti [25] explored the optimal operation strategy in order to minimize the total annual cost based on a MILP (mixed integer linear programing) model for a distributed energy supply system including a CHP plant, a DH network system, a ST plant and conventional components such as heat only boilers (HOB) and compression chillers. Christidis and Koch [26] optimized the design of TES devices together with the operation of a power plant supplying a large district heating network (DHN) by formulating a MILP problem in GAMS (The General Algebraic Modeling System) and solving it in CPLEX (IBM ILOG CPLEX Optimization Studio). Kim and Edgar [27] used a MINLP (mixed-integer nonlinear programming) approach for the scheduling of CHP plants in the day ahead wholesale energy market. Long-term planning of Croatian power system using multi-objective optimization with focus on renewable energy and integration of electric vehicles has already been carried out [28].Never the less future DH infrastructures should, however, not be designed for the present energy needs but for future system demands. One of the future challenges will be to integrate DH with the electricity sector as well as the transport sector [29].

The goal of this work is to demonstrate a long-term optimization tool capable of taking building refurbishment and the utilization of several different heat sources into account with a calculation time step of one hour and a time horizon of one year. The model optimizes the size and operation of the storage and production units as well as the refurbishment rate based on costs, project lifetime, energy demands and other parameters described in the text below. The problem has been formulated in MALAB and solved using an open source MINLP solver SCIP (Solving Constraint Integer Programs) [30] capable of solving both linear programing (LP) and MILP problems in a quick and efficient way.

2. Methods

2.1. Superstructure

The developed mathematical model is a MILP problem defined by all three types of variables: continuous, binary and integer. The model itself was developed using MATLAB and solved with a non-commercial MILP solver SCIP, from the OPTI toolbox [30]. Due to the limitation of computational power, the solution of such a problem cannot be obtained at once for an entire year with a one hour time step in a reasonable amount of time on an average computer. For this purpose, a superstructure consisting of three modules has been created and presented in Figure 1. The main advantage of this method is its ability to find near-optimal solutions in reasonable amount of time. The simulation time hugely depends of the input data, enforced constraints and initial starting points provided by the user. In most cases when using an average notebook (CPU: Intel i7-6500U, 2.5 GHz; RAM: 8 GB) simulation time varies between 20 and 90 minutes. On the other hand the main disadvantage of the model is its inability to find globally optimal solutions for the whole time series of one year.

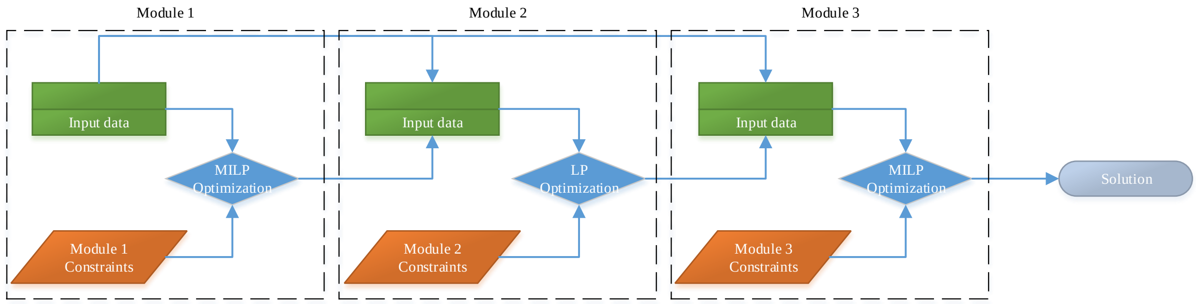

Figure 1 Flow chart diagram of the proposed superstructure

2.1.1. Module 1

In the first module, an optimization with a larger time step (several hours or days) is performed for the entire optimization horizon. In this step, the possible solutions are narrowed down by ignoring tight constraints such as unit commitment, ramp up and ramp down constraints, hourly temperature variations and electricity prices. For this purpose, the annual hourly values of all input variables that include space heating and DHW preparation demands, average hourly global solar irradiation and outside temperature as well as hourly electricity prices from the day ahead market have been either summed or averaged depending on the data needed. For the visualization purposes of the method, the electricity prices from the electricity market have been averaged and the heating demand has been summed for every τ time steps in order to obtain the total heating demand for each period. The time step factor (τ) used for the calculation of an average value of every m elements from the initial time series, has to be a multiple of 2. This is necessary as the new time series has to be integer based in order to allow vectorization of the given problem. The most important factor in a given problem is the amount of energy stored in the TES in the following time intervals:

$$j_n = \lfloor l_n \cdot \left(\frac{t_{max}}{\tau^2}\right) \rfloor \qquad (1)$$
$$l_n = \{m \in \mathbb{Z} | n \le m \le \tau\}$$

where j_n are the integer rounded values of time intervals used for evaluating the amount of heat stored in the TES, l_n is the multiplication factor that ranges between 0 and τ, t_{max} is the whole time series (eg. 8760 h) and τ is the time step factor. As an example the critical time intervals of a time series of 8760 time intervals and time step factors of either 2, 4 or 6 are presented in Table 1.

Table 1 Examples of the critical time intervals for the time series of 8760 hours and time step factors of 2, 4 and 6

Symbol	$t_{max} = 8760;\ \tau = 2$			$t_{max} = 8760;\ \tau = 4$					$t_{max} = 8760;\ \tau = 6$						
n	0	1	2	0	1	2	3	4	0	1	2	3	4	5	6
l_n	0	1	2	0	1	2	3	4	0	1	2	3	4	5	6
j_n	0	2190	4380	0	547	1095	1642	2190	0	243	486	730	973	1216	1460

Because of its complexity the rate of refurbishment is determined only in this module. All other results from this module are approximate values of the final solution and are passed onto the second one as input data.

2.1.2. Module 2

The second module is a linear problem where all the results from the first module are used either as lower bounds for determining the installed capacity of each technology or guiding curves for demand reduction and the heat accumulation in TES. In this module, the time series of one year is divided into few smaller ones which are individually optimized but now with a time step of one hour. The results obtained in this module represent the final capacities of all heat generation technologies and the final volume of TES. In the next step, the results from all of the simulations are analyzed and the maximum capacities of all the available technologies are obtained. These results are than passed onto the third module as fixed input data.

2.1.3. Module 3

The third module finally takes into account the tight constraints and performs the unit commitment problem optimization of the system. Constraints related to ramping up and ramping down limits as well as on and off states are introduced. Third and final MILP optimization is performed and the total annual costs for the proposed system are obtained.

This model combines the unit commitment problem and the energy planning concept into one model enabling component sizing and scheduling of the system [31]. Considerations taken into account for each technology modeled in this problem are presented in Table 2.

Table 2 Technology considerations

Technology	*Considerations*
Heat only boiler	*Installed heat capacity, capacity dependent specific investment cost, ramp up and ramp down limits, on and off states, specific greenhouse gas emissions for fuel and fixed fuel price*
Heat pump	*Installed heat capacity, capacity dependent specific investment cost, on and off states, specific greenhouse gas emissions for electricity, variable electricity prices from electricity market and outside temperature dependent coefficient of performance*
Electric heater	*Installed heat capacity, capacity dependent specific investment cost, specific greenhouse gas emissions for electricity, variable electricity prices from electricity market and fixed efficiency*
Solar thermal collectors	*Heat capacity, available roof area, optic efficiency, first and second order heat loss coefficients, tilt, orientation, supply and return temperature, other losses and capacity dependent specific investment costs*
Thermal energy storage	*Storage capacity, storage volume, available park area, temperature regime, heat loses, storage media and type of storage, capacity dependent specific investment costs*
Building envelope retrofit	*Thickness of thermal wall insulation, heat losses through windows and doors, heat losses through walls floors and roofs, equivalent insulation thickness dependent annual heat consumption and equivalent insulation thickness dependent specific investment costs*

2.2. The exact input data used in this work is presented with more details in chapter 4.Heating demand

The total annual heat consumption has been calculated according to the method for the evaluation of energy performance of buildings HRN EN ISO 13790 [32]. This is a standard method that is used for the evaluation of all heat gains and losses for any given type of room, building or clusters of buildings. It takes into account transmission and ventilation heat losses as well as internal heat gains from various heat sources such as the number of occupants or other heat emitting devices. Heat gains from solar irradiation as well as heat losses due to the building orientation and shading are also taken into account. The input data required for this method includes knowing the types of materials used, location specific climate data and data related to the building types (residential, commercial or industrial). The same method can be used to calculate the potential reduction of the annual heat consumption through the installation of thermal insulation and new windows. For simplification purposes the method for the estimation of specific costs of equivalent insulation thickness has been proposed. The equivalent insulation thickness has been calculated as follows:

$$\bar{\delta} = \frac{A_{ins} + A_w}{\delta} \tag{2}$$

where $\bar{\delta}$ is the equivalent insulation thickness (m), A_{ins} is the surface area of the thermal insulation (m^2), A_w is the surface area of the double glass windows (m^2), and δ is the insulation thickness (m).

2.3. Domestic hot water demand

It is reasonable to assume that the DHW curve is not constant in every hour of a day. Literature suggests that its consumption varies greatly from 0.4 %, at 4 AM, up to 9.2% of total daily consumption at 8 AM as presented in Figure 2 [33]. The DHW demand in old uninsulated residential buildings in Eastern European countries is estimated to be about 20 to 25% of total annual space heating demand whereas in developed Northern European countries it almost never reaches below 40%. For the purpose of replicating a real systems, a DHW demand curve that takes into account all these estimations has been modeled as proposed by the literature [33].

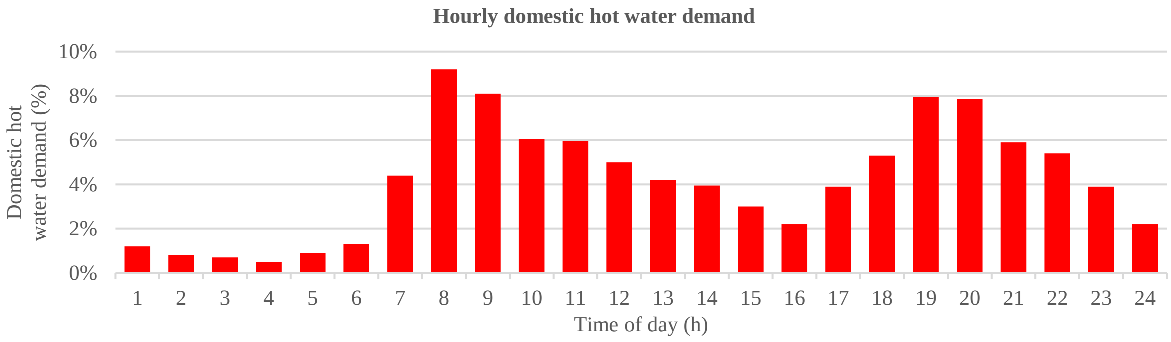

Figure 2 Hourly domestic hot water demand of a typical residential neighbourhood [33]

2.4. Heat pump efficiency

Literature suggests that the calculation of the coefficient of performance (COP) of HPs directly depends on the temperature of the heat source and the heat sink as well as the temperature difference between these two [34]. For compression air to water HPs, the practical heat output is usually 3 to 5 times higher than the compressor drive. For the purpose of the model, the value of the COP factor is calculated in advance with the knowledge of the hourly outside air temperature distribution, supply and return temperatures in the DHN and the temperature difference of 5°C on the side of heat source (eg. outside air is cooled from 10 to 5°C).

3. Optimization model

The intended use of the developed model is to provide a support for the planning of the optimal configuration of a new DH system from an economic point of view. The model optimizes the following components: the size of the TES, production capacities of each heat generation unit, energy flows between them as well as the reduction of the heating demand due to the building envelope retrofitting in a given area.

3.1. Objective function

The objective function is a typical cost function representing the total annual costs of the system. It has to be minimized in order to obtain the optimal sets of variables that represent the optimal solution. The objective function, given in eq. (3), is linear with respect to all decision variables and is a linear combination of the discounted value of annual investment costs of all available technologies as well as building refurbishment C_{inv} (€/a), fixed operation and maintenance costs ${C_{O\&M}}_f$ (€/a), variable operating and maintaining costs ${C_{O\&M}}_v$ (€) and variable fuel costs C_{fuel} (€).

$$minC = C_{inv} + {C_{O\&M}}_f + \sum_{t=1}^{t_{max}} {C_{O\&M}}_v + \sum_{t=1}^{t_{max}} C_f \tag{3}$$

The total investment costs and the fixed operation and maintenance costs are discounted to annual values according to the commonly used method [25]. This method takes into account the life span of each component and technology specific interest rates contained in the superstructure of the model.

3.1.1. Investment costs

The overall investment consists of several items that represent individual heat production technologies, TES, ST collectors, DHN and building envelope retrofitting are presented as follows

$$C_{inv} = I_{HT} + I_{ST} + I_{TES} + I_{DHN} + I_{BER} \tag{4}$$

Investment into the heat production technologies are calculated as follows:

$$I_{HT} = c_{HOB}(P_{HOB}) \cdot P_{HOB} + c_{HP}(P_{HP}) \cdot P_{HP} + c_{EH}(P_{EH}) \cdot P_{EH} \tag{5}$$

where $c_{HOB}(P_{HOB}), c_{HP}(P_{HP})$and $c_{EH}(P_{EH})$ are the capacity dependent prices of the HOB, HP and electric heater (EH) (€/MW) and P_{HOB}, P_{HP} and P_{EH} are their installed capacities (MW). Investment in the ST collectors I_{ST} is:

$$I_{ST} = c_{ST}(A_{ST}) \cdot A_{ST} \tag{6}$$

where $c_{ST}(A_{ST})$ is the surface area dependent price of the ST collectors (€/m^2), A_{EH} is the surface area of the ST collectors (m^2). Investment in the TES I_{TES} is:

$$I_{TES} = c_{TES}(V_{TES}) \cdot V_{TES} \tag{7}$$

where $c_{TES}(V_{TES})$ is the volume dependent price of the TES (€/m^3), V_{TES} is the volume of the TES (m^3). The total investment costs in the DHN I_{DHN} are:

$$I_{DHN} = c_{DHN} \cdot L_{DHN} \tag{8}$$

where c_{DHN} is the average price per length of pipes in the DHN (€/m), L_{DHN} is the planed length of DHN (m). Investment in the building envelope retrofit I_{BER} is:

$$I_{BER} = c_{BER}(\bar{\delta}) \cdot A_E \cdot z_{BER}(\bar{\delta}) \tag{9}$$

where $c_{BER}(z_{BER})$are the total equivalent insulation thickness dependent costs of building envelope refurbishment (€/m2), $A_E$is the area of building envelope including surface areas to roofs and basements (m2),$z_{BER}(\bar{\delta})$ is the equivalent insulation thickness dependent annual heat demand reduction (%).

3.1.2. Other fixed and variable costs

The overall maintenance costs are divided into fixed and variable costs which are discounted to an annual value. Fixed operation and maintenance costs are:

$$C_{O\&M_f} = f_{O\&M_{HOB}} \cdot P_{HOB} + f_{O\&M_{HP}} \cdot P_{HP} + f_{O\&M_{EH}} \cdot P_{EH} + f_{O\&M_{ST}} \cdot A_{ST} + f_{O\&M_{TES}} \cdot V_{TES} \tag{10}$$

where $f_{O\&M_{HOB}}$, $f_{O\&M_{HP}}$ and $f_{O\&M_{EH}}$ are the fixed costs charged for servicing and maintaining each of the three production technologies (€/MW), $f_{O\&M_{ST}}$ are the fixed costs charged for servicing and maintaining ST collectors (€/m^2) and $f_{O\&M_{TES}}$ are fixed costs for servicing and maintaining the TES. The variable operation and maintenance costs represent the costs of CO_2 emissions and maintenance costs related to the annual heat production:

$$\begin{aligned} C_{O\&M_v} = {} & \left(\varepsilon_{EL} \cdot \left(\frac{\dot{Q}_{HP_t}}{COP_t} + \frac{\dot{Q}_{EH_t}}{\eta_{EH}}\right) + \frac{\dot{Q}_{HOB_t} \cdot \varepsilon_{HOB}}{\eta_{HOB}}\right) \cdot c_{CO_2} + v_{O\&M_{HOB}} \cdot \dot{Q}_{HOB_t} \\ & + v_{O\&M_{HP}} \cdot \dot{Q}_{HP_t} + v_{O\&M_{EH}} \cdot \dot{Q}_{EH_t} + v_{O\&M_{ST}} \cdot \dot{Q}_{ST_t} + v_{O\&M_{TES}} \cdot \dot{Q}_{TES_t} \end{aligned} \tag{11}$$

where ε_{EL} and ε_{HOB} are the national, fuel dependent, CO_2 emissions factors (t_{CO2}/MWh), $\dot{Q}_{HP_t}$, $\dot{Q}_{EH_t}$, $\dot{Q}_{HOB_t}$, $\dot{Q}_{ST_t}$ and $\dot{Q}_{TES_t}$ are the heat outputs from the HP, EH, HOB, ST collectors and the TES in the optimization interval t (MWh), COP_t, η_{EH} and η_{HOB} are their efficiencies (%), c_{CO_2} is the price of CO_2 emissions (€/t_{CO2}) and $v_{O\&M_{HOB}}$, $v_{O\&M_{HP}}$, $v_{O\&M_{EH}}$, $v_{O\&M_{ST}}$ and $v_{O\&M_{TES}}$ are their variable costs (€/MWh). The costs related to the fuel and electricity consumption are:

$$C_f = \left(\frac{\dot{Q}_{HP_t}}{COP_t} + \frac{\dot{Q}_{EH_t}}{\eta_{EH}}\right) \cdot c_{EL_t} + c_F \cdot \frac{\dot{Q}_{HOB_t}}{\eta_{HOB}} \tag{12}$$

where c_{EL_t} is the variable electricity price from the electricity market (€/MWh) and c_F is the price of fuel (€/MWh).

3.2. Model constraints

Different mathematical constraints can be identified in the proposed model: component related constraints, specific investment costs related constraints, energy flow balances and network limitations. Component related constraints represent the energy inputs and outputs of each component and their sizing. The specific investment costs related constraints represent the relation between the component size and the specific investment cost. These specific investment costs are usually much higher for smaller components and vice versa. This constraints represent either equalities, especially if the relation between the specific investment costs and the technology capacities are approximated with only one linear equation, or inequalities if the same relation is described with either two or more linear equations. Equality constraints in this model also represent relations between the fuel consumption and the heat production while inequality constraints also describe minimal and maximal power outputs. Energy balances ensure that the sum of all energy inputs is equal to the sum of all the energy outputs in each time interval and for each node. These are all equality constraints that represent thermal and electricity balances of the analyzed system in each time interval. Network heat flow limitations are related to the losses of each connection between different components and their maximal thermal energy transfer capacity. These are mainly pipe losses that represent the thermal energy balance of the network.

3.2.1. Demand

The model is driven by the heating and DHW demands. The mentioned demands need to be covered in every time interval t throughout the year by a single component or a combination of components:

$$\begin{gathered}\dot{Q}_{DEM_t} \cdot z_{BER}(\delta) + \dot{Q}_{DHW_t} + \dot{Q}_{DHNL_t}\left(\dot{Q}_{DEM_t}, z_{BER}, \dot{Q}_{DHW_t}\right) = \dot{Q}_{HOB_t} + \dot{Q}_{AD_t} \\ \dot{Q}_{HP_t} + \dot{Q}_{EH_t} + \dot{Q}_{ST_t} = \dot{Q}_{TESin/out_t}\left(\dot{Q}_{TES_{LVL_t}}, \dot{Q}_{TES_{LOSS_t}}\right) + \dot{Q}_{AD_t}\end{gathered} \tag{13}$$

where $\dot{Q}_{DEM_t}$ is the heat demand from the DHN (MWh), $\dot{Q}_{DHW_t}$ is the DHW preparation demand (MWh), $\dot{Q}_{DHNL_t}$ are demand dependent DHN losses (MWh), $\dot{Q}_{AD_t}$ is the energy in the pipeline connecting renewable energy sources with the HOB and the demand side of the network (MWh), $\dot{Q}_{TES_{LVL_t}}$ is the amount of heat energy stored in the TES in every time interval t (MWh), $\dot{Q}_{TES_{LOSS_t}}$ are heat accumulation dependent heat losses of the TES (MWh) and $\dot{Q}_{TESin/out_t}$ is the charge/discharge rate of the TES (MWh).

3.2.2. Heat only boiler

In the proposed configuration the HOB is the only component not directly connected to the TES. This is common setup in most of the renewable powered DH systems as the HOBs are usually only used for covering peek loads or as a backup unit [35]. This technology is in most cases limited by the operation at the technical minimum, that is usually somewhere in between 15 and 35% of installed capacity. Unit commitment constraints are introduced in order to enforce this limitation. They force the HOB to be either in off state or to operate between the technical minimum $P_{HOB_{min}}$.(MW) and technical maximum $P_{HOB_{max}}$ (MW).

$$\begin{gathered}P_{HOB_{min}} \cdot x_{HOB_t} \leq \ \leq P_{HOB_{max}} \cdot x_{HOB_t} \\ x_{HOB_t} = \{x \in \mathbb{Z} | 0 \leq x \leq 1\}\end{gathered} \tag{14}$$

where x_{HOB_t} is the binary variable representing either on and off states of the HOB. The proposed ramping up and ramping down constraints limit the ability of the HOB to constantly switch between on and off states:

$$\begin{gathered}P_{HOB_{max}} \cdot r_{HOB_{min}} \leq P_{HOB_t} - P_{HOB_{t-1}} \leq P_{HOB_{max}} \cdot r_{HOB_{max}} \\ c_{HOB}(P_{HOB}) = a_{HOB} \cdot P_{HOB_{max}} + b_{HOB} \\ x_{HOB_t} = \{x \in \mathbb{Z} | 0 \leq x \leq 1\}\end{gathered} \tag{15}$$

where $r_{HOB_{min}}$and $r_{HOB_{max}}$ are minimum and maximum ramping rates expressed as fraction of maximal installed capacity (%). The specific investment costs are approximated by a linear correlation between the specific investment costs and the maximal installed capacity of HOB

$$c_{HOB}(P_{HOB}) = a_{HOB} \cdot P_{HOB_{max}} + b_{HOB} \tag{16}$$

where a_{HOB} and b_{HOB} are linear coefficients (€/MW, €).

3.2.3. Heat pump

More and more often renewable DH systems are built to be able to utilize heat from the surrounding environment. There are endless possibilities for the implementation of HPs. They are able to utilize almost any type of heat source by using electrically powered compressor to transfer it to the heat sink. The HPs are very flexible heat generation units that can operate at almost any capacity but their technical minimum is usually around 5 to 15%

of the installed capacity [34]. In order to realistically describe such an operation, another set of unit commitment constraints is introduced.

$$P_{HP_{min}} \cdot x_{HP_t} \leq P_{HP_t} \leq P_{HP_{max}} \cdot x_{HP_t}$$
$$x_{HP_t} = \{x \in \mathbb{Z} | 0 \leq x \leq 1\} \tag{17}$$

where x_{HP_t} is the binary variable representing both on and off states of the HP and $P_{HP_{max}}$ is the maximal installed heat capacity of the HP. The specific investment costs into the HPs are also approximated by a linear correlation between the specific investment costs and its maximal installed capacity:

$$c_{HP}(P_{HP}) = a_{HP} \cdot P_{HP_{max}} + b_{HP} \tag{18}$$

where a_{HP} and b_{HP} are linear coefficients (€/MW, €).

3.2.4. Electric heater

One of the first, simplest and least expensive power to heat (P2H) technologies are EHs. Their application is widespread, ranging from small sized EHs, commonly used for DHW preparation, up to large scale industrial or DH utilities, used to quickly generate great amounts of heat for many different applications. They are extremely flexible and can operate in almost any range as usually even the smallest amount of electricity starts to produce heat. This type of unit is only constrained by the variable specific investment costs:

$$c_{EH}(P_{EH}) = a_{EH} \cdot P_{EH_{max}} + b_{EH} \tag{19}$$

where a_{EH} and b_{EH} are linear coefficients (€/MW, €) and $P_{EH_{max}}$ is maximal installed heat capacity of the EH.

3.2.5. Thermal energy storage

There are many variations of TES: hot water tanks, large insulated solar pits, aquifers and boreholes. These are the most common types that vary greatly in size, ability to store heat, maximal discharge capacity and price. Most of them can be used for both long-term (seasonal) and short-term (hourly or intraday) heat storage. When it comes to short term storage hot water tanks are usually the best choice as they can be easily integrated inside the buildings. On the other hand, when there is a need to store great amount of heat that could be utilized at a later point in time, solar pits are in most cases the cheapest and simplest variant. In order to as accurately as possible, but at the same time computationally least demanding, describe these variants, a three step linear piecewise function has been introduced.

$$c_{TES}(V_{TES}) \geq a_{TES_y} \cdot V_{TES_{max}} + b_{TES_y}$$
$$a_{TES_y} = \{y \in \mathbb{Z} | 1 \leq y \leq 3\} \tag{20}$$

where $V_{TES_{max}}$ is the maximal volume of TES (m^3) and a_{TES_y} and b_{TES_y} are linear coefficients (€/m^3, €). The operation of the TES is optimized by taking thermal loses due to the contact with the surrounding area into account:

$$\dot{Q}_{TES_{LVL_{t=1}}} = C_p \cdot \varepsilon_{start}\left(V_{TES_{max}}\right) \cdot V_{TES_{max}} + \dot{Q}_{TESin/_{out_{t=1}}}$$
$$\dot{Q}_{TES_{LVL_t}} + \dot{Q}_{TES_{LOSS_t}} = \dot{Q}_{TES_{LVL_{t-1}}} + \dot{Q}_{TESin/_{out_t}}$$
$$\dot{Q}_{TES_{LOSS_{t=1}}} = 0 \tag{21}$$
$$\dot{Q}_{TES_{LOSS_t}} = \dot{Q}_{TES_{LVL_{t-1}}} \cdot \eta_{stor}\left(\dot{Q}_{TES_{LOSS_t}}\right)$$

where ε_{start} is the amount of heat available in the first interval (%), C_p is the amount of heat stored per volume of TES (MWh/m^3), and η_{stor} are the heat losses that occur due to the heat exchange with the surrounding area (%). The storage levels ensure that the storage is always filled between the minimum and maximum set value, the energy balances ensure that sum of energy inputs and outputs equals zero if not stated otherwise, the heat loses depend on the amount of heat stored in the storage and the size of the storage is cost driven and takes into account the possibility to store as much heat from the Sun or other cheaper technologies during the summer period.

3.2.6. Solar thermal collectors

Solar heat production technologies have a relatively low penetration in covering the total heating and DHW demands. It is a relatively simple and straight forward technology that gathers heat from solar irradiation and delivers it to the heating network or, in many cases, stores it in some type of TES. Its base production price doesn't change much with the increase of the solar collector area. The main price variability comes from the type of installation as rooftop collectors are almost twice as expensive as the filed ones. Another factor that hugely impacts the specific investments costs are the carrying constructions which are cheaper for the installation of large scale unit compared to a small scale one [36]. In order to take this factors into account, a linear correlation between specific investment costs and ST collector area has been introduced:

$$c_{ST}(A_{ST}) = a_{ST} \cdot A_{ST_{max}} + b_{ST} \tag{22}$$

where a_{ST} and b_{ST} are linear coefficients (€/MW, €) and $A_{ST_{max}}$ is the maximal installed surface area of the ST collectors.

3.2.7. Demand reduction

The focal point of this paper is related to the reduction of heating demand in DH networks. This is an ongoing topic that should always be directly related to the development of future and refurbishment of existing DH systems and networks. One of the main objectives of this model is, among others, the optimization of the rate of refurbishment of old thermally uninsulated buildings. In order to mathematically as accurately as possible represent the refurbishment rate, buildings with no thermal insulation have zero specific investment costs. Installation of 1 cm thick equivalent insulation, including all other facade materials and installation, is separated into two specific investment costs. The fixed part of specific thermal insulation investment costs covers all of the installation costs while the variable part depends on the equivalent insulation thickness and represents material costs. To tackle this issue, the following linear piecewise constraints have been introduced:

$$\begin{gathered} c_{BER}(\bar{\delta}) \geq a_{\bar{\delta}} \cdot \bar{\delta} + b_{\bar{\delta}} \\ z_{BER}(\bar{\delta}) \geq a_{BER_y} \cdot \bar{\delta} + b_{BER_y} \\ \bar{\delta} = \{z \in \mathbb{Z} | 0 \leq z \leq 20\} \end{gathered} \tag{23}$$

where $a_{\bar{\delta}}$ and $b_{\bar{\delta}}$ are linear, specific investment cost related, coefficients (€/m, €), a_{BER_y} and b_{BER_y} are linear, demand reduction related coefficients (%/m; %). In order to force the model to either do the refurbishment or not a binary variable has been introduced. It enables the possibility to either have zero costs when there is no refurbishment or to have linear relation between specific investment costs and the thermal insulation thickness:

$$\begin{gathered} c_{BER_{min}} \cdot x_{BER} \leq c_{BER} \leq c_{BER_{max}} \cdot x_{BER} \\ x_{BER} = \{x \in \mathbb{Z} | 0 \leq x \leq 1\} \end{gathered} \tag{24}$$

where $c_{BER_{min}}$, $c_{BER_{max}}$ are minimal and maximal value of specific refurbishment related investment costs (€/m) and x_{BER} is binary decision variable that determines whether there is any thermal insulation installed or not.

3.3. Decision variables

The described model is a complex, computationally intensive and time consuming MILP model. It consists of 23 different types of decision variables that are used in various stages of the superstructure optimization process. Not all decision variables are optimized simultaneously. A list of all the decision variables and their occurrence in various modules inside the superstructure optimization are presented in Table 3.

Table 3 overview of the usage of decision variables in various stages of the superstructure optimization

Decision variable	*Module 1*	*Module 2*	*Module 3*
$\dot{Q}_{TES^{in}/_{out_t}}$	+	+	+
$\dot{Q}_{TES_{LOSS_t}}$	+	+	+
$\dot{Q}_{TES_{LVL_t}}$	+	+	+
$\dot{Q}_{AD_t}$	+	+	+
$\dot{Q}_{EH_t}$	+	+	+
$\dot{Q}_{HP_t}$	+	+	+

$\dot{Q}_{ST_t}$	+	+	+
$V_{TES_{max}}$	+	+	-
x_{HOB_t}	-	-	+
x_{HP_t}	-	-	+
P_{EH}	+	+	-
P_{HOB}	+	+	-
P_{HP}	+	+	-
c_{BER}	+	-	-
c_{EH}	+	+	-
c_{HOB}	+	+	-
c_{HP}	+	+	-
c_{ST}	+	-	-
c_{TES}	+	+	-
x_{BER}	+	-	-
z_{BER}	+	-	-
$\bar{\delta}$	+	-	-
$A_{ST_{max}}$	+	-	-

In the considered integrated system, the HOB, HP, EH and ST collectors cooperate together for the satisfaction of the required thermal demand. From this point of view this is considered as a unique DH system from which the average heat cost can be evaluated as follows:

$$\overline{P_{heat}} = \frac{C}{\sum_{t=1}^{t_{max}}\left(\dot{Q}_{DEM_t} \cdot z_{BER} + \dot{Q}_{DHW_t} + \dot{Q}_{DHNL_t}\right)} \tag{25}$$

It is clear that the average heat cost corresponds to the minimization of the objective function C because the variables $\dot{Q}_{DEM_t}$, $\dot{Q}_{DHW_t}$ and $\dot{Q}_{DHNL_t}$ are constant.

4. Scenarios

The model was applied to the neighborhood of Trnsko located in the city of Zagreb. It is a highly populated area constructed in the early 1960s. According to the Croatian census from 2011 it has 5.331 inhabitants living on 29,99 ha [37]. Most of the buildings are of type "Bartolić" that was very popular residential apartment building in that time period [38]. All these buildings are made of 30 cm solid brick walls, internal and external 3 cm glaze and a facade. Since this is a residential-only neighborhood there are no commercial or industrial consumers except a small 1.500 m^2 shopping mall and 4.500 m^2 primary school. Due to the lack of data related to these two buildings their connection to the DH network was not considered. Through visual on-site inspection it was determined that almost 60% of the apartments already have new double glass and PVC frame windows, while the rest still has original single glass and wooden frame windows. These buildings were never refurbished and today still have minimal or almost no thermal insulation.

The specific costs of building envelope refurbishment, including thermal insulation, new double glass windows for the rest of the apartments and other materials as well as installation costs, were estimated according to the current Croatian wholesale market prices from various building material stores. The prices are presented in the top right diagram in Figure 3. Using the earlier described method for the evaluation of the equivalent insulation thickens, the annual heating demand reduction has been evaluated. The results are presented in the upper left diagram in Figure 3. The analyzed neighborhood currently has no DH infrastructure and uses individual gas boilers for space heating and DHW preparation. The natural gas prices in Zagreb, including consumption, distribution and other related costs, sums up to around 45 €/MWh [39]. In February of 2016, a new day ahead electricity market CROPEX [40] has opened and, at the time of the writing of this paper, operates at almost the same price range as the regional energy exchange day ahead market SouthPool [41]. For the purpose of the evaluation of the P2H technologies such as EHs and HPs it was estimated that those units would be able to take part on the Croatian electricity market. Since CROPEX has been operating for less than a year at this point, the electricity prices were collected from the SouthPool market for the year 2014. The minimum, maximum and average values of electricity prices are presented in Table 4. The specific investment costs of EHs and HPs are presented in the middle diagrams in Figure 3. The costs of these two technologies have been estimated according to the price range from the reports of the Danish Energy Agency [34][42]. The utilization of solar energy is becoming more popular as new large scale solar DH system are being constructed around Europe. More than 216 plants with more than 350 kW of nominal power were put in operation in Europe, mainly northern countries such as Sweden, Denmark, Austria and Germany [35]. Even though global solar irradiation in these countries is around 1000 kWh/m^2/a [43] many of these system produce heat at competitive prices at around 50 €/MWh [35]. Capacity related specific investment costs in TES are approximated by a piecewise linear curve and presented in the bottom right diagram in Figure 3. These prices were obtained from the report of the Danish Anergy Agency [34] and scientific publications [25][35][44][45][46]. ST collectors could potentially produce heat at competitive prices for space heating and DHW preparation especially in Southern and Southeast EU countries. The Annual global solar irradiation in the city of Zagreb amounts to 1.364 kWh/m^{2}a. A recent study for the nearby city of Velika Gorica has shown that the prices of solar DH, excluding DHN costs, could be in a range from 28,07 €/MWh up to 48.58 €/MWh for pessimistic predictions [44]. Specific ST collector prices were approximated given the data from [35] and are presented in the lower left diagram in Figure 3. Since the observed area in the case of the developed scenarios has no DH, the installation of a DH grid has been taken into account. The specific investment costs in a DH network mostly depend on the pipeline system, nominal diameter and insulation class. Usual specific investment costs range from 308 to 1755 €/m as presented in [47]. For this particular case, an average investment costs of 900 € per length meter have been used.

Table 4 electricity prices from regional day ahead market SouthPool [32]

SouthPool (2014)	*Unit*	*Minimum*	*Average*	*Maximum*
Electricity price	*€/MWh*	*0,50*	*42,61*	*145,03*

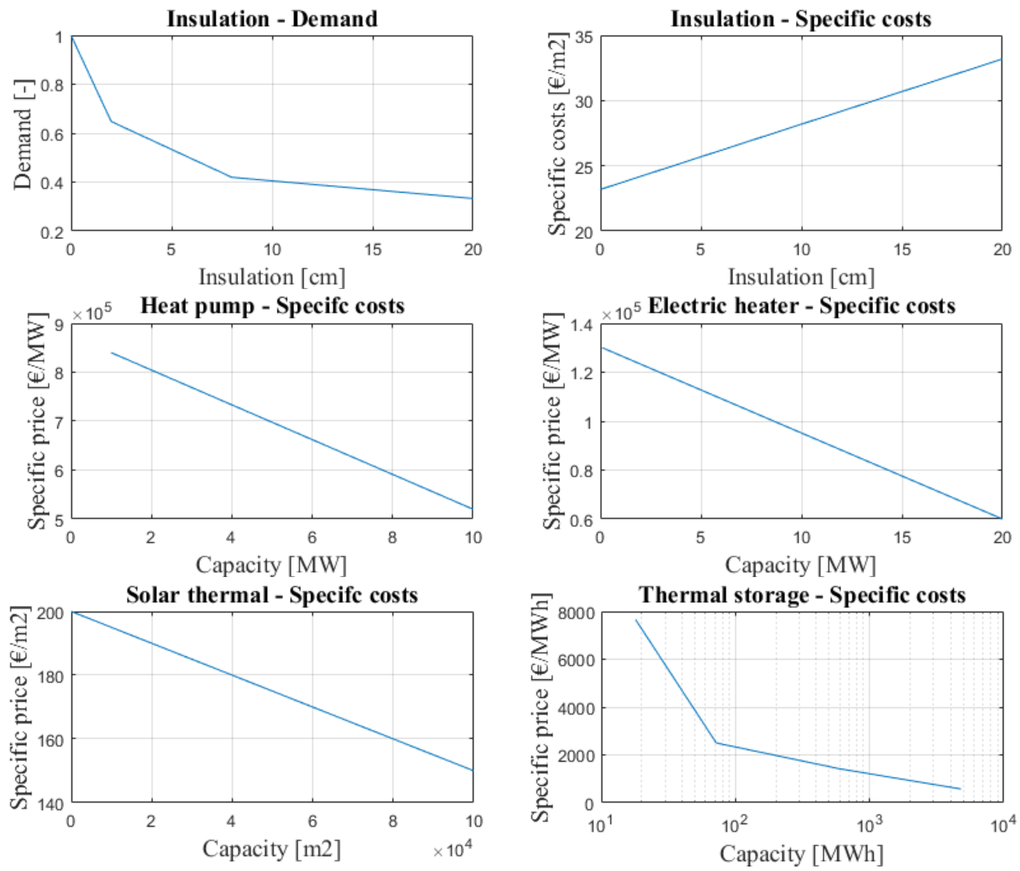

Figure 3 Specific investment costs of all the available technologies and insulation thickness dependent demand reduction

For the purpose of validation of the developed model, nine scenarios were analyzed, one reference and eight alternatives. The purpose of this was to demonstrate the impact of different constraints from the model on the average heating cost. In all of the analyzed scenarios, investment costs have been analyzed from the systems perspective.

4.1. Reference scenario

The reference scenario represents an approximation of current heating system in the neighborhood of Trnsko, which is a typical example of the Eastern European system. The scenario describes an ideal case where all of the apartment owners decide to replace old, less efficient boilers with new condensing ones. In the observed case the installed capacity of all boiler units is high enough to cover the maximal value of heating demand combined with the DHW preparation. In the proposed scenario the apartment owners are the only investors willing to invest into the new boilers. According to this a specific heating price per MWh of heat is calculated. This serves as a reference point for the comparison with other scenarios. In this scenario the HOBs are constrained by the operation at least at the technical minimum which is set to 15% of the nominal installed capacity. No other technologies are available for implementation.

4.2. Scenarios 1 – 2

Scenarios 1 and 2 are somewhat different from the reference scenario as they are limited to the use of centralized HOB that delivers heat to the end consumers through a DH network. Another limitation is also a heat demand reduction achieved by the refurbishment of the outside building envelope. In these two scenarios maximal installed capacity of HOB and the rate of refurbishment are determined by the model. Investment costs into the new DH network are included in the total investment costs of the proposed system. Scenario 1 presents the least expensive solution for the given set of constraints. On the other hand Scenario 2 focuses on the deep refurbishment of the buildings. In it an installation of at least 8 cm thick equivalent thermal insulation is enforced. This way model searches for the cheapest transition to a low temperature DH system. In this two scenarios the centralized HOBs is optimized in such a way that its installed capacity is high enough to cover all the heating and DHW demands. The HOB is constrained by the operation at least at the technical minimum. This is again set to 15% of the nominal installed capacity, same as in reference scenario. In these two scenarios no other technologies beside HOB are available for the implementation.

4.3. Scenarios 3 – 5

Scenarios 3 to 5 are modeled freely according to the least cost of heat produced. In Scenario 3 there are, beside the capacity dependent specific investment costs, no other constraints applied to the model. Optimal mix of all the available technologies and the rate of refurbishment are determined by the model. Scenarios 4 and 5 are different in a way that in both cases demand reduction due to the outside building envelope refurbishment is forced. In Scenario 4 the optimization model is constrained by the equivalent insulation thickness of at least 1 cm, whereas in Scenario 5a deep refurbishment of the outside building envelope is forced. This means that the equivalent thermal insulation thickness of over 8 cm has to be installed in order to check how expensive the transition to a renewable low temperature DH system would be. In this three scenarios optimization model is constrained with the HOB constraints from the earlier scenarios as well as with the operation of HP. As mentioned earlier HP is also allowed to operate at least at the technical minimum which is also set to 15% of the maximal installed capacity. The sizing of TES is limited by the available park area that sums up to 7.42 ha. This is enough for the installation of a unit with equivalent water volume of up to 200,000 m^3 (150x205x6.5 m).

4.4. Scenarios 6 - 8

Utilization of ST collectors is in the focus of the last three scenarios. In this three scenarios, 6 to 8, optimization model is constrained by the minimum amount of solar fraction in the system. Due to the relatively small surface area to space heating area ratio, the minimum amount of solar fraction has been set to 10% of the total heat demand. Similar as before in the case of scenarios 7 and 8 minimum equivalent thermal insulation thickness of at least 1 cm and over 8 cm is forced. Furthermore, the use of HPs in these three scenarios has been banned due to the favorable results from the scenarios 3 to 5, in which the optimal solution heavily relied on their integration into the system. This decision has been made in order to demonstrate the use of all the other available technologies.

Short summary of all the constraints from the scenarios is presented in the Table 5.

Table 5 Short description of the constraints from the analysed scenarios

Scenario	Constraints
Reference	Decentralized condensing HOBs must cover both the space heating demand and DHW demand. They have to operate at least at the technical minimum which is set to 15% of the nominal installed power. No other technologies, nor the demand reduction due to the building envelope refurbishment are available for implementation.

Scenario 1	Centralized HOB must cover both the space heating demand and the DHW demand. It has to operate at least at technical minimum which is set to 15% of the nominal installed capacity. There are no limits on the installation of equivalent thermal insulation. Investment costs of DHW are included in the total heat production costs.
Scenario 2	Centralized HOB is constrained as the one from the Scenario 1. The utilization of a deeper refurbishment, where installation of at least 8 cm thick equivalent thermal insulation is mandatory. All other parameters are the same as in the Scenario 1.
Scenario 3	The model is free to choose from all the available technologies. HP are limited by the operation at least at the technical minimum which is set to 15% of nominal installed capacity. The HOB is also constrained by the operation at least at the technical minimum, same as in Scenario 1. No other constraints are applied.
Scenario 4	The model is constrained by the operation of both the HP and HOB at least at the technical minimum same as in the Scenario 3. There are no restrictions on choosing an optimal mix of all the available technologies. The minimum rate of refurbishment of at least 1cm thick equivalent thermal insulation is mandatory.
Scenario 5	The same constraints as the ones from the Scenario 4 are valid as well. The model is free to choose the optimal mix from all the available technologies. The deep refurbishment of buildings where at least 8cm thick equivalent thermal insulation is mandatory.
Scenario 6	The constraints related to the operation of HOB are the same as in the earlier scenarios. HPs are not allowed and solar fraction of the system is set to a minimum of 10%.
Scenario 7	All the constraints from the Scenario 6 are valid here as well. HOB has to operate at least at the technical minimum and HPs are not allowed. The solar fraction of the system is set to a minimum of 10%. Building refurbishment with the installation of at least 1cm thick equivalent thermal insulation is mandatory.
Scenario 8	The same constraints from the earlier two scenarios apply here as well. The HOB has to operate at least at the technical minimum and the HPs are not allowed. The solar fraction of the system is set to a minimum of 10%. The deep refurbishment of the buildings where installation of at least 8 cm thick equivalent thermal insulation is mandatory

5. Results and discussion

The results of the proposed nine scenarios represent the cost driven annual demand reduction due to the outside building envelope refurbishment, sizing and scheduling of the available technologies and impact such a system has on the environment. In most scenarios optimized levelized cost of heat (LCOH) is higher than the one from the reference scenario. This is expected as total investment costs into the new renewable technologies, DHN and building refurbishment have much higher impact on the LCOH in comparison to the reference scenario where no DH network nor the building refurbishment is considered.

5.1. General results

The results of the first eight days of February and June are presented in Figure 4. It can be seen that in the total hourly heat demand both the space heating and the DHW preparation are included. In coldest days when outside air temperature is around -9°C the total heat load of the neighbourhood of Trnsko sums up to 22.4 MW. On the other hand in summer period when there is no need for space heating, as the outside air temperature rarely falls below 15°C, the total heat load of the neighbourhood sums up to 1.47 MW at 8 AM and to 0.13 MW at 4 AM.

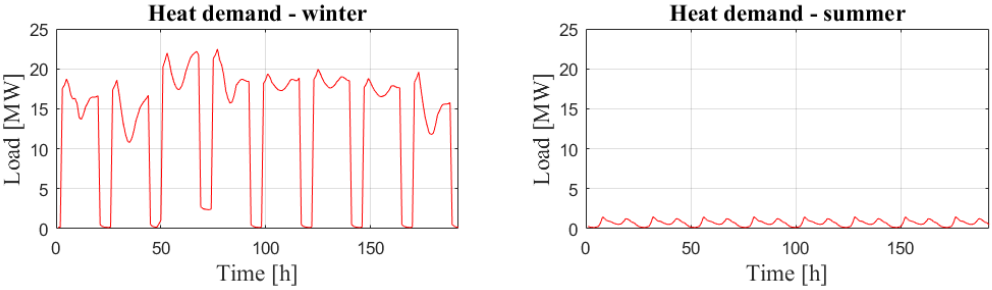

Figure 4 Space heating and hot water demand for the first 8 days of February (left) and June (right)

Figure 5 demonstrates the relation between the outside air temperature and the COP factor of the air to water HP. It can be seen that the COP factor closely follows the curve of the outside air temperature. As expected the COP factor is lower when the temperature drops and vice versa, when the outside temperature rises the COP factor is higher. Its highest value of 3.66 is reached at the end of the June when the outside air temperature averages to around 36.1°C.On the other hand lowest value of the COP factor is around 1.9 at the beginning of February when the outside air temperature averages to around -8.8 °C.

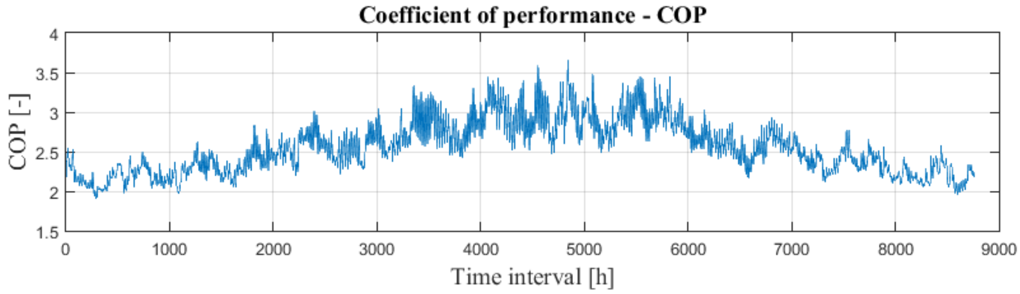

Figure 5 Hourly variation of the outside temperature dependent COP factor of the HP.

The time series of the solar irradiation on an optimally inclined surface area in the neighbourhood of Trnsko is presented in Figure 6. The highest values are regularly above 1000 W/m^2 making this neighbourhood a good potential location for the installation of ST collectors. The highest solar irradiation averages to about 1,255.8 W/m^2 at the end of June when long dry periods with no clouds are common in this particular neighbourhood.

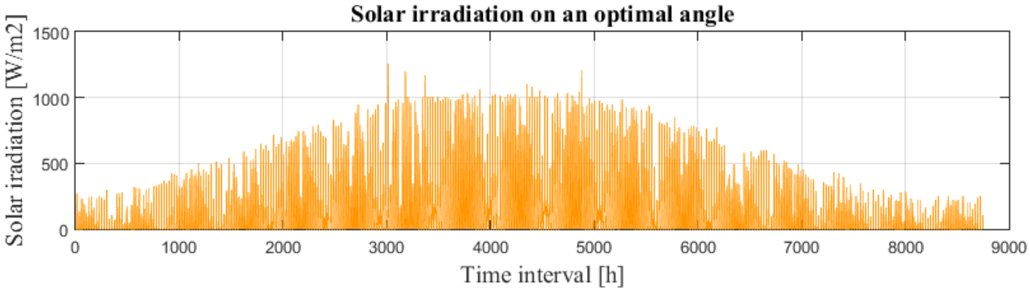

Figure 6 Hourly variation of the solar irradiation on an optimally inclined surface area.

5.2. Demand reduction

The main results related to the demand reduction due to the outside building envelope refurbishment are presented in Table 6. As it can be seen the total heat demand is, according to expectations, reduced in six scenarios. The total space heating demand has been reduced by 59% in scenarios 1, 4 and 7 and by 66.6% in scenarios 2, 5, and 8. The reason why this values are same in these two sets of three scenarios is the linear piecewise approximation of the specific investment costs. The optimal values of such approximation, in most cases, tend to converge to the interception points of the two neighboring lines from the piecewise approximation. In this particular case optimal rate of refurbishment is expected to converge to the installation of either 1, 4, 8 or 20 cm thick equivalent thermal insulation. Results have proven that these assumptions were indeed correct as the installation of 8 cm thick equivalent thermal insulation is determined to be optimal solution in scenarios 1, 4 and 7 and 20 cm in scenarios 2, 5 and 8. Annual space heating demand has been reduced from 195 kWh/m^2 in the reference scenario and scenarios 3 and 6 down to 80.3 kWh/m^2 in scenarios 1, 4 and 7; and 65.2 kWh/m^2 in scenarios 2, 5 and 8. The total heated area in the neighborhood of Trnsko sums up to 158.130 m^2. The total surface area of the building envelopes sums up to 79,484 m^2 of which 32% or 26,229 m^2 are both new and old types of windows and outside doors, as presented in Figure 7. The composition of thermal insulation costs is also presented in the same figure.

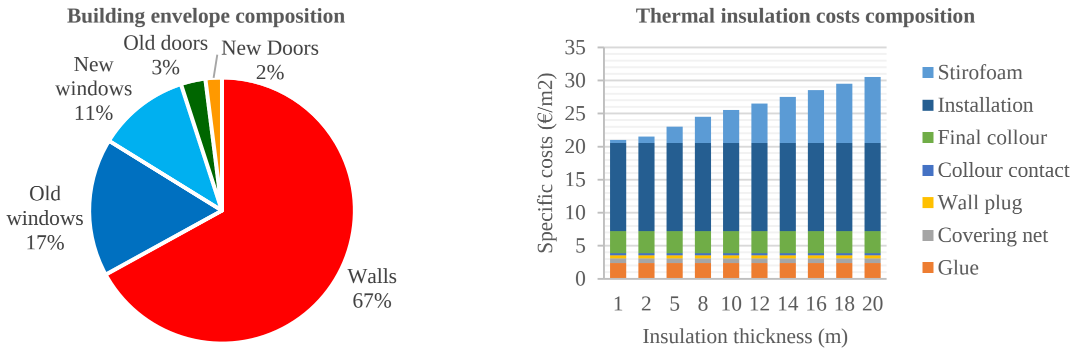

Figure 7 Building envelope composition (left) and thermal insulation costs composition (right).

Table 6 Scenario results

	Unit	Ref	Scen 1	Scen 2	Scen 3	Scen 4	Scen 5	Scen 6	Scen 7	Scen 8
HOB	kW	22,486	11,904	8,470,0	3,397	2,525	1,662	13,170.8	5,435.3	4,521.6
HP	kW	-	-	-	1,440	1,440	1,440	-	-	-
EH	kW	-	-	-	-	-	-	1,000	281.9	155.3
ST collectors	m2	-	-	-	-	-	-	6,696.7	6,696.7	6,696.7
	MWh	-	-	-	-	-	-	2,462	2,462	2,462
TES	m3	-	-	-	200,000	1,881	1,477	29,480	29,497	29,480
	MWh	-	-	-	12,000	112	89	1,768.8	1,769.8	1,768.8
Retrofit										
Envelope	m2	79,484	79,484	79,484	79,484	79,484	79,484	79,484	79,484	79,484
Heated area	m2	158,130	158,130	158,130	158,130	158,130	158,130	158,130	158,130	158,130
Annual heating demand	kWh/m²	195.9	80.3	65.2	195.9	80.3	65.2	195.9	80.3	65.2
Refurbishment rate	%	0	59	66.66	0	59	66.66	0	59	66.66
Insulation thickness	cm	0	8	20	0	8	20	0	8	20
Costs										
Annual inv. Costs	€/a	357,950	537,330	552,060	1,187,100	590,410	605,400	858,680	798,790	821,960
Operation costs	€/a	1,951,500	992,020	866,810	1,187,100	563,820	457,380	1,829,400	867,180	741,620
Maintenance costs	€/a	111,980	56,221	47,850	28,724	22,726	16,950	82,690	39,519	34,741
Cost of electricity	€/a	-	-	-	463,870	258,350	241,660	102,610	28,090	14,993
Cost of natural gas	€/a	1,818,200	924,240	807,590	433,830	142,560	65,892	1,538,000	722,100	666,420
Total costs	€	2,421,400	1,585,600	1,466,700	2,318,100	1,177,040	1,079,730	2,628,400	1,705,500	1,598,300
Average heat cost	€/MWh	65.14	83.91	88.84	58.53	62.29	65.39	70.71	90.26	97.00
Environmental impact										
HOB	t_{CO2}	8,897	4,523	3,952	2,123	697	322	7,525	3,729	3,261
HP	t_{CO2}	-	-	-	2,688	1,591	1,513	-	-	-
EH	t_{CO2}	-	-	-	-	-	-	793	219	118

Total	*t_{CO2}*	*8,897*	*4,523*	*3,952*	*4,811*	*2,288*	*1,845*	*8,318*	*3,948*	*3,379*
Specific	*t_{CO2}/MWh*	*0.239*	*0.239*	*0.239*	*0.129*	*0.121*	*0.111*	*0.216*	*0.196*	*0.188*

5.3. Component sizing and system operation

The results related to the component sizing and system operation are presented in Table 6. The installed capacities of all available technologies are in all nine scenarios high enough to cover the maximal heating demand load. The capacity of HOB is, as expected, reduced as cheaper, more efficient and less carbon intensive technologies are introduced in scenarios 3 to 8. Its lowest installed capacity of only 1.6 MW is noticed in scenario 5 where 1.44 MW HP is installed in combination with a 1,477 m^3 and 89 MWh TES. The scenario with highest solar fraction of 23 % and ST collector area of 6,696.7 m^2 is Scenario 8. Scenario with highest utilization of heat from EH is Scenario 6 where installation of 1 MW EH is proposed. The maximal available TES of 200,000 m^3 and 12,000 MWh is optimal solution in Scenario 3 while the smallest one with only 1,477 m^3 and 89 MWh is optimal solution in Scenario 5.

The diagrams on the left side of theFigure 8 demonstrate the hourly operation of the system in scenarios 3 (top), 4 (middle) and 5 (bottom) starting from the 1st January until the 31st December. The three diagrams on the right side of the figure show the load duration curves of TES, HP and HOB. As expected in Scenario 3 the optimization model is maximizing the utilization of the HP. This is due to the fact that the HPs are highly efficient technology that has relatively low operational costs. From load duration curve it is clear that HP produces heat almost during the whole year, nearly 8000 working hours. Large amounts of excess heat, produced in time periods outside the heating season, is stored in the TES in order for it to be available for consumption when necessary. . This is mainly done in order to minimize the installed capacity and total investment costs in the HP. This effect is much less pronounced in scenarios 4 and 5 which are subjected to some kind of building envelope refurbishment, and with that have a significantly reduced heating demand.

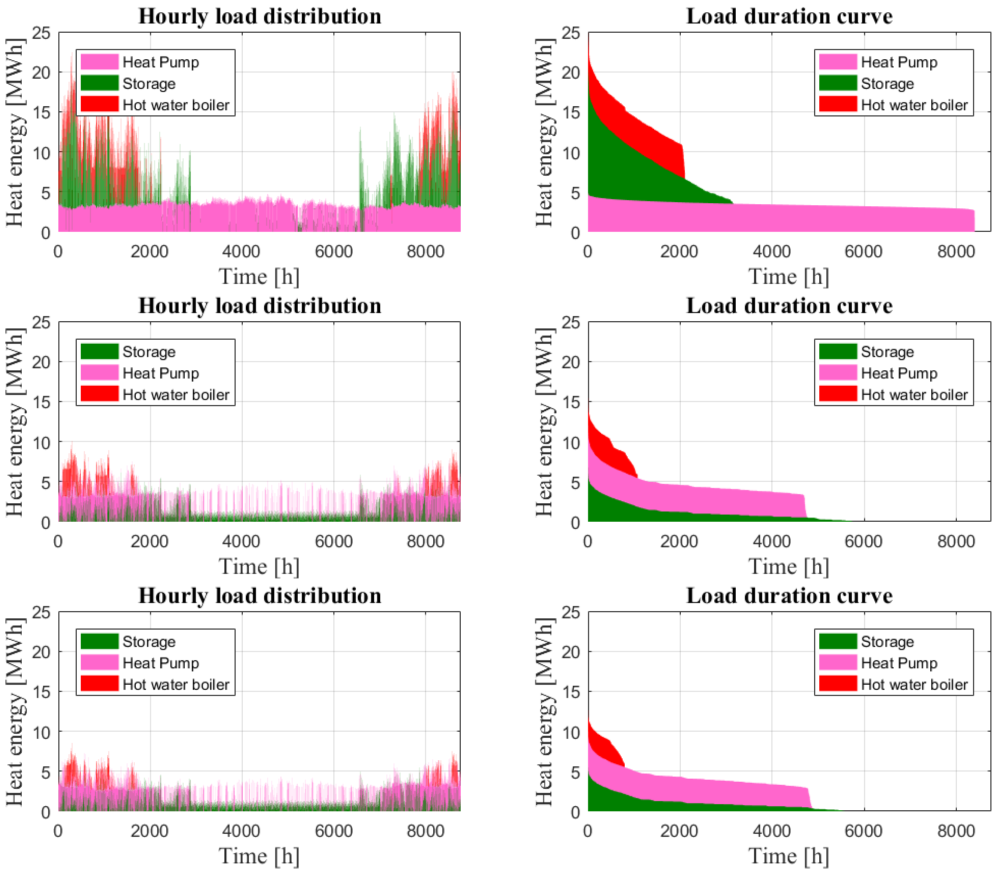

Figure 8 Hourly load distribution and load duration curves for Scenarios 3 (top), 4 (middle) and 5 (bottom)

Figure 9 presents the same set of results but for scenarios 6 (top), 7 (middle) and 8 (bottom). Due to the limitations imposed on the installation of rooftop ST collectors, which can only cover at most 60% of building rooftops and which have higher operational and installation costs than the ground ones, and the installation of electrical heaters which have high grid connection costs, these scenarios are still highly dependent on the HOB. As the refurbishment rate is increased, larger amount of the total heat demand is covered by the ST collectors and the TES while at the same time utilization of the HOB and EHs is significantly reduced.

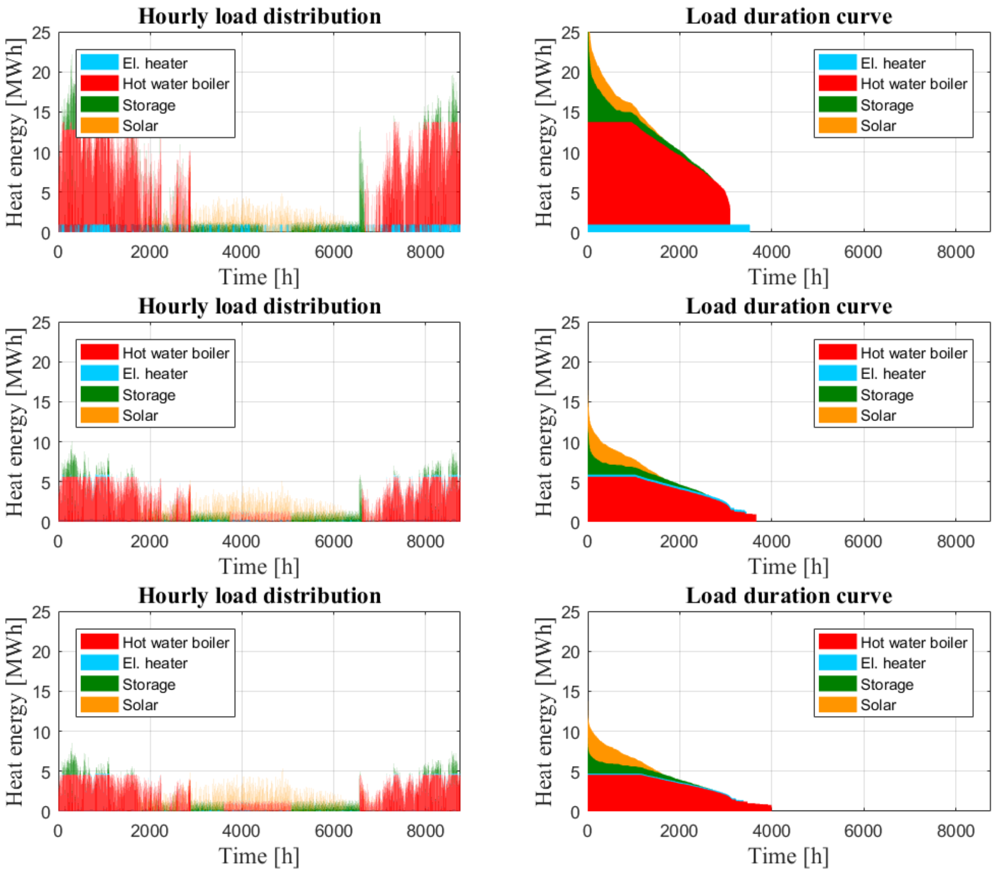

Figure 9 Hourly load duration curves and load duration curves for Scenarios 6 (top), 7 (middle) and 8 (bottom)

The hourly storage level for scenario 3 (top) and 4 (bottom) can be seen on Figure 10.This two diagrams demonstrate the models capability to choose between both large capacity seasonal storage system, as presented in scenario 3, as well as a smaller buffer storage in scenario 4. As presented in figure, the seasonal storage is being charged during the warmer period, outside of the heating season, and discharged during the heating season. The smaller buffer storage is continuously being charged and discharged according to the systems heat requirements.

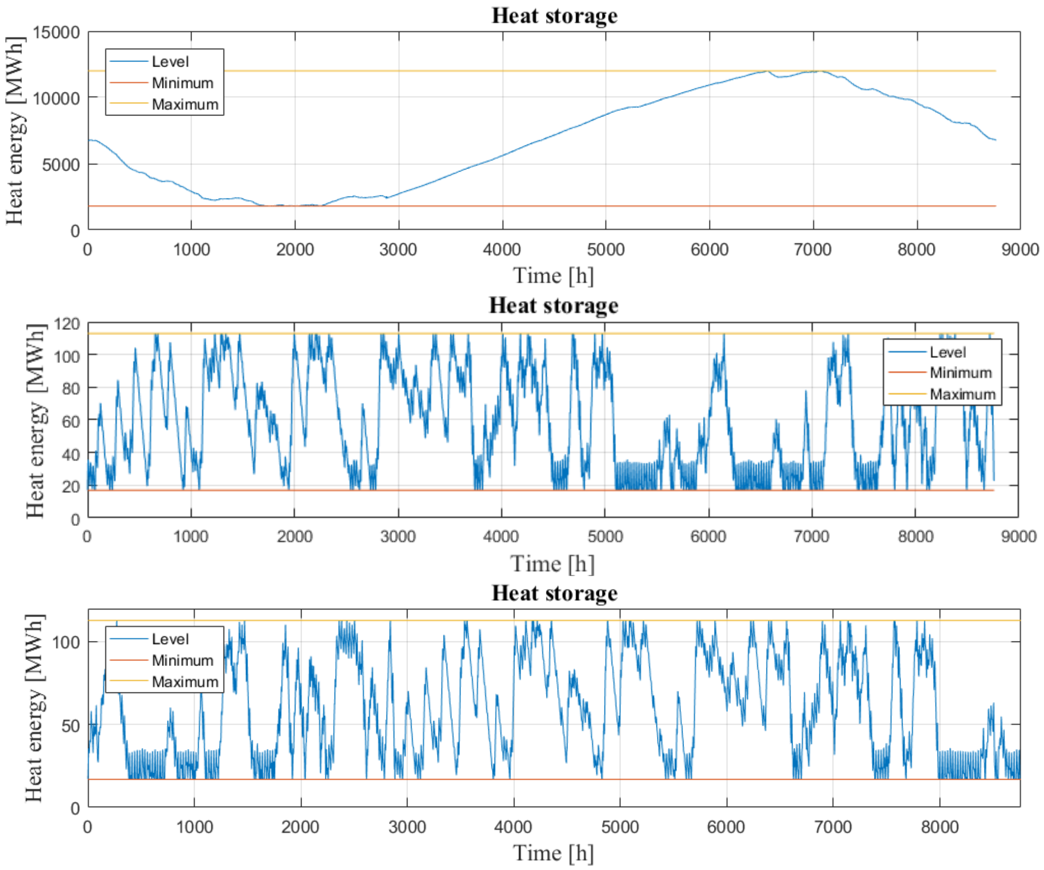

Figure 10 Hourly storage levels from Scenario 3 (top) and Scenario 4 (bottom)

5.4. Levelized cost of heat

In all nine scenarios LCOH of the total system is determined and presented in Table 6. The final LCOH in the Reference scenario totals 65.14 €/MWh. The LCOH is relatively cheap as there is no investment costs into the new DHN, nor are there any additional costs related to the building envelope refurbishment. The LCOH in scenarios 1 and 2, which do have these additional costs, are therefore higher and sum up to 83.91 and 88.84 €/MWh. The LCOH in scenarios 3, 4 and 5, which utilize heat from the HP and HOB and store it in TES, sum up to 58.53, 62.29 and 65.39 €/MWh respectively. In these scenarios LCOH are, despite the additional investments into the DH network and building envelope refurbishment in case of scenarios 4 and 5, even cheaper than the one from the Reference Scenario. These results prove that the investment into a new renewable DH system could indeed be profitable inside the observed framework. The LCOHs in the last three scenarios are much higher than LCOH from the Reference scenario and sum up to 70.71, 90.26 and 97.00 €/MWh. The main reason for such high values of LCOH is the fact in these three scenarios optimization model was additionally constrained by the total CO_2 emissions and the minimum amount of solar fraction in the system.

5.5. Environmental impact

The environmental impact in the paper is measured through the equivalent value of the total annual CO_2 emissions. As expected highest emissions of 8.897 t_{CO2} were recorded in Reference Scenario where condensing gas fired boilers are used for covering the total heating demand of the neighborhood of Trnsko. In all other scenarios environmental impact is reduced as a direct consequence of both the building envelope refurbishment that reduces the space heating demand and the utilization of renewable and P2H technologies. The most environmental friendly scenario is the Scenario 5 where the total annual CO_2 emissions of all available technologies sum up to 1.845 t_{CO2}. This sum up to only 20.74 % of the total annual emissions from the Reference Scenario. In first three scenarios, where only HOBs are used, specific equivalent CO_2 emissions of 0,239 t_{CO2}/MWh have been recorded. In all other scenarios, where RES have been used for covering some part of the heating demand, specific equivalent CO_2 emissions are lower. The lowest ones have been recorded in Scenario 5 where they amount to 0,111 t_{CO2}/MWh, which is almost 46.5% lower than ones from the Reference scenario.

5.6. Discussion

It is important to note that when left with the option to create an optimal scenario from a cost perspective and when only the technical limitations are in place, the model chooses not to refurbish the buildings envelope. It also chooses to utilize a large scale HP as well as the largest possible TES unit. The reasons behind this are primarily the high cost of refurbishment and relatively low electricity prices from the power market. This can be observed in scenarios 3 to 5 where fraction of heat from HP was above 50 %. If the model has restricted access to HPs it firstly chooses to maximize the installation of solar thermal collectors. In that case the rest of the total heating demand is covered by a combination of HOB and EHs as presented in scenarios 6 to 8. The model also choses to utilize a TES unit in almost all scenarios except the Reference Scenario and scenarios 1 and 2. Storage sizing strongly depends on the available heat technologies and the total heating demand. The TES is not utilized by the model in the scenarios where the HOB is the only heat source. This is due to the initial assumption and the setup of the system where HOB is not connected to the TES and serves either as a base heat production unit or for heat load peek shaving purposes. The overall efficiency of HOB is assumed to be constant across the whole operation range. This assumption was made with a purpose of reduction of computation time that in most scenarios exceeds 45 minutes.

6. Conclusion

This paper presents an optimization model that combines the unit commitment problem and the energy planning concept as well as building refurbishment in the planning process of a new and the evaluation of existing DH systems. It is capable of optimizing the mix and sizing of the available technologies, given the predefined constraints related to the scheduling of the system as well as the technology costs (investment, fixed and variable), efficiencies, operational parameters and GHG emissions. The model also takes into account the potential heating demand reductions, resulting from the thermal insulation of buildings, the level of which is also optimized based on the lowest total heat price. Its superstructure is divided into three substructures called modules. The first module narrows down the possible solution by ignoring tight constraints such as unit commitment, ramp up and ramp down constraints, hourly temperature variations and electricity prices by either averaging or summing necessary input data for a larger time step of several days or hours. The results from this module are passed onto the second module as input data and guiding curves representing lower bounds. In the second module, the time series of one year is divided into smaller ones which are individually optimized on an hourly level. The results related to component sizing and TES scheduling are than passed onto the third module as fixed inputs. The third module finally takes into account the tight constraints and performs the unit commitment problem optimization of the system. The whole model is cost driven from where optimal value of LCOH is obtained.

This model has been implemented on nine scenarios for the neighborhood of Trnsko which is located in the city of Zagreb. The results of this scenarios have shown the economic benefits of the utilization of highly efficient and renewable energy sources compared to a gas fired HOB. The achieved heat prices for the optimal scenario, Scenario 3, which incorporates a HP, HOB, TES and no refurbishment equals 58.53 €/MWh, which is 10.14% less than the price in the reference scenario. The CO_2 emissions in this case were 4.811 t_{CO2} annually which is a reduction of 54.07%. A deep level of refurbishment in Scenario 5 resulted in an increase of the heat price by 0.38 % compared to the Reference Scenario with a reduction of the CO_2 emissions by 79.26%.

This paper has proven that in the observed framework a DH system with a high share of renewable energy can indeed produce competitive heating prices. Furthermore, such configuration can significantly reduce fossil fuel consumption and consequently greatly impact the GHG emissions. The paper also proved that, although investment costs in thermal insulation may seem expensive, in the long run thermally insulated buildings can greatly influence planning and development of new DH systems. This is an important step for the transition from old, inefficient and fossil fuel intensive DH systems to the newer, low temperature ones which can incorporate high shares of heat from renewable energy sources. Such a transition is of utmost importance for all Eastern European cities as their current heating systems meet the need to reach higher standards on both production and consumption sides. The future work related to this paper will focus on the integration of the heating and power sector through the inclusion of additional technologies and energy markets.

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