

Performance Analysis of a Hybrid District Heating System: A Case Study of a Small Town in Croatia

**Robert Mikulandrić^{*1,2}, Goran Krajačić³, Neven Duić⁴, Gennadii Khavin⁵,
Henrik Lund⁶, Brian Vad Mathiesen⁷, Poul Østergaard⁸**

¹Department of Biosystems, Faculty of Bioscience Engineering, KU Leuven, Kasteelpark Arenberg 20, 3000 Leuven, Belgium

e-mail: robert.mikulandric@biw.kuleuven.be

²Department of Energy, Power Engineering and Ecology, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Ivana Lučića 5, 10002 Zagreb, Croatia

³Department of Energy, Power Engineering and Ecology, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Ivana Lučića 5, 10002 Zagreb, Croatia

e-mail: goran.krajacic@fsb.hr

⁴Department of Energy, Power Engineering and Ecology, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Ivana Lučića 5, 10002 Zagreb, Croatia

e-mail: neven.duic@fsb.hr

⁵The National Technical University "Kharkiv Polytechnic Institute", Frunze Street 21, Kharkiv, Ukraine

e-mail: gennadiy.khavin@mail.ru

⁶Department of Development and Planning, Aalborg University, Fibigerstraede 13, 9220 Aalborg, Denmark

e-mail: lund@plan.aau.dk

⁷Department of Development and Planning, Aalborg University, A.C. Meyers Vænge 15, Room A2, 2450 Copenhagen SV, Denmark

e-mail: bvm@plan.aau.dk

⁸Department of Development and Planning, Aalborg University, Fibigerstraede 13, 9220 Aalborg, Denmark

e-mail: poul@plan.aau.dk

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ABSTRACT

Hybridisation of district heating systems can contribute to more efficient heat generation through cogeneration power plants or through an increase in the share of renewable energy sources in total energy consumption while reducing negative aspects of particular energy source utilisation. In this work, the performance of a hybrid district energy system for a small town in Croatia has been analysed. A mathematical model for process analysis and optimisation algorithm for optimal system configuration have been developed and described. The main goal of the system optimisation is to reduce heat production costs. Several energy sources for heat production have been considered in 8 different simulation cases. Simulation results show that the heat production costs could be reduced with introduction of different energy systems into an existing district heating system. Renewable energy based district heating systems could contribute to heat production costs decrease in district heating systems up to 30% in comparison with highly efficient heat production technologies based on conventional fuels.

KEYWORDS

District heating system hybridisation, Renewable energy systems, District heating system analysis, System optimisation.

* Corresponding author

INTRODUCTION

Potential of district heating systems

A District Heating System (DHS) should be a reliable, efficient and safe system that supplies energy for space and water heating to residential homes and commercial buildings. DHS can provide highly efficient heat generation and environmental and economic benefits to communities and energy consumers [1]. DHS significantly contributes to achieve national energy policy objectives, especially those concerning increasing share of renewable sources of energy in total energy consumption [2-4]. In addition, they provide higher overall efficiencies [5] and higher customer satisfaction [6]. The research conducted by Connolly *et al.* [7] has showed that the expansion of district heating systems could decrease the European primary energy consumption by 7%, fossil fuels by 9%, and the carbon dioxide emissions by 13% while still supplying exactly the same energy services. The future potential of DHS depends on its possibility to meet heat demands through highly efficient and flexible heat production with a high share of renewable energy sources. DHS flexibility can be improved by introducing heat storage systems [8], improvement of system control technology [9] or system hybridisation [10]. The economics of DHS depends on the production cost of the thermal energy, the cost of the thermal energy distribution network (which depends on network size), DHS thermal loads and customer connection costs. DH systems are generally more feasible in densely populated urban areas with high-density building clusters and industrial complexes rather than low-density residential areas where heat demand density is low [11].

Overview of the status of DHS in Eastern European countries

In the Eastern European countries, heating systems are a legacy of the centralized economic planning and have been traditionally the most important source of heat for space heating in highly populated urban areas. However, one of the most important problems related to DHS in these countries is the high thermal plant and combined power plant operating and maintenance costs which exceeded revenue from produced heat and power. Hence district heating companies do not have economic interest to invest in system modernisation or expansion. These problems, together with the social problems and “energy poverty” (difficulty in paying the bills), are important issues that still need to be resolved. National energy plans, strategies and recommendations [12, 13] generally support development of DHS in terms of market liberalisation, reliability and efficiency improvement of the DHS, better DH regulation (heat metering, energy plans, demand forecasts) and reduction of operation and production costs. In Croatia, DHS cover around 10% of household heating requirements and it is reasonable to say that this share will increase within this decade [13]. The rest of the heating requirements is covered by small, on-site fossil fuelled, biomass or electrical boilers. Further development of DHS (especially those based on combined heat and power technology) is limited by relatively high fossil fuel prices and transportation problems, low DHS efficiency, seasonal heating character and lack of large heat consumers (industry).

Energy sources of district heating systems

It is widely accepted that the Combined Heat and Power (CHP) or trigeneration [14, 15] plants are an energy-efficient technology due to simultaneous production of heat and electricity. CHP generation may result in consistent energy conservation up to 30% [16] and could contribute to grid energy balancing processes with a large number of renewable energy systems [17, 18]. The economic viability of CHP-DH networks depends on the optimisation and engineering of the DHS, national regulatory framework [14] and financial and economic factors [20].

Renewable energy sources, especially biomass or those that are under government subsidy are slowly increasing their share. They are increasingly applied in district heating systems either stand-alone or as a supplement to traditional fossil fuels. Solar and geothermal energy are becoming also very popular in countries where their use is under subsidy. A lot of new biomass based DHS installations have been realised during the last decade, mostly in Scandinavian countries, Germany and Eastern Europe [21]. Biomass district heating systems in Eastern European countries that are EU members have been more extensively used in the last decade and there are currently more than 20 biomass DH systems in operation [22]. The share of these systems in fulfilling overall heating demand is still relatively small. Biomass based district heating systems are generally an effective way to increase the use of renewable energy sources in highly populated urban areas.

The use of the high temperature geothermal energy for heat production conserves non-renewable fossil fuels and thereby decreases emissions. The utilization modes of geothermal energy for heating in buildings can be divided into three categories: direct, step utilization and geothermal heat pumps [23]. Low and moderate temperature geothermal energy could also be used as a Geothermal Heat Pump (GHP) to increase efficiency and to reduce the operational costs of existing heating and/or cooling systems. Heat pumps use less energy than traditional heating systems because they use the earth as a heat source whose temperature is more constant than the outside air. Geothermal pump systems can reach a Coefficient Of Performance (COP) up to 6 and can reduce building's energy consumption by 30-50%, compared to the conventional electric heating [24]. Even if their temperature level is too low for direct heating purposes, they could be suitable as a heat source for heat pumps in combination with a high-temperature heat source. Geothermal energy may also be utilised in combination with heat exchangers and air heat pumps [25]. In combination with gas boilers, this technology reduces the system's total fuel demand as the efficiency of the system is higher [26].

An Air-source Heat Pump (AHP) extracts heat from the air, concentrates it and transfers it to indoors or outdoors, depending on the season. These units generally are more suited to mild climates for heating because their capacity is limited by size [27, 28]. Air temperatures fluctuate considerably, so coefficient of performance of these kinds of heat pumps varies considerably during the day. Heat pumps and, in particular systems that integrate heat pumps and cogeneration units, could offer a significant potential for greenhouse gas reduction [29, 30].

Thermal Storage Systems (TSS) comprise technologies that store thermal energy in energy storage reservoirs for later use. In district heating systems, thermal energy storage systems are mostly used for short-term thermal storages. Short term water storage in steel tanks is a traditional feature of CHP systems. The main reason for short-term storage is to balance the heat production in general, and particularly during peak load periods. Advantages of short-term thermal storage are: reduction of partial load operation and increase in power generation [3].

Hybridisation of district heating systems

The hybridisation of a DHS combines two or more renewable or non-renewable energy sources for heat production. Particular energy sources could complement each other on daily and yearly basis and therefore reduce negative aspects of a particular energy source utilisation [31]. In district heating systems, hybridisation could be performed through utilisation of renewable and non-renewable energy sources. In order to research possibilities to reduce heat production costs and to improve efficiency of a particular heating system with DHS hybridisation, several studies have been performed. Li *et al.* [32] coupled absorption heat pumps with municipal DH network and concluded

that both heating capacity and the energy efficiency of the DH system could be improved. Blake *et al.* [33] showed that a hybrid DHS that consists of a heat pump and a CHP unit offers significant reductions in fuel consumption and operational costs. Scarpa *et al.* [34] analysed the performance of a hybrid DHS composed of a heat pump and a gas boiler. A hybrid DHS composed of heat pumps and a thermal storage was analysed in research done by Pardo *et al.* [35]. Hackel *et al.* [36] studied the performance of a hybrid DHS where a ground source heat pump was combined with a gas boiler. Coskun *et al.* [9] proposed a hybrid system that is consisted of a biogas based electricity production and a water-to-water geothermal heat pump unit for improving the efficiency of geothermal district heating systems. These studies have been focused mostly on the efficiency and system design improvement.

Li *et al.* [37] analysed influence of different operation strategies of a hybrid system that consists of a centrifugal heat pump and a gas boiler on energy production costs. Pirouti *et al.* [38] showed that a DHS operating strategy has a great influence on annual DHS performance. Optimisation of district heating network configuration has been done by Li *et al.* [39]. Operation strategy of different renewable energy sources for zero CO₂ emission region has been presented by Morel *et al.* [40].

However, a comprehensive matching analysis for the hybrid energy systems that involve various energy forms on a DHS performance is still lacking [41]. In the research performed by Sundberg *et al.* [42, 43] a comprehensive analysis of a municipal hybrid energy system configuration has been conducted. However, heat demands are considered only on yearly and seasonal level and facility efficiency changes due to partial loads have been neglected.

In this work, the economic performance and the operation strategy analysis that incorporates several district heating technologies (a CHP system, a biomass based boiler, heat pumps and a thermal storage system) has been done for Pokupsko district (Croatia). Optimal operation of DHS facilities has been defined on an hourly basis. Several cases have been simulated in order to analyse economical potential of different hybrid district heating systems and optimal system configuration has been defined.

MATHEMATICAL MODEL

The scope of this work is the performance analysis of a hybrid district heating system (that will be described in the next section) in terms of distributed heat and heat production costs. A mathematical model that finds the optimal hourly heat production load of particular heat production facility in the hybrid district heating system is developed. Calculation has been performed in MATLAB[®] software package. The objective of the optimisation is to find the optimal set of heat production operation loads for particular system to meet DHS heat demand (set by goal function – eq. (1) in order to minimise costs of heat production for DHS (set by optimisation function – eq. (2)). Optimisation has been conducted for several cases of hybrid district heating system types.

The goal function is set to meet hourly (h) heat demand (P_{thDHS}) in the hybrid DHS (i) in one average day for a particular month (m). The goal function can be described:

$$P_{thDHS,hm} = \sum_{i=1}^6 P_{th,ihm} \quad \text{for} \quad i = 1 - 6, h = 1 - 24, m = 1 - 12 \quad (1)$$

The first optimisation goal is to find an optimal set of heat production operation loads in order to minimise hourly heat production cost (C_{thDHS}). Eq. (2) describes hourly expenditure for the heat production (C_{thDHS}) where investment and operation and maintenance costs are not included:

$$C_{thDHS,hm} = \sum_{i=1}^6 C_{th,ihm} \quad \text{for} \quad i = 1-6, h = 1-24, m = 1-12 \quad (2)$$

The optimisation function can be described:

$$\min C_{thDHS,hm} \begin{cases} \sum_{i=1}^6 P_{th,ihm} = P_{thDHS,hm} \\ P_{th \min,ihm} \leq P_{th,ihm} \leq P_{th \max,ihm} \end{cases} \quad \text{for} \quad i = 1-6, h = 1-24, m = 1-12 \quad (3)$$

Equations that describe a particular heat production facility performance are shown in Table 1 (eq. 4 – eq. 15). The efficiency of CHP production plant is given as a function of the ratio between delivered heat and power (eq. 4), followed by efficiency of an air heat pump as a function of ambient temperature and delivered temperature (eq. 6), efficiency of a ground heat pump where temperature of ground has been taken as constant (eq. 8), efficiency of biomass boiler as a function of thermal load (eq. 10) and efficiency of thermal heat storage as a function of heat losses (eq. 14). Eqs 5, 7, 9, 11, 13 and 15 describe heat production costs for particular DHS technology. Convection coefficient for heat losses calculation in a TSS has been calculated for slowly moving air. The average TSS area (A_6) has been determined to be 52 m²/MWh of storage capability.

Table 1. District heating facility performance

	Efficiency	Heat production cost
CHP micro-turbine [44]	$\eta_{1hm} = -0.0387 \times \left(\frac{P_{el,1hm}}{P_{th,1hm}} \right)^3 + 0.2507 \times \left(\frac{P_{el,1hm}}{P_{th,1hm}} \right)^2 - \dots$ $\dots - 0.5124 \times \left(\frac{P_{el,1hm}}{P_{th,1hm}} \right) + 0.8446$	$C_{th,1hm} = \frac{P_{th,1hm} + P_{el,1hm}}{\eta_{1hm}} \times c_1$ (5)
Air heat pump [24]	$\eta_{2hm} = -0.001 \times (\Delta T_{hm})^2 - 0.0681(\Delta T_{hm}) + 6.4311$ (6)	$C_{th,2hm} = 0$ (7)
Ground heat pump	$\eta_{3hm} = 2.7$ (8)	$C_{th,3hm} = \frac{P_{th,3hm}}{\eta_{3hm}} \times c_{el}$ (9)
Biomass boiler [22]	$\eta_{4hm} = 2.901 \times \left(\frac{P_{th,4hm}}{P_{th \max,4}} \right)^3 - 5.6066 \times \left(\frac{P_{th,4hm}}{P_{th \max,4}} \right)^2 + \dots$ $\dots + 3.507 \times \left(\frac{P_{th,4hm}}{P_{th \max,4}} \right) + 0$	$C_{th,4hm} = \frac{P_{th,4hm}}{\eta_{4hm}} \times c_4$ (11)
Electrical boiler	$\eta_{5hm} = 0.9$ (12)	$C_{th,5hm} = \frac{P_{th,5hm}}{\eta_{5hm}} \times c_{el}$ (13)
Thermal heat storage	$\eta_{6hm} = \alpha \times A_6 \times \Delta T_{6hm}$ (14)	$C_{th,6hm} = 0$ (15)

In order to calculate total hourly heat production costs (C_{totDHS} - described in eq. 13) investment, and Operation and Maintenance (O&M) costs are added. Investment, and operation and maintenance costs are averaged on hourly basis as function of total investment costs (c_{in}), yearly O&M costs ($c_{O\&M}$), economic lifetime (y) and discount rate (r). These costs are evenly distributed (and constant) through the whole year for

every hour in the year (eq. 14). Average yearly heat production costs (per MWh of produced heat) are then calculated (eq. 15).

$$C_{totDHS,hm} = \sum_{i=1}^6 C_{th,ihm} + \sum_{i=1}^6 C_{in,ihm} \quad \text{for } i = 1-6, h = 1-24, m = 1-12 \quad (16)$$

$$C_{in,ihm} = \frac{\frac{c_{in,ihm} \times (1+r)^y}{y} + c_{O\&M,ihm}}{8760} \quad \text{for } i = 1-6, h = 1-24, m = 1-12 \quad (17)$$

$$C_{avDHS} = \frac{\sum_{h=1}^{24} \sum_{m=1}^{12} C_{totDHS,hm}}{24 \times 12 \times \sum_{h=1}^{24} \sum_{m=1}^{12} P_{thDHS,hm}} \quad \text{for } h = 1-24, m = 1-12 \quad (18)$$

To solve the nonlinear constrained optimisation function with the described equations and constraints, MATLAB[®] nonlinear optimisation software has been used (FMINCON function). The detailed description of how the software works can be found in [45].

The goal of the second optimisation method is to find minimum average yearly heat production costs (C_{avDHS}) as function of DHS configuration (maximum thermal load of individual facilities). The scheme of this optimisation methodology for one considered facility is given in Figure 1. Second optimisation methodology uses investment costs, fuel costs and efficiency dependence of considered facilities as input variables. In the first iteration, maximum thermal outputs of considered facilities are assumed. Based on this information and predicted hourly heat demand for particular day in the month, the prediction of thermal storage charge or discharge is predicted. Afterwards, with use of nonlinear optimisation software for Nonlinear Constrained Optimisation (NCO) of the first optimisation function, the optimal facility operation during the year and average heat production costs are calculated. If the calculated average heat production cost is smaller than the average heat production cost that are calculated before, then current DHS configuration settings become optimal. At the end of the iteration process, the maximum capacity of the facility/facilities is increased by a certain number (defined by user) and the process is repeated. Table 2 presents input parameters related to particular investment costs, particular operation and maintenance costs, fuel costs, predicted economical lifetime and discount rate for considered DHT technologies.

Mathematical model consists of several constraints. A short description of each constraint follows:

- Power output of the CHP micro-turbine is set to be at its maximum. The goal is to maximise electricity production for high efficiency air heat pump:

$$P_{el,1hm} = P_{el,max,1hm} \quad (19)$$

- The heat production from the turbine in CHP facility is defined with the power output and thermal output ratio together with related efficiency and it is limited by the system operating characteristics. When the thermal output tends to be lower than designed minimum value, the facility is shut down:

$$P_{th\min,1hm} \leq P_{th,1hm} \leq P_{th\max,1hm} \quad (20)$$

- In cases where the air heat pump is not attached to the CHP facility, the electricity produced from the facility is sold to the utility based on current electricity prices (no subsidies) and the heat production costs are reduced by this number:

$$C_{th,1hm} = \frac{P_{th,1hm} + P_{el,1hm}}{\eta_{1hm}} \times c_1 - P_{el,1hm} \times c_{el} \quad (21)$$

- The thermal storage system is charged with heat when the heat demand is lower than the maximum capacity of a DHS. When the heat demand is higher than the DHS heat production capacity, heat from the thermal storage system is discharged. When the thermal storage system is full (over 95% of its capacity – $Q_{\sigma\max}$), the heat from the system is sequentially discharged in order to become empty at the end of a day. The thermal storage system cannot be charged and discharged at the same time (see Figure 1);

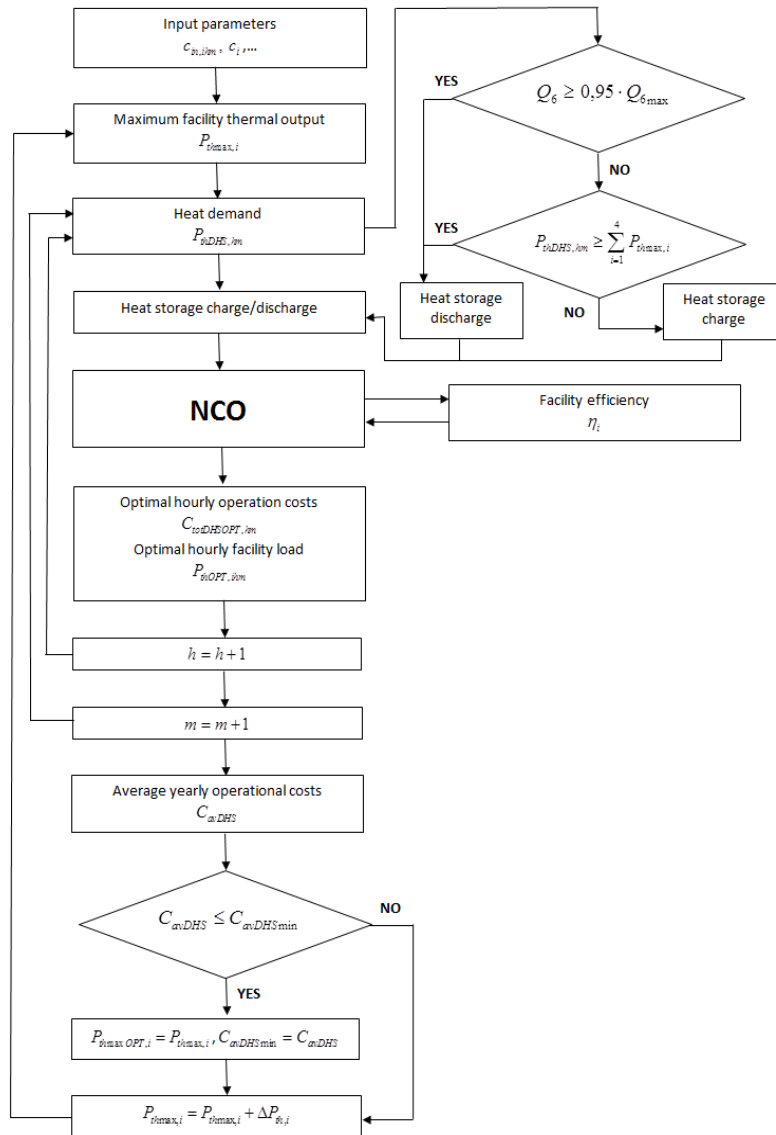


Figure 1. System optimisation scheme

- Particular facility maximum thermal output is set to be lower or equal to the maximum thermal load of the DHS:

$$P_{th\max,i} \leq P_{thDHS\max} \quad (22)$$

Table 2. Model input parameters

	CHP micro-turbine	Air heat pump	Ground heat pump	Biomass boiler	Electrical boiler	Thermal heat storage
Investment cost	890 EUR/kW _{el} [44]	590 EUR/kW _{th} [46]	500 EUR/kW _{th} [46]	520 EUR/kW _{th} [47]	0 EUR/kW _{th} [47]	3 EUR/kWh [48]
O&M costs	50 EUR/kW _{el} /a [44]	50 EUR/kW _{th} /a [49]	39 EUR/kW _{th} /a [49]	52 EUR/kW _{th} /a [49]	8 EUR/kW _{el} /a [47]	40 EUR/MWh/a [48]
Fuel cost	53 EUR/MWh _{th} [50]	0 EUR/MWh	100 EUR/MWh _{el} [51]	13 EUR/MWh _{th} [52]	100 EUR/MWh _{el} [51]	0 EUR/MWh
Economical lifetime	15 years					
Discount rate	10%					

POKUPSKO DISTRICT HEATING SYSTEM

Pokupsko district is located in the central part of Croatia, 30 km south of Zagreb (Figure 2). This region generally offers a high potential in terms of biomass and biomass residues production. The population of Pokupsko is around 2,500. Pokupsko district plans to install biomass based DH system in the near future. DHS will be used for heating and hot water purposes. There are no large industrial facilities in that region that require large amount of high temperature water or steam.

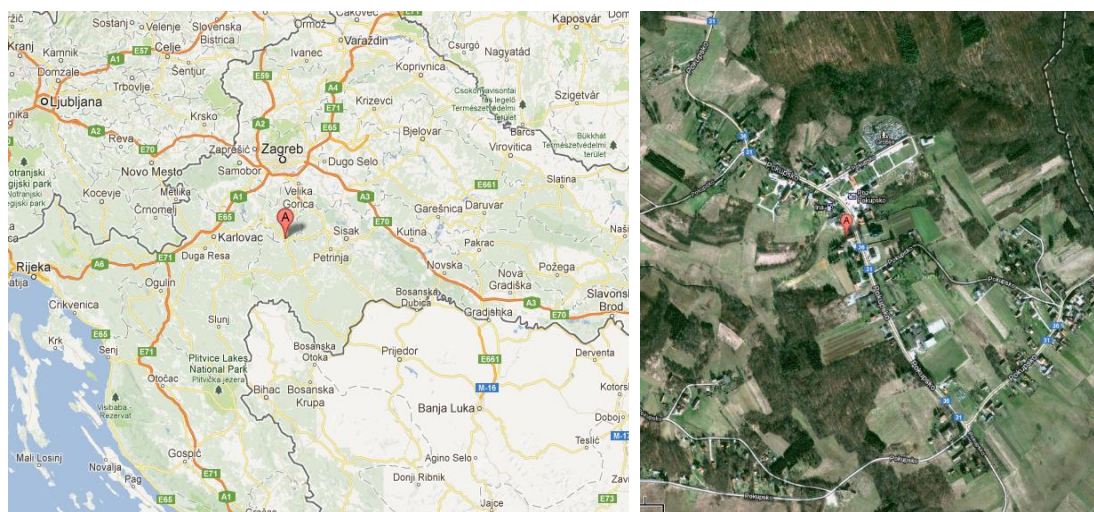


Figure 2. Location of Pokupsko district [53]

Heat produced from DHS will be used for residential household heating and hot water purposes. There are several individual heat consumers that require higher heat demand such as municipal building, elementary school and a market. A list of all heat consumers

in Pokupsko district is shown in Table 3. The daily maximum heat load has been measured for an average day in December (presented data has been collected on 16.12.2010, 4:30 AM). The maximum heat load is 1,850 kW.

Table 3. Heat consumers during the peak load in Pokupsko DHS

Consumers	Heat demand [kW]
Households (60)	470
Residential building	80
Office buildings	610
Municipal building	160
Nursery school	50
Culture municipal building	60
Elementary school	250
Church	25
Market	120
Veterinary building	25
Total	1,850

Due to absence of an industry (chemical or food industry) and requirements for high temperature water (hospitals, hotels) in Pokupsko district, lower outgoing temperature from heat production facilities could be obtained. That will also lead to lower heat losses in a district heating network. Therefore, designed outgoing temperature in Pokupsko DHS is 60 °C while returning temperature is 40 °C. Other characteristics of Pokupsko DHS can be found in Table 4.

Table 4. Pokupsko DHS characteristics

Pokupsko district heating system characteristics		
Maximum heat load	[kW]	1,850
Length of DHS network	[m]	2,940
Outgoing temperature	[°C]	60
Returning temperature	[°C]	40
Number of heat consumers	-	71

The daily heat load trajectory in January was assumed to be similar as in Zagreb district heating system [54] due to similar climatic characteristics but the actual values have been fitted to match peak heat consumption for Pokupsko district. The daily heat load has 2 peaks. One heat load peak is around 5 AM when the house heating systems are turning on and when there is higher demand for hot water. The second heat load peak is around 4 PM when people are coming home from their work (Figure 3). Heating degree days are one of the most important factors in defining heat demands for specific area. Therefore, the monthly heat load has been correlated with respect to the number of heating degree days in each month. Value of heating degree days has been gathered from [55] for Pokupsko district area. The highest peak load is in December (1.82 MW_{th}) and in January (1.7 MW_{th}) around 4 AM. During May, June, July and August heat load do not exceed 0.5 MW_{th} (Figure 3).

The analysed hybrid district heating system will consist of an electrical heating boiler (connected to the electrical grid), a biomass fired boiler, a CHP micro-turbine, a ground heat pump that will be connected to an electrical grid, air heat pumps that will be connected to an electrical generator of the gas CHP micro-turbine and a thermal storage system (hot water tanks). The heat pumps are used as separate heat sources (if they meet

the required temperature in DHS) or as water preheaters in CHP production process. Heat pumps raise the water temperature from the inlet temperature (assumed to be ambient air temperature or ground temperature) to the level that is required by DHS (in this case 60 °C). If due to technical reasons the pumps are unable to reach this temperature, then the water is sent to CHP system to raise the temperature to the required level. The hybrid DHS scheme is presented in Figure 4. The outgoing and returning water temperatures inside of the DHS network have been assumed as constant. The capacity of hybrid DHS components will be varied in order to analyse their effect on system performance.

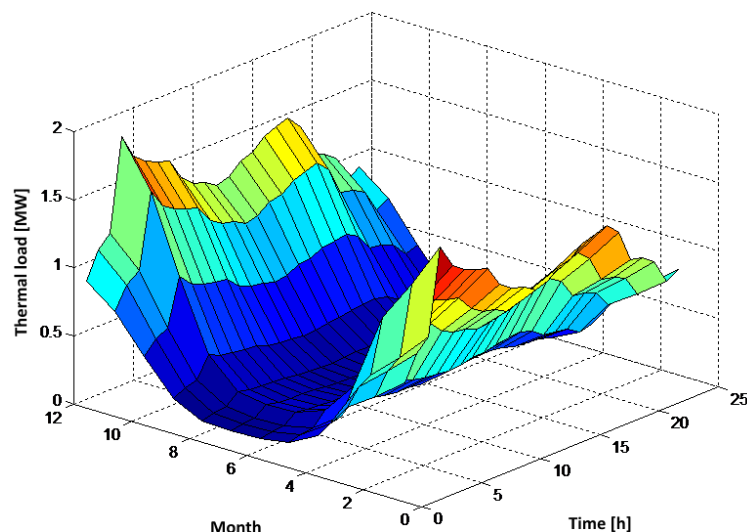


Figure 3. Daily heat load for Pokupsko DHS

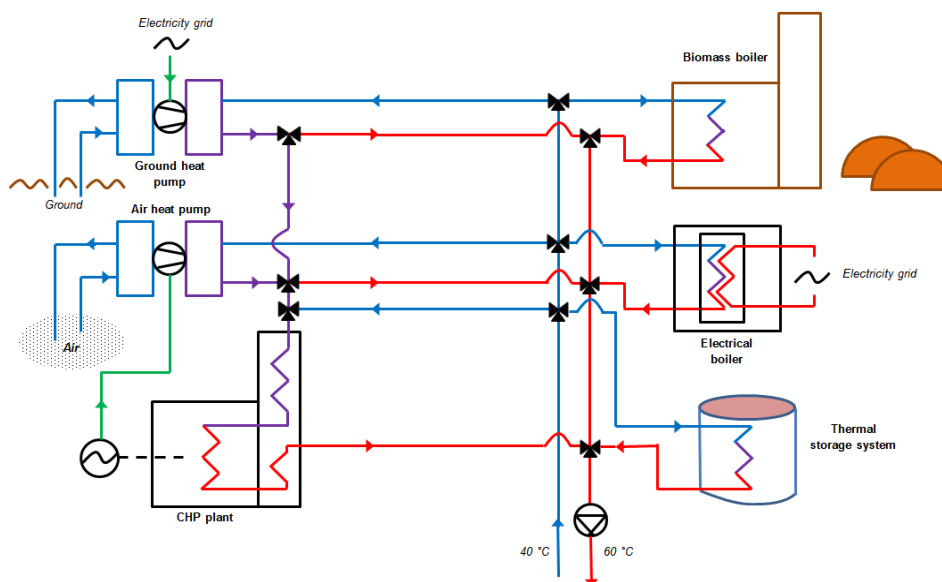


Figure 4. Scheme of hybrid district heating system

Due to variations in the heat demand, it is assumed that heat generation facilities (the biomass boiler, the CHP plant) would have to operate on different loads during the day in order to meet heat demand. Due to air temperature variations during the day (and month), air heat pumps will have variation in COP during DHS operation. The efficiency of the CHP micro-turbine is calculated as a ratio of total produced energy (heat and electricity) and total energy introduced with the fuel. It depends on operation power-to-heat ratio. In

operation, the CHP micro-turbine will have to change the power-to-heat ratio in order to satisfy the particular heat demand. The efficiency can reach up to 75% [56]. The efficiency of a biomass fired boiler is dependable on its load. On lower loads, the efficiency of a boiler is very low while on higher loads, the efficiency can reach up to 84% [57, 58]. The COP of an air heat pump mostly depends on the difference between external (ambient) and outgoing water temperature. When the difference between these two values is large, COP of the system is small. COP of AHP can reach up to 5.2 [59]. COP of a ground heat pump is constant due to relatively constant ground temperature and it is set to be 2.7 [59]. Efficiency of the electrical boiler is set to be 90%.

RESULTS AND DISCUSSION

The system optimisation method described in the mathematical model section has been performed in order to analyse the performance of different hybrid DHSs and to calculate an average heat production cost (on a yearly basis). The calculation has been done for 8 different cases that are described in Table 5. The maximum thermal output of the existing electrical boiler is fixed at 2 MWh_{th}. The air heat pump is connected to the CHP generator and its output depends on power output generated in CHP system and current COP. The total capacities of other DHS facilities have been varied in order to find optimum values. Case 1 represents the existing case. In Case 2 a proposed system without optimisation of facility capacities has been analysed (in order to show operation of first optimisation algorithms). In the other cases, optimisation algorithms for system capacity optimisation have been implemented.

Table 5. Hybrid DHS test cases

DHS configuration		CHP [MW _{th}]	Air source heat pump [MW _{th}]	Ground source heat pump [MW _{th}]	Biomass boiler [MW _{th}]	Electrica l boiler [MW _{th}]	Thermal heat storage [MWh _{th}]	Heat cost [EUR/ MWh]
Case 1	Considered	-	-	-	-	√	-	111.11
	Proposed capacity	-	-	-	-	2.00	-	
Case 2	Considered	√	√	√	√	√	-	98.35
	Proposed capacity	0.50	0.30	0.60	0.50	2.00	-	
Case 3	Considered	√	-	-	-	√	√	91.41
	Optimal capacity	1.95	-	-	-	2.00	2.00	
Case 4	Considered	√	√	-	-	√	-	90.75
	Optimal capacity	1.05	0.84	-	-	2.00	-	
Case 5	Considered	√	√	-	-	√	√	90.75
	Optimal capacity	1.05	0.84	-	-	2.00	0	
Case 6	Considered	√	-	√	-	√	-	67.35
	Optimal capacity	1.65	-	0.83	-	2.00	-	
Case 7	Considered	√	-	√	-	√	√	67.35
	Optimal capacity	1.65	-	0.83	-	2.00	0	
Case 8	Considered	√	√	√	√	√	√	64.07
	Optimal capacity	0	0	0	1.00	2.00	0	

Optimal hourly operation loads (for all 8 cases) have been calculated for an average day in every month of the year. Optimal DHS configuration has been calculated for Cases 3-8. The example of an optimal hybrid DHS operation performance during one day in January for Case 2 is presented in Figure 5. In the beginning of a day only the biomass boiler and in-ground heat pumps are in operation. The biomass boiler is on maximum load due to model constraints. The GHP is on 60% of its maximum load. Around 4 AM when the first heat demand peak occurs, in operation are biomass boiler, ground heat pump and CHP system, together with the air heat pump. The AHP and the CHP system are on their maximum load. This causes increase of a specific heat production cost due to consumption of natural gas. Around 10 AM, the heat demand reaches its local minimum. The CHP system reaches its technical minimum of heat production and it goes out of operation. It is more economically viable to turn off the CHP system (and AHP) and to turn on the expensive electrical boiler than to reduce heat output of GHP and to operate CHP system on its minimum technical value. However, it causes increase of heat production due to high cost of heat production in electric boiler. When the heat demand reaches its second peak, the CHP system is turned back into operation. Similar calculations have been performed for all 8 cases.

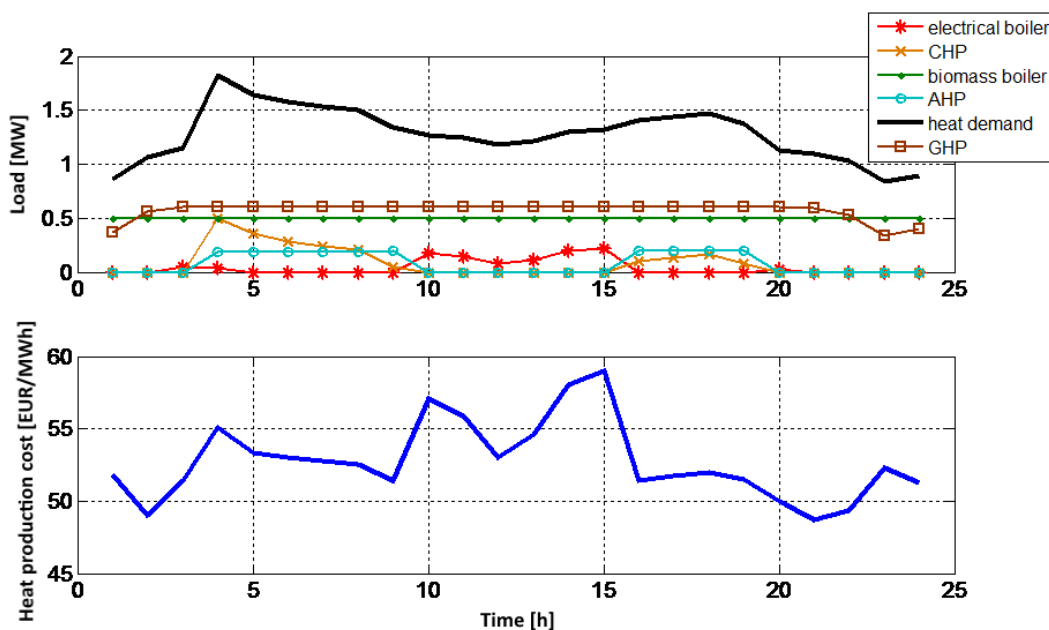


Figure 5. Operation of hybrid DHS for Case 2 (in January)

For DHS configuration optimisation, several cases have been considered (Cases 3-8). For some cases, some of the facilities have not been considered due to possible technical, environmental or other reasons. In cases where AHP is not considered it was assumed that all the electricity (that was produced by CHP facility) was sold to the utility at the normal electricity price (without subsidies).

In Case 3, where CHP and thermal storage facility have been considered, the maximum optimal thermal output of CHP facility has been set to be $1.95 \text{ MW}_{\text{th}}$. This implies that DHS is dimensioned in such a way that CHP facility could cover heat demand peaks and to operate during most of a day. The rest of the energy that is produced by CHP facility is stored in thermal storage system.

With introduction of AHP (that is connected to CHP system like in Cases 3 and 4) the necessity for thermal storage system drops and the heat production costs are reduced by 0.7%.

DHS where CHP facility and ground heat pump are in operation (Cases 6 and 7) shows a higher reduction in heat production costs. The maximum thermal output of CHP facility is reduced in comparison with Case 3 but increased in comparison with Cases 4 and 5. The flexibility of DHS has been improved with introduction of GHP which is now utilised to cover high heat demands and low heat demands during summer season.

In Cases 3-5, lower heat demands were covered by electrical boiler due to technical constraints of the CHP system. Due to high investment costs in thermal storage system, it is not economically viable to install such a system (under considered conditions) into DHS with CHP and GHP facilities.

In Case 8, all facilities were considered. However, the optimal system configuration comprises of 1 MW_{th} biomass boiler which is used to cover low heat demands and heat demands during most of the year. To cover high heat demands the combination of biomass and electrical boiler is used. Heat production costs are reduced by almost 30% in comparison with DHS with only a CHP facility and more than 40% in comparison with the DHS with only an electrical boiler.

Simulation results from Cases 1-8 show that with current investment and fuel costs (Table 2) it is most economically viable to utilise biomass boiler together with electricity boiler for given heat loads. If biomass is not available then the optimal system configuration will consist of a CHP facility and a GHP. However, the heat production costs in that case will be increased by 5%. Simulation results also show that a DHS that consists of CHP facility together with TSS has a lower heat production cost than a DHS without TSS.

Heat production cost and the DHS operation performance from the Case 8 have been shown in Figures 6 and 7. During the winter, heat production costs are below 70 EUR/MW_{th}. This is a result of extensive use of biomass boiler. During the summer when the heat demand is low, specific prices for heat production are much higher. This is a result of averaged (on hourly basis) investment and O&M costs that are introduced in heat production costs during lower heat demands. In this case, only the biomass boiler is utilised for heat production. During most of the year, heat demand is covered with operation of the biomass boiler. Electrical boiler is used only to cover peak loads during the winter season.

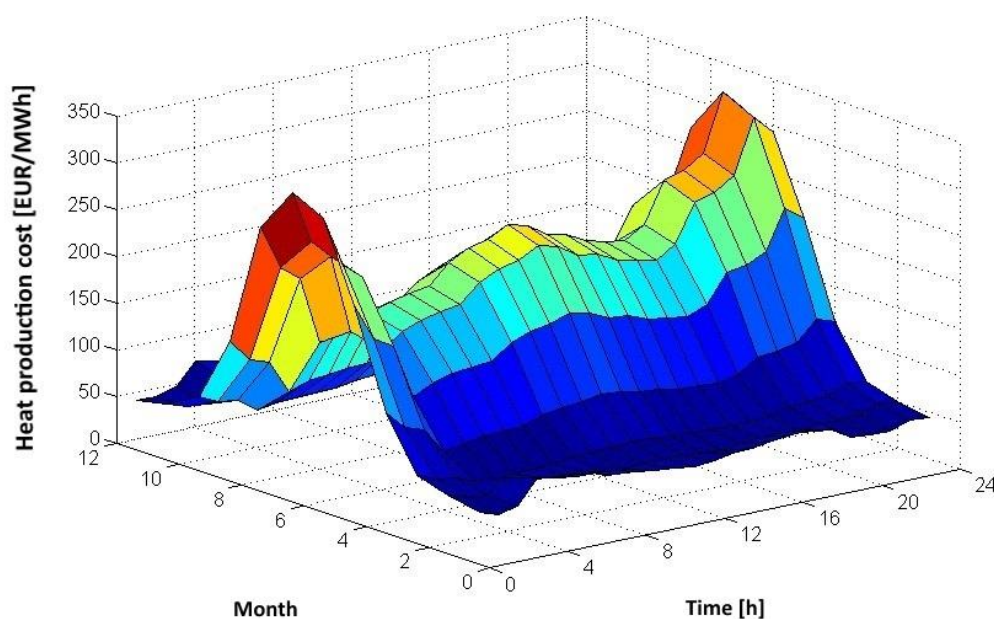


Figure 6. Heat production costs for Case 8

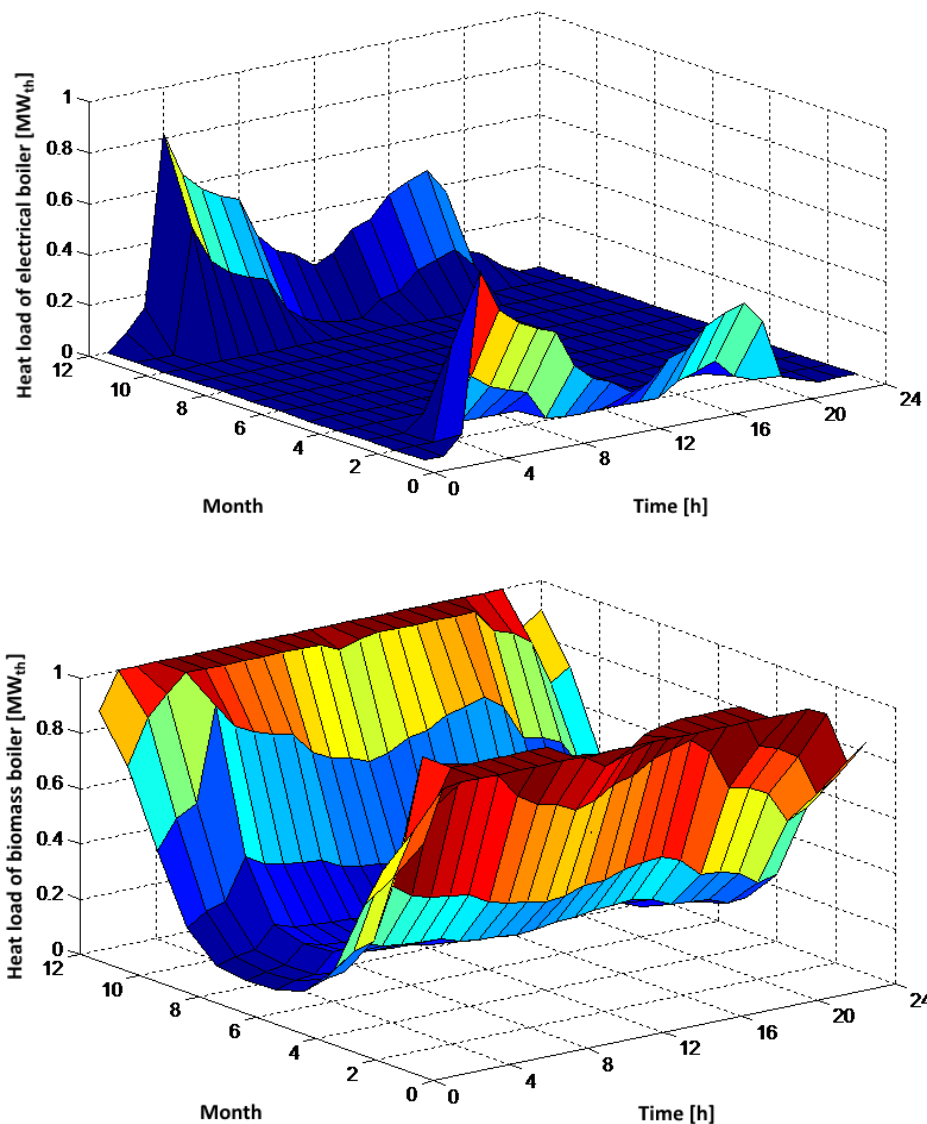


Figure 7. Optimal system operation for Case 8

Due to the methodology that has been used in this research, the accuracy of the determination of final heat production costs can be compared with the uncertainty of specific facility efficiency, investment costs, O&M costs and fuel costs that can be found in [22, 24, 44, 46-50]. For instance, investment costs for small CHP plant can range up to $\pm 25\%$, for biomass boiler up to $\pm 15\%$ and for AHP and GHP up to $\pm 10\%$. Therefore, a sensitivity analysis of the optimisation model has been performed. For sensitivity analysis, several cases have been considered (Cases 9-12), described in Table 6. For each case an optimal system configuration and yearly averaged heat production price has been calculated. All facilities have been considered for possible implementation.

In Case 9, changes have been made in order to moderately encourage implementation of the heat pumps and thermal storage system. Despite the fact that the investment costs in such systems have been reduced, the optimal system configuration has not been changed considerably. Due to electricity cost increase, it is more economically viable to install a biomass boiler with higher maximal output to cover more heat demand during the year. Due to increase of biomass fuel prices, averaged heat production costs have been increased in comparison with Case 8.

In Case 10 the implementation of heat pumps and heat storage systems is encouraged even more. Therefore, the maximal thermal output of biomass boiler has been reduced and a GHP has been introduced. Due to a high increase of biomass fuel price and higher consumption of electricity, the average heat production costs have risen significantly.

In Case 11, where the implementation of heat pumps and heat storage systems has been highly encouraged, the system configuration has not been changed significantly. Due to smaller investment costs, the share of GHPs in fulfilling heat demand has been increased. Due to higher electricity prices (GHP consumes electricity from the grid) the heat prices have been increased. The overall impact of electricity cost increase on heat production price has been reduced with implementation of GHPs.

In Case 12, due to high electricity prices it is more economically viable to produce electricity from CHP system to power AHP than to use electricity from grid to power GHP. In Case 12 the DHS comprises of different technologies which shows that under conditions from Case 12 (described in Table 6) a hybridisation of DHS is highly encouraged. The overview of simulated average heat production costs for different cases is presented in Figure 8.

Table 6. Sensitivity analysis

	Case 9	Case 10	Case 11	Case 12
CHANGES				
Biomass price	+30%	+150%	+150%	+200%
Gas price	+10%	+20%	+25%	-5%
Heat pumps investment costs	-15%	-25%	-40%	-40%
CHP and biomass boiler investment costs	-5%	-10%	-15%	-5%
Thermal heat storage investment costs	-10%	-20%	-30%	-40%
Electricity cost	+15%	+20%	+75%	+100%
OPTIMAL VALUES				
CHP [MW _{th}]	0	0	0	0.11
Air heat pump [MW _{th}]	0	0	0	0.09
Ground heat pump [MW _{th}]	0	0.05	0.30	0.1
Biomass boiler [MW _{th}]	1.20	0.90	0.90	0.90
Thermal heat storage [MWh]	0	0	0	0
Heat production costs [EUR/MWh _{th}]	66.89	86.05	88.17	98.55

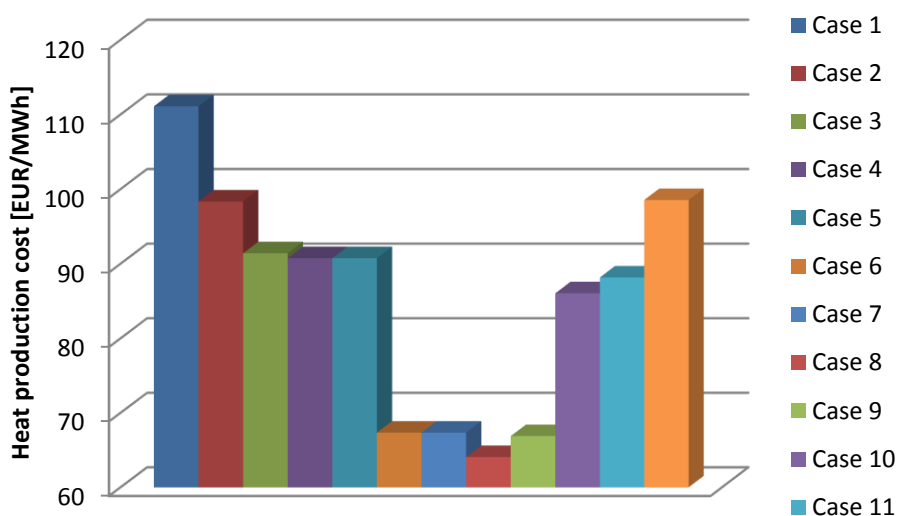


Figure 8. Average heat production costs for different cases

With introduction of renewable energy sources (especially biomass and GHPs as in Cases 6-8), the average heat production costs are reduced in comparison with DHS that are comprised of non-renewable energy systems (Cases 3-5). Even with potential situations that are not favourable for biomass based DHS (Cases 9-11) the heat production costs are still lower than in CHP based DHS where the electricity is sold at current market price. The heat production costs are dependent on electricity cost (for heating purposes) but its influence could be reduced with implementation of different types of DHS configuration. With increasing biomass prices the increase of heat pumps share in DHS should be expected.

CONCLUSION

In this work, the economic performance of different types of a hybrid district heating system has been analysed. District heating systems have high potential as highly efficient and economically viable means of heat production. District heating systems have the possibility to implement larger amount of renewable energy in the existing energy system. A hybridisation of a district heating system combines two or more different (renewable or non-renewable) heat production systems that could complement each other on daily and yearly basis. To analyse the economic performance of a hybrid district heating system in Pokupsko district, a mathematical model has been developed. In comparison with the optimisation models from literature, the developed model enables optimisation of district heating system configuration and operation on yearly, monthly and daily basis where various district heating technologies can be considered. Simulation results from 8 different cases show that a hybridisation of district heating system has potential in terms of heat production cost reduction. The hybridisation of an existing district heating system with renewable and/or non-renewable based systems can reduce average heat production costs and improve the flexibility of the system. The effects of novel heat production technologies or waste heat utilisation in a district heating system could be analysed in future.

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NOMENCLATURE

A	area	[m ²]
c	fuel costs	[EUR/MWh]
C_{avDHS}	averaged total heat production costs	[EUR/MWh _{th}]
C_{in}	investment and operation and maintenance costs	[EUR/MWh _{th}]
c_{in}	specific investment cost	[EUR/kW]
$c_{O\&M}$	specific operation and maintenance costs	[EUR/kW/a]
C_{th}	costs of heat production	[EUR/MWh _{th}]
C_{thDHS}	total costs of heat production	[EUR/MWh _{th}]
C_{tot}	total heat production costs	[EUR/MWh _{th}]
i	hour in a day	[-]
j	month in a year	[-]

P_{el}	electrical output	[MW _{el}]
P_{th}	thermal output	[MW _{th}]
P_{thDHS}	heat demand	[MW _{th}]
$P_{th\max}$	maximal thermal output	[MW _{th}]
$P_{th\min}$	minimal thermal output	[MW _{th}]
Q	stored energy	[MWh]
r	discount rate	[%]
ΔT	temperature difference	[°C]
y	economic lifetime	[years]

Greek symbols

η	efficiency	[%]
α	convection factor of a slowly moving air	[W/m ² K]

Subscripts

el	electrical
i	number that represents facility type
h	hour
m	month
\max	maximal
\min	minimal
OPT	optimal
th	thermal

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