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Integration of large-scale heat pumps in the district heating system of Skopje

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Abstract *In the residential sector in EU countries space heating and domestic hot water system participate with more the 80% in the final energy consumption. Cost-effective and energy efficient option for residential and commercial buildings is DHC which is currently dominated by fossil fuels, such as coal and gas. Upgrading existing systems with integrating renewable technologies can lead to significant benefits regarding climate change mitigation, energy security and human health. The main aim of this paper is analyzing the possibilities for integrating heat pump together with thermal storage in the district heating system in Skopje, R. North Macedonia, considering current network system, growing population, climate conditions and pollution issue. Different scenarios will be analyzed by changing the COP of the heat pump in order to get an overview of the most feasible option taking into consideration the heat production, electricity consumption and payback period. The energy model is developed and analyzed for the part operated by Balkan Energy Group. It tends to provide insight of the benefits provided by the system upgrade and cost analysis for installation, operation and maintenance of the equipment.*

Keywords *heating, heat pump, thermal storage*

INTRODUCTION

In the final energy consumption 50% attributes to heat used in the residential and industrial sector [1]. Space heating and domestic hot water system in the residential sector in EU countries participate with more than 80% in the final energy consumption [2]. The renewable sector provides still modest 16% of the total energy consumption in the EU because it is still based on fossil fuels [3].

Heating and cooling are required throughout

the year, but demand depends on climate conditions. In cold climates, home heating in winter accounts for the majority of energy use in buildings, whereas in hot climates, cooling is needed in the summer months. In every region, hot water is needed throughout the year. In most countries, these needs are met by decentralized heating or cooling systems, such as boilers or air conditioners, installed in buildings [4]. Individual heating solutions only allow one specific type of fuel, e.g. coal, oil or natural gas and mean that the heating bill is fully financially exposed to price increases of a specific fuel.

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Deaistrict heating (DH) is a cost-effective and energy efficient solution which can provide at least half of the total heat demand in the 14 countriros [5]. With DH, it is possible to achieve independence from fuel import and

CO₂ targets, as well as take advantage of the free-market forces driving price changes on different types of fuel [6]. However, DH supply in general is currently dominated by fossil fuels and needs time to become decarbonized. Several studies have shown that the potential to make it more efficient and renewable is very high achieving significant benefits for energy security, human health and climate change mitigation.

According to the Heat Roadmap Europe 2050 scenario, DH is supplied mostly by decarbonized energy sources and 25% of the total DH demand is met by large-scale heat pumps (HPs). Based on the project results (HRE4) it is suggested that large - scale HPs could have a big role in future DH systems, providing flexible and supply safe systems making DH systems meet rising urban energy needs, improve efficiency, reduce emissions and provide cost-effective temperature control [5].

Cogeneration and large-scale HP are the main sources for DH supplying around 38% and 25% respectively considered data from over 14 countries [7]. They possess their own set of low-carbon benefits offering supply of both low-carbon electricity and low-carbon heat. Combined heat and power and renewable energy sources (RES) represent a series of proven, reliable and cost-effective technologies that are already making an important contribution to meeting global heat and electricity demand and are fully technically capable for implementing in other systems in Europe [8-10]. HPs have the potential of establishing connections between different energy systems such as the electrical grid, the gas grid and the DH grid providing increase of the flexibility of the CHP and the profitability of existing heating networks [5]. Also, they can be the link between the need for cooling and the need for heating. By adding thermal energy storage (TES) tank to the system the excess heat produced during summer months by the HP can be used during winter periods when the heat demand is greater [11].

The potential of HPs in meeting the cooling needs is given in study [10] which shows that 49 units out of 143 supply cold water in district cooling networks. The cooling sector is

developing and growing fast and is expected to double until 2050 mainly in the service sector, such as hospitals, schools, offices and commercial buildings. This means that the connection between cogeneration heating plant (CHP) and large-scale HPs for 'cold storage' can have future prospects [10].

Studies suggest that DH, together with thermal storage and large-scale HPs, is more feasible, fuel-efficient, and cheaper than individual solutions in areas with high urban density. Together with cogeneration they can respond to both high and low electricity availability hours and both high and low heat demand hours [5].

BACKGROUND

DH systems provide hot water to commercial, residential, service buildings as well as to industrial users, and heat for space heating. Heat is generated centrally by a CHP and distributed to the consumers by network of pipelines. CHP can use different types of fuels, both fossil and renewable-based fuels and can operate at high level of fuel utilization. CHP technology can be distributed quickly, almost without geographic limitations, can provide highly efficient process heat and electricity. The heating network pipelines are usually made of polyurethane and are designed for a maximum supply temperature of 130 °C because it is the highest temperature that the material can withstand in continuous operation [12].

The classification of DH system may be done based on many parameters, as: size of the DH system depending on the length of the piping system, number of substations or number of connected consumers; historical developments in geographical regions; technology generations (1st, 2nd, 3rd and latest 4th generation); technical issues as: heat generation (centralized, decentralized), heat distribution (steam, water), heat consumption (direct/ indirect system), operational temperature level etc. [13].

According to the temperature levels the DH systems can be divided into several categories: High Temperature DH Systems, abbreviated as HT, with supply and return temperature of

100/50 °C accordingly; Low Temperature DH Systems, abbreviated as LT, 80/40 °C; Very Low Temperature DH Systems, abbreviated as VLT, 60/30 °C; Ultra Low Temperature DH System, abbreviated as ULT, 45/30 °C; Thermal Grids, abbreviated as TG, 28/8 °C; and District cooling systems, abbreviated as DCS, 10/15 °C [14].

HP projects in connection to DH can be complex and very different. There are a lot of different types and possibilities in relation to heat sources and temperature levels as well as in which part of the DH grid they are implemented. According to the latter there are two main ways of integrating HPs into the thermal networks, centralized and decentralized integration. Centralized integration is when the main large capacity feed-in points are few or one. On the opposite, the decentralized integration is composed of smaller generation technologies on many locations in the network. If the integration is centralized the mitigating circumstance is that the required infrastructure is available and needs small adjustments [14].

According to historical data the first case where large HPs embedded and were used to supply district heating systems was in Switzerland in 1942. The installation was composed of three units providing total heat capacity output of 5.9 MW. Afterwards, in the beginning of 1980s the interest in use of large HPs in DH systems was growing, while the peak in the use of power-to-heat plants occurred in 1990 when it supplied more than 30% of the heat demand. Nowadays, this share is around ten percent represented only by the large-scale HPs. Countries with highest HPs capacities installed in DH are Sweden, Denmark, Norway, Italy, Finland, and China [15]. Historically, HPs with greater capacities as of 16 MW were installed in the period 1980-2000, whereas HPs with capacities of approximately 5 MW were popular until 2016 which according to the study is due to the refrigerant used. In the case study for this paper are predicted several HP units with total capacity of 20MW [10].

The main types of HPs are compression and absorption HPs. A compression HP is used to supply to energy sink with higher temperature

heat than those provided by heat source, usually using a compressor to perform the additional work [16]. Additionally, HPs differ according to the heat source and can use internal or external heat source. External sources bring energy into the system from outside, while internal sources do not bring additional energy to the system [14]. Whereas, the three general types of heat sources of HPs are water, air and ground sources, whereas there is huge variety in terms of their deviation inside these divisions, as sewage water, ambient water, geothermal heat, flue gas, industrial excess heat or solar heat storage etc. [10,17]. Industrial excess heat is a low temperature heat recovery deriving from the industrial processes and its temperature range is 15–40 °C. Lake, river, sea water and groundwater belong to the category of ambient water and their temperatures usually depend on the seasons and very between 2 to 14 °C. Sewage water is generated by human activity and is treated before being used in the system. The temperature range of sewage water is from 12 up to 20 °C [15]. HPs vary based on the refrigerants used where the global split is to synthetic and natural refrigerants, and as expected in the later years HPs using natural refrigerants are encouraged due to different EU regulations [18].

The way to evaluate the HP performance is using the coefficient of performance (COP) which is a quotient between the heating or cooling energy provided to electrical energy consumed and usually is in the range between 3 and 4 [16, 19]. Current world research is implemented in order to improve the HPs efficiency because several percent increase of COP gives considerable savings in the operation of the HPs and increases the environmental impact [20]. The COP of the HPs is dependent from the source of energy, technological solution, temperature levels and other parameters. The capacity of the HP depends on the DH system characteristics and is usually selected based on the heat load demand ranging between 50–70% ($k=0.5-0.7$) of the max heat load demand [21].

MODEL DEVELOPMENT

Based on the Survey conducted by the State Statistical Office on energy consumption in

Households in R. Macedonia, it was obtained that the average specific consumption in 2014 in the Households was around 160 kWh/m², and it is projected that with the implementation of the obligations from the EE Law it will converge to the EU level in 2018 – 112 kWh/m². For comparison, the highest energy consumption in 2014 for heating in Households in the EU was 188.8 kWh/m² consumed by Luxembourg and the average consumption was around 115.5 kWh/m². Until 2018 the average heating consumption in Households decreased by 3 kWh/m², amounting 112 kWh/m² and the highest heating consumption was realized by Latvia with 178.6 kWh/m². The overview of the average heating energy consumption of Households per heating area in the EU in a time period from 2000 until 2018 and in Macedonia for 2014 and 2018 is given in Figure 1 below [22].

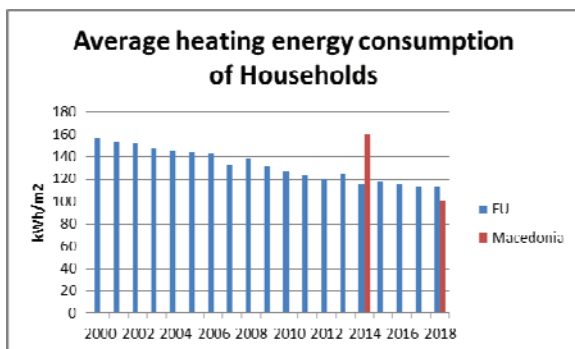


Fig. 1: Overview of the average heating energy consumption of Households from 2000 till 2018

Figure 2 shows the annual demand for heating energy for Skopje divided by months, as well as the electricity produced by the CHP „TE-TO“ AD Skopje for 2019. As expected, the heat demand is highest during the winter periods especially January and December, whereas from May till August the heat demand equals zero.

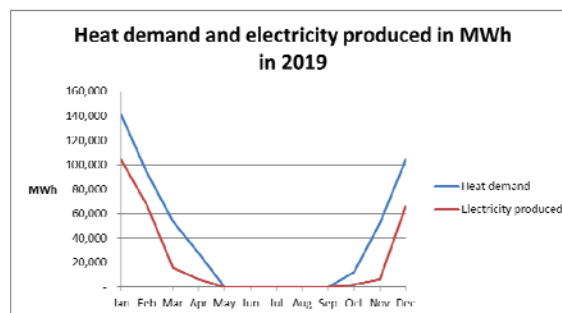


Fig. 2: Energy balance by BEG for 2019

The DH system of the city of Skopje meets the heating needs of about 40% of the city, with a total connected heat capacity of 630 MW, which consists of three independent heating systems operated by: Balkan Energy Group, ESM Energetika and Toplifikacija Skopje North.

The main aim of this study is analyzing the possibilities for integrating HPs in the DH system of the capital city Skopje, considering climate conditions in R. Macedonia. Therefore, energy model for the DH system in Skopje was developed and analyzed for the part operated by Balkan Energy Group (BEG).

Namely, the largest central heating system is the one operated by BEG, which connects active consumers with a total capacity of 450 MW and disconnected customers (possible quick connection to the system only by opening the valves) with a capacity of 100 MW. The BEG system actively operates two heating plants with hot water boilers and one combined thermal power plant (TPP).

Heat generation in DH system operated by BEG is provided by three heating plants and one CHP, as follows: HP „Toplana Istok“ is located in the eastern industrial zone of the city, with installed hot water capacity of 279.12 MW and HP „Toplana Zapad“, located in the western zone of the city, with installed hot water capacity of 162.82 MW. The HP “11 Oktomvri” has installed hot water capacity of 28.25 MW and it is preserved - not in function since 2015. The total available installed hot water capacity of the heat plants is 470.19 MW. The CHP „TE-TO“ AD Skopje has combined cycle gas turbine (CCGT) with installed heat thermal capacity of 160 MW for district heating and electrical power of 220 MW. It is located in the

immediate vicinity of „Toplana Istok“. It should be noted that the „TE-TO“ AD Skopje is an unregulated producer of thermal energy and its participation in the system primarily depends on the market conditions of profitability of the plant. As average the yearly heat production of the system is around 500 GWh_{th} whereas the share between the heat from CHP plant and heating plants in total heat production is variable, considering yearly variations in the factors influencing the operational feasibility of the CHP.

The production of thermal energy in the heating plants is realized through hot water boilers that work on natural gas as primary fuel, while as a reserve fuel in case of lack of natural gas they can also operate on fuel oil. The produced heat energy in the heating plants is distributed through the distribution network with a length of about 200 km to the end users, through 2700 heating substations. [12].

In the DH system, two distribution pipelines are directly connected, which creates a connection between the two heating plants, as follows: Pipeline B from heating plant „Toplana Istok“ is connected to the pipeline „Partizanska“ from heating plant „Toplana Zapad“, where the connection is provided by a pumping station, ie a pump placed on the bypass of the pressure line B in the direction of flow towards heating plant „Toplana Zapad“. Pipeline A from heating plant „Toplana Istok“ is connected with the pipeline Kozle from heating plant „Toplana Zapad“.

This study considers the possibility for coupling DH system and CHP with RES by adding HPs and TES as complementary solution to the system, as well as analyses the cost-effectiveness of the existing heating system upgrade for Skopje city with four scenarios containing different technical characteristics. The benefit of integrating HPs in the DH system which is connected to CHP is that the process can be adjusted in order to optimize the efficiency, according to the use of RES as well as to the electricity/ fuel prices.

In this case the HP would be supplied with electricity needs from the CHP, whereas the excess heat produced would be stored in the heat storage tank and used in case of necessity.

The idea for the HPs is to cover the peak demands of heat energy and use them as addition to the base heat energy produced by the boilers and CHP. The planned HPs would be electric large-scale HPs with total electrical capacity of 20 MW. Depending on the considered scenario the COP of the HPs would be variable in the range between 3 and 4. That is an average practical COP of a HP according to [10]. The output temperatures of the HP are defined by the DH system and vary between < 70 °C and > 80 °C, which should be taken into consideration when defining the HPs technical characteristics.

As a modeling software for the dynamic simulations is used TRNSYS (Transient System Simulation). The general scheme of the model development is presented on Figure 3.

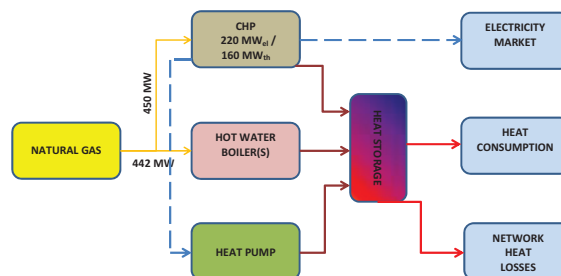


Fig. 3: Scheme of the system including heat pump and heat storage tank

The main application of tank storages is for buffering daily peaks. The DH network pressure level and the main source temperature are most relevant for pressure and temperature levels of the TES. Generally, the tanks for hot water storage can be separated into 3 major types: unpressurized storages with maximal temperature of 98 °C; 2-zone storages with highest temperature up to 120 °C; and pressurized storages with temperature no more than 150 °C. Empirical formula used for dimensioning a heat storage given in [12] is 50 m³/MW peak load of thermal output. Generally, the storage capacity of heat storage tanks is designed to cover from 5 to 12 h [12].

The control strategy of the system is choosing the heat sources that can provide heating energy with the lowest production price at the considered moment. Therefore it is analyzed

the influence of the TES integration, as a potential measure to increase the flexibility of the CHP and HP in providing heat energy. The planned TES in the analyzed scenarios is foreseen to have 10,000 m³ water storage capacity, with operating temperatures of 90 °C at the top and 50 °C at the bottom. The water would be heated using HPs and used to charge the heat energy store. In the work process of the thermal storage it is important to follow the thermodynamic properties of the tank, to check the yearly energy balances and the interaction of the tank with the environment [11].

Nevertheless, TES embedded in the DH systems are conventional and cost-efficient technology that provide flexibility in power systems [24, 25].

As previously mentioned, four different scenarios will be analyzed as follows:

- scenario 1 – DH system with HPs of 20 MW with COP 4 and storage tank of 10,000 m³;
- scenario 2 – DH system with HPs of 20 MW with COP 3 and storage tank of 10,000 m³;
- scenario 3 – DH system with HPs of 20 MW with COP 4 without storage tank; and
- scenario 4 – DH system with HPs of 30 MW with COP 3 and storage tank of 10,000 m³.

In the presented scenarios hourly values for heating power and the temperature regime of the heating system are given as measured values i.e. the HP maximal outlet temperature is set at 75°C. Also, the hourly market prices for electrical energy from HUPEX exchange are used for the same year for which the data for the heating system is given. The CHP is optimized depending on the electricity price if it will deliver heat to the network when the electricity price is acceptable, or it will supply the HPs and thermal energy to the heat network. In the case if there is no need for heating energy to the DH system the heat is accumulated in the TES which is the main idea behind the integration in the system.

In order to calculate the gained net cash from the operation the following financial parameters were taken into consideration:

- price for purchase of natural gas 0.32 €/nm³,
- price for maintenance of boilers 10 €/MWh,
- price for maintenance of CHP 6 €/MWh,
- price for maintenance of HP 15 €/MWh,
- price for heat energy sold 53 €/MWh,
- electricity price for HP operation 53 €/MWh
- price for electricity on spot market – HUPEX 2019

The model intends to provide insight of the benefits provided by the system upgrade and cost analysis for installation, operation and maintenance of the equipment [7].

RESULTS AND DISCUSSIONS

In general, the parametrical analysis is directed toward estimation of the influence of the HP efficiency (COP) and implementation of TES on the overall system performance and cost-effectiveness. On Figure 5 are presented the results gained from the model simulation regarding heating energy share by heat source for each of the previously defined three Scenarios.

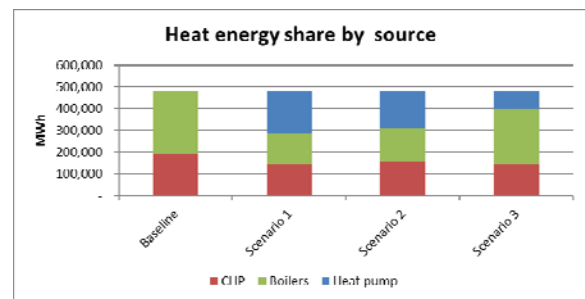


Fig 4: Heat share in total heating energy by heat source as function of a Scenario

According the presented data on Figure 4 can be drawn conclusion that the Scenario 1 has larger heat energy share from the HP as a result of higher COP=4 compared with COP=3 of Scenario 2, considering that all other system elements are the same in those two scenarios.

Regarding the Scenario 3, can be noticed that has significantly lower HP share and higher boilers share in the total required heating energy. The main reason for the significant differences is that in Scenario 3, the system is without TES. The heat share from the HP in the Scenarios with thermal energy storage tank is between 30%-40% and without TES is less than 20% which confirms the significance of TES in providing flexibility and increase utilization of HP and CHP.

On the next Figure 5 are presented data for the fuel consumption (electricity for HP) by heat source for each of the Scenarios. The fuel consumption (natural gas) is presented in energy terms in order to be comparable with the electrical energy consumption for the HP.

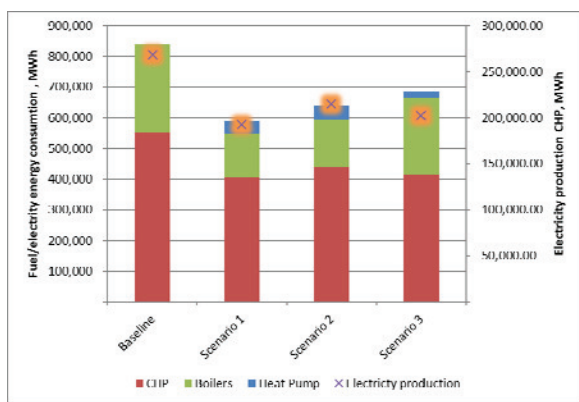


Fig. 5: Fuel consumption by heat source for each scenario and CHP electricity production

According the presented data on Figure 5, can be concluded that the least total fuel/electricity consumption has the system in Scenario 1 (the fuel consumption of the CHP considers the total consumption for heat and electricity production). It is noticeable that within the Scenario 1 and Scenario 2 the dominating fuel consumption is by CHP which is positively affecting the cons-effectiveness of the system, since it has highest energy efficiency coefficient (considering that is operating in combined regime). Also Scenario 1 and 2 have considerably less total fuel/electricity consumption compared to the Scenario 3 and the electricity production has nearly same values for all three scenarios.. On Figure 6 is presented cash flow overview for the baseline and the Scenarios. On the Figure 8 is given overview for the payback period for installing

HP into the DH system as a function from the investment costs and heat energy price.

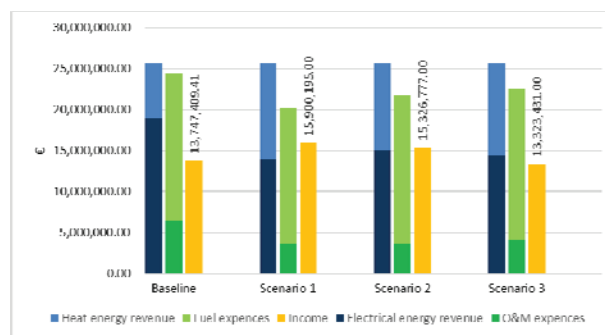


Fig. 6: Cash flow overview

Analyzing Figure 6, a difference can be made between the total revenues and total operating expenditures that arise from the systems' operability. It can be notice that the income for the Scenario 3 is lower compared to baseline case which indicates that this DH systems settings are not feasible. The reason can be located that in this Scenario it is not foreseen TES and the system lacks flexibility causing lack of utilization of the HP and CHP potentials. It is obvious that TES in DH has significant contribution toward increasing the operational flexibility of CHP and HP. It should be noted that within the payback period calculations, in the total investment costs are considered equipment costs, electrical grid connection costs, construction costs and costs for heat source. The investment costs of HPs are described in detail by [18] and emphasize the importance of the choosing the heat source, size, components and configuration of the HP when calculating the budget needed. The investment costs for HPs vary largely but have a linear correlation with the thermal capacity of the HPs [12]. So, this gives us the possibility to form an approximate value of the expenditures for HPs with total capacity of 20 MW to cost of around 8 M€. The construction costs of the HPs depend mainly of the thermal capacity of the HP and by using the graph presented in the analysis done by [18] it can be noted that the construction costs have also a linear dependence from the capacity of the HP, so the total construction costs for HPs with capacity of 20 MW would be 2 M€. The electricity related investment costs would be around 2.6 M€ whereas the heat source investment costs would be 2.4 M€. In the results from the detailed analysis done by [18]

where the total investment costs for HPs using different heat sources are calculated for the largest capacity of 10 MW, and the linear dependence which shows that the costs double with doubling the capacity of the HP, it can be concluded that the total investment cost for HP with capacity of 20 MW will be 15 M€ where half of the investment costs correspond to the price of the HP and the others are almost equally split between the costs for heat source, electricity and construction. According to [11] the construction costs of thermal energy store depend from its size and type. For 10,000 m³ storage tank the price will be 1.2 M€. Giving all the above mentioned, the total investment costs for heat pump and thermal store amount 16.2 M€ and this value is taken as reference in the following calculations. Considering this data, the simple payback period for the Scenario 1 is 7,5 years, for the system in Scenario 2 is 10 years and Scenario 3 has negative value i.e. it is not feasible. Main difference between Scenario 1 and Scenario 2 is in the HP efficiency, where it is considered COP = 4 and COP = 3 accordingly. It is performed analysis regarding the influence of the technology cost (HP specific investment costs) on the system cost-effectiveness i.e. payback period, presented on the next Figure 7. On the diagram on Figure 7, the results for Scenario 3 are not presented since in all cases the payback periods have negative values i.e. the income is lower than the compared baseline scenario.

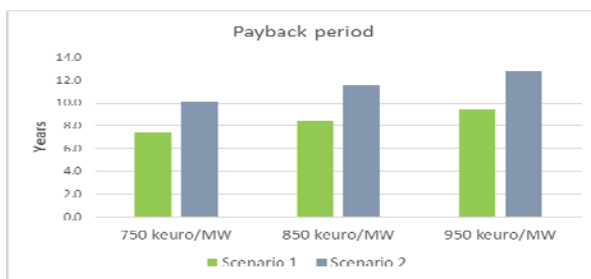


Fig.7: Payback period vs. investment costs

It is important to note that the payback period has high sensitivity to the changes in the electricity prices and those changes affect also the supply of the DH system These is result

mainly of the revenue from the CHP electricity (by HPs) to being based on fuel combustion. Visual representation of the payback periods is given in Figure 7 as well as the variations of the payback time when the investment costs for the HPs and the electricity price are different. Whereas, the sensitivity analysis in brought insight that the technology cost and discount rates does not affect the heat pump technology and that the system coupled with the large-scale HPs sensitivity is lower compared to the system without large-scale heat pumps implemented.

CONCLUSION

The cash flow and payback period times were analyzed for four different scenarios including HPs and thermal energy storage with different capacities, taking into consideration the heat production, energy consumption and investment costs. For all categories were done cost correlations on the real values with assumptions for integration RES in the DH system. Also, payback period variations were done with variable input parameters regarding HPs' investment costs and sold heating energy price. The results showed that it's a must integrating TES in the systems with renewable energy sources in order the system to be feasible and same time it improves system cost effectiveness. Also it must be noted that Scenario 3 which is without TES it is not feasible even with 30% decreased investment cost.

HPs have the potential of establishing connections between the electricity and heating sector providing increase of the flexibility of the CHP and the profitability of existing heating networks. Implementing large-scale HPs to the existing energy system enables more operating hours of CHP and reduces the number of boilers operating hours in DH system. Additionally, with coupling large-scale HPs with CHP and their implementation in the DH system the CO₂ emissions reduce, the possible critical excess in electrical energy decreases and higher fuel savings can be achieved.

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