DOI: 10.14621/ce.201601009

Modelling and Analysis of Thermal Energy Storage Implementation in the District Heating Systems of the City of Zagreb

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Abstract

Thermal energy storage (TES) is not a novel concept and is already used at many locations, especially in systems with an abundance of renewable energy sources (RES). TES is favoured since it is much easier to store thermal energy than electricity.

When it comes to district heating (DH) systems whose primary purpose is heat energy supply and which are not directly affected by RES, a question arises: is the implementation of TES financially viable and under which conditions? Complex DH systems usually consist of different types of production units (e.g. gas/fuel oil boilers, electric boilers, cogeneration units, combined cycle cogeneration units). Implementation of TES in this kind of DH systems represents a complex task since the characteristics of the TES system (i.e. power and heat capacity) have to be determined with consideration to the different production units and their ability to interact with the TES.

It is almost intuitively clear that implementation of a TES as a part of a DH system improves the system stability and security of supply. It is a little less obvious that TES implementation may also increase the profitability of the DH system through utilisation of the diurnal variations of heat consumption and electricity prices. However, this is not necessarily true but depends on the characteristics of the heat production units, the heat consumption profile, electricity and heat energy tariffs etc.

This paper is based on techno-economic analyses dealing with implementation of TES at the locations of the two heat production plants in the city of Zagreb. The analyses were conducted in order to quantify the financial and technical advantages of TES implementation in these specific DH systems (east and west DH system of the city of Zagreb). The goal was to determine the optimal capacity of the TES to be built and to prove their financial viability. In the paper, a short description of the TES and the basic assumptions are given. The advantages and disadvantages of the different kinds of production units available coupled with the TES are explored. Furthermore, an optimisation method for production unit priority determination and TES work mode is proposed.

Keywords:	Thermal energy storage; Zagreb DH systems; Security of supply

Article history:	Received:	29 July 2015
	Revised:	06 October 2015
	Accepted:	29 January 2016

1. Introduction

Thermal energy storage (TES) is not a novel concept and is already used at many locations, especially in systems with an abundance of renewable energy sources (RES) [1], [2]. TES is favoured since it is much easier to store thermal energy than electricity.

The implementation of TES as a part of a DH system improves the system stability and security of supply while reducing the necessary maximum production capacity by reducing the maximum load. However, the profitability of TES implementation highly depends on multiple factors, which makes it hard to predict by simply using some rule of thumb.

This paper proposes an optimisation method for production unit priority determination and TES work mode definition. Based on the results obtained with this method, it is possible to quantify the financial and technical advantages of a TES implementation. The algorithm is developed specifically for finding the optimal TES capacity at the location of the production plant EL-TO Zagreb, but with minor changes it can be applied for evaluating TES implementation profitability at other locations as well [3].

2. Basic principles

TES units can simply be described as huge water reservoirs. The TES are filled with stratified water - a hot water layer above a cold water layer, with a narrow boundary layer in between. The water layer arrangement (also including the protective layers and the top vapour layer) is shown in Figure 1. The terms charging and discharging do not apply to the water content of the TES but to the heat energy content. When charging, hot water enters the storage unit while pushing out the same amount of cold water and vice versa; when discharging, cold water enters the storage

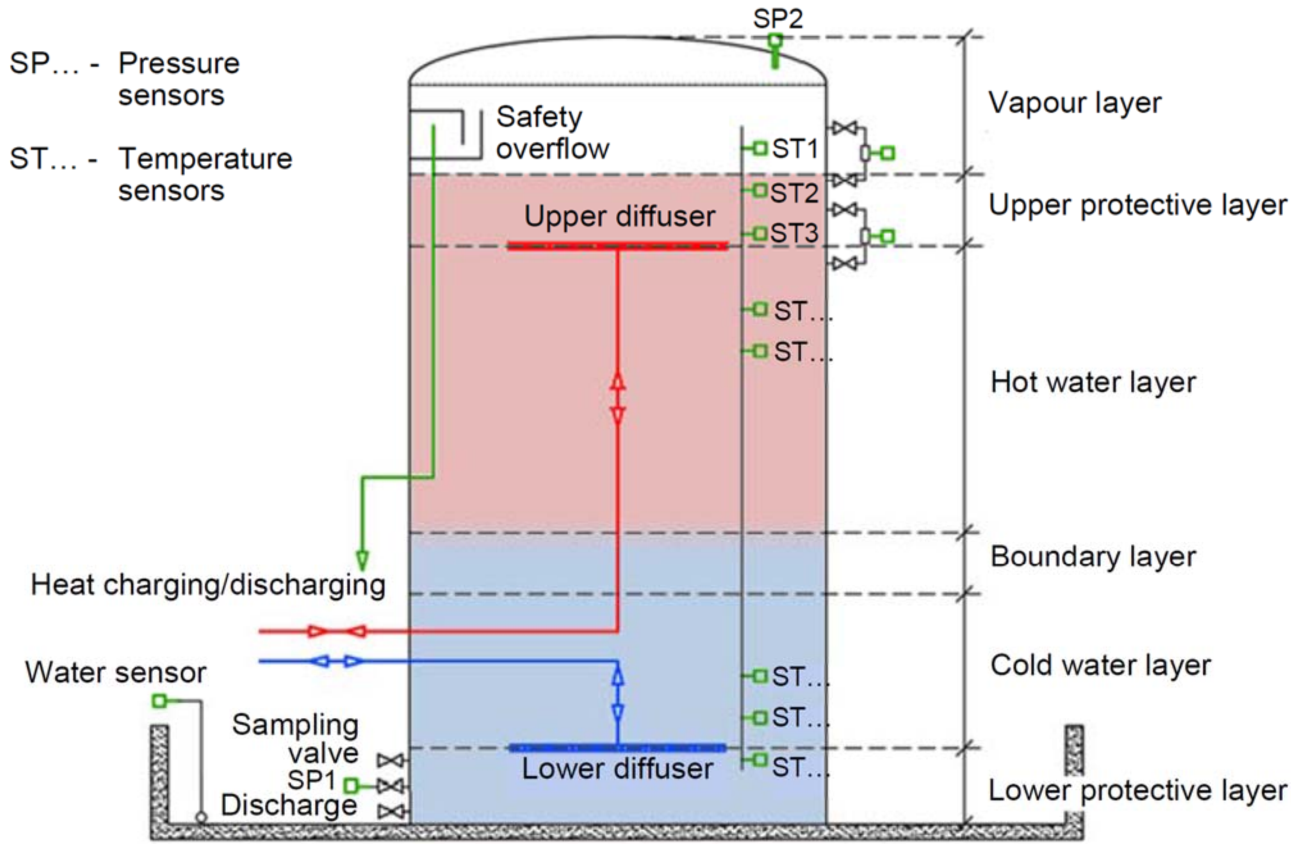

Figure 1: Basic scheme of a TES unit

unit while pushing out hot water. Both hot and cold water have to enter the TES via special diffusers which ensure that the vertical stratification stays intact, which is crucial for the TES functioning.

The big TES implemented in DH systems are generally not pressurised, but atmospheric. This limits the charging water temperature to around 98 ^{0}C.

3. Factors influencing the TES implementation profitability

Generally, implementation of TES results in increased security of supply, system availability and stability. It reduces the necessary maximum production capacity by reducing the maximum load thus reducing the need for building extra production units. An increase in profitability of the DH system is also expected, but this is not necessarily true. The profitability is increased trough utilisation of the diurnal variations of the heat consumption and the prices of the fuel, electricity, heat energy, etc. Furthermore, TES usage reduces the number of annual hours of operation of the peak boilers and the number of unit start-ups.

The characteristics of the available production units also have significant impact on the profitability. As an example we can consider usual diurnal cycles of heat consumption at the EL-TO production plant in Zagreb and electricity prices. Both electricity prices and heat consumption reach minimum values during the night. Since the goal is to charge the TES during the night and discharge it during the peak hours, the heat production during the night would be increased while the peaks during the day will be reduced. By doing this, the heat production fluctuations would be partially or completely eliminated. If production units such as condensing steam turbines with steam extraction for DH steam exchangers are used, the heat production increase would result in electricity production reduction. In that case, the usage of TES would yield positive financial results [4].

However, if production units with positive correlation between the heat and electricity production are used, such as backpressure steam turbines with heat exchangers at the outlet or gas turbines coupled with HRSG, the TES usage would result in increased electricity production during the night when the electricity prices are low and reduced electricity production in the peak hours when electricity prices are high. In that case, the TES usage may even yield negative financial results [5].

Third type of units that deserve special consideration is electric boilers. Lately, we are witnesses of relatively high natural gas prices and low electricity prices. Electricity prices are often extremely low during the night. On the other hand, electric boilers have low capital and maintenance costs, high efficiency (>99 %) and precise load control [6]. Therefore, electric boilers represent a great option for TES charging during the night. If building a TES at a location of a production plant consisted of units with positive correlation between the heat and electricity production is considered, building electrical boilers in addition to the TES should almost certainly be considered as well.

Finally, the heat capacity and the charging/discharging power of the TES itself significantly influence the profitability. The optimal values of those variables should be carefully chosen within the physical design limitations.

It should be noted that not only production unit characteristics are site specific. The electricity, fuel and heat prices/tariffs depend on the contracts the production plant has with its suppliers and customers. For example, some production plants sell the heat at a unique daily price while others have a double tariff system. Heat consumption profiles, maximum load and daily fluctuations also significantly differ from site to site. Furthermore, some production plants are obligated to deliver heat (or domestic hot water) during the night while others shut down.

All these factors combined produce a huge number of combinations making it hard to predict the profitability of a TES implementation without a comprehensive analysis.

4. TES implementation calculation model

As previously explained, predicting the profitability of a TES implementation by some rule of thumb would be imprecise and unreliable. For that reason, a model for calculating the TES implementation profitability was developed. In the following subchapters a description of the algorithm and the input data is given. This model was used for predicting the TES implementation profitability at the location of the production plant EL-TO Zagreb. Some of the obtained results will be shown in chapter 5.

4.1. Input data

Input data of the model consist of:

1) Heat (and process steam) consumption profile
   - In the mentioned example hourly data from one year period was used
2) Characteristics of the production units available at the site
   - Max./min. production capacity, efficiency, fuel type, start-up expenses, etc.
3) Prices and tariffs
   - Buying prices/tariffs of natural gas, fuel oil and electricity
   - Selling prices/tariffs of heat energy, process steam and electricity
4) TES characteristics (existing or planned TES)
   - Heat capacity and charging/discharging power
5) Parameters for the financial analysis
   - Investment costs, expenses for additional employees, maintenance costs, etc.
   - Cost of capital, inflation, financing methods, depreciation rate, etc.

4.2. Model for determining the production unit engagement priority

The production unit engagement priority is closely dependant on the production profitability of the units. A problem arises if the energy and fuel prices are variable, which is usually the case. Then, the production profitability and consequently the engagement priority of the units are also variable.

To determine the unit engagement priority on an hourly basis, a variable expressing the specific heat production expenses was defined. This variable is appropriate for determining the production unit engagement priority since heat supply is usually the primary obligation of the production plants while the electricity is a by-product of the cogeneration and combined cycle cogeneration units. The specific heat production expenses are calculated by the following expression

$$P_{HE} = \frac{P_F * c_F + (P_{EE} + P_{tEE}) * c_{EE} - P_{EE} * EE}{HE + PS * (h_{PS} - h_{fw})} \quad (1)$$

where P_{HE} denotes the specific heat production expenses [€/MWh], P_{F} the fuel price [€/m^3], c_{F} the fuel consumption [m^3/h], P_{EE} the electricity market price [€/MWh], P_{tEE} the electricity transportation costs [€/MWh], c_{EE} the electricity consumption [MWh], EE the electricity production [MWh], HE the heat energy production [MWh], PS the process steam production [t], h_{PS} the process steam enthalpy ,[MWh/t] and h_{fw} the feedwater enthalpy [MWh/t].

Obviously, in the periods of low electricity prices, the electric boilers would probably have lowest specific heat production expenses and thus highest priority. On the other hand, in the periods of high electricity prices, the cogeneration units would probably have lowest specific heat production expenses and thus highest priority.

The model then engages the units according to their specific heat production expenses, starting with the unit with lowest value of that variable. If the first unit cannot satisfy the whole heat demand, the second unit is engaged and so on. If at one point, the remaining heat demand is lower than the minimum capacity of the next unit according to the priority order, than the production load of the previous unit is lowered so that the next one can be engaged. At the end, the algorithm makes additional corrections in order to avoid frequent start-ups and turndowns. The priority determination and the engagement algorithm are identical in cases with or without TES.

4.3. TES working mode and security of supply

The next question that needs to be answered is how we want or plan to use the TES. The answer is again case dependant. In the case of the production plant EL-TO Zagreb, the goal was to flatten the production curve, in other words to eliminate the extreme production fluctuations. As previously explained, by doing this, the number of units' start-ups and operating hours of the peak boilers would be reduced. Full load engagement of the electric boilers during the night when the electricity price is low would also be possible.

For predicting the ideal target production, the statistical function moving average for periods of 48 hours was used on the available heat consumption data. The areas above the moving average curve and below the heat consumption curve are approximately equal to the areas below the moving average curve and above the heat consumption curve (Figure 2). These areas represent the discharging and charging energy respectively. However, since the TES capacity and charging/discharging power are limited, in reality the TES is not always able to respond to the demand defined by the difference between the heat consumption and the ideal targeted production. Therefore, the real production will not always coincide with the ideal targeted production, but will adjust to fulfil the heat demand.

The heat demand (blue area), the ideal targeted production (black dashed line), and the real production (red line) in a sample 10 day period are shown in Figure 2. Also note the yellow transparent area showing the TES charging/discharging energy.

Four different cases are shown. In the first diagram, which shows the case without a TES, the real production curve coincides with the heat consumption curve. The second diagram shows the case with a 500 MWh capacity TES. The production curve somewhat follows the ideal targeted production curve but it can be seen that in some hours of peak demand (e.g. around the 138th or 160th hour) the TES has already given out all the accumulated heat and in order for the heat demand to be satisfied the real production has to be increased. Hours of extremely low demand can be almost equally problematic. The most extreme example in the represented sample period is around the 120th hour when the TES is fully charged and cannot take in any more heat so the heat production has to be reduced. This may require turning down some of the production units which we actually want to avoid.

In the next two diagrams the cases with 1,000 MWh capacity and 1,500 MWh capacity TES are shown. It can be noticed that with the increase of the TES capacity the number of hours in which the TES is fully charged or fully discharged and thus cannot cover the difference between the heat demand and the ideal targeted production, is reduced.

The frequent occurrence of situations in which the TES cannot cover the difference between the heat demand and the ideal targeted production, or in other words when the real targeted production curve does not coincide with the ideal targeted production curve, is a sign of insufficient capacity of the TES. In the case of the production plant EL-TO Zagreb, a period of one year was analysed. The number of hours in which the TES could not cover the difference between the heat demand and the ideal targeted production as a function of the TES capacity is shown in Figure 3 (left). It is shown that this number for 500 MWh capacity TES is around 1,100 hours, but it significantly drops to around 370 hours for a 750 MWh capacity TES. It further drops to around 160 hours for a 1,000 MWh capacity TES. No significant drop of the number of hours in which the TES could not cover the difference between the heat demand and the ideal targeted production is observed with further increase of the TES capacity above 1,000 MWh.

Another interesting parameter is the maximum production load. In the sample period shown in Figure 2, the maximum production load in the case without TES equals around 350 MW while it drops for about 100 MW in the case with the TES with capacity of 1,500 MWh. The results of the one year period analysis are shown in Figure 3 (right). The reduction of the maximum production load with the increase of the TES capacity is not as dramatic as the reduction of the number of hours in which the TES could not cover the difference between the heat demand and the ideal targeted production, but it still reaches significant 15-30 % depending on the TES capacity. This clearly shows how TES implementation reduces the necessary installed production capacity.

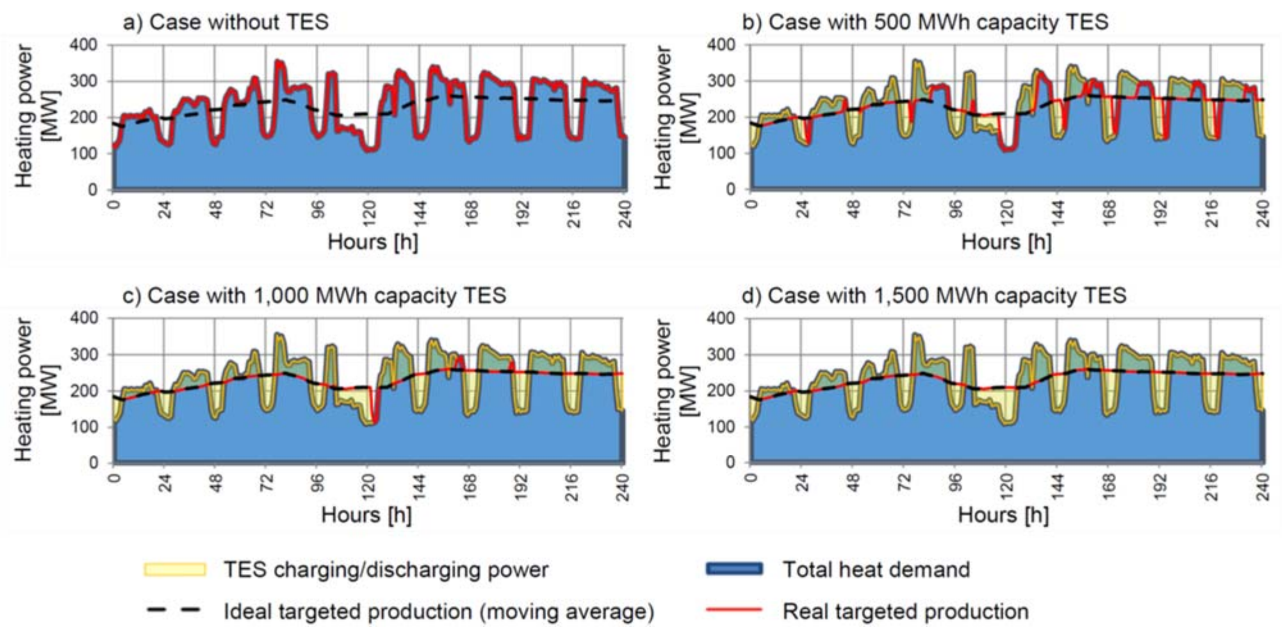

Figure 2: Heat demand and production in a sample 10 day period

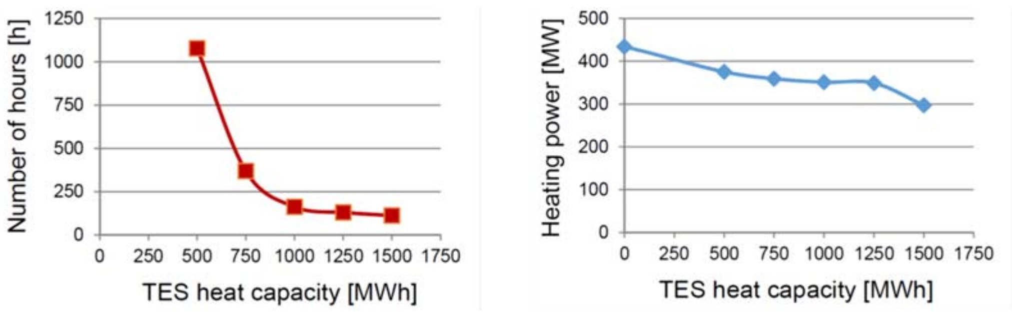

Figure 3: Number of hours in which the TES could not cover the difference between the heat demand and the ideal targeted production in a one year period (left) and maximum production load (right)

5. Results for the case of the production plant EL–TO Zagreb

The goal of the analysis conducted in the case of the production plant EL-TO Zagreb was to determine the optimal capacity of a TES for that location if the implementation of TES proves to be profitable. Cases with TES capacities from 500 MWh to 1,500 MWh and a case without TES installed were analysed. All the analyses were repeated using electricity market prices from two different years to determine the TES profitability in long term periods of low and high electricity prices. Cases with different combinations of available production units and with different heat demand, based on the expected future conditions, were also analysed. In total, there were 48 different scenarios.

The annual amount of the produced heat energy, process steam and electricity, as well as the annual amount of the consumed fuel and electricity were calculated and used to predict the annual income and expenses. The unit start-up costs were also taken into account. These data were used as an input for the financial analysis.

5.1. Production unit engagement model results

Two sample 10 day periods of the production unit engagement in the case without TES and with 1,000 MWh capacity TES are shown in Figure 4. Both sample periods are from the winter season and are characterised by high heat demand and big fluctuations of the heat demand. In the first period the electricity prices were generally high while in the second one the electricity prices are lower. In both periods, continuous engagement of the CCGT block (red area) is observed. The reason for this is the incentive price of electricity produced by this block which makes it most profitable by far, thus always having highest priority.

In the first period, more frequent engagement of cogeneration units (green and blue areas) is observed because of higher electricity prices. These units are turned down during the night because of electricity price drop, as well as heat demand drop. In the night periods of low electricity prices, electric boilers (orange areas) are turned on. If the mentioned units cannot satisfy the heat demand, peak boilers (purple areas) are started up. In the second period, more frequent engagement of electrical boilers (orange areas) is observed. The peak demand is again covered by the peak boilers (purple areas).

5.2. Financial analysis results

Based on the production unit engagement during the one year period, the annual profit was calculated for each of the analysed cases. But, what is relevant for the financial analysis is the incremental profit – the difference between the annual profit in a case including TES of certain capacity and the profit in a corresponding case without TES installed. The results are shown in Figure 5 (left).

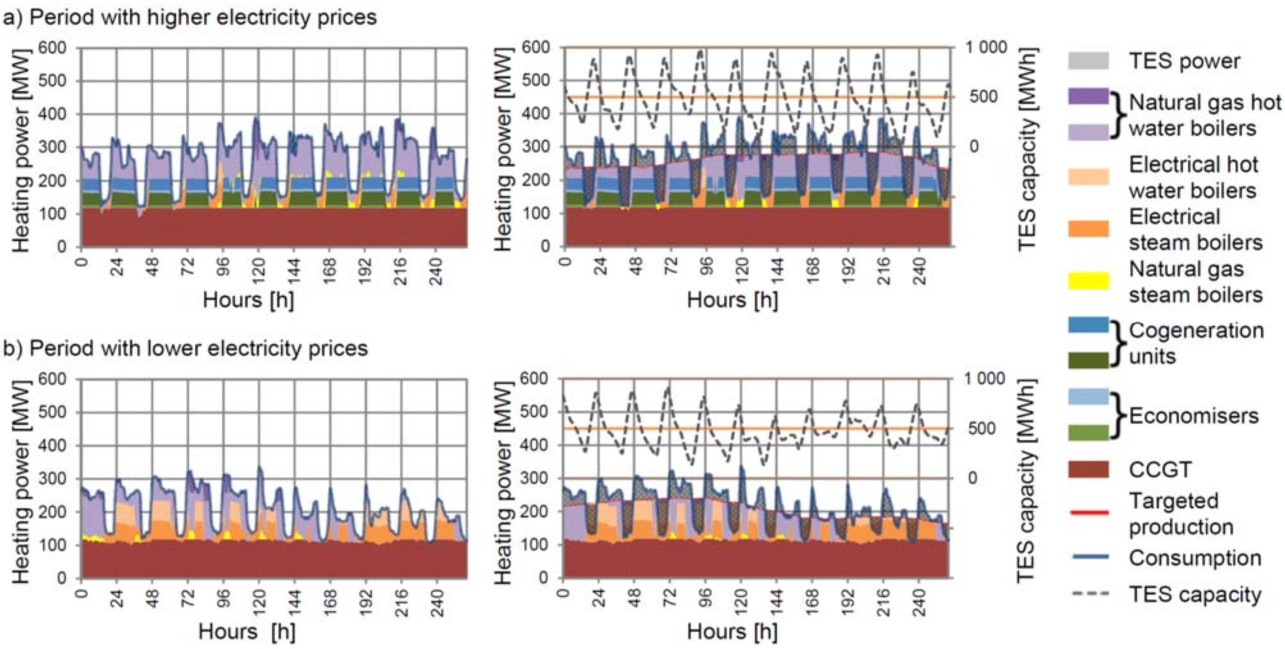

Figure 4: Production unit and TES engagement in a sample 10 day period, no TES installed (left) and 1,000 MWh capacity TES (right)

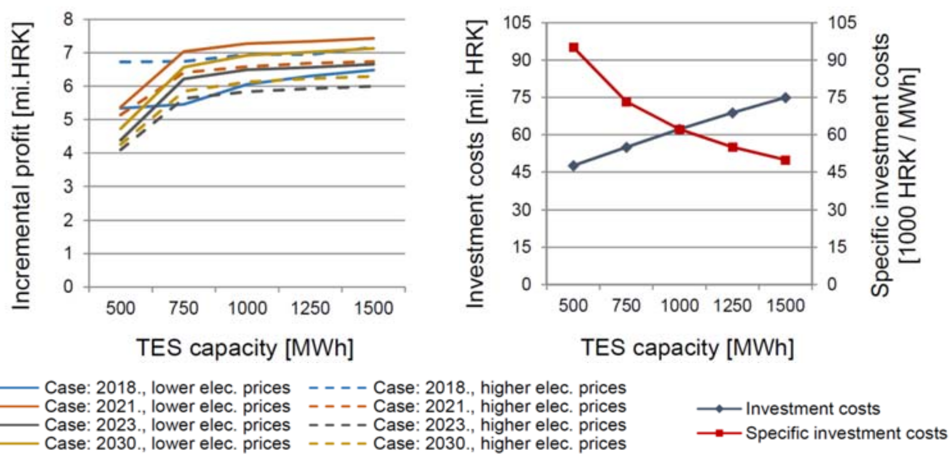

Figure 5: Annual incremental profit for the production plant EL-TO Zagreb (left) and prediction of the investment costs (right)

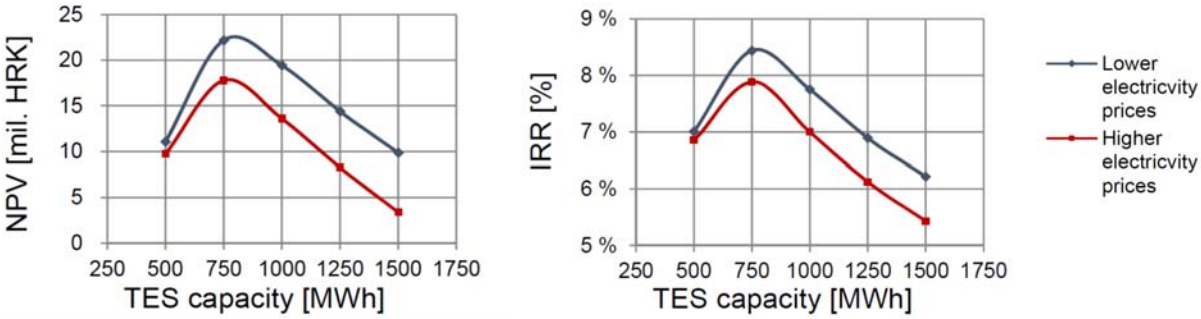

Figure 6: Financial analysis results, NPV (left) and IRR (right)

Detailed description of each specific case with respect to the available production units is beyond this article. However, from the presented results, it can be concluded that the electricity prices reduction has a positive effect on the incremental profit. This shows the dominant positive influence of the electric boilers usage in the periods of low electricity prices. An exception is the year 2018 in which the analysis with higher electricity prices returns better financial results. The explanation for this discrepancy is that in 2018 the CCGT unit will still not be commissioned. As a result, the engagement of the cogeneration units in that case is much more frequent and that type of unit is more profitable when the electricity prices are higher.

The increase in the heat demand results in an increase in the incremental profit. This can be most clearly noticed by comparing the results for the years 2023 and 2030 since in those two years the same production units are available while the heat demand is increased.

Since the analysis objective was to determine the optimal TES capacity, the parameter of greatest interest was actually the TES capacity. From the diagram in Figure 5 (left) it can be noticed that the incremental profit increases with the increase of the TES capacity to 750 MWh. After that, the increase of the incremental profit with the further increase of the TES capacity is almost negligible.

To complete the financial analysis it is also necessary to predict the investment costs and to determine the rest of the economic parameters needed (expenses for additional employees, maintenance costs, cost of capital, inflation, financing methods, etc.). In the case of the TES implementation at the location of the production plant EL-TO Zagreb, the investment costs were predicted according to the investment costs for the reference accumulator with a capacity of 750 MWh (at the location of the production plant TE-TO Zagreb). The investment costs for the TES units of capacity different than 750 MWh were predicted based on the assumption that one part of the investment costs (e.g. auxiliary equipment, design, preparatory work) are independent of the TES dimensions, the other part is proportional to the volume of the TES (e.g. foundation costs) and the rest are proportional to the TES surface (e.g. steel construction and skin fabrication and assembly). The predicted investment costs, together with the capacity specific investment costs are shown in Figure 5 (right).

Finally, the results of the financial analysis performed over a period of 20 years are presented in Figure 6. They show that the TES implementation at the location of the production plant EL-TO Zagreb is justified and financially viable for all analysed cases except for the case with TES with capacity of 1,500 MWh in the analysis with higher electricity prices. The optimal TES capacity is the one for which the maximum NPV and IRR values are reached. According to Figure 6, the optimal TES capacity is around 750 MWh. It is also interesting to notice that in this case the electricity price has a significant effect on the profitability of the TES implementation, however, it does not affect the optimal capacity of the TES.

5.3. Other consideration

The financial analysis results clearly show that the optimal TES capacity is around 750 MWh. Nevertheless, other factors such as the security of supply and system stability also have to be taken into account in the decision-making process. Eventual supply interruption or sudden unplanned unit turndown would directly or indirectly generate additional expenses. So, the security of supply and system stability, although not considered and quantified in the model itself, may have significant financial effects. That means that the number of hours in which the TES could not cover the difference between the heat demand and the ideal targeted production as a function of the TES capacity shown in Figure 3 (left) as well as the maximum production load as a function of the TES capacity shown in Figure 3 (right) should most definitely be considered.

Finally, it should be noticed that in the case with 750 MWh capacity TES the model operates the TES in a way that it is almost fully charged and fully discharged in each cycle (in the winter period). However, the general attitude of the experts in the field is that during normal operation the TES should always contain some reserve of stored energy. The amount of the stored energy to be kept as a reserve depends on the size of the DHS.

Considering all of the above, a TES with a capacity of 1,000 MWh was recommended for the

6. Conclusion

TES implementation in a DHS would in any circumstances improve the system stability and the security of supply. Furthermore, it reduces the maximum production capacity needed by reducing the maximum load, thus reducing the need for building extra production units. However, the profitability of the TES implementation highly depends on multiple factors, most important of which are the heat (and process steam) consumption profile, the characteristics of the available production units, the fuel and energy prices/tariffs and the characteristic of the TES itself.

All these factors combined produce a huge number of combinations making it hard to predict the profitability of TES implementation without a comprehensive analysis. An algorithm to analyse available data from a reference long term period, to predict the production units and the TES engagement and to calculate the TES implementation profitability was created. The model was developed specifically for the production plant EL-TO Zagreb, but with minor changes it can be applied for evaluating TES implementation profitability at other locations as well. However, at this point it is difficult to give any further general suggestions since the problem is highly case specific.

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