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# Feasibility of Thermal Energy Storage Integration into Biomass CHP-Based District Heating System

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Despite the advancements in thermal energy storage (TES) systems for combined heat and power plants (CHP) operation, these technologies are not implemented in CHP-based district heating (DH) systems in some of the countries where DH systems are still in development. An analysis of economic and environmental benefits that can be reaped as a result of the TES integration within the DH system is required to successfully promote TES as a technology for the DH system improvement. An actual large-scale biomass CHP-based DH system is explored as a case study. Scenarios for two types of support policies (feed-in premium electricity produced by biomass CHP and high-efficiency biomass CHP) were examined by varying the size of TES. The aim of the research was to evaluate the impact of the biomass CHP support policy on TES integration feasibility. Calculations show that TES installation combined with biomass CHP is less feasible when all of the electricity produced by biomass CHP is subsidised.

## 1.Introduction

### 1.1 Background

The district heating (DH) sector plays a crucial part in potential energy savings (Mashatin et al. 2014). DH has been widely used in various European cities over many years, both for space heating and domestic hot water supply. DH supplies 9 % of total EU heating (EU Commission, 2016). More than half of residents in some of the European countries, such as Estonia, Denmark, Lithuania, Poland, Sweden and Latvia have their heat supplied by DH (Latõšov et al., 2017). The DH system must change and improve to become competitive in comparison to local heating, as well as provide better customer service. Since 2014, the concept of the 4th Generation DH summarising the ideas on the required improvements for the future sustainable development of DH, has been widely discussed in the international scientific community (Volkova et al., 2018). According to this concept, one of the more significant conditions for the future sustainable DH system is its ability to become an integrated part of smart energy systems, including smart electricity, gas, thermal grids and district cooling(Lund et al., 2014).
One of the possible solutions for the matter is to use CHP together with thermal energy storage (TES). TES is a system, which can store heat or cold for later use under different conditions, such as temperature, location or storage tank (Cabeza et al., 2015). There are a number of TES types, such as sensible heat storage (hot water accumulator tanks), latent heat storage and thermochemical storage. Hot water accumulator tanks are widely used in European DH systems at the moment. For example, more than 75 % of heat produced in Sweden is stored in accumulator tanks (Smith et al., 2013), and about 280 DH plants have accumulator tanks installed in Denmark (Noussan et al., 2014). The main advantage of using TES together with CHP is the reduction of heat and electricity production dependence on consumer heat load variations.
Despite the widespread use of CHP combined with TES in European DH systems, TES are not used in Estonia (Volkova et al., 2012) and Latvia (Pakere et al., 2016). This can be explained by the fact that new CHPs are often intended to provide baseload power during the year, and in this case, the installation of TES won't lead to a rapid payback.
Due to the national support policy for newly installed biomass CHPs in Estonia, the number of biomass CHPs has increased. New CHPs are installed to provide heat during the cold months when the heat load is rather high.

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The interest in the TES integration with the DH system among energy companies has increased over the last years; however, to this day no company has installed an accumulator tank to improve biomass CHP operation process. One of the possible reasons for such a setback could be the fact that the actual biomass CHP support scheme is supposed to support both electricity produced in the CHP mode and heat produced in CHP that cannot be utilised and is rejected to the atmosphere by the coolers. The aim of the research was to evaluate the influence of subsidies on the feasibility of TES integration.

**1.2 Biomass electricity support scheme**

CHP production has not been a widespread heat/electricity generation option in Estonia, as along with electricity generation from renewable fuels. At the same time, the policy and targets for electricity production influenced by the European Union and local Estonian legislation have a significant effect on the development of biomass CHP plants. According to the National Development Plan for the Electricity sector until 2018, the target level for the share of renewable electricity in gross electricity consumption for 2010 was 5.1 % and 15 % for 2015. The target level for the share of CHP electricity in gross electricity consumption was 20 % for 2020. The actual statistical data for the aforementioned indicators in 2007 showed 1.8 % and 10.2 % respectively. Overall, the support scheme (the mandatory feed-in tariff was 51.77 €/MWh, which was quite similar to the electricity generation costs) has not worked efficiently up until May 2007. The main idea of this policy was to provide a moderate profit to the most cost-efficient plants, and, as a result, no new plants were built before 2007 when several important changes were made to the support schemes for electricity production from renewable sources and by CHP. Under the current feed-in premium (FIP) scheme, electricity from renewable energy sources (including biomass CHP) is sold on the electricity spot market and producers receive a premium (0.0537 €/kWh) on top of the market price of their electricity. Due to FIP, new biomass CHP plants have launched in all big cities in Estonia with a sufficient DH heat load (Tallinn, Pärnu, Tartu). The impact of the FIP implementation on electricity produced from renewable fuels, including biomass CHP is shown in Figure 1.

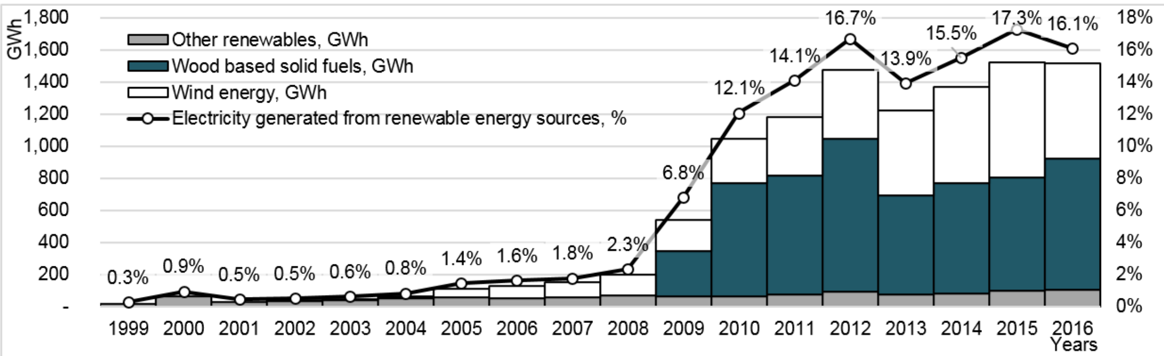


*Figure 1: The amount of electricity produced from renewable fuels and the share of electricity generated from renewable energy sources out of gross electricity consumption in Estonia*

It should be mentioned that according to the Electricity Market Act definition and biomass cogeneration process calculations differ from the efficient cogeneration process calculations. The core differences between the biomass CHP process and the efficient CHP process are:

- Efficient CHP is calculated on a monthly basis. The amount of electricity generated through an efficient CHP process is calculated based on the methods presented in Annex 2 to Directive 2004/8/EC of the European Parliament and of the Council.
- The biomass CHP process is calculated on an annual basis. It is assumed that all electricity produced in a biomass-fuelled CHP plant was produced through a CHP process, if the annual total efficiency of this plant exceeds 40 %. If the total efficiency is less than 40 %, then the share of electricity produced in the cogeneration process out of the total electricity generated should be equal to the share of efficiently utilized heat (total heat production minus the heat rejected to the atmosphere). It is evident that the criteria for efficient cogeneration calculations are stricter than for biomass cogeneration process.

The FIP scheme allows the production of electricity when heat is not utilised. Energy companies install air heat exchangers as auxiliary coolers to deal with excess heat when the heat load in the DH system is not sufficient.

## 2. Methodology

To evaluate the influence of the FIP scheme on the accumulator tank feasibility integrated into the biomass CHP-based DH, a model was built using EnergyPro software, with the largest DH system in Estonia was used for reference. A block diagram of the DH system is shown in Figure 2.

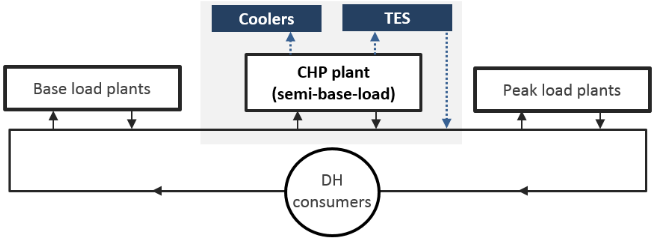


*Figure 2: A block diagram of the DH system*

The following heat sources are present in the DH system: base load CHP (biomass CHP and a waste-to-energy plant providing space heating and domestic hot water preparation throughout the year); peak boilers operating during the high heat load periods (winter months), and biomass CHP installed for the semi-base load, providing heat supply mainly during autumn, winter and spring. Semi-base load biomass CHP launched in 2017, and has only operated in the CHP mode up until 2018, tracking heat load profiles, as there were no technical facilities to reject heat to the atmosphere, but starting in 2018, it has become possible to produce electricity by rejecting the heat due to the installation of coolers. The feasibility of coolers and TES installation depends on the FIP scheme implementation features. Two main scenarios were simulated for the DH system:
**Scenario A:** the electricity produced by biomass CHP is subsidised using the current FIP scheme features. According to this scenario, the heat that cannot be utilised or stored, is rejected to the atmosphere by the coolers.
**Scenario B:** only the electricity produced in the efficient CHP mode is subsidised. In this case, CHP operates only when the heat load is sufficient and all produced heat is utilised or stored.
According to the heat load in Estonia, the time when the hot water tank can be used efficiently is when air temperature changes rapidly, and the heat load changes during the daytime. In Estonia this period is usually in May and October. Figure 3 shows operation strategy for CHP, when all electricity produced by CHP is subsidised (Scenario A). In this case, the coolers are installed for heat rejection in order to increase electricity production. Two weeks of May are given as an example, showing CHP operating with and without an accumulator tank (7,000 $m^3$). Without the accumulator tank (Figure 3a) when the heat load is lower than the CHP capacity CHP continues to operate but the heat is partially rejected to the atmosphere, and when the heat load is higher than CHP, peak boilers are switched on. If the accumulator tank is installed (Figure 3b), the heat from CHP can be used for DH over a longer period. The amount of rejected heat decreases and the amount of heat transmitted to the DH network increases.

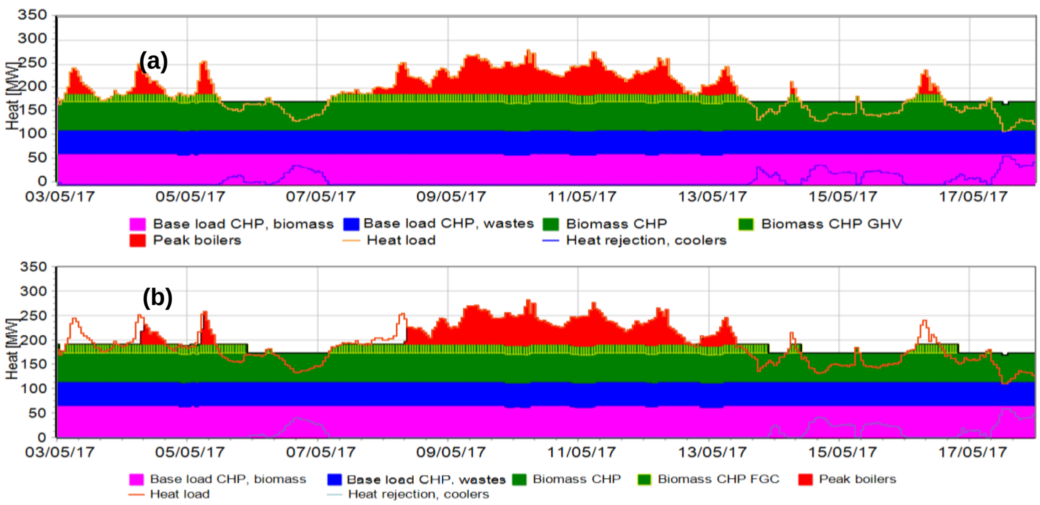


*Figure 3: Scenario A: An example of CHP operation without (a) or with (b) an accumulator tank (7,000 $m^3$)*

Figure 4 portrays the situation when only electricity produced in the CHP mode is subsidised, the coolers are not installed, and all produced heat must be utilised or stored (Scenario B). When there are no possibilities to store the produced heat (Figure 4a), and the heat load is lower than the CHP capacity, the DH operator switches off CHP; and when the heat load is higher, peak boilers are used. Figure 4b shows how the operational process can be improved when a hot water tank is installed. If the heat load is lower than the CHP capacity, the tank is charged by the surplus heat from CHP, but when the heat load is higher than the CHP capacity, the tank discharges and compensates the lack of heat while avoiding the use of peak boilers.

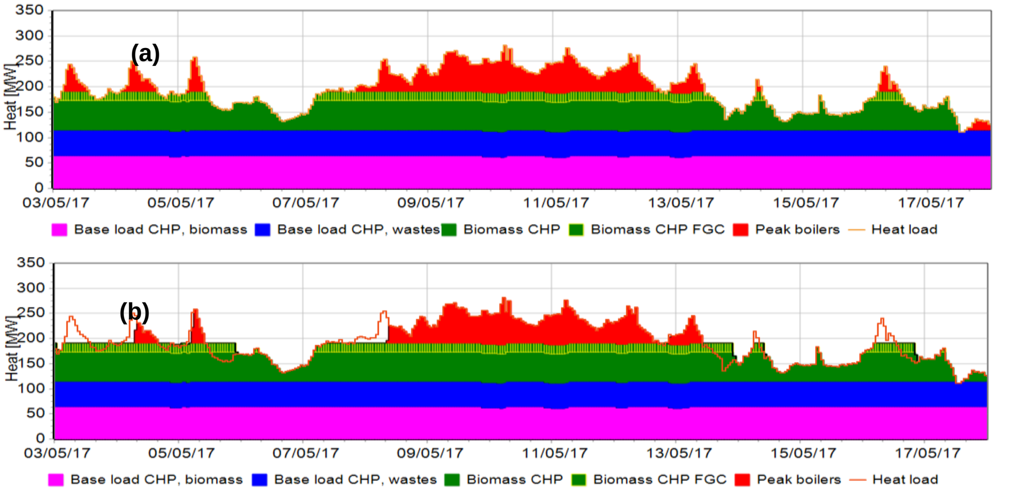


*Figure 4: Scenario B: An example of CHP operation without (a) or with (b) an accumulator tank (7,000 m$^3$)*

Figure 5 shows the charging-discharging of an accumulator tank. This TES operation strategy is appropriate for both scenarios (Figure 3b and Figure 4b).

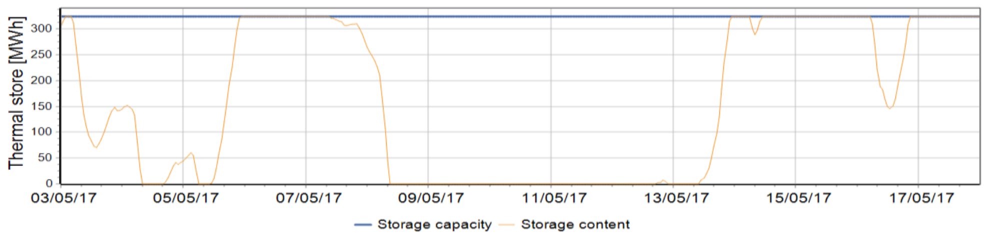


*Figure 5: An example of an accumulator tank (7,000 m$^3$) charging and discharging for scenarios A and B.*

The calculations are based on the fact that TES has a positive effect due to the possibility of charging from the heat during the transition period but there also are other ways to use the accumulator tank, for example, the installation of the accumulator tank helps TES in preventing daily heat load changes (Pakere et al., 2016), the stability of the DH system can be increased, and the operational strategy of CHP can become more flexible and be based on the electricity market price changes (Volkova et al., 2012), that were not taken into account for these simulations.

The main model input data and assumptions are as follows:

1. CHP: heat capacity: 58 MW (with flue gas condenser: 76 MW), power capacity: 21 MW, fuel: wood chips, fuel input: 87 MW. Peak boilers sum heat capacity: 900 MW, fuel: natural gas, energy efficiency: 85 %
2. Base load plants: biomass CHP: heat capacity: 50 MW (including the flue gas condenser: 67 MW), power capacity: 25 MW, Waste-to-energy plant, heat capacity: 50 MW
3. Heat load is based on historical data of the district heating area and is the same for all scenarios.
4. Accumulator tank: 1,000 m$^3$ up to 30,000 m$^3$, temperature at the top: 90 $^o$C, temperature in the bottom: 50 $^o$C, insulation thickness: 300 mm, thermal conductivity: 0.037 W/m$^o$C.
5. Economic inputs: electrical market prices are based on Nordpool historical data, FIP is 53.7 €/MWh$_{el}$, wood fuel price: 12 €/MWh$_{fuel}$, operational costs: 10 €/MWh$_{th}$, price of heat sold to the DH system is 34 €/MWh$_{th}$,, NPV

calculated based on expected IRR=7 %, calculation time duration is 12 y. Tank installation costs are based on technology Data for Energy Plants, provided by Danish Energy Agency (Danish Energy Agency, 2012)
5. Emission factors and primary energy factors are based on Estonian regulations and shown in Table 1
The scenarios were compared and analysed using economic parameters NPV and IRR; as well as environmental parameters: annual $CO_2$ emission savings and primary energy savings.

*Table 1: Primary energy factors and $CO_2$ emission factors in Estonia (Latõšov et al., 2016; Government of Republic of Estonia, 2015)*

| | Primary energy factor | $CO_2$ emission factor (t $CO_2$/MWh) |
|---|---|---|
| Natural gas | 1 | 0.198 |
| Biomass fuel | 0.75 | 0 |
| Electricity | 2 | 1.1 |

## 3. Results

After the scenarios were simulated for various heat storage sizes, NPV and IRR were calculated for each scenario (Figure 6). One can see that for scenario A the optimal TES size is about 2,000 $m^3$. It is rather small and if to compare it to the best practice examples, it can be seen that the size range for such type and capacity of the CHP accumulator tank, usually starts at 3,500 $m^3$. As for scenario B, when only electricity produced in the biomass CHP mode is subsidised, the optimal size for TES is about 7,000 $m^3$. IRR is much higher for scenario B, than for scenario A. For scenario A, the installation of the accumulator tank leads to an increase in income stemming from sales of the heat that was not rejected to the atmosphere, but stored and later distributed to DH. For scenario B, the annual net cash flow is much higher, because in addition to the income from the heat sales, electricity market prices and premium are added to it.

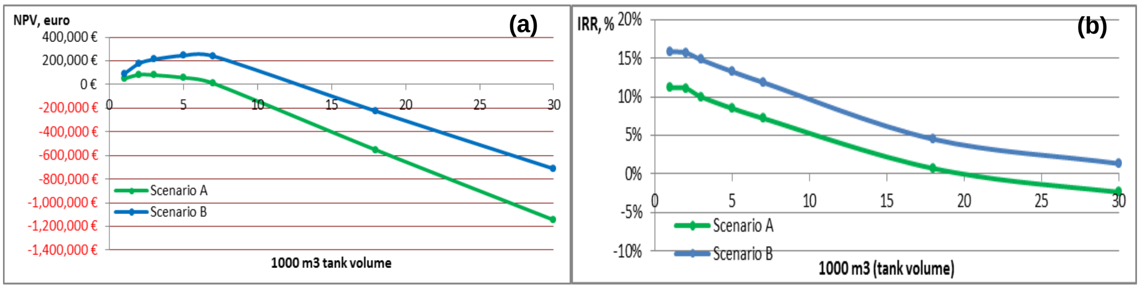


*Figure 6: Economic indicators NPV (a) and IRR (b) based on heat storage size*

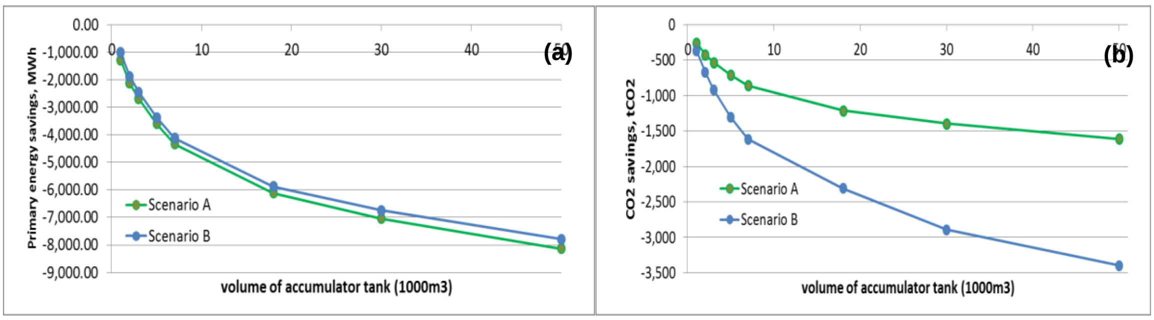


*Figure 7: Environmental indicators: Primary energy savings (a) and $CO_2$ emission savings (b) based on heat storage size*

Figure 7a shows primary energy savings increase due to the installation of an accumulator tank. Figure 7b shows how many tons of $CO_2$ emissions can be saved due to the installation of an accumulator tank for scenarios A and B.
In scenario B, with the accumulator tank installed, it is possible to produce more electricity and heat, which means that $CO_2$ emissions are reduced due to avoiding heat production in gas boilers and electricity production at power plants. But in scenario A, with CHP producing electricity, regardless of whether or not the heat is

utilised, only $CO_2$ emissions from gas boilers are avoided. It means that the use of accumulator tanks would result in a much smaller $CO_2$ emission saving for scenario A. As for the primary energy savings in scenario A, with the heat rejected, the integration of an accumulator tank makes it possible to increase CHP heat utilisation and decrease natural gas consumption. For scenario A, produced electricity and consumed biomass fuel do not depend on heat storage size and remain the same in all cases. For scenario B, the integration of an accumulator tank leads to changes in electricity production, biomass fuel consumption and natural gas consumption. The results of calculations show that primary energy savings for the case study's DH system are almost the same for both cases.

## 4. Conclusions

Accumulator tanks are widely used to improve the biomass CHP operation process in Europe. Due to the FIP scheme, many new biomass CHPs were launched in Estonia, without the integration of TES into a CHP-based DH system.

The existing FIP support scheme allows the DH operator to produce electricity by CHP and reject the heat when the heat load is not sufficient. The aim of the research was to evaluate how the FIP support scheme in Estonia influences the feasibility of the TES integration into the DH system. A large DH system (Tallinn, Estonia) was used in case study, a model of the system was built with two scenarios simulated: the first scenario with the FIP support scheme, where all electricity produced by biomass CHP is subsidised and the second scenario, where only the electricity produced in the CHP mode is subsidised. The study found that under the conditions of the FIP support scheme, the TES integration is less reliable; in addition, the reduction of $CO_2$ emissions is lower, as compared to the case, where CHP cannot reject the heat to the atmosphere. When only the electricity produced in the CHP mode is subsidised, the accumulator tank integration has a positive effect on the economic parameters: NPV is positive and IRR is high. $CO_2$ savings are much higher for this type of support.

### Acknowledgments

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