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Effects of Coupling Combined Heat and Power Production with District Cooling

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Abstract: Over the past decades, combined heat and power production (CHP) has proven itself to be an efficient means of meeting both heat and power demands. However, high efficiency can be achieved with CHP plants when the heat load is sufficient, while lower-priority CHP plants must deal with the excess heat associated with power generation. This excess heat can be used for district cooling with absorption chillers. Although the absorption chiller is an efficient technology for using excess heat for cooling generation, its efficiency is very sensitive to driving hot water temperature. This paper provides a detailed analysis of how cooling generation in CHP plants using absorption chillers affects power generation and primary energy consumption. This study is based on the operational parameters of the Mustamäe CHP plant (Tallinn, Estonia) and the cooling demand of the Tehnopol science and business campus and proposes a sufficient cooling production capacity based on the estimation of the campus' cooling demand. Additional cooling production opportunities to meet district cooling demand are discussed and compared in this paper in terms of primary energy savings and economic profit. The study finds that for the effective use of CHP excess heat and efficient cooling production, the use of an 0.8 MW absorption cooler and 11.6 MW heat pumps is recommended. This system would use 1.9 times less primary energy for cooling generation than local cooling.

Keywords: absorption chiller; cogeneration; cooling demand; district cooling; energy planning; power generation

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1. Introduction

Final energy consumption for cooling purposes has been increasing in recent years. In the European Union (EU), it was 2.7% in 2019 for commercial buildings [1]. The cooling demand is expected to triple by 2050 [2]. The building sector accounts for about 40% of the total final energy consumption in Europe and about 36% in the world [3]. Local energy grids, including district heating (DH), cooling and electricity networks, can be maintained, energy consumption reduced and efficiency improved with the help of district energy networks and careful planning [4,5].

Compared to local cooling, district cooling (DC) has several advantages. First, DC is more environmentally friendly than local cooling because DC can often use a variety of renewable energy sources to produce cooling energy. There are several technologies that can be used to generate cooling energy in DC systems. The most common techniques are absorption chillers, free cooling, heat pumps and cooling towers [6]. For example, DC can use free cooling from lakes, rivers and seawater [7]. The aforementioned natural sources can be also used for heat pump cooling when the temperature of the heat source is too high for free cooling [8,9]. Free cooling requires about 0.05 kW of electricity per 1 kW of cooling power [10]. When cooling is produced using heat pumps, the energy efficiency ratio is normally around 13–16, which means that 0.25 kW of electricity is needed per 1 kW [11]. Industrial waste heat and excess heat from combined heat and power (CHP) plants can also be used with absorption chillers [12]. In this case, the energy consumption for cooling generation is almost as low as for free cooling, about 0.2 kW per 1 kW of cooling energy [13]. Local cooling units usually use electricity, and the electricity consumption for 1 kW of cooling energy production is up to 1.2 kW [14]. Even if electricity is produced using renewable energy sources, DC production usually is more energy efficient.

Similarly, the authors of [15] conducted extensive research into the establishment of a DC network in Italy. In [15], various installations were evaluated in addition to the absorption chiller. The goal was to find an economically viable solution that could contribute to primary energy savings. The Italian study [15] compared four different scenarios, each with a different technical configuration involving electric chillers, boilers, CHP plants, absorption chillers, thermal energy storage units and heat pumps. It has been demonstrated that combining many different technologies produces the best results in terms of energy and economic compromise.

More renewable energy can be introduced into the system using solar energy [16]. Solar DC systems also use absorption chillers for cooling generation, but their main difference from CHP plants is that instead of excess heat, solar energy is used to generate hot water to drive the process. The main components of a typical solar absorption cooling system are a solar thermal collector, an absorption chiller, storage tanks, and an auxiliary boiler [16]. In addition to solar heat, hot flue gases can also be used as a heat source for absorption chillers. A similar system was explored in [17]. Like DH systems, solar-powered DC systems also need thermal energy storage to function optimally. It is argued that by using both cold and hot storage, the overall coefficient of performance (COP) of the system can be increased and the cooling plant's capacity can be lower than peak demand, which can also reduce costs.

When absorption chillers are used, special attention should be paid to their heat rejection systems. Typically, the heat rejection system capacity of an absorption chiller is about 2.35 times the cooling capacity of the chiller [18]. When thermal energy storage units are also integrated into the system and there is a demand for DH, the rejected heat from the cooling process can be used for heating.

Absorption chillers can help alleviate the problem of low summer heat loads in CHP plants because absorption chillers require hot water to start the cooling process in the summer, when the cooling demand is high. Over the past decade, the number of CHP plants in Estonia has increased, and there are currently over 20 CHP plants in Estonia, four of which are located in Tallinn [19]. The main operational issues of CHP plants are related to fluctuating and low heat loads during the summer period. In the case of low heat demand, the plant either does not work at all or uses coolers to reject heat. Heat rejection can allow the CHP system to continue producing electricity; however, since all heat energy is wasted, this is an inefficient use of energy. This kind of practice is only feasible when subsidies are provided for producing electricity. In case of Estonia, this refers to biomass CHP plants that are not older than 12 years. These types of CHP plants receive 53.7 EUR/MWh_{el}, which makes heat rejection feasible. In Tallinn, there are three CHP plants that have coolers installed on the roof [20].

CHP plants are important for power grid stabilisation, that is, for ensuring and maintaining the frequency and voltage in the power grid [21]. In light of climate change, when non-combustion heat sources are more relevant than ever, the importance of CHP plants in the energy system may be questionable. While there are several ways to generate electricity and/or heat from non-combustion sources such as solar, wind, geothermal, etc., CHP plants have advantages compared with these technologies, such as the generation of electricity and heat in a single process with very little loss and non-fluctuating energy production. In addition, CHPs plan an important role in balancing the energy system. When CHP plants run on biomass, the energy produced can be considered renewable.

Absorption chillers play an important part role in coupling DC with CHP plants. Various absorption designs are available, mainly single-stage and two-stage absorption chillers. Single-stage machines can be driven by hot water (90–115 °C) or low-pressure steam (1 bar) and are often used with reciprocating engine CHP plants. Compared to single-stage chillers, two-stage machines require higher-temperature hot water (e.g., 175 °C) or higher-pressure steam (e.g., 8 bar) and are often used with combustion turbine CHP plants. Typically, the COP for a single-stage absorption chiller is about 0.75, while for a two-stage absorption chiller, the COP is 1.35 or higher [22].

Absorption chillers also couple well with solar collectors and solar ponds. In [23] a thorough review and comparison of solar enhanced heating and cooling systems was provided. As a result, the study showed that although solar radiation intensity graphs and cooling consumption graphs have similar profiles, absorption chillers require an extra heat flow that can be provided by natural gas boiler, as was demonstrated in [23]; however, in terms of primary energy usage and the cost of energy, they also suggest the use of heat pumps. To gain even more savings on a primary energy CHP, excess heat can be used. In [24], a novel solar pond and absorption chiller conception is introduced for cooling energy production. Using solar ponds can increase the flexibility of using solar energy, but it was also pointed out that as driving hot water temperature is crucial to the absorption chiller's coefficient of performance (COP), a sufficient amount of solar radiation is necessary, and the pond must be designed carefully.

For coolant temperatures of 4 °C and above (for example, in air conditioning systems in buildings), a mixture of water (refrigerant) and lithium bromide (LiBr) (absorbent) is usually used. For coolants with temperatures below 4 °C (e.g., cold storage), the usual mixture is ammonia (refrigerant) and water (absorbent) [22]. Absorption chillers are most cost-effective in facilities that have significant air conditioning needs or year-round cooling loads. Facilities with significant year-round air conditioning loads include hospitals, hotels, large commercial office buildings and college campuses. Facilities that may require constant year-round cooling include manufacturing plants with process cooling needs, cold storage warehouses, data centres and district energy plants [22].

Another advantage of DC is cooling load diversification [25]. In [25], a techno-economic analysis of a DC system was carried out in which a cold storage unit was also integrated into the system to smooth the load profile. The effect was similar to using thermal energy storage in DH systems [26]. It provided more flexibility for load switching, made the system more reliable and helped integrate more renewable energy sources into the system.

Similar to DH, DC systems can also be more beneficial if more consumers are connected to the network [27], although DC systems are never as large as DH systems because DH consumers are mostly multi-family buildings and office buildings, while DC is mainly only for office buildings and very large consumers such as hospitals, supermarkets, etc. As the temperature difference between supply and return in DC systems is much smaller compared to DH systems, the pipe diameter in a DC system is therefore also larger compared to a DH network with same capacity. This leads to the need for larger pipes and greater investments to establish a DC network [6].

This study focuses on coupling CHP plants with DC using absorption chillers and offers advice on how to plan for flexible and cost-effective cooling production. In this study, the Mustamäe CHP plant and the nearby Taltech university campus and Tehnopol science and business park were used as a case study. The paper investigates the relationship between electric power and cooling energy generation. There are several studies on the efficiency of trigeneration [24–26], improving the absorption chiller's coefficient of performance (COP) through various operational changes and the use of thermal energy or cold storage [28]. This article fills the gap between trigeneration power and cooling energy production. As in the case of cogeneration of heat and electricity, the more heat is generated, the less power is produced [29,30]. The same can be said for cooling and power cogeneration. However, because the processes are different, the relationship between the two technologies—heat and power cogeneration vs. cooling and power cogeneration—is different since cooling production is not as simple as the production of heat [31,32].

In the Ülemiste district of Tallinn, a DC network is being constructed that will use the excess heat from the Tallinn CHP plant [33]. According to the absorption chiller datasheet, the cooling capacity corresponds to the temperature at the hot water inlet, where a 39% loss in cooling capacity is indicated when the driving hot water temperature is lowered to 77 °C. This study hereby investigates the roots of these problems.

The future of Tallinn's DC network was postulated and thoroughly examined in [34]. A comprehensive planning procedure was followed, beginning with an analysis of potential DC network locations, followed by an assessment of potential cooling needs and piping, and finally a suggestion of potential facilities for cooling production. The Mustamäe district was not evaluated in [34] because it is not located in the city centre and there may not be sufficient cooling demand for the district energy company. Nevertheless, this paper investigates the cooling demand in the Mustamäe district to determine whether it would be beneficial to couple the CHP plant with district cooling. As in [34], potential consumers were identified, and appropriate production facilities were recommended based on their cooling demand.

This paper thoroughly explores the cooling energy production process, examining each step. For the analysis, calculations were performed for the Mustamäe CHP plant using the data from the Tallinn DH system on the heat load and the estimated DC demand in the Mustamäe district. In this study, the following research caps are addressed:

- How does coupling with an absorption chiller affect the operation and electricity production of the CHP?
- Which operational regime would be the most energy efficient for cooling production, and which would be the most energy efficient for electricity production? Which regime should be preferred?
- Would using an absorption chiller be cost-effective, and how large of a cooling load could it cover?

The Mustamäe CHP plant was launched in 2019. The plant uses woodchips as fuel and provides heat to the united DH network of Tallinn, which is about 470 km long, with an annual heat consumption pf around 1750 GWh [35]. Flow temperatures in the Tallinn DH network are rather high—the supply temperature is around 65 °C, and the return temperature is around 44 °C. The Mustamäe CHP plant's nominal thermal power is 47 MW_{th}, and its electrical power is 10 MW_{el}. The plant has auxiliary coolers installed to maintain sufficient heat load for electricity generation.

Since the absorption chiller load is largely dependent on the available heat flow, it is clear that an auxiliary cooling unit is required in the event of a fluctuating cooling demand. In this study, various auxiliary cooling technologies were evaluated in terms of cost efficiency and primary energy savings.

This paper could be useful to district energy planners, district heating and cooling companies, CHP plant engineers, and real estate developers.

2. Method

This section explains how to determine the cooling production volume of an absorption chiller based on hot water temperature. The Method section also provides an estimate of the Mustamäe district's cooling demand. The system boundaries are shown in Figure 1.

As can be seen on Figure 1, the study concentrates on the generation of cooling by the absorption chiller and auxiliary cooling generation, which could be achieved, for example, by a heat pump, and the devices that either have effect on cooling generation or are affected by it. Within these boundaries are also the turbine that effects the absorption chiller and drives the generator. Within the boundaries there is also DC heat exchanger, which is connected to cooling sink, that is the DC network.

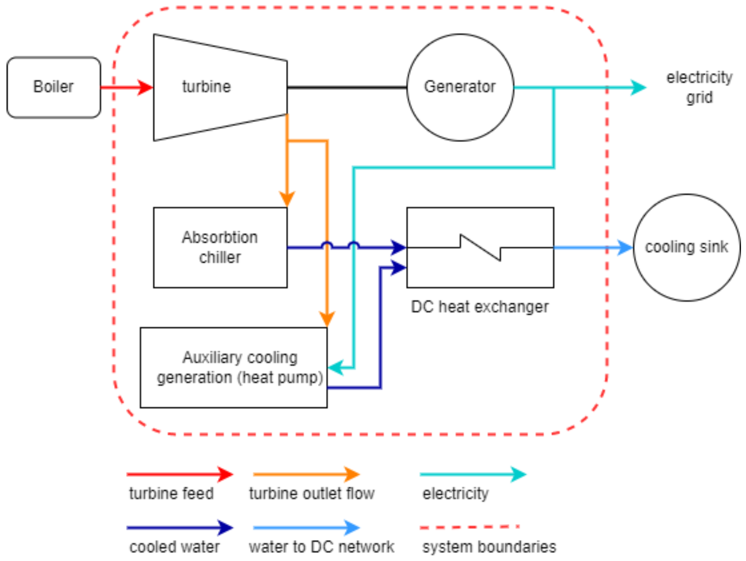

Figure 1. System boundaries.

2.1. Technical Process

In this study, the effects of coupling DC with CHP plants on electricity production are examined via the technical processes that take place in absorption chillers. Many simultaneous, interdependent processes take place in an absorption chiller, and all these processes and the interrelationships between these processes are examined in this paper. The aim of this study is to determine the effects of coupling DC with CHP plants.

Absorption chillers require a heat flow to initiate processes that ultimately create a cooling effect. When DC and a CHP system are connected, this heat flow comes from the CHP turbine condenser. The heat flow is necessary for the desorption process to separate the strong lithium–bromide (LiBr) solution from the water prior to the absorption process that creates the cooling effect.

A diagram of the absorption chiller processes and their interconnections is shown in Figure 2. Driving hot water flow form the turbine is marked with red lines, cold water flow to DC heat exchanger is marked with light blue lines, strong LiBr solution flow from desorber to absorber is marked with orange line, weak LiBr solution flow from evaporator to desorber is marked with yellow line. Condensate flow from the desorbtion process from condenser to evaporator is marked with green line and chiller condenser cooling circuit is marked with dark blue lines.

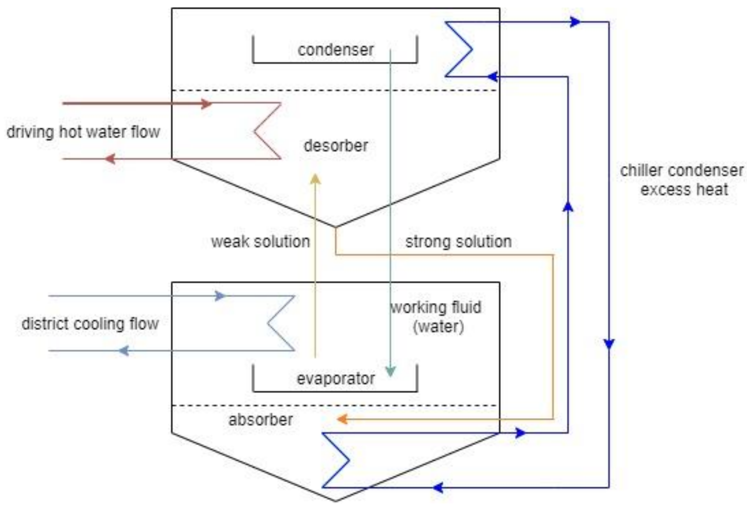

Figure 2. Absorption chiller flow diagram.

In this study, the following parameters of the absorption chiller's flows and the CHP turbine condenser's flow are most relevant: the temperature t (°C), pressure p (bar) and flow rate G (kg/s).

The cooling effect in the absorption chamber of an absorption chiller is caused by near-vacuum pressure, which causes the water to evaporate at very low temperatures (around 3–7 °C, depending on the chamber pressure). Water that is sprayed into the absorption chamber evaporates, creating the cooling effect. The cooling effect is greater when the desorption of water and LiBr is caused by the driving hot water flow. The more intense the desorption, the greater the flow of the strong LiBr solution and the greater the flow of water vapour into the absorption chamber. The water that evaporates during the desorption process is condensed again and then sent to the absorption chamber as well. The flows of the strong LiBr solution and condensate water are important for maintaining near-vacuum pressure in the absorption chamber. The condensate water flow is also necessary for obtaining the cooling effect from the evaporation of water in the absorption chamber.

The relationship between the specific enthalpy h_1 (J/kg) of the driving hot water flow and the desorption of a weak LiBr solution can be illustrated using Figure 3. The driving hot water flow is from the same flow as the turbine inlet flow. The mass concentration of a weak solution x_W is usually 60%, and the mass concentration of a strong solution x_S is usually around 64–65%. The higher the specific enthalpy of the driving hot water flow, the higher the concentration of the strong solution [36].

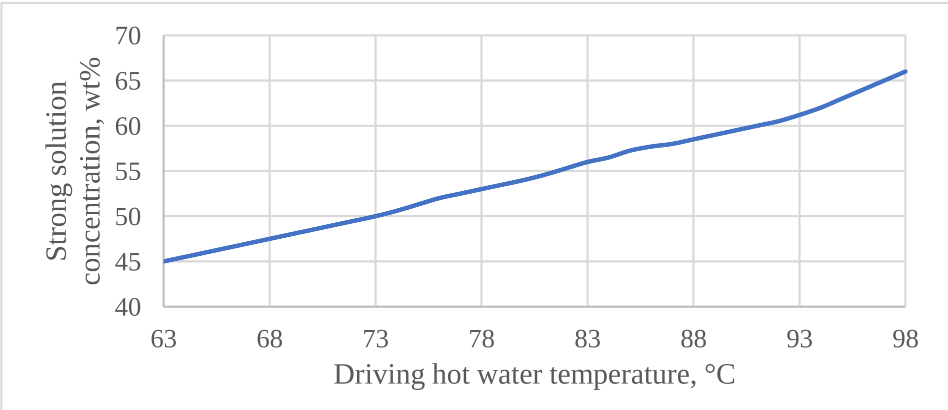

Figure 3. Strong solution concentration in relation to driving hot water temperature [37].

As can be seen in Figure 2, the higher the specific enthalpy and temperature of the flow, the more intense the process is. However, there is a limiting factor for the flow temperature that is set by the turbine condenser that the driving hot water flow comes from. For the electricity generation process, it is important that the steam passing through the turbine condenses in the condenser, so it sets a limiting factor for the maximum driving hot water specific enthalpy, which is about 2680 kJ/kg, that is, about 95 °C at a low vacuum (about 0.5 bar).

The low pressure in the absorption chamber is important for obtaining the cooling effect from water evaporation. Low pressure is created by the absorption of the water and the strong LiBr solution. The higher the concentration of the LiBr solution, the more intense the absorption process is, and the lower the pressure that can be maintained in the absorption chamber. The relationship between the concentration of the strong solution, the pressure in the absorption chamber and the saturation temperature of water vapour is shown in Figure 4.

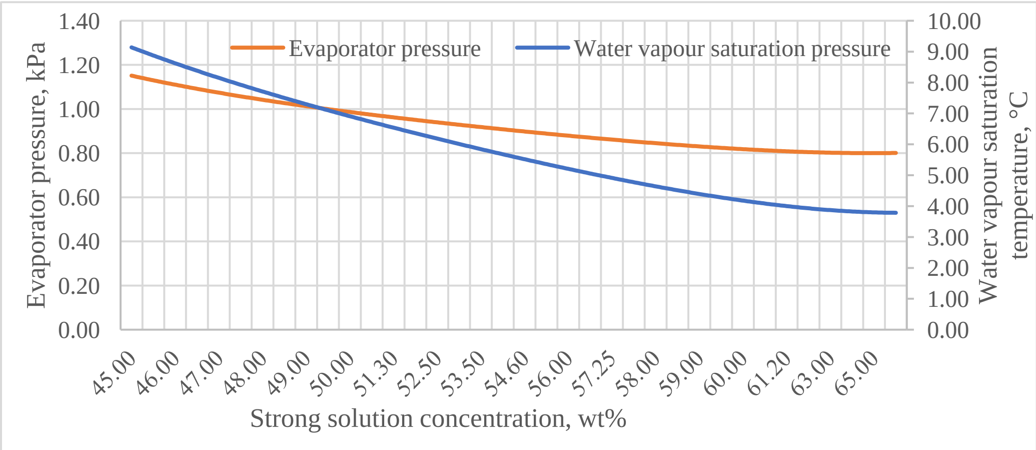

Figure 4. Evaporator pressure and water vapour saturation temperature at strong solution concentrations from 45 to 66%.

As seen in Figure 4, a strong solution concentration is crucial for the cooling effect because the lower the saturation temperature of the water vapour, the more water that can be evaporated and the more heat that can be absorbed.

The district cooling water flow rate determines the COP of the system since the DC supply temperature affects the heat transfer during the cooling process. The higher the temperature of the DC return flow, the more intense the evaporation process is and the better the COP and cooling capacity are.

Figure 5 depicts the relationship between the driving hot water flow temperature and the COP of an absorption chiller.

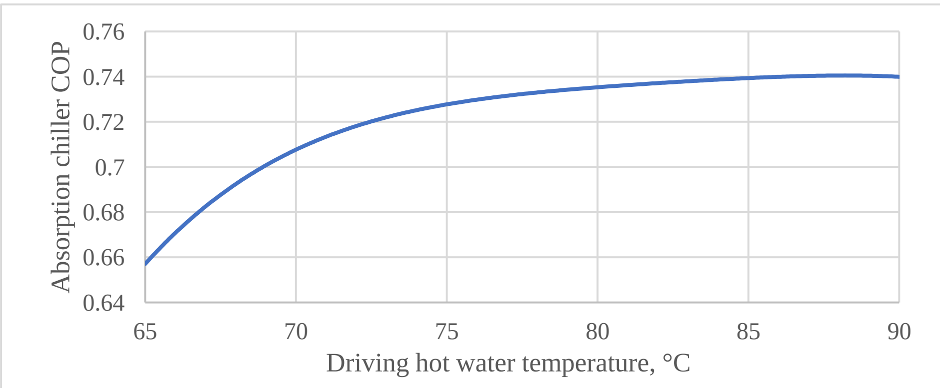

Figure 5. Absorption chiller COP at driving hot water temperatures ranging between 65 and 90 °C.

For power generation, the turbine output power E (W) can be determined via the enthalpies of the steam at the inlet and outlet of the turbine using Equation (1):

$$E = G_T(h_1 - h_2), \tag{1}$$

where G_T is the turbine steam mass flow rate (kg/s), h_1 (J/kg) is the turbine steam inlet specific enthalpy and h_2 (J/kg) is the turbine steam outlet specific enthalpy.

As can be seen in Equation (1), if the specific enthalpy of the flow at the outlet of the turbine is lower, then more power can be generated. Since the specific enthalpy of the flow at the turbine inlet is fixed, and the outlet flow can be adjusted to fit the needs of DH (or, in our case, DC) power generation depending only on the flow at the turbine outlet.

2.2. *Mustamäe District Cooling Demand Estimation*

The influence of district cooling on power generation was studied using a case study of the Mustamäe CHP plant and potential district cooling consumers in Mustamäe. First, potential consumers located near the Mustamäe CHP plant were selected. Figure 6 provides a map showing the Mustamäe CHP plant (marked with red lines), Tallinn University of Technology campus buildings (marked with pink lines) and Tehnopol Science park office buildings (marked with yellow lines).

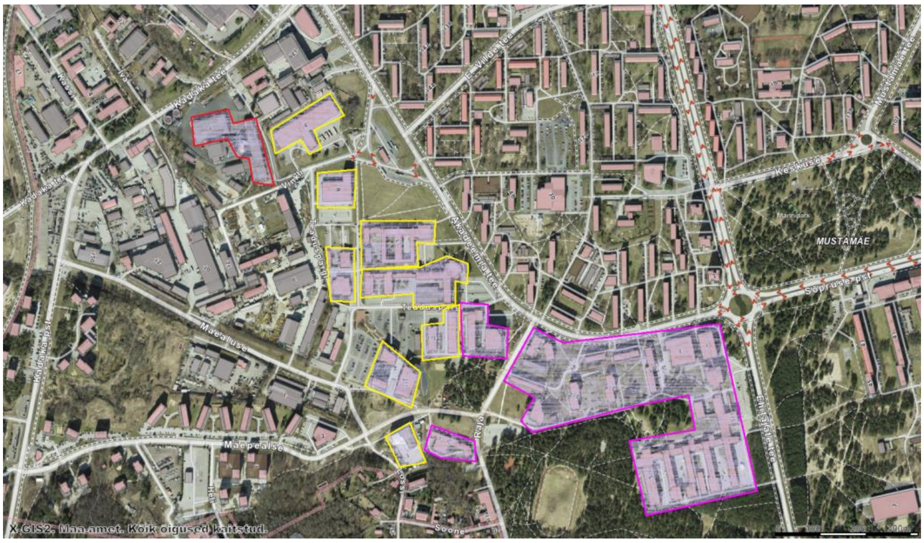

Figure 6. Mustamäe DC region. Mustamäe CHP plant—red lines; Tallinn University of Technology campus—pink lines; Tehnopol Science Park—yellow lines.

At the moment, there is no district cooling in the Mustamäe district. There is the Mustamäe CHP plant, which supplies heat to the entire Tallinn DH network. The thermal capacity of the Mustamäe CHP plant is 47 MW, of which 9 MW comes from the flue gas condenser, and during summer period, the heat is rejected. The plant's electric capacity is 10 MW.

Since there are several office buildings on the Tallinn University of Technology campus and other types of public buildings that could be excellent potential consumers of DC, local utilities are in the process of planning a district cooling region there.

The TalTech campus consists of 26 buildings, including administrative buildings, research laboratories and auditoria. The campus is partially connected to the DH network (14 buildings), while the remaining buildings (12 buildings) are connected to a small local, gas-fired DH network. Cooling is provided by local electric chillers. A climate-neutral TalTech campus is one of the university's ambitious sustainable development goals and is set in its strategic development plan until 2035. Cooling decarbonisation will reduce energy-related CO_2 emissions. Data on the cooling demand of the Tallinn University of Technology were provided by the university's administrative department. The plan to achieve a carbon neutral university campus for TalTech was developed in [38].

The Tehnopol Science Park is located near the Tallinn University of Technology and provides offices for over 200 technology companies and working spaces for over 4000 employees. Two laboratories and more than 55,000 m^2 of office space are leased. The Science Park was designed with an emphasis on the well-being of workers and the park's small ecological footprint. In addition to offices, the Science Park has several eating areas, sports facilities and other amenities [39].

For Tehnopol Science Park's cooling demand, data from the Estonian Building Register [39] about the buildings' useable surface were used. It was multiplied with the average cooling demand per 1 m^2, which in case of Tallinn, Estonia, is about 50 W/m^2 [40]. For the Tallinn University of Technology campus, the cooling demand is 7.4 MW, and for Tehnopol Science Park, the cooling capacity should be around 5 MW. Part of the cooling energy will be provided by absorption chillers, which will use the excess heat from the Mustamäe CHP plant. It should be noted that there are several other potential DC consumers located nearby.

According to the technical specifics of a conventional absorption chiller, the maximum capacity of the absorption chiller for the Mustamäe CHP plant is about 0.8 MW. This means that other cooling units are needed to cover the area's cooling demand, and the absorption chiller would have to operate at full load almost 24/7. The best location for the prospective absorption chiller would be in the territory of the CHP plant, which is marked with red borders in Figure 5, so it would be convenient to access driving hot water with minimal losses.

To obtain accurate operational data for the absorption chiller, a cooling demand profile was generated for the Tallinn University of Technology campus and the Tehnopol Science Park using EnergyPRO software. For input data, temperatures from 2018 to 2021were used. The cooling demand profile for the Mustamäe district and the proportion of the cooling demand that can be covered by the Mustamäe CHP plant's absorption chiller are shown in Figure 7. Figure 7 also takes into account the availability of excess heat as DH has a higher priority than district cooling, meaning that if heat is needed for heating purposes, it cannot be used for absorption.

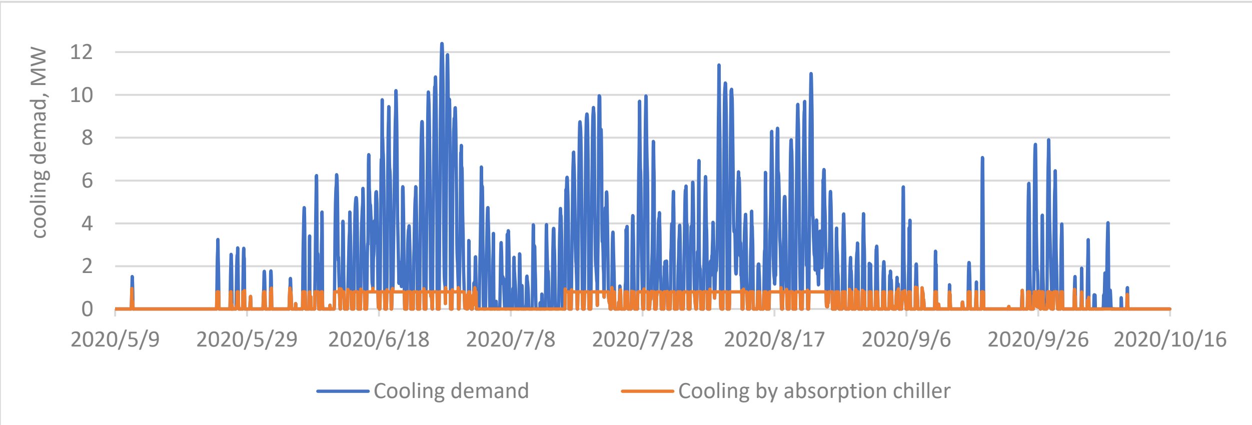

Figure 7. Tallinn University of Technology and Tehnopol Science Park cooling needs, and the cooling produced by the absorption chiller.

As can be seen in Figure 7, absorption chillers need some type of backup since in the summer, when the cooling demand is the highest, there is a two-week period during which the CHP plant undergoes repairs and maintenance and the plant ceases operation. There is another two-week period when the CHP plant must cover the heat demand of the DH network since a CHP plant with a higher priority is undergoing annual maintenance. Thus, there are about four weeks in the summer when the absorption chiller cannot operate due to a lack of heat. This issue can be solved by using auxiliary boilers or extra chillers.

Technical specifics of the proposed absorption chiller are provided in Table 1.

Table 1. Technical specifics of the absorption chiller.

Parameter	Value
Absorption chiller type	Single-stage
Heat input	1.1 MW
Cooling output	0.8 MW
Required condenser heat rejection	2 MW
Driving hot water input temperature	90 °C
Driving hot water output temperature	68 °C
Driving hot water flow rate	43.7 m^3/h
Chilled water input temperature (DC return)	15 °C
Chilled water output temperature (DC supply)	7 °C
Chilled water flow rate	86.5 m^3/h

2.3. Mustamäe District Cooling Demand Estimation

To cover the cooling needs of the Tallinn University of Technology campus and the Tehnopol Science Park, extra cooling units must be used in addition to the absorption chiller. The capacity of the extra cooling units can be discussed as cooling peak loads, as the cooling demand depends upon the outdoor temperature. The number of peaks in the demand graph can vary over the years, as can the height of the peaks. In this study, normalised temperatures for the year 2020 were used. This means that temperatures were generated according to long-time climate average so that they would represent the annual average temperature and normal temperature amplitude. Nevertheless, the peaks should be considered for the determination of cooling capacity to provide a sufficient load for covering the demand on the days when it is the most necessary. As the climate is warming and the frequency of heat waves in the summer is increasing, installing a sufficient amount of cooling generation is justified. There are several possible solutions for cooling generation. In the case of Mustamäe, cooling towers and heat pumps can be recommended. Cooling towers are recommended since there is land available for the installation. Heat pumps can also be a good solution if located at the CHP plant since they can be used as similar power-to-heat technologies. In the summer, it would be beneficial to use electricity for cooling generation rather than supply it to the power grid due to low electricity consumption and the greater availability of solar electricity. In addition, there are photo-voltaic panels installed in the power plant that can be used in the summer period for powering heat pumps. Since there are no natural sources of free cooling in the vicinity of Mustamäe, free cooling will not be an option to meet the cooling demand. Table 2 provides the data required to assess the best technical solution for cooling production in the district.

Table 2. Parameters for cooling technology evaluation.

Cooling Technology	Installation Costs, EUR/MW	Annual O&M Costs, EUR/MW/year	Estimated Service Life, Years
Absorption chiller [22,41]	68,000	900	30
Cooling towers [42,43]	12,000	11,000	20
Heat pumps [44,45]	44,000	2000	20

Cooling towers are a common cooling solution due to their low installation costs and ease of use. The biggest disadvantage of this technology concerns the high operation and maintenance (O&M) costs, which are caused by sewage costs, which account for approximately 58% of total operation and maintenance costs, and the costs of treated cooling water, which account for approximately 31% [46]. High investment costs can be a barrier to using an absorption chiller to produce cooling, but when the installation costs are divided by the estimated service life, it turns out to be the least expensive option, even with the O&M costs.

In the case of the Mustamäe district, there are several possible technology combinations for cooling production:

1. The use of 12.4 MW cooling towers;
2. The use of 12.4 MW heat pumps;
3. The use of 11.6 MW cooling towers and a 0.8 MW absorption chiller;
4. The use of 11.6 MW heat pumps and a 0.8 MW absorption chiller;
5. The use of a 0.8 MW absorption chiller and various combinations of heat pumps and cooling towers.

Cooling towers are not recommended in this case since their annual costs are higher than the annual costs of the heat pumps [47]. They would only be recommended and economically feasible for smaller loads, where the benefit of low investment costs is greater. As a result, technical options that contain only heat pumps or a combination of heat pumps and an absorption chiller were compared based on their economic parameters, with the results provided in Table 3.

Table 3. Economic parameters for technical solutions proposed.

Technical Solution	Total Investments, EUR	Annual Costs, EUR
12.4 MW heat pumps	545,600	52,100
0.8 MW absorption chiller and 11.6 MW heat pumps	564,800	51,250

The annual costs are determined by dividing the investment costs of the equipment by its service life and then adding its O&M costs. The economic difference between these two solutions is negligible, as shown in Table 3. The electricity consumption of the heat pumps and the absorption chiller is considered in the O&M costs. The main difference is that using an absorption chiller improves the overall primary energy efficiency of a CHP plant, whereas using heat pumps has no effect on this.

3. Results

This section investigates the possible annual production and operating hours of an absorption chiller. According to the methodology that was provided in the previous section, the power loss caused by the absorption chiller maintaining a hot water temperature is discussed, in addition to the proper temperature for a hot water supply using the methodology described in the previous section.

Absorption Chiller Operation Mode

According to the data provided in Figure 7, the absorption chiller will operate for about 1530 h per year at normal year temperatures. For about 1260 h, the chiller will operate at full load, which is 82% of the operating time. The annual cooling demand of the chosen DC network will be 5713 MWh, and the absorption chiller can cover 1104 MWh, which is 19.3% of the total cooling demand.

According to the absorption chiller processes described in the Methods section and the proposed absorption chiller capacity, the power produced and the cooling capacity for the driving hot water temperatures between 63 and 98 °C are shown in Figure 8.

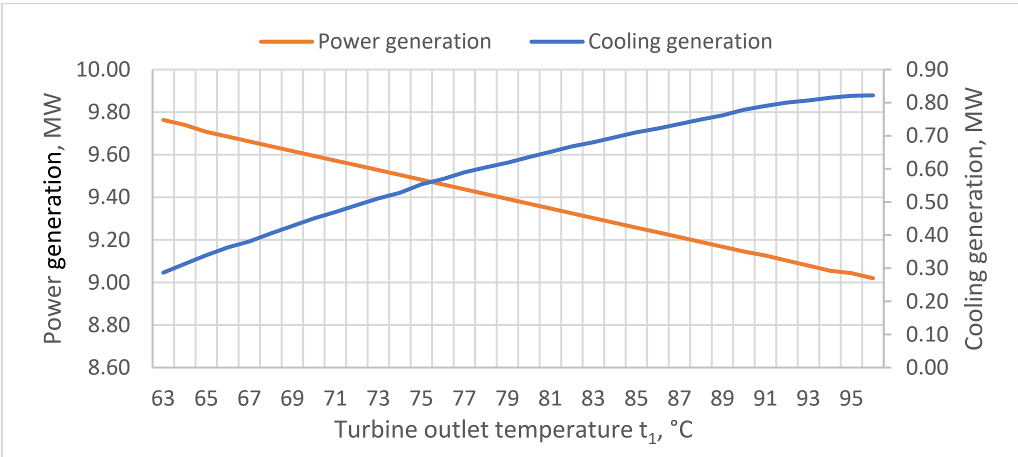

Figure 8. Mustamäe CHP plant power generation and absorption chiller cooling generation at driving hot water temperatures ranging between 63 and 98°.

As shown in Figure 8, when the absorption chiller is operating at full load, i.e., 0.8 MW, then the turbine's electrical power will be 9.14 MW, which means that using the absorption chiller at full load will reduce the turbine's power generation by 6.3%. If the turbine is operated at maximum load and the chiller is using 70 °C driving hot water, then the absorption chiller will only be able to operate at a capacity of 0.45 MW, with a 45% reduction in capacity.

When using local cooling, the annual primary energy consumption (PEC) for cooling will be calculated according to Equation (2):

$$PEC = \frac{Q_c \cdot PEF_{el}}{COP_{ac}} \tag{2}$$

where Q_c (MWh) stands for the cooling consumption, PEF stands for the primary energy factor and COP is the coefficient of performance. When the primary energy factor for electricity is PEF_{el} = 2 [48], the COP of a normal air conditioning and cooling system is estimated to be COP_{ac} = 3 [49,50] and the cooling demand for the observed district is 5713 MWh, then the PEC of Mustamäe local chillers would be also 3808 MWh. In the case of using an absorption chiller and heat pumps for cooling generation, the PEC would then be calculated according to Equation (3):

$$PEC_{abs+hp} = Q_{c,abs} \cdot PEF_{abs} + \frac{Q_{c,hp} \cdot PEF_{el}}{COP_{hp}} \tag{3}$$

where $Q_{c,abs}$ (MWh) stands for the cooling demand covered by the absorption chiller, which, according to this study, is Q_{abs} = 1104 MWh, and PEF_{abs} is the primary energy factor for cooling generation using an absorption chiller, which is PEF_{abs} = 0.7 according to the methodology for calculating building energy efficiency in Estonia [51], this gives a PEC value for the cooling energy provided by absorption chiller of 773 MWh. The $Q_{c,hp}$ (MWh) represents the cooling demand covered by the heat pump, which is $Q_{c,hp}$ = 4609 MWh in the case of this study. The COP value for the heat pump is estimated to be COP_{hp} = 4 [11]. This provides 2304 MWh for cooling energy generated by the heat pumps. The total PEC for the absorption chiller and heat pump solution for cooling generation is therefore 3077 MWh, which is 19% lower than the energy consumption for local cooling.

If all cooling demands were covered by heat pumps, the annual PEC would then be 2857 MWh, which would be even lower than using an absorption chiller with heat pumps; this would be a PEC of 25% less than local cooling and a PEC of 7% less than using an absorption chiller with heat pump. Table 4 shows the PEC results of each cooling generation option.

Table 4. Primary energy consumption (PEC) for technical solutions proposed.

Technical Solution	Primary Energy Consumption, EUR
12.4 MW local cooling (air conditioners)	3808
12.4 MW heat pumps	2857
0.8 MW absorption chiller and 11.6 MW heat pumps	3077

For future development, it is recommended to install solar collectors in combination with thermal energy storage units. Since the absorption chiller's condenser needs cooling, this excess heat can also be utilised. It should be noted that this is low-grade excess heat, the temperature of which can be around 35–40 °C. The absorption chiller at the Mustamäe CHP plant will produce 2760 MWh of excess heat during the operating period. This heat can be used to preheat the DH supply or for DH via heat pumps. Thermal energy storage will make the system more flexible.

4. Discussion

District cooling can help improve the efficiency of primary energy use in CHP plants as in this way, excess heat from electricity production can be used for cooling generation. District cooling is a more environmentally friendly option than local cooling as it uses less primary energy to generate cooling energy. In the case of the Tallinn University of Technology and the Tehnopol Science Park, the annual primary energy consumption for cooling will be 19% less when using an absorption chiller and heat pumps compared to local cooling solutions.

A reduction in power generation should not be a concern if an absorption chiller is installed. As can be seen from this study, the impact on power generation is insignificant. In the case of the Mustamäe CHP plant, an absorption chiller operating at full load would only reduce power generation by 6.3%. The effect will be different when the absorption chiller's driving hot water is reduced, since lowering the temperature of the driving hot water from 90 °C to 70 °C will result in a 45% decrease in cooling generation. Installing absorption chillers at the CHP plant will certainly have a positive effect on the plant's energy efficiency since it utilises excess heat from power generation instead of rejecting it via coolers.

It should also be noted that absorption chillers that use excess heat from CHP power generation will require auxiliary boilers or other cooling generation units to cover the cooling demand because CHP plants have a two-week downtime period during the summer for maintenance and repairs. If there are other CHP plants in the area, there may be another two-week period without excess heat because the CHP has to cover the heat load, compensating for the higher-priority CHP while it undergoes its annual maintenance.

Absorption chillers work very well with both cold and thermal energy storage. Cold storage can help smooth out peaks in cooling demand, while thermal energy storage can provide driving hot water for absorption chillers or store excess heat from the chiller's condenser for DH. Thermal energy storage using option should be further studied.

The cooling demand can also be covered by using only heat pumps, which was also a proposed in this paper as an option. This would result in an even smaller PEC, 7% smaller, than a solution in which absorption chiller and heat pumps are combined. In addition, when only heat pumps are used for cooling generation, the CHP electricity production would not be affected because unlike absorption chillers, heat pumps do not require a high-temperature heat source. The negative aspect of this solution is that the CHP plant would need to reject heat with chillers during the summer period, which would not be an effective use of energy. When an absorption chiller is used for cooling generation, it uses the excess heat of the power plant that would have otherwise been rejected by chillers.

5. Conclusions

As a conclusion it can be said that for cooling generation for a DC network, heat pumps would result with the best primary energy consumption, as is shown in Table 4. Nevertheless, heat pumps can be used only in a district where are also low-grade energy sources or industrial heat sources available, which, in case of this study, is a CHP plant. The aim of this study was to find a good solution for cooling generation for a DC network that is located near a CHP plant. Another aim of the study was to find a good way to utilise the CHP plant's excess heat that is normally rejected by chillers, which is not an efficient use of energy. As an option that could do both—produce cooling and utilise excess heat—an absorption chiller is examined. In this study, the operation of an absorption chiller is thoroughly analysed, and the results show that when absorption chillers are used, power generation would decrease by 6.3%. As absorption chillers cannot cover the whole cooling load of the district, heat pumps should also be used. Heat pumps could be used for cooling generation without absorption chiller; however, in this case, the excess heat of the CHP plant would not be completely utilised.

Both proposed solutions would result in a smaller PEC than local cooling and would have approximately the same installation and operation and maintenance costs.

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Nomenclature

Abbreviation	
CHP	combined heat and power
COP	coefficient of performance
DC	district cooling
DH	district heating
EU	European Union
Parameters	
E	output power, W
G	flow rate kg/s
G_T	turbine steam mass flow rate, kg/s
h_1	turbine steam inlet specific enthalpy, J/kg
h_2	turbine steam outlet specific enthalpy, J/kg

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