Concept of cold generation in a district heating substation by using adsorption heat pumps supported by heat and cold storage units

Wojciech Bujalski[a], Arkadiusz Szczęśniak[b*], Kamil Futyma[c] and Andrzej Grzebielec[d]

[a] *Warsaw University of Technology, Warsaw, Poland, Wojciech.Bujalski@pw.edu.pl*
[b] *Warsaw University of Technology, Warsaw, Poland, Arkadiusz.Szczesniak@pw.edu.pl*
[c] *Warsaw University of Technology, Warsaw, Poland, Kamil.Futyma@pw.edu.pl*
[d] *Warsaw University of Technology, Warsaw, Poland, Andrzej.Grzebielec@pw.edu.pl*

Abstract:

District heating systems in northern Europe experience large seasonal differences in heat demand, rendering summertime profitability marginal at best. This study discusses a novel concept of a district heating substation that increases heat consumption during the summer period for the purpose of conversion into cold for an air conditioning system. Cold is generated by an adsorption chiller driven by heat from the district heating system. The study numerically models the system and examines its operation during a 24-hour period. The research indicated the need for a cold storage unit to cover cooling demand when ambient temperature limits the operation of the chiller. Additionally, a heat storage unit is required in order to equalize heat consumption from the district heating network.

Keywords:

District heating network, district heating substation, adsorption chillers, PCM storage

1. Introduction

District heating networks (DHNs) are a key element in strategies designed to meet the goals set by the European Union's Renewable Energy Directive [1] as they help deliver reductions in emissions of greenhouse gases among other things. This study deals with bolstering the profitability of DHNs by increasing heat consumption during the summer period [2]. In Poland, the typical heat consumption curve in a DHN is extremely seasonal, with the ratio of summer to winter heat demand being 1:10, as shown in Figure 1 below.

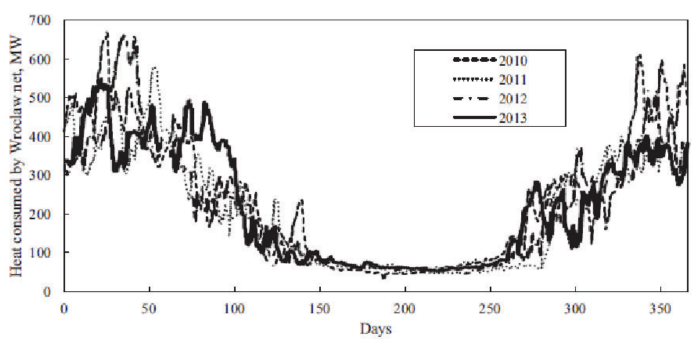

Figure. 1. Annual profile of heat consumption in a mid-sized Polish city, as per Chorowski [3]

Researchers report very similar heat demand profiles in other European countries, e.g., in the Netherlands [4] and Finland [5]. Extreme seasonal fluctuations put the profitability of DHNs into question and this issue is driving research into increasing heat consumption during the summer period. A review of district heating and cooling systems by Lake [6] concluded that DHNs could be enhanced with new technologies. The author cited thermal energy storage and absorption chillers as possible avenues to increase DHN efficiency.

 https://doi.org/10.52202/069564-0311

The idea of cold district heating is widely discussed in the available literature [7], which defines it as cold water distribution in the range 10°C to 25°C. Pellegrini [7] notes that water cooling in such systems is done by electric reversible heat pumps. However, these pumps increase electricity consumption and fail to make use of the DHN. In contrast, replacing compressor heat pumps with adsorption refrigeration units boosts summertime consumption of heat thereby reducing summertime heat losses.

Grzebielec et al. [8] examined the possibility of using an adsorption refrigeration unit in a district heating substation (DHS). The authors concluded that it is feasible to use adsorption heat pumps for cold generation, and that this appears to be a promising solution because it uses existing infrastructure for cold generation on the customer's side without requiring long-distance cold transmission. Halon et al. [9] reported on an adsorption heat pump driven by heat from the DHS. The heating temperature was 55°C and the released heat was directed to a rooftop cooling tower.

Wu et al. [10] analyzed a composite heating substation with another type of absorption heat pump with water-LiBr as the working agent and a two-plate heat exchanger. The paper sought to improve the utilization efficiency of geothermal water and the primary supply water.

Another idea of improving DHS efficiency was reported by Turski [2], where the authors compared a 150 kW DHS operating with and without a heat storage accumulator: heat storage accumulators improved the efficiency of the entire heating system by 22%.

McNally et al. [12] experimentally investigated the performance of an adsorption chiller operation in two modes:

- Constant hot water temperature – to represent the DHN.
- Varying hot water temperature – to represent the heat from flat plate solar collectors.

The temperature variations of hot water impacted performance more than the flow variations. Therefore, adsorption chillers are suitable for use with DHNs.

The issue limiting the integration of adsorption chillers for cold generation is the temperature of the heating medium, which is too low for commercial adsorption heat pumps. The temperature of the available heat source could be raised by upgrading the substation with thermal storage tanks linked to renewables [15]. A promising heat storage technology is the PCM storage unit, as it requires 40% less volume than a water-based heat accumulator [13]. Due to a paucity of publicly available information, the potential of PCM heat storage is not widely recognized [14]. The influence of using heat storage with PCM on inlet and outlet temperatures in substations was investigated by Nogaj et al. [15]. The authors examined the integration of PCM with a single-function substation whose thermal power is 150 kW. Once the PCM was integrated, the difference in average return water temperature fell from 7.15K to 2.29K. This allowed the accumulation of 69.5% of excess heat and improved the efficiency of the entire heating system by 22%. The authors concluded the use of PCM accumulators gives potential energy savings of up to 6.7%.

1.1. Paper objective

A review of available literature indicates an opportunity to implement new technologies in DHNs in order to achieve enhanced efficiency. The study models a novel hybrid district heating substation designed to ensure increased summertime heat consumption; the period when heat losses peak due to very low heat consumption. The concept is to supplement the DHS with an adsorption chiller, which will be used to generate cooling for the air conditioning system of a building. The proposed solution uses existing DHN infrastructure for trigeneration and generates cooling directly on site. Thus, heat from the hybrid district heating hub will be used for heating the building in winter, and in summer will drive a chiller for air conditioning needs.

This paper introduces the following novelties:

- Concept of a novel hybrid DHS for cold generation
- Integration of PCM heat and cold storage units for heat load consumption equalization and to provide cold for air conditioning systems in very hot periods.

The concept is verified with a numerical study, which examined system behavior in Polish conditions.

2. Theory

The substation is a key element of the DHN, which is responsible for transferring heat from the medium that circulates in the DHN to the internal heating system inside buildings. Currently, summertime use of heat is very low. Integrating the cooling loop in the DHN would boost summertime heat consumption as it will be used for cold generation by adsorption heat pumps.

The general concept of the hybrid DHS is shown in Figure 1. The main system elements are an adsorption heat pump, DHS heat exchangers, and cold and heat storage units. The idea is to deliver cold for an office air conditioning system. The DHS is tasked primarily with producing cold by means of an adsorption chiller driven by heat from the DHN. The DHS is also equipped with cold and heat storage units. The heat storage unit is used to equalize heat consumption from the DHN, while the cold storage unit covers peak cooling demand

https://doi.org/10.52202/069564-0311

from the storage units. Thus, the installed capacity of the adsorption chiller could be lower in terms of power than the maximum peak power and its operation will be smoother.

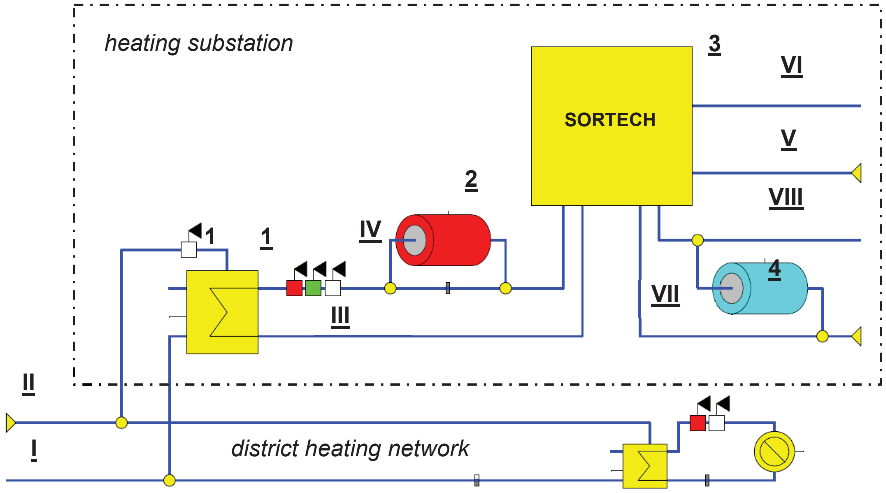

Figure 2. Topology of a hybrid DHS, (1) heat exchanger, (2) PCM for heat storage, (3) adsorption chiller, (4) PCM for cold storage

The thermodynamic parameters for the nominal operating points are shown in the table 1. The points from the table correspond to the above topology diagram.

Table 1. Basic thermodynamic parameters

Point	Temperature	Mass flow rate	Comment
I	65.0°C	10 kg/s	DHS heat supply pipe
II	64.5°C	10 kg/s	DHS return pipe
III	55.0°C	0.607 kg/s	Return pipe
IV	60.0°C	0.607 kg/s	Heat for driving adsorption heat pump
V	28.2°C	1.33 kg/s	Return from dry cooler
VI	25.0°C	1.33 kg/s	Heat for dry cooler
VII	16.0°C	0.806 kg/s	Cold for air conditioning
VIII	14.3°C	0.806 kg/s	Return from air conditioning

For the purpose of this study, we assumed the DHS delivers heat and cold to an office building of total area 142 m^2, total volume 426 m^3 with 6 rooms. Cooling demand is determined by a mathematical model, where the air conditioning is to maintain the interior at a temperature not exceeding 25°C during the summer period. Air temperature inside the rooms changes as per the equation:

$$\frac{\partial T}{\partial t} m \cdot c_p = \dot{Q}_{air} + \dot{Q}_{el} + \dot{Q}_{people} + \dot{Q}_{wall,out} + \dot{Q}_{wall,in} + \dot{Q}_{floor} + \dot{Q}_{ceil} + \dot{Q}_{window} + \dot{Q}_{sun,window}, \quad (1)$$

To simplify the model, $\dot{Q}_{floor}$, $\dot{Q}_{ceil}$ and $\dot{Q}_{wall,in}$ were omitted in the final calculations. The resulting cold demand for the office is shown in Figure 2 below.

 https://doi.org/10.52202/069564-0311

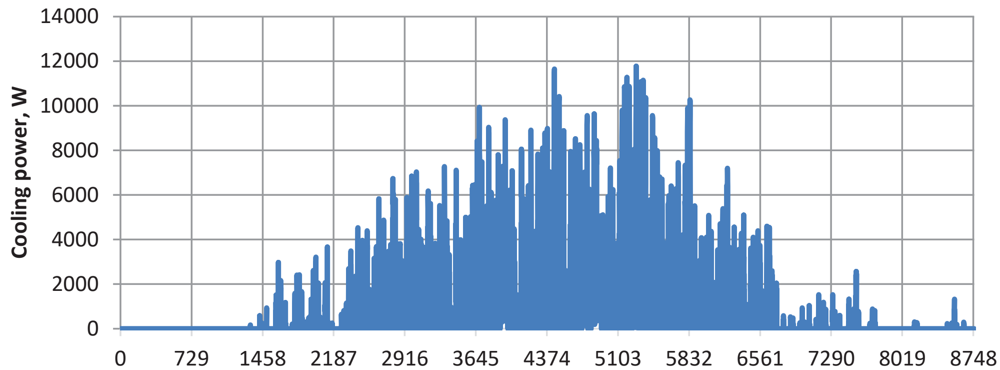

Figure 3. Demand for cooling power of the office building for each hour in the year

To investigate system behavior, the system was modeled in Ebsilon v.15, which is recognized as a robust tool for the simulation of energy systems [11,12]. The topology of the DHS implemented in Ebsilon is shown in Figure 1. The cold is generated by an adsorption chiller, which is driven by heat from the DHN. The DHS operates with SORTECH eco 2.0, which generates cooling water at a temperature of 16°C.

The basic technical data of adsorption heat pump SORTECH, eCoo 2.0 are presented in Table 2.

Table 1. Basic thermodynamic parameters

Parameter	Value
Cooling power	16 kW
Heating power	50 kW
COP	0.65 kW
The temperature of hot water	50 .. 95°C
Recooling water temperature	22 .. 40°C
Cooling water temperature	8 .. 21°C

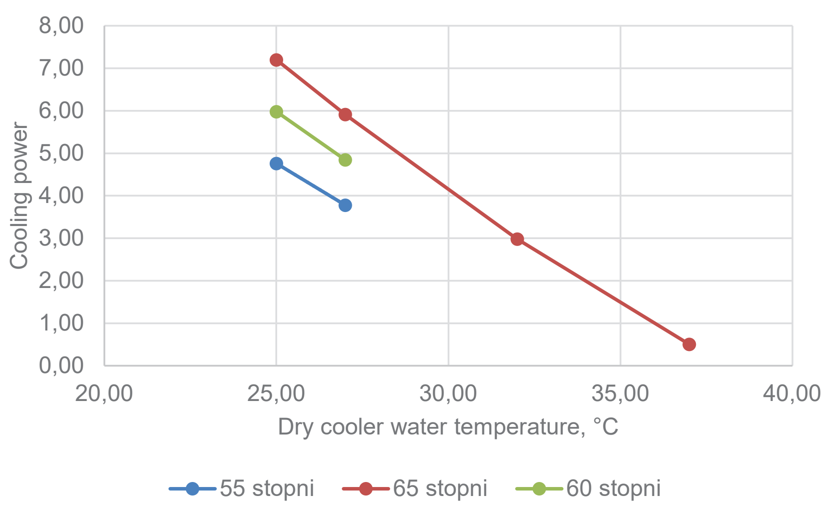

Figure 4. Cooling power of an adsorption chiller as a function of dry cooler water temperature for various temperatures of water in DHS

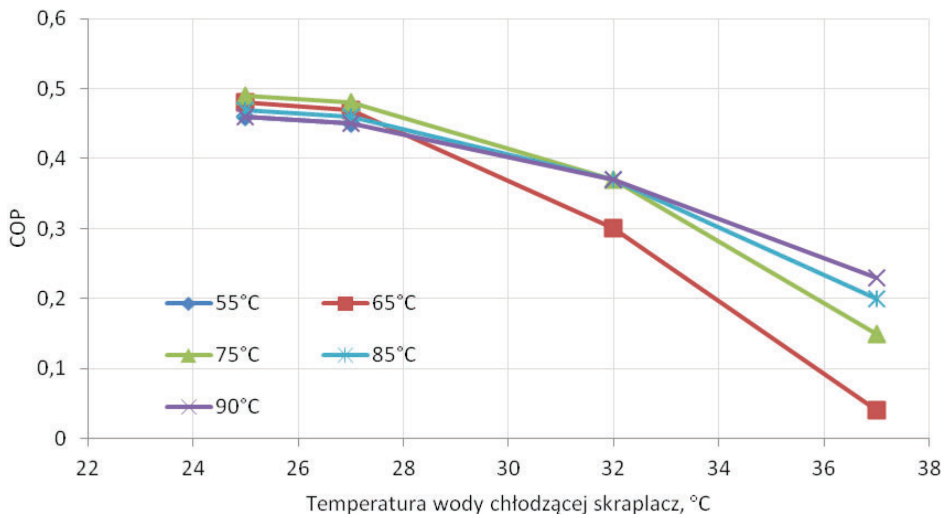

Figure 5. COP of an adsorption chiller as a function of cooling water, for various temperatures of DHS

For simulation purposes, we implemented SORTECH characteristics to determine the performance of an adsorption chiller. The adsorption chiller power as a function of cooling water is shown in Figure 3. The system is driven by the water network at temperature 60°C. Figure 4 shows that the COP of the chiller reaches very low values when the cooler water temperature rises above 34°C. Thus, a higher temperature of the driving source is required in order to increase COP. However, as the driving source is the DHN, it is not always possible to increase the temperature.

The DHS has two PCM storage units for storing heat and cold. CrodaTherm 60 PCM and CrodaTherm 15 were selected for heat and cold storage, respectively. Their storage properties are shown in Fig. 5.

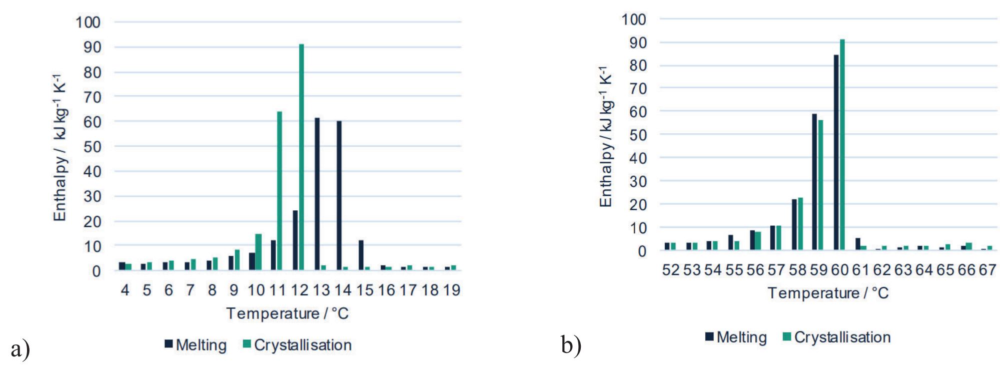

Figure 6. Thermal profile of heat and cold storage units, a) and b) respectively

The PCM storage units are simulated by component 119 Indirect Storage, which calculates the non-steady state heat exchange of the material with the fluid that flows through and around it. Based on the initial state of the temperature field, component 119 calculates the change in the temperature field of the pipe due to a change of the determining factors within a defined period of time. The determining factors are defined by the specification values of the component and by the state variables of the fluid at the component inlet. For the purpose of the study, the characteristics curve for heat and cold storage PCM, respectively, were implemented for this component, as shown in Fig. 5a and 5b.

https://doi.org/10.52202/069564-0311

3.Results

The behavior of the hybrid DHS was tested on operational data from the DHN in the town of Ostrołęka in northeastern Poland. The DHN operates at varying water flow rates and supply temperatures. The design operating temperature is 120/65°C, which corresponds to ambient temperature -20°C. The summertime heating medium is 65°C and the return water is 50°C. The heating medium is water, whose pressure is 0.9 MPa and 0.2 MPa during winter and summer, respectively. The temperature variations with respect to ambient temperature are shown in Fig. 7.

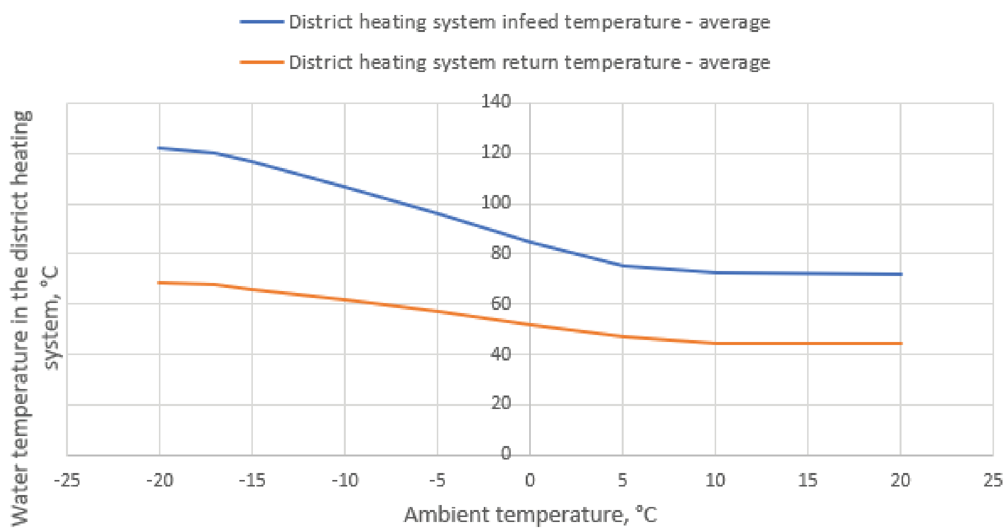

Figure 7. Hot and cold pipe temperature variations as a function of ambient temperature

The behavior of the novel hybrid DHS was examined during a 24-hour sunny summer day operation. Demand for cold and ambient temperature are shown in Figure 6 below.

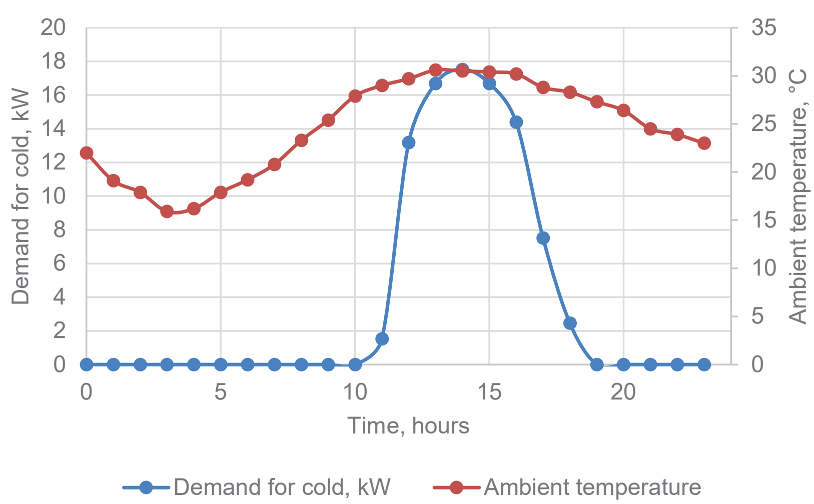

Figure 8. Adsorption chiller power as a function of hour of day

Firstly, the study revealed that the adsorption chiller does not operate when the ambient temperature exceeds 25°C (see Figure 7). Therefore, either the refrigeration technology must change or a cold storage facility is required. A cold storage unit was selected, as it can cover demand for cold during hot periods.

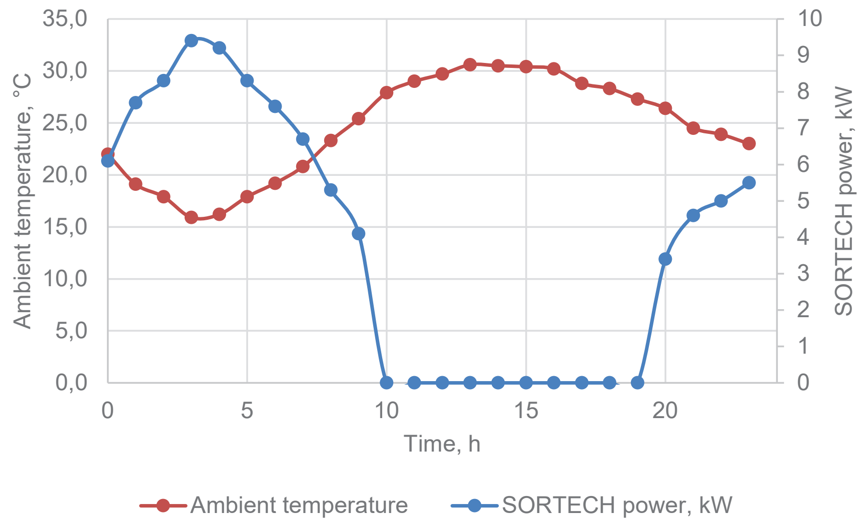

Figure 9. Adsorption chiller power during the day

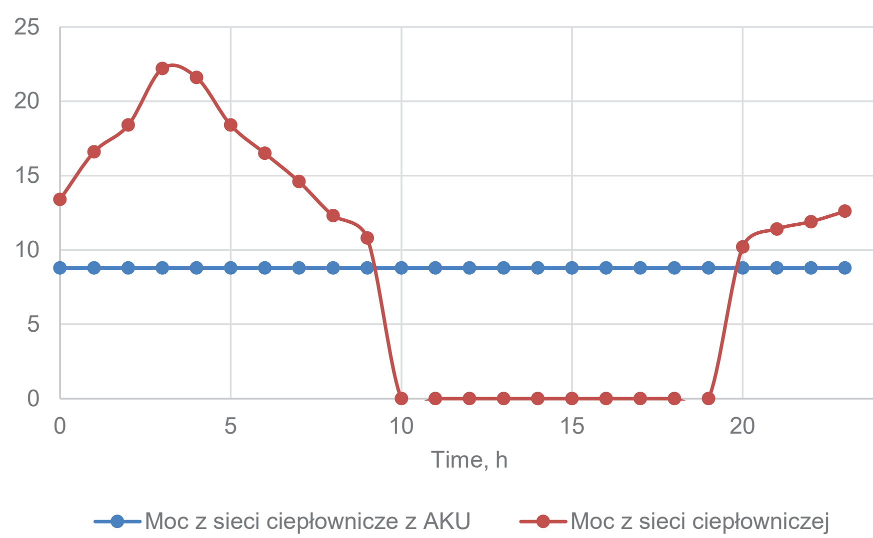

Figure 10 Heat consumption with system with PCM heat storage (blue line) and without (red line)

Figure 10 shows heat consumption from the DHN for two scenarios: operation with and without a heat storage accumulator. The implementation of heat storage enables constant heat consumption by the DHS.

The loading/unloading curves of heat and cold storage units are shown in Figure 9.

https://doi.org/10.52202/069564-0311

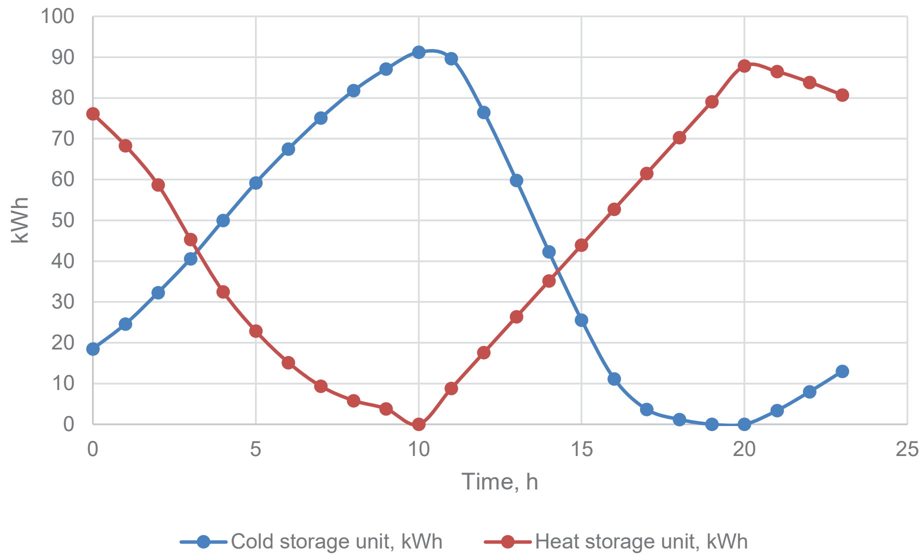

Figure. 11. Loading and unloading curves for heat and cold storage units

The above chart shows that the heat storage units are loaded until 10 am and when the adsorption chiller is unable to operate due to the high ambient temperature, heat storage loading begins (red line).

4. Conclusions

The aim of the research was to examine the concept of a hybrid district heating substation for heat and cold generation. The operation of the DHS was examined using representative data from the system operating in a small city in northeastern Poland, where the summertime temperature of the medium is 65°C. The DHS was assumed to deliver cold for an office air conditioning system. Cold was generated by an adsorption heat pump (SORTECH eCO 2.0) supported by two accumulators: for heat and cold storage.

Operation of the system was simulated across a 24-hour period on a sunny day, when ambient temperature reaches the maximum possible value of 30°C. The examination revealed there is a limiting ambient temperature for the selected adsorption heat pump, i.e., it is unable to operate when the ambient temperature exceeds 25°C, and the cold for the office air conditioning system has to be supplied from the PCM cold storage unit. System operation indicated a need to use a heat storage accumulator to equalize heat consumption, which should reduce summertime heat losses from the DHS.

To conclude, the numerical study proved the concept for the novel hybrid DHS and indicated the operating limits for this technology. The main advantage of our solution is the ability to use existing heating infrastructure to generate cooling with adsorption chillers. This reduces electricity consumption for air conditioning and boosts summertime heat consumption, increasing the efficiency of the DHN. The preliminary study revealed that the modeled DHS is a promising solution to increase heat consumption during the summer period, which should deliver increased profitability for DHNs. However, more detailed study is required to optimize PCM storage tanks and control strategy selection.

ACKNOWLEDGEMENTS

This work was financially supported by the National Research and Development Center in Poland in the framework of the POIR.04.01.04-00-0100/17-00 research project "Innovative heat and cold storage with PCM, operating in a modern installation intended to generate system heat", project acronym: Innostorage.

Nomenclature

DHS	district heating substation
DHN	district heating network

T	indoor temperature
m	mass of the air,
c_p	specific heat of the air,
$\dot{Q}_{air}$	heat exchanged via ventilation,
$\dot{Q}_{el}$	heat gain from electric devices,
$\dot{Q}_{people}$	heat coming from people inside,
$\dot{Q}_{wall,out}$	heat exchanged via convection on the outer walls,
$\dot{Q}_{wall,in}$	heat exchanged via convection on the inner walls,
$\dot{Q}_{floor}$	heat exchanged via convection on the floor,
$\dot{Q}_{ceil}$	heat exchanged via convection on the ceiling,
$\dot{Q}_{window}$	heat exchanged via convection on the windows
$\dot{Q}_{sun,window}$	heat exchanged via solar radiation through the windows.

References

[1] European_Union, Renewable energy directive | Energy, Off. J. Eur. Union. (n.d.). https://ec.europa.eu/energy/topics/renewable-energy/renewable-energy-directive_pl (accessed March 1, 2021).

[2] M. Turski, K. Nogaj, R. Sekret, The use of a PCM heat accumulator to improve the efficiency of the district heating substation, Energy. 187 (2019) 115885. https://doi.org/10.1016/j.energy.2019.115885.

[3] M. Chorowski, Z. Rogala, P. Pyrka, System options for cooling of buildings making use of district heating heat, Int. J. Refrig. 70 (2016) 183–195. https://doi.org/10.1016/j.ijrefrig.2016.06.018.

[4] R. Cuypers, N. Maraz, J. Eversdijk, C. Finck, E. Henquet, H. Oversloot, H. van't Spijker, A. de Geus, Development of a Seasonal Thermochemical Storage System, Energy Procedia. 30 (2012) 207–214.

[5] M. Rämä, S. Mohammadi, Comparison of distributed and centralised integration of solar heat in a district heating system, Energy. 137 (2017) 649–660. https://doi.org/10.1016/j.energy.2017.03.115.

[6] A. Lake, B. Rezaie, S. Beyerlein, Review of district heating and cooling systems for a sustainable future, Renew. Sustain. Energy Rev. 67 (2017) 417–425. https://doi.org/10.1016/j.rser.2016.09.061.

[7] M. Pellegrini, A. Bianchini, The Innovative Concept of Cold District Heating Networks: A Literature Review, Energies 2018, Vol. 11, Page 236. 11 (2018) 236. https://doi.org/10.3390/EN11010236.

[8] A. Grzebielec, A. Rusowicz, M. Jaworski, R. Laskowski, Possibility of using adsorption refrigeration unit in district heating network, Arch. Thermodyn. 36 (2015) 15–24. https://doi.org/10.1515/aoter-2015-0019.

[9] T. Halon, E. Pelinska-Olko, M. Szyc, B. Zajaczkowski, Predicting Performance of a District Heat Powered Adsorption Chiller by Means of an Artificial Neural Network, Energies 2019, Vol. 12, Page 3328. 12 (2019) 3328. https://doi.org/10.3390/EN12173328.

[10] Z. Wu, Y. Wang, S. You, H. Zhang, X. Zheng, J. Guo, S. Wei, Thermo-economic analysis of composite district heating substation with absorption heat pump, Appl. Therm. Eng. 166 (2020) 114659. https://doi.org/10.1016/J.APPLTHERMALENG.2019.114659.

[11] Y. Li, N. Wang, H. Guan, Z. Jia, Y. Zhang, G. Zhao, M. Gao, Optimization study of CO2 capture unit for subcritical coal-fired power generation unit based on Ebsilon and Aspen plus, Energy Convers. Manag. 269 (2022) 116111. https://doi.org/10.1016/J.ENCONMAN.2022.116111.

[12] P. Ziółkowski, P. Madejski, M. Amiri, T. Kuś, K. Stasiak, N. Subramanian, H. Pawlak-Kruczek, J. Badur, Ł. Niedźwiecki, D. Mikielewicz, Thermodynamic Analysis of Negative CO2 Emission Power Plant Using Aspen Plus, Aspen Hysys, and Ebsilon Software, Energies 2021, Vol. 14, Page 6304. 14 (2021) 6304. https://doi.org/10.3390/EN14196304.

 https://doi.org/10.52202/069564-0311