Schweizerische Eidgenossenschaft
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Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech

SWEET Call 1-2020: DeCarbCH

Deliverable report

Deliverable n°	D3.3.1
Deliverable name	Integral optimization of high-temperature BTES with thermal network parameters and deduction of design recommendations
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Delivery date	01 / 2023

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Summary

In the frame of the DeCarbCH project within WP3, a high-temperature borehole thermal energy storage (BTES) has been assessed along with its integration into a district heating network of different temperature levels. The high temperatures of the BTES, compared to the undisturbed ground temperature level, leads to a more effective seasonal load shifting from winter to summer, thus increasing the winter energy performance of the heat pumps and significantly reducing operational CO_2 emissions. The modelling of a district heating and cooling system comprised of heat pumps/chillers, BTES and solar collectors and subsequent optimization towards minimal CO_2 emissions and cost have indicated a potential annual CO_2 emission reduction of up to 43.1% when compared to a baseline system with heat pumps/chillers but without BTES and solar collectors. Design optimization further indicated that the integration of the BTES with a heating network at a network temperature of 40°C performed consistently better than the one with a respective temperature level of 65°C, both, in terms of CO_2 emissions and cost.

1 Introduction

Motivated by the goal of decarbonizing heating and cooling in buildings and districts, a high-temperature borehole thermal energy storage (BTES) was investigated in the frame of the DeCarbCH project and the SFOE funded research project LeSoPot (SI/501938). Thermal energy storage (TES) in general and seasonal thermal energy storage (STES) in particular enable the integration of renewable energy sources such as solar with the effect of reducing CO_2 emissions in the process of heat and cold generation. The reduction of operational CO_2 emissions through the integration of energy storage is amplified by the variable carbon intensity of the Swiss electricity supply (Figure 1), significantly varying between summer and winter time. This reflects the shortage of renewable electricity supply in winter time and asks for an energy system design that is optimized for the highest energy efficiency during this period of shortage.

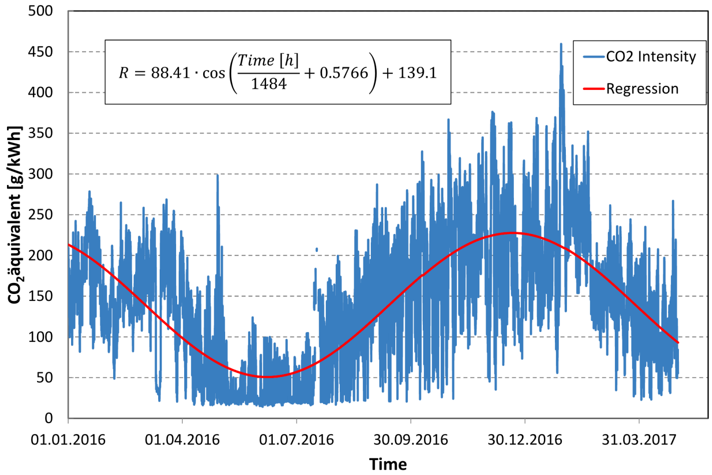

Figure 1: Regression for dynamic CO2 emissions [1] based on data from (http://www.electricitymap.org)

As an answer to this challenge, the integration of a high-temperature BTES was proposed (in contrast to classical low-temperature BTES), leading to a pronounced seasonal load shifting from winter to summer that enables a higher discharge efficiency for heating, and thus reduced CO_2 emissions in winter while accepting a lower charging efficiency for cooling, when CO_2 intensity in the electricity grid is low.

Research regarding the implications of a high-temperature BTES covered both, an operational and a design optimization. The results of this investigation were published in two journal articles and a conference contribution. In a first publication regarding operational optimization [2], a control-oriented BTES model was presented and validated against a high-fidelity simulation model. It was shown, that the model provided allowed for high predictive power at low computational cost, thus allowing for its use for operational optimization. This research has been extended towards design optimization [3] and [4], considering also the effect of variable storage and equipment size/capacity on total operational CO_2 emissions and cost.

2 Deliverable content

The deliverable D3.3 within the DeCarbCH project covers the integration of a high-temperature BTES into a thermal heating network. To this end, an optimization on the operation and design of the heating and cooling has been performed for two different network temperature levels with the aim of minimizing CO2 emissions and cost. Detailed results of this study are presented in [3].

As a case study, the Empa research campus in Dubendorf was investigated with its heating and cooling demand. The heating system is comprised of heat pumps, chillers, solar collectors, a BTES and a distribution network. For the heat pumps and the chillers is is differentiated between one of them running with ambient air as heat source or sink and the other one directly using the BTES as heat source or sink. Depending on the size of the BTES, the available source heat or heat transfer rate is insufficient to cover the demand such that the ambient air has to be used as an auxiliary source. The optimization performed with the goal of minimizing CO_2 emissions for different prices assumed per tons of CO_2 identifies best suitable BTES and equipment size. The optimization was run explicitly for two thermal network cases, once assuming a network temperature of 65°C and once a lower one of 40°C.

Results of the optimization performed are shown in Figure 2 to Figure 4. Figure 2 shows the effect of CO_2 prices on equipment sizing and fractions of heat and cold demand covered by individual technologies. It can be observed that the higher the CO_2 price gets, the larger the importance of solar collectors become for either direct covering of the heating demand or for recharging the BTES during summer time. Solar recharging is generally important as heat rejection from cooling is insufficient due to lower cooling than heating loads and particularly important in the high-temperature network case (Figure 2a) because of higher heating COP achieved when operating the heat pumps with the BTES as the heat source. This is also visible from the larger relative importance of the BTES in the high network temperature case. In case of lower network temperatures (Figure 2b), consequently, a larger share of the heat source for heating is provided from the ambient air. For the low network temperature, a small amount of heat from the BTES can be used for direct heating without the need of running the heat pumps.

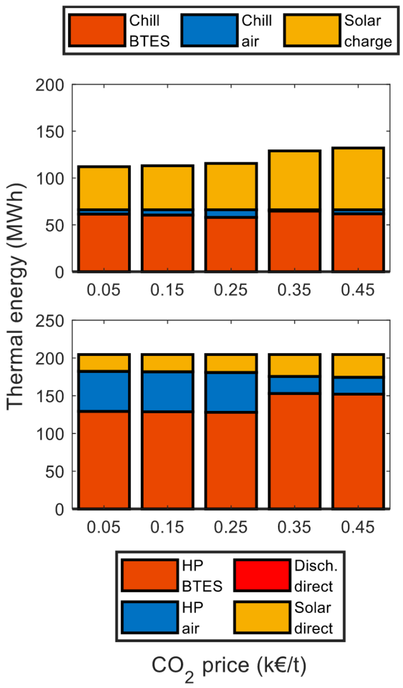

Figure 2a: Effect of CO_2 price on the annual heating and cooling supply mix in the 65°C temperature network. Cooling operation (top), heating operation (bottom) - taken from [3].

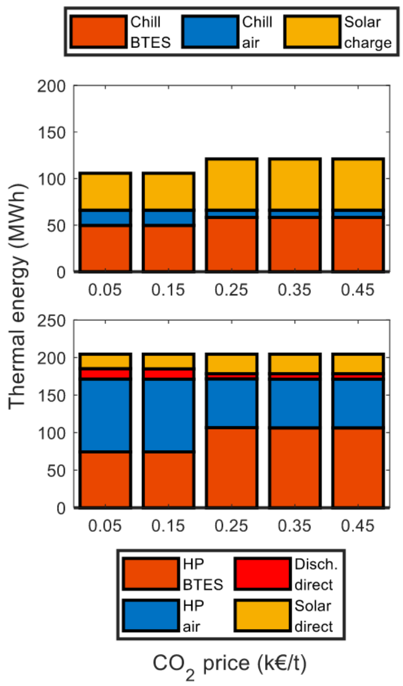

Figure 2b: Effect of CO_2 price on the annual heating and cooling supply mix in the 40°C temperature network. Cooling operation (top), heating operation (bottom) - taken from [3].

In Figure 3, results in terms of heating and cooling demands covered by different sources as well as the resulting BTES temperature are shown for a fixed CO_2 price of 150 EUR/t. It can be seen from the figure that maximum storage temperature is reached after summer, reaching slightly above 40°C. The temperature swing in the BTES remains the same for both network temperatures but in case of the 65°C network temperature the BTES volume and thus capacity is chosen to be larger.

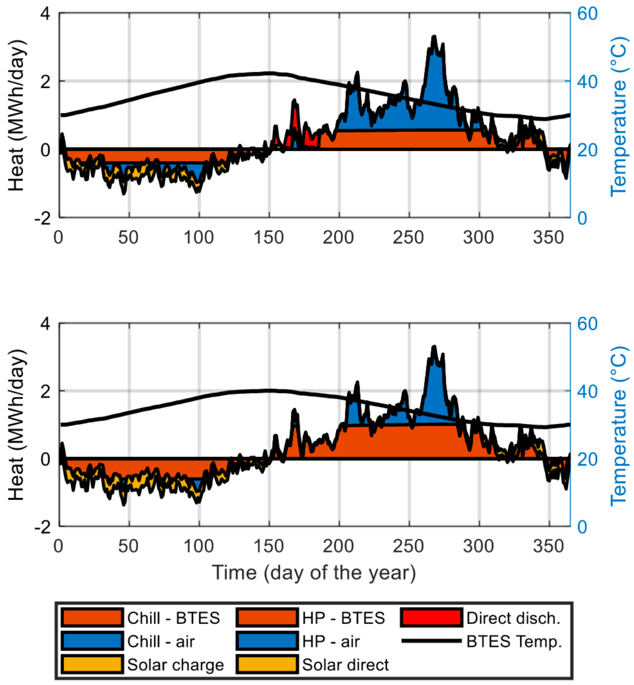

Figure 3: Optimal operation of the system for 40°C (top) and 65°C thermal networks (bottom) - taken from [3].

In Figure 4, a comparison between the systems with the two different network temperatures is presented in terms of annual CO_2 emissions and cost. It turned out that the low temperature network is performing consistently better along both dimensions, independent of whether the minimum or maximum CO_2 price is assumed. The reason for the consistently lower CO_2 emissions in case of the low network temperature is due to the significantly higher COP in discharging because of the reduced temperature difference and thus lower electricity consumption for providing the same amount of heat.

When comparing the heating/cooling system with BTES to the baseline system without BTES and solar collectors a total CO_2 emission reduction of 33.0 - 43.1% can be achieved.

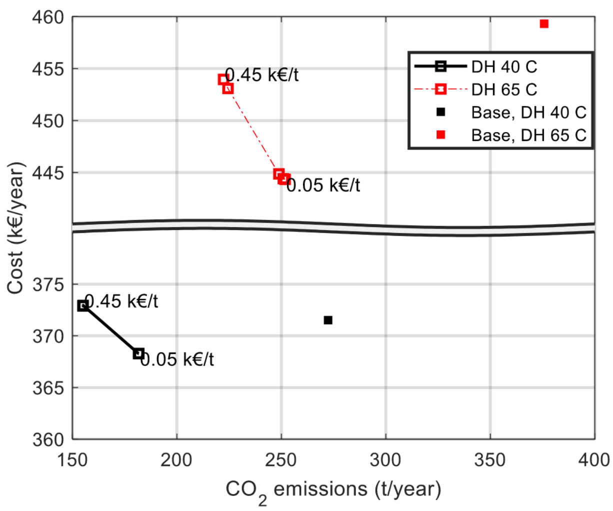

Figure 4: Economic vs environmental cost of the optimal solutions - taken from [3].

3 Conclusion

In conclusion, some design recommendations can be deduced from the optimization results achieved. These recommendations hold for a similar heating and cooling system operated in a heating-dominated climate and thus for a system with a heating load significantly higher than the cooling load.

i) It is always beneficial to have a seasonal storage to absorb the waste heat from cold generation with the chillers as well as solar collectors for further charging of the storage to higher temperatures. The size of both, the BTES and solar collector area, need to increase in size with an increasing CO_2 price.

ii) The maximum accepted base temperature of the BTES is picked by the optimizer leading to a more efficient discharge when CO_2 intensity in the electricity grid is the highest. This implies that if possible the BTES should be precharged before operation or consistently be overcharged (positive heat balance), e.g. with solar collectors to allow for a high base temperature to be reached.

iii) The maximum storage temperature reached is depending on several aspect, among others on the aformentioned initioal storage temperature. In the study, the maximum temperature was found to be limited by the available maximum heat transfer rate during charging of the BTES. Latter can be influenced by the available ground heat exchanger areas. Consequently, it can be beneficial to consider higher borehole densities or aspect ratios of the BTES to improve heat transfer and thus allow for higher BTES temperature. This would then enable the integration of even more solar or waste heat and a larger fraction of direct discharge and heat supply without operation of a heat pump, leading to even higher winter electricity performance and thus further reductions in CO_2 emissions.

4 References

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