15TH IEA HEAT PUMP CONFERENCE
MAY 26–29, 2026 | HOFBURG
VIENNA 2026
DECARBONISATION THROUGH INNOVATION

Adsorption Cooling with Biochar Thermochemical Storage: Integration Strategy for District Heating

Raffaele D'Urso[a,b*],Alessia Arteconi[a,b]

[a]Department of Mechanical Engineering, KU Leuven, Leuven, 3000, Belgium
[b]EnergyVille, Genk, 3600, Belgium

Abstract

The integration of thermochemical storage with adsorption chillers offers a promising solution to decouple heat generation from cooling demand, enhancing the flexibility and efficiency of thermal energy systems. The solution developed within the European CharCool project is based on high-density, rechargeable thermopiles made of biochar plates, an agricultural by-product, impregnated with widely available and environmentally friendly inorganic salts. These thermopiles function both as adsorbent beds and mid-term thermal energy storage media. The thermopile is coupled with a compact, low-cost adsorption chiller using pure water as refrigerant, offering reduced system volume and environmental footprint. These systems can potentially be integrated into district heating networks to provide on-demand cooling services.
This study investigates the integration of this system with district heating to supply the cooling demand of multi-apartment residential building. A model was developed to evaluate the system performance in terms of operating cost, CO_2 emissions, and Levelized Cost of Cooling (LCOC). The analysis considers the influence of both economic and technical parameters, including heat cost, transport distance, thermopile volume, and district heating emission factor. A sensitivity analysis was carried out using Partial Rank Correlation Coefficient, Standardized Rank Regression Coefficient, and Sobol indices to identify the parameters with the greatest impact on system performance, followed by a comparative assessment against a vapor compression chiller. The results show that the CharCool system can achieve competitive operating costs and emissions in configurations combining large thermopile volumes with low-cost, low-emission district heating sources, supporting its potential as a flexible and sustainable alternative for future district energy applications.

Selection and/or peer-review under the responsibility of the organizers of the 15th IEA Heat Pump Conference 2026.

Keywords: Adsorption Chiller; Thermochemical energy storage; District heating;

1. Introduction

The building sector accounts for approximately 30% of the world total final energy consumption [1]. According to the Eurostat data [2] space heating, hot water and space cooling represent about 78.2 % of the final energy use in the EU residential sector, responsible for approximately 720 million tonnes of CO_2 equivalent greenhouse-gas emissions [3]. Among the available technologies, electrically driven vapor compression heat pumps (VCHPs) are considered one of the most promising solutions for the decarbonization of the building sector. However, despite the rapid expansion of the European heat pump market, the sector faces several critical bottlenecks that have the potential to limit its ability to meet the growing demand. Supply chain fragilities, including dependence on imported components, semiconductor shortages and volatile material prices, pose immediate challenges to production stability [4]. Meanwhile, the fast phase-down of fluorinated gases to the updated F gas Regulation commits manufacturers to the swift transition to natural refrigerants like propane and carbon dioxide. Although this is the key to decarbonisation, this poses technical, regulation, and safety concerns that complicate the design of the system and the manufacturing processes [4]. Adsorption heat pumps (AHPs) represent a promising complementary technology to electrically driven vapor compression systems for the decarbonisation of the residential heating and cooling sectors. Their main advantages lie in the use of environmentally friendly refrigerants with low global warming potential, such as

* Corresponding author. *E-mail address:* raffaele.durso@kuleuven.be

water or ammonia, and in their ability to operate with low-grade heat sources including industrial waste heat or solar thermal energy. Nevertheless, the widespread deployment of AHPs is still hindered by several technical challenges, including relatively low coefficients of performance (COP), the need for large quantities of adsorbent material to achieve the desired heating or cooling capacity, and a strong dependence on the availability and temperature level of the driving heat source [5]. These limitations currently confine adsorption heat pumps to niche applications and represent a major barrier to their large-scale deployment in residential heating and cooling systems. To address these limitations, current research is investigating both new adsorbent–refrigerant pairs and innovative system concepts, as well as more generalized modelling approaches that seek to describe the fundamental transport processes governing adsorption systems in a way that is applicable across different designs and operating conditions [6–8]. A particularly promising strategy is to use the adsorbent bed itself as a thermal energy storage unit. In this configuration, the adsorption–desorption cycle serves not only for heat transformation but also for energy storage, enabling the decoupling between intermittent heat source availability and building thermal demand. By integrating thermal energy storage directly into the adsorption bed, this approach fundamentally alters the interaction between the heat source, the cooling or heating demand, and the operating cycle of the heat pump, enabling a higher degree of operational flexibility compared to conventional adsorption systems. Adsorption-based thermal energy storage belongs to the broader class of thermochemical heat storage (TCHS) technology, which offers the highest energy storage density among thermal storage approaches and therefore the greatest compactness. Thermochemical storage is based on a reversible sorption process between an adsorbent and a working fluid, allowing energy to be stored as chemical potential rather than as sensible or latent heat, reducing the heat losses [9]. Depending on the system design, adsorption-based thermal storage can operate in closed or open configurations. In closed systems, the adsorbent and the adsorbate are confined within a sealed environment, which minimizes losses and allows for efficient cyclic operation suitable for compact AHP applications. In open systems, by contrast, the working vapor, typically moist air, flows through the adsorbent bed, allowing direct interaction with the surrounding environment [10]. In this context, the European project CharCool aims to develop a new class of heat-driven cooling systems powered by a thermal storage unit, employing biochar impregnated with salt as a thermochemical material. This material forms modular thermopiles that enable the decoupling of the cooling demand from the heat source [11]. This decoupling addresses one of the key limitations of conventional adsorption heat pumps, namely the need for simultaneous availability of heat input and cooling demand, and therefore has the potential to significantly improve system utilization and overall performance. In this study, an integration scenario of an adsorption-based CharCool thermal storage and cooling system, working in a closed configuration, was selected, focusing on the supply of cooling demand for a reference multi-apartment building. The heat input is assumed to be supplied by a district heating network, which plays a central role in the decarbonization of both heating and cooling sectors in Europe. As highlighted in the EU Strategy on Heating and Cooling [12], these systems enable the large-scale integration of renewable and waste heat sources, offering an efficient pathway to reduce fossil fuel dependence and emissions in urban areas. In a broader sense, this analysis can be easily extended to other heat sources with comparable temperature and availability. The competitiveness of the proposed system against a vapor compression chiller was evaluated within this framework, by performing a sensitivity analysis to identify the most influential parameters, followed by a comparative assessment to determine the operating conditions under which the CharCool system achieves cost and emission advantages. More generally, the proposed analysis framework provides a systematic methodology to assess the techno-economic and environmental feasibility of adsorption-based cooling systems integrated with thermal energy storage, supporting informed design and deployment decisions beyond the specific system configuration considered.

2. Methods

The aim of this study is to evaluate the techno-economic and environmental performance of the CharCool adsorption-based cooling system, focusing on two main indicators: the operating cost and the CO_2 emissions, for the purpose of serving a multi-apartment building using heat supplied by a district heating network. An integration scenario was therefore defined, including a storage management logic describing the charging, transport, and discharging of the thermopiles. The cooling demand was estimated through a reference building model developed in Python, while the system behaviour was represented by a simplified model suitable for performing scenario simulations. Based on this framework, the model allows the calculation of operating costs and CO_2 emissions of the system over the summer period (June–August) through appropriately defined functions. Subsequently, a sensitivity analysis was carried out by varying the main simulation parameters to identify those exerting the greatest influence on the selected indicators, using Partial Rank Correlation Coefficient (PRCC), Standardized Rank Regression Coefficient (SRRC), and Sobol indices. Finally, a benchmark comparison with a vapor compression chiller was performed to determine the conditions under which the CharCool system becomes competitive.

2.1. Integration scenario definition

The integration concept of the CharCool system is illustrated in Fig. 1. In this configuration, the thermopiles are charged and stored in a centralized facility, where heat from a generic district heating network is used to drive the desorption phase. Regarding the heat source, a supply temperature of 70 °C was assumed, and no source dynamics were considered, meaning that sufficient thermal energy was always available during the analyzed period. Since the storage process is thermochemical, only minor sensible heat losses occur, allowing the charged thermopiles to be kept for extended periods without significant degradation. When cooling is required, the charged thermopiles are transported to the end user (in this specific case a multi-apartment building) where a dedicated local storage unit is available and gradually discharged to supply the cooling demand over time. Once fully discharged, the thermopiles are replaced with newly charged units transported from the central charging site. For this preliminary analysis, management and handling costs associated with the storage operations have been neglected.

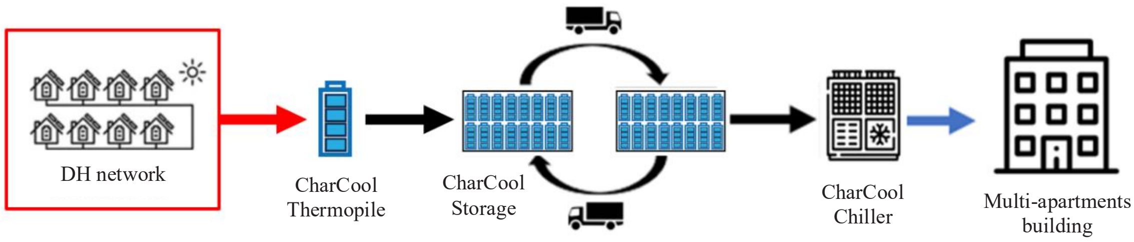

Figure 1. Integration concept of the CharCool system within a multi-apartment building scenario

2.2. Building and CharCool cooling system

A multi-apartment building located in Milan, Italy, was selected and modelled as the reference case. Statistical data from ISTAT [13] describing the composition of the building stock in the reference city were analysed to define representative building features. The analysis led to the selection of a five floor building with three apartments per floor as the reference configuration. The floor area of each dwelling was estimated based on ISTAT data [13] resulting in an average value of 90 m². All dwellings are assumed to have a storey height of 2.7 m and a window-to-floor area ratio of 12.5% [14], with the glazed area equally distributed across the external façades. A natural air change rate of 0.2 h^{-1} was considered for all buildings. Representative wall and roof stratigraphy were derived from the Tabula database [15], while the thermal properties of individual layers were taken from the Italian technical report UNI/TR 11552. The resulting thermal transmittance values (U-values) were compared against, and aligned with, the minimum requirements defined by DM 26/06/2015 [16]. The thermal behaviour of the building was modelled using the lumped-parameter model developed by Mugnini et al. [17], where the main envelope components are represented through equivalent thermal resistances and capacitances to capture dynamic heat transfer phenomena. With this model, the hourly cooling demand was retrieved using meteorological data for Milan from a representative reference year, considering the summer period between the 1st of June and the 31st of August and imposing a maximum indoor comfort temperature threshold of 26 °C. The resulting load profile showed a peak of the total cooling demand of 17.7 kW, which was used to define the nominal capacity of the chiller at 20 kW.

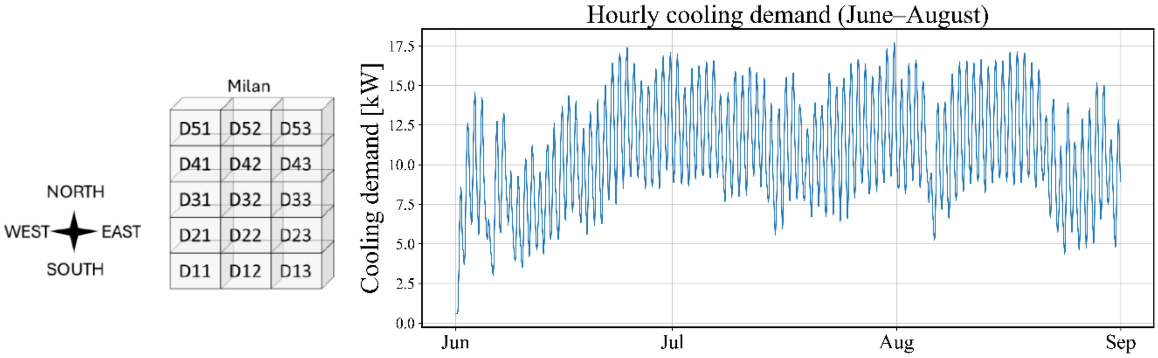

Figure 2. Schematic representation of the reference building and hourly cooling demand

The CharCool system model includes a representation of a set of thermopiles available in a charged state, containing a stored thermal energy proportional to its total volume and energy density. During operation, the thermopiles are progressively discharged to meet the cooling demand. The COP is defined as the Carnot COP multiplied by a correction factor of 0.42, derived from project KPIs to represent realistic operating efficiency (i.e. target adsorption chiller efficiency >0.65). Accordingly, at each time step, the residual thermal energy within the thermopiles is updated as:

$$COP_{carnot}^{i} = \frac{T_e \cdot (T_h - T_c^i)}{T_h \cdot (T_c^i - T_e)} \tag{1}$$

$$Q_{th}^{i} = Q_{th}^{i-1} - \frac{Q_c^i}{0.42 \cdot COP_{carnot}^{i}} \tag{2}$$

where T_e, T_c, and T_h represent the evaporator, condenser, and generator temperatures, respectively, expressed in Kelvin. The condenser temperature was computed as a function of the outdoor air temperature. The indices i and $i{-}1$ denote consecutive time steps within the simulation. When the residual stored heat Q_{th} reaches zero, the thermopile unit is considered fully discharged and is replaced by a newly charged unit of the same volume. Q_c denotes the cooling demand.

2.3. Formulation of operating cost and CO_2 emission functions and retrieved data

To evaluate the system performance and compare it with that of conventional vapor compression chillers, the operating cost function (Eq. (1)) and the CO_2 emission function (Eq. (2)) were defined. These functions account for factors such as the source of thermal energy from the district heating network, as well as logistics-related costs and emissions.

$$C = c_r \cdot V + n_t \cdot (c_t \cdot D + c_h \cdot E_v \cdot V) \tag{3}$$

$$M_{CO_2} = n_t \cdot (f_{CO_2,fuel} \cdot LHV \cdot \ C_s \cdot D \ + f_{CO_2,heat} \cdot E_v \cdot V) \tag{4}$$

Table 1 summarizes the main parameters used in the analysis, including both fixed values and the variation ranges considered in the sensitivity analysis.
The first term in Eq. (1) represents the cost associated with space constraints of local storage unit, while the second term refers to the cost of a single transport, which includes both the transportation cost and the cost of the thermal energy required to charge the thermopiles carried during that trip. Both components are multiplied by the number of transports obtained from the simulation, which depends on the transported thermopile

volume. Similarly, Eq. (2) accounts for the emissions associated with each transport and with the thermal energy used to charge the thermopiles, both multiplied by the total number of transports.
Eq. (3) reports the calculation of the Levelized Cost of Cooling (LCOC), which expresses the average cost of the cooling energy delivered over the system lifetime, accounting for both capital and operating expenditures. The LCOC was evaluated over a 20-year lifetime to enable a consistent comparison with a reference vapor compression chiller.

$$LCOC = \frac{\sum_{t=1}^{n} \frac{I_t + C_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Q_t}{(1+r)^t}} \quad (5)$$

where I_t denotes the investment or capital-related expenditure incurred in year t, C_t represents the operating costs in year t, Q_t is the useful cooling energy delivered in year t, r is the discount rate, and n is the economic lifetime of the system.

Table 1. Summary of literature data used in the simulation

Symbol	Description	Range	Unit	Reference
c_r	Rental cost of space	10 - 40	€/m^2	[18]
c_t	Transportation cost	0.5 - 4	€/km	[19]
c_h	District heating cost	0.02 – 0.137	€/kWh	[20–22]
$f_{CO2,fuel}$	Fuel CO_2 emission factor	0.249	kgCO_2/kWh	[23]
LHV	Lower Heating Value	10	kWh/l	[24]
Cs	Fuel consumption	0.2 - 0.35	l/km	[25]
$f_{CO2,heat}$	District Heating CO_2 emission factor	0 - 0.392	kgCO_2/kWh	[26,27]
$f_{CO2,el}$	Electricity CO_2 emission factor	0.284	kgCO_2/kWh	[28]
r	Discount rate for HP	0.03	-	[29]
$I_{r,VCHP}$	VCHP installation cost	1200	€/kW	[30,31]
c_{el}	Electricity price	0.32	€/kWh	[32]

The values related to the system, such as the energy density (700 kWh/m^3), the bulk density of biochar (2000 kg/m^3), and the installation cost of the CharCool system (400 €/kW), were derived from project target KPIs [11]. The variation ranges for the transported thermopile volume (0–5 m^3) and transport distance (0–50 km) were defined as realistic operational limits based on the intended application context.

2.4. Sensitivity analysis

To determine the parameters exerting the greatest influence on the operating cost and CO_2 emissions, a sensitivity analysis was performed. To assess how the main input parameters influence the model results, they were varied within the ranges defined in the previous subsection. The analysis examined their effect on both operating cost and CO_2 emissions, considering the rental cost of space, district heating cost, and transportation cost for the former, and fuel consumption together with the district heating CO_2 emission factor for the latter. In addition, both functions were found to be influenced by the transported thermopile volume and the delivery distance, which were therefore also included as input factors in the sensitivity analysis. The sensitivity assessment employed Partial Rank Correlation Coefficient (PRCC), Standardized Rank Regression Coefficient (SRRC), and Sobol indices [33]. PRCC and SRRC were used to evaluate monotonic and approximately linear dependencies between inputs and outputs, offering computational efficiency for local analysis. Sobol indices were additionally applied to capture non-linear effects and parameter interactions, providing a broader understanding of the model response.

2.5. *Benchmarking*

A simplified model of a vapor compression chiller, selected as the reference technology, was simulated to meet the same building cooling demand. The COP of this model was calculated as a function of the evaporator and condenser temperatures. The results in terms of operating cost, CO_2 emissions, and LCOC were then compared with those of the CharCool system, by varying the most influential parameters identified through the sensitivity. This approach made it possible to identify the parameter ranges defining the competitiveness of the system, and, for those related to district heating (such as heat cost and emission factor), to associate each range with the corresponding type of district heating network to which it realistically applies.

3. Results and Discussion

Fig. 3 presents the results of the sensitivity analysis on the operating cost of the CharCool system. Both PRCC and SRRC analyses indicate that the heat cost and the transported thermopile volume are the most influential variables, while distance, transport cost, and rental cost exhibit considerably lower effects. This effect of the volume is especially pronounced for small volumes, as shown in Fig. 5, where the high number of required transports has a stronger impact than the lower cost per single transport. The operating cost shows a strong positive correlation with the heat cost (PRCC = 0.91; SRRC = 0.55) and a marked negative correlation with the thermopile volume (PRCC = –0.64; SRRC = –0.37), confirming their dominant roles in shaping system performance. The Sobol indices corroborate these findings, with the sum of first-order indices ($\Sigma S_1 \approx 0.79$) indicating that most of the output variance arises from additive effects. The thermopile volume (S_1 = 0.38; ST = 0.57) and heat cost (S_1 = 0.30; ST = 0.32) are the main contributors, while distance and transport cost play secondary roles and rental cost remains negligible. Overall, the analysis identifies the heat cost as the primary cost driver and the thermopile volume as the key design parameter, whereas the remaining inputs exert only minor influence on the operating cost.

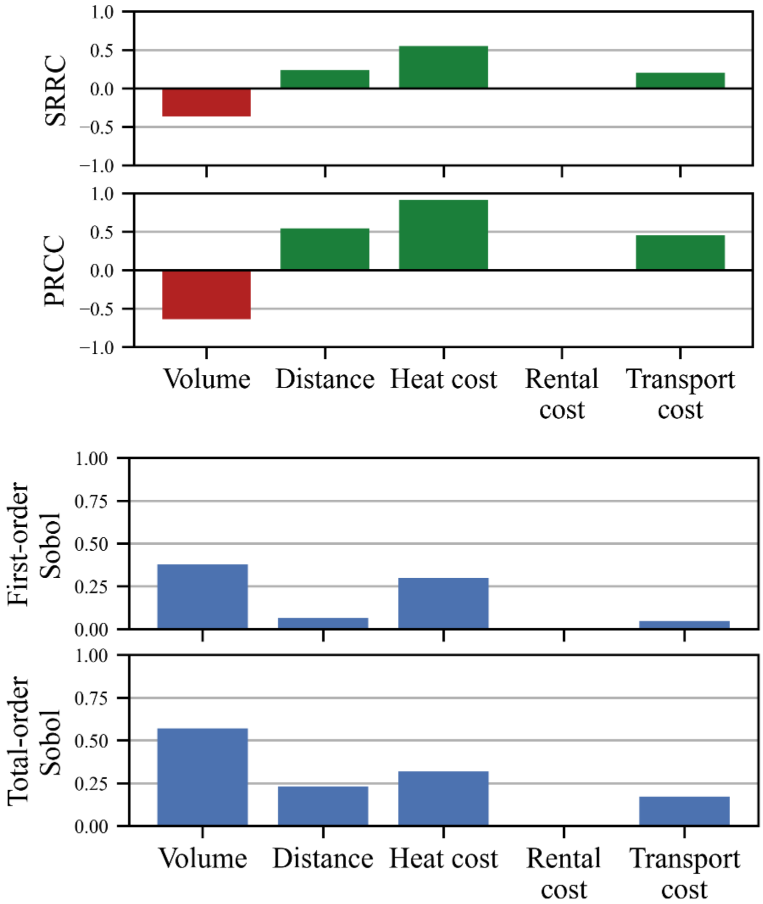

Figure 3. Sensitivity indices (PRCC, SRRC, and Sobol) for the operating cost function inputs

Fig. 4 presents the sensitivity analysis of the CO_2 emissions for the CharCool system. Both PRCC and SRRC analyses identify the district heating emission factor as the predominant variable (PRCC = 0.96; SRRC = 0.85), confirming that the carbon intensity of the heat source is the main driver of the system's environmental performance. The thermopile volume shows a similar effect to that observed for the operating cost function, with a moderate negative influence (PRCC = –0.53; SRRC = –0.21), indicating that larger storage capacities slightly reduce emissions by limiting transport frequency. Distance and fuel consumption display only secondary effects. The Sobol indices corroborate these results, with the emission factor explaining most of the output variance (S_1 = 0.72; ST = 0.72), while the remaining parameters contribute marginally ($\Sigma S_1 \approx 0.88$). Overall, CO_2 emissions are mainly governed by the heat source emission factor, with the thermopile volume providing a smaller but consistent mitigating effect.

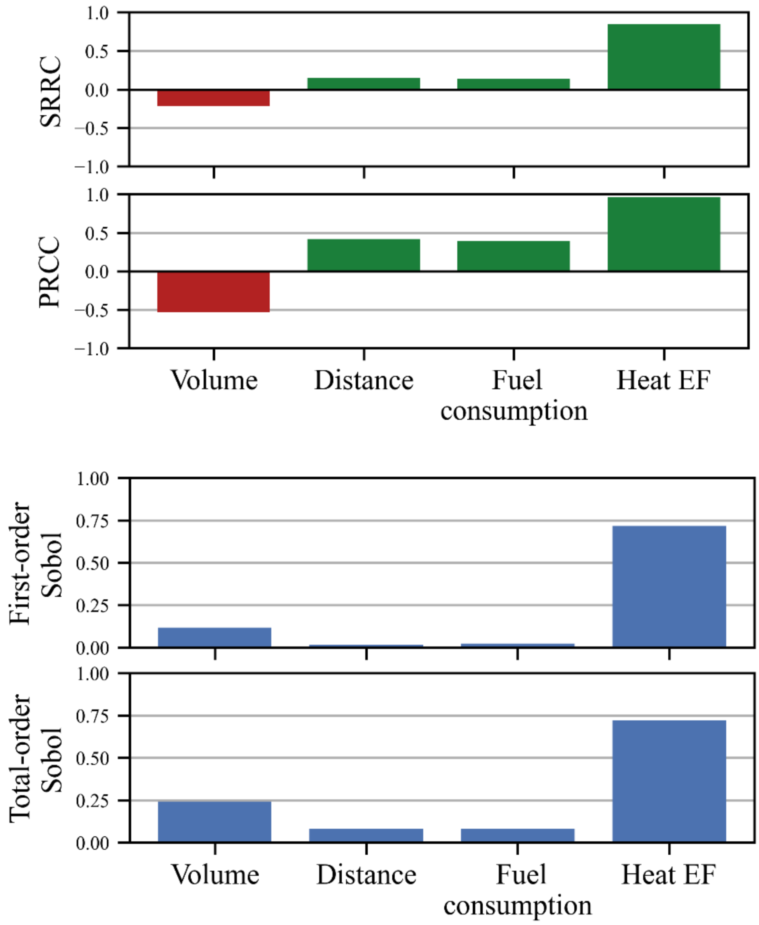

Figure 4. Sensitivity indices (PRCC, SRRC, and Sobol) for the CO_2 emission function inputs.

Fig. 5 shows the operating cost of the system as a function of the transported thermopile volume and parametrized with respect to the heat cost from the district heating network, while all other parameters fixed at the mean values of their respective variation ranges. As previously mentioned, the volume has a strong influence, particularly for small values, where the number of required transports significantly affects the overall cost. Beyond a transported volume of approximately 1.5 m^3, the effect of the number of transports and the one of the cost of the single transport reach an equilibrium, and the total operating cost remains nearly constant. The curve appears stepped due to the fact that the number of transports can only take integer values. The figure compares the operating cost of the CharCool adsorption system with that of a reference vapor compression chiller (dotted blue line), which amounts to approximately 1540 €/year. When only operating costs are considered, the CharCool system becomes competitive only for large transported volumes and low district heating heat costs. The figure also shows the operating cost threshold that the CharCool system must not overcome to achieve the same LCOC as the vapor compression chiller (dotted orange line), equal to about

2670 €/year. For a representative heat cost of 0.06 €/kWh, close to the average values reported in the literature, this threshold is reached for thermopile volumes larger than 1.5 m³, indicating that under these conditions the CharCool system can achieve economic competitiveness and offer potential advantages in several applications.

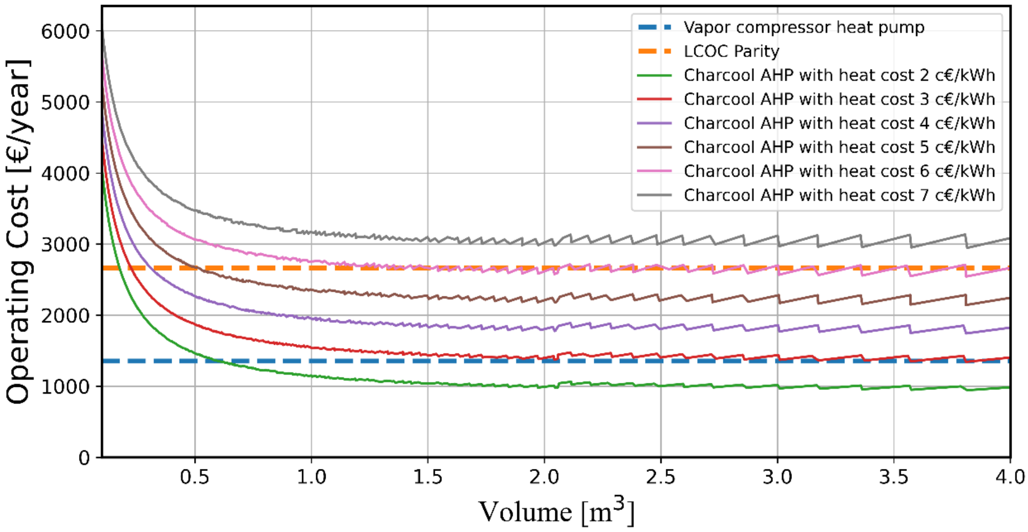

Figure 5. Operating Costs of CharCool Chiller as Function of Heat cost and Bed Volume Compared to Vapor Compression chiller

Similarly, Fig. 6 shows the CO_2 emissions (in kg/year) as a function of the transported thermopile volume and parametrized with respect to the heat emission factor of the district heating source. As confirmed by the sensitivity analysis, the heat emission factor has a stronger influence than the volume itself. Compared with the previous case, the slope of the curves for small volumes is noticeably smaller, indicating a reduced sensitivity to volume variations. The CharCool system achieves lower annual CO_2 emissions than the vapor compression chiller, which amount to approximately 1355 kg/year, only for low emission factor values.

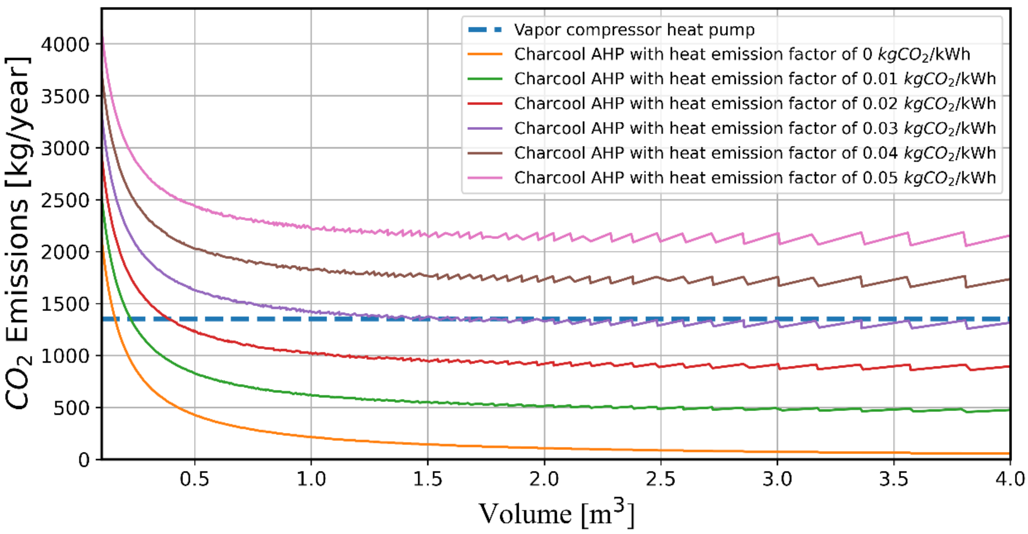

Figure 6. CO_2 emission of CharCool Chiller as Function of Heat cost and Bed Volume Compared to Vapor Compression chiller

Once the approximate ranges of competitiveness were identified, it became essential to understand which specific district heating configurations these ranges correspond to. In particular, it was necessary to examine the factors influencing the heat cost in district heating systems and the associated CO_2 emission levels, in order to relate the identified parameter ranges to real operating conditions. District heating costs are mainly divided into distribution and generation components. The distribution cost covers the investment and operating expenses of the network and substations and is largely affected by demand density and network extension. The generation cost includes the capital, operation, and fuel costs of heat production at the plant, which depend on the specific technology and energy source used. [34]. The study by Werner et al. [35] identify linear heat density, determined by population and building density, specific heat demand, and pipe length, as the main factor influencing district heating distribution costs. The results show average distribution costs ranging from 0.003 to 0.005 €/kWh in dense urban areas and up to 0.01–0.012 €/kWh in low-density or suburban zones, with respect to a total heat price of 0.047–0.061 €/kWh. In a more recent study, Fallahnejad et al. [36], evaluated the district heating potential in the EU-27 by combining heat demand projections with network expansion modelling. The results show that, despite a 45% reduction in total heat demand by 2050, district heating could still cover up to 31% of total demand. The average distribution cost ranges between 0.028 and 0.032 €/kWh, with values as low as 0.02 €/kWh in dense urban areas and exceeding 0.035 €/kWh in low-density or dispersed regions. The heat generation cost fundamentally depends on the type of heat source and its conversion technology. In this context, Thommessen et al. [37] analyse how the integration of novel heat sources, including large heat pumps, electric boilers, and industrial waste heat, can transform the cost structure of district heating systems. The results show that waste heat and renewable heat from large heat pumps achieve the lowest marginal costs, ranging between 0.01 and 0.06 €/kWh, while CHP units operate at intermediate levels (0.06–0.08 €/kWh) and fossil boilers exceed 0.16 €/kWh. Combining these findings, it can be observed that for sufficiently large transported thermopile volume (above 1.5 m^3), the CharCool system can become competitive in terms of operating costs both under current conditions and in future scenarios, when integrated with cost-effective an renewables heat sources and implemented in densely built areas where distribution conditions remain favourable. In particular, in future contexts, the expected increase in distribution costs could be partially offset by the reduction in generation costs driven by the greater integration of renewable energy sources within district heating systems.

Both [26] and [27] report that the lowest CO_2 emission factors in district heating are associated with waste heat and geothermal energy, ranging between 0.003 and 0.025 kg CO_2/kWh. Solar thermal systems show slightly higher values, typically 0.04–0.07 kg CO_2/kWh, while biomass-based systems vary more widely, between 0.01 and 0.12 kg CO_2/kWh, depending on the fuel type and conversion technology. Natural gas–based systems generally exhibit higher emissions, around 0.13–0.20 kg CO_2/kWh, highlighting the much lower carbon intensity of renewable and residual heat sources. Considering these emission ranges, the competitiveness of the CharCool system in terms of CO_2 emissions compared to a vapor compression chiller appears to be limited to specific cases where waste heat or renewable sources are fully integrated within the district heating network.

4. Conclusion

This work evaluated the performance and competitiveness of the CharCool adsorption-based cooling system equipped with thermochemical storage and supplied by a heat from a district heating network. The analysis combined simplified system and building models to assess operating costs and CO_2 emissions, highlighting the influence of key technical and economic parameters. The sensitivity analysis showed that the thermopile volume and the district heating heat cost are the main factors affecting the operating cost, while the heat emission factor has the strongest impact on CO_2 emissions. Both functions exhibit a clear dependence on the transported volume for small capacities, which becomes negligible above roughly 1.5 m^3, where the number of required transports stabilizes. The comparison with a vapor compression chiller indicated that the CharCool system can reach comparable or lower operating costs only for large transported volumes and low district heating heat prices. When the Levelized Cost of Cooling (LCOC) is considered, competitiveness can also be achieved for moderate volumes, suggesting that the system may be viable in several practical configurations. From literature data, distribution costs for district heating were found to range between 0.003 and 0.012 €/kWh in dense urban areas, increasing up to 0.035 €/kWh in low-density zones. The generation cost strongly depends on the heat source, with waste heat and renewable-based systems showing the lowest values. In terms of environmental performance, waste heat and geothermal energy present the lowest emission factors, typically below 0.03 kg CO_2/kWh, confirming their suitability as low-impact heat sources. In a longer-term perspective, potential increases in distribution costs could be partly balanced by lower generation costs resulting from greater renewable integration, further supporting the relevance of adsorption-based thermal storage in future district heating frameworks. Quantitatively, the analysis identifies a clear competitiveness threshold, with operating costs and emissions becoming comparable to or lower than those of a vapor compression chiller when transported volumes exceed approximately 1.5 m^3 and the supplied heat cost and emission factor remain within the lower ranges reported for urban district heating networks.

Acknowledgements

This project has received funding from the European Union's Horizon Europe programme (HORIZON-EIC-2023) under grant agreement No. 101162196 (CharCool).
Further, during the preparation of this work the author(s) used ChatGPT–OpenAI's language-model-based assistant–to improve the English language proficiency of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

References

[1] Energy Agency I. World Energy Outlook 2024. 2024.
[2] Eurostat. Energy consumption in households by type of end-use (nrg_d_hhq). European Commission / Eurostat 2023. https://ec.europa.eu/eurostat/databrowser/view/nrg_d_hhq/default/table?lang=en (accessed October 7, 2025).
[3] [env_ac_ainah_r2] Air emissions accounts by NACE Rev. 2 activity n.d. https://ec.europa.eu/eurostat/databrowser/view/env_ac_ainah_r2/default/table?lang=en (accessed November 4, 2025).
[4] Toleikyte A, Reina R, Lyons J, Gasparella L, Koolen A, Felice D, et al. The Heat Pump Wave: Opportunities and Challenges Analysis of the largescale deployment of heat pumps by 2030 following the REPowerEU plan, 2023. https://doi.org/10.2760/27877.
[5] Dias JMS, Costa VAF. Adsorption heat pumps for heating applications: A review of current state, literature gaps and development challenges. Renewable and Sustainable Energy Reviews 2018;98:317–27. https://doi.org/10.1016/J.RSER.2018.09.026.
[6] Boruta P, Bujok T, Mika Ł, Sztekler K. Adsorbents, working pairs and coated beds for natural refrigerants in adsorption chillers—state of the art. Energies (Basel) 2021;14. https://doi.org/10.3390/en14154707.
[7] Shamim JA, Nawaz K, Hu MH, Pasqualin P, Krishnan EN, Kowalski SP, et al. Review of the potential and challenges of MOF-based adsorption heat pumps for sustainable cooling and heating in the buildings. Energy 2025;323:135846. https://doi.org/10.1016/J.ENERGY.2025.135846.
[8] Zivariravan A, Santori G, Arteconi A. A dimensionless framework for adsorber dynamics. Thermal Science and Engineering Progress 2026;71:104569. https://doi.org/10.1016/j.tsep.2026.104569.
[9] Farulla GA, Cellura M, Guarino F, Ferraro M. A review of thermochemical energy storage systems for power grid support. Applied Sciences (Switzerland) 2020;10. https://doi.org/10.3390/app10093142.
[10] Vasta S, Brancato V, La Rosa D, Palomba V, Restuccia G, Sapienza A, et al. Adsorption heat storage: State-of-the-art and future perspectives. Nanomaterials 2018;8. https://doi.org/10.3390/nano8070522.
[11] CharCool n.d. https://www.charcool.eu/ (accessed November 6, 2025).
[12] Carriages preview | Legislative Train Schedule n.d. https://www.europarl.europa.eu/legislative-train/package-energy-efficiency/file-eu-strategy-on-heating-and-cooling?utm_source=chatgpt.com (accessed November 6, 2025).
[13] Popolazione 2011 – Istat n.d. https://www.istat.it/statistiche-per-temi/censimenti/censimenti-storici/popolazione-e-abitazioni/popolazione-2011/ (accessed October 10, 2025).
[14] MicheleSantoro. Decreto ministeriale Sanità 5 luglio 1975. 1975.
[15] TABULA WebTool n.d. https://webtool.building-typology.eu/#bm (accessed October 16, 2025).
[16] Decreto del Ministero dello sviluppo economico 26 giugno 2015 2015.
[17] Mugnini A, Ramallo-González AP, García ÁM, Arteconi A. An integrated approach to assess thermal mass and passive cooling: mapping cooling need and overheating risk under climate change scenarios. Build Environ 2026;287:113843. https://doi.org/10.1016/J.BUILDENV.2025.113843.
[18] Housing Shortage in Europe further deteriorate: Rental Prices Increase by 2.4% Within Six Months, Overcrowding on the Rise – Catella Research - Catella n.d. https://www.catella.com/en/germany/news-and-press-releases/press-releases/2025/housing-shortage-in-europe-further-deteriorate-rental-prices-increase-by-2.4-within-six-months-overcrowding-on-the-rise--catella-research?utm_source=chatgpt.com (accessed October 16, 2025).
[19] Persyn D, Díaz-Lanchas. Estimating road transport costs between EU regions JRC Working Papers on Territorial Modelling and Analysis No 04/2019. 2019.
[20] Werner S. European District Heating Price Series. 2016.
[21] Ranta T, Karhunen A, Laihanen M. The effect of fuels and other variables on the price of district

heating in Finland. Renewable and Sustainable Energy Reviews 2025;209:115086. https://doi.org/10.1016/J.RSER.2024.115086.
[22] Nielsen S, Grundahl L. District heating expansion potential with low-temperature and end-use heat savings. Energies (Basel) 2018;11. https://doi.org/10.3390/en11020277.
[23] Darío Gómez AR, Watterson Branca B Americano JD, Ha C, Marland G, Matsika E, Nenge Namayanga L, et al. Chapter 2: Stationary Combustion 2006 IPCC Guidelines for National Greenhouse Gas Inventories 2.1 C H A P T E R 2 STATIONARY COMBUSTION Volume 2: Energy 2.2 2006 IPCC Guidelines for National Greenhouse Gas Inventories Contributing Author. 2006.
[24] Martin Schmied D-I, Wolfram Knörr D-W-I, Hepburn L. Calculating GHG emissions for freight forwarding and logistics services in accordance with EN 16258 Calculating GHG emissions for freight forward-ing and logistics services (April 2012). 2012.
[25] ICCT. COMPARISON OF FUEL CONSUMPTION AND EMISSIONS FOR REPRESENTATIVE HEAVY-DUTY VEHICLES IN EUROPE. 2018.
[26] Toleikyte A, Jimenez Navarro JP, Carlsson J. Consumers in district heating and cooling, Publications Office of the European Union, 2023. https://doi.org/10.2760/13565.
[27] Malcher X, Tenorio-Rodriguez FC, Finkbeiner M, Gonzalez-Salazar M. Decarbonization of district heating: A systematic review of carbon footprint and key mitigation strategies. Renewable and Sustainable Energy Reviews 2025;215:115602. https://doi.org/10.1016/J.RSER.2025.115602.
[28] Joint Research Centre Data Catalogue - GHG Emission Factors for Electricity Consumption - European Commission n.d. https://data.jrc.ec.europa.eu/dataset/919df040-0252-4e4e-ad82-c054896e1641 (accessed November 13, 2025).
[29] Levelised cost of heating for air-to-air and air-to-water heat pumps and gas boilers for selected countries, and sensitivity to fuel prices, H1 2021 - H1 2022 – Charts – Data & Statistics - IEA n.d. https://www.iea.org/data-and-statistics/charts/levelised-cost-of-heating-for-air-to-air-and-air-to-water-heat-pumps-and-gas-boilers-for-selected-countries-and-sensitivity-to-fuel-prices-h1-2021-h1-2022 (accessed October 16, 2025).
[30] CLEAN ENERGY TECHNOLOGY OBSERVATORY. Heat Pumps in the European Union STATUS REPORT ON TECHNOLOGY DEVELOPMENT, TRENDS, VALUE CHAINS & MARKETS, 2024. https://doi.org/10.2760/7205477.
[31] Renewable solutions in end-uses : heat pump costs and markets. International Renewable Energy Agency; 2022.
[32] Household electricity prices in the EU stable in 2024 - News articles - Eurostat 2024. https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20250506-2?utm_source=chatgpt.com (accessed October 16, 2025).
[33] Dellino G, Meloni C. Operations Research/Computer Science Interfaces Series Uncertainty Management in Simulation-Optimization of Complex Systems Algorithms and Applications. 2015.
[34] Renewable Energy Agency I. Renewable Energy in District Heating and Cooling, A sector roadmap for REmap. 2017.
[35] Persson U, Werner S. Heat distribution and the future competitiveness of district heating. Appl Energy 2011;88:568–76. https://doi.org/10.1016/J.APENERGY.2010.09.020.
[36] Fallahnejad M, Kranzl L, Haas R, Hummel M, Müller A, Sánchez-García L, et al. District heating potential in the EU-27: Evaluating the impacts of heat demand reduction and market share growth. Appl Energy 2024;353:122154. https://doi.org/10.1016/J.APENERGY.2023.122154.
[37] Thommessen C, Verheyen J, Roes J, Hoster H. Estimating the value of novel heat sources in district heating systems from the perspective of energy utilities using a merit order approach. Appl Energy 2025;401:126594. https://doi.org/10.1016/J.APENERGY.2025.126594.