PROCEEDINGS OF ECOS 2023 - THE 36TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
25-30 JUNE 2023, LAS PALMAS DE GRAN CANARIA, SPAIN

Thermo-economic comparison of CO_2 and water as a heat carrier for long-distance heat transport from geothermal sources

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Abstract:

Deep geothermal energy has tremendous potential for decarbonizing the heating sector. However, one common obstacle can be the mismatch between geologically attractive regions in the countryside and urban areas with a high heat demand density, which are therefore attractive for district heating systems. In the last years, an increasing number of regions consider the transport of geothermal heat into urban clusters. One example of such a region is the South German Molasse Basin in Upper Bavaria. However, such heat transport pipelines come along with massive upfront investment costs due to the required large pipe diameter and insulation thickness. While the classic concept foresees the use of water as a heat carrier in such long-distance heat transportation pipelines, CO_2 can be an attractive alternative. This study investigates the thermo-economic performance of CO_2 as a heat transport carrier for a potential long-distance heat transmission pipeline with a length of 20 km, which could connect a planned geothermal project in the South of Munich with the existing district heating network of Munich. The results of the base case scenario demonstrate that for both heat carrier options water and CO_2 rather low LCOH for the transport of the heat can be achieved. The resulting additional LCOH by the long-distance heat transport of around 0.6 c€/kWh are rather small compared to the typical overall LCOH of geothermal district heating systems. Comparing the thermo-economic performance of water and CO_2 reveals rather similar achievable LCOH, with a slight advantage for the classical concept of using water. However, this changes if the installation of a high temperature heat pump (HTHP) is considered in order to increase the thermal capacity of the heat transport system. In the case of using CO_2, the additional temperature increase takes place directly within the CO_2 stream by just installing a compressor, while in the case of the water system, a complete HTHP system needs to be installed. In combination with a higher achievable COP, the CO_2 HTHP configurations results in lower overall LCOH compared to the water system.

Keywords:

District Heating Networks, Geothermal Energy, Heat Transfer, Economic Analysis, Carbon Dioxide

1. Introduction

Deep geothermal energy can play a significant role in the necessary transformation of the heating sector [1]. While there is an increasing number of geothermal projects worldwide [2], the vast majority of the worldwide potential is still untapped [3]. However, one major challenge for the utilization of geothermal energy is the common mismatch between urban areas with a high heat demand density and areas with favourable geological conditions for heat extraction. For example, promising geothermal resources in the countryside with temperatures between 80 - 110 °C can not be economically utilized without long-distance heat transport. While such resource temperatures are highly suitable for district heating supply, their temperature is too low for economic power generation by a binary cycle such as an Organic Rankine Cycle (ORC) [4].

Thus, since the local heat demand is too low in order to justify the high investment costs, without the ability to transport the heat over long distances, many promising geothermal resources would remain untapped. Molar-Cruz et al. [5] have recently studied the application potential of long-distance heat transport for geothermal energy in the Greater Area of Munich, Germany. The findings demonstrate that applying long-distance heat transportation systems can reduce the overall cost of heat supply by 15 % compared to a scenario without heat transport. Furthermore, despite the high investment costs of the transportation system, the resulting heat costs are still competitive with other heating technologies. Kavvadias and Quoilin [6] show that long-distance heat transport from conventional combined heat and power plants (CHP) can be economical and is already applied in several European countries. Furthermore, Moser and Puschnigg [7] investigated the concept of a supra-regional district heating network for a use-case area in Austria. Their results suggest that long-distance

 https://doi.org/10.52202/069564-0233

heat transport networks between several different actors might become economical in a future non-fossil energy system and has a high potential to connect industrial waste heat and renewable energy heat sources. Thus, long-distance heat transport is a promising approach to boost the utilization of geothermal energy and the transformation of the heating sector in general.

However, due to high upfront investment and operational costs, an optimal design of the transportation system is pivotal. While the classical concept foresees the use of water as a heat carrier, CO_2 has gained increasing attention as an alternative heat carrier in both geothermal systems [8]–[10] and district heating networks (DHN) [11]. The concept of urban CO_2 district energy systems is mainly investigated for modern networks that provide both heating and cooling by heat pump systems being installed in each building. Thus, due to the low operating temperature of such systems and the corresponding CO_2 phase change, the costs of heat distribution can significantly be reduced [12].

Thus, while CO_2 is currently investigated as an energy carrier within DHN systems, its application potential for long-distance heat transport has not been evaluated in existing studies so far. The scope of this work is the evaluation of the thermo-economic potential of CO_2 as a heat carrier for a potential application case in the greater area of Munich. This area is a promising case study since the connection of the geothermal attractive region in the South of Munich with the existing DHN system of Munich is currently under discussion and within a preliminary planning phase [13]. This work investigates several technical options for the heat transport of CO_2 and compares the resulting thermo-economic performance with a conventional concept using water as a heat carrier.

2. Methodology

In the system under scrutiny, the heat is transported circulating fluid between the geothermal field and the DH (district heating) network as shown in Fig. 1.

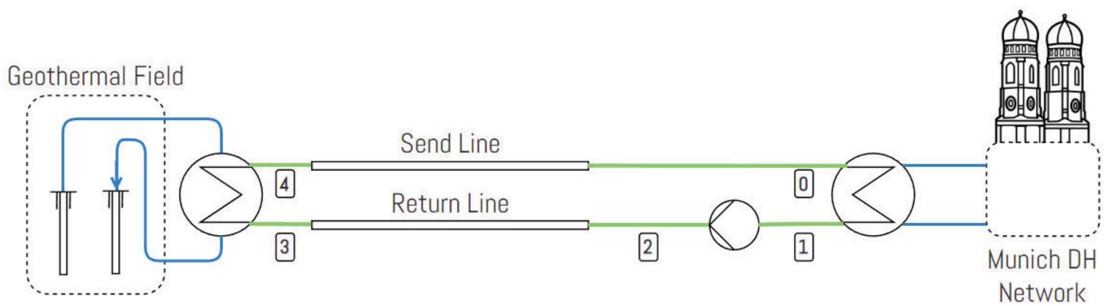


Figure 1: Base transport system scheme

2.1. Pipeline Model

The behavior of the system is highly dependent on the model of the pipelines connecting these two locations due to their length. To assess the condition of the fluid within the pipeline, pressure and enthalpy balances (1) were integrated over its length using the Runge-Kutta solver [14] implemented in Scipy [15].

$$\begin{cases} \frac{dp}{dx} = f\frac{1}{2\rho d}\left(\frac{4\dot{m}}{\pi d^2}\right)^2 \\ \frac{dh}{dx} = \frac{\Delta T}{r_{tot}\dot{m}} \end{cases} \tag{1}$$

The friction factor in (1) has been calculated using the Churchill correlation [16] while the linear thermal resistance in (1) has been defined as follows:

$$r_{tot} = r_{conv} + r_{ins}, \; r_{conv} = \frac{1}{Nu\,\pi k_{fluid}}, \; r_{ins} = \frac{\ln\left(1 + \frac{2s_{ins}}{d}\right)}{2\pi k_{ins}} \tag{2}$$

with:

$$Nu = 0.023 Re^{0.8} Pr^{0.3} \tag{3}$$

The formulation of the balance equations (1) implies that the kinetic and gravitational terms have been neglected in both the momentum and energy balances. The integration process used in the analysis provides a high level of accuracy while still maintaining a reasonable computational time. However, especially for water-based systems, it is possible to achieve an acceptable level of accuracy by discretizing the duct into a few sections (less than 10).

2.2. System Model

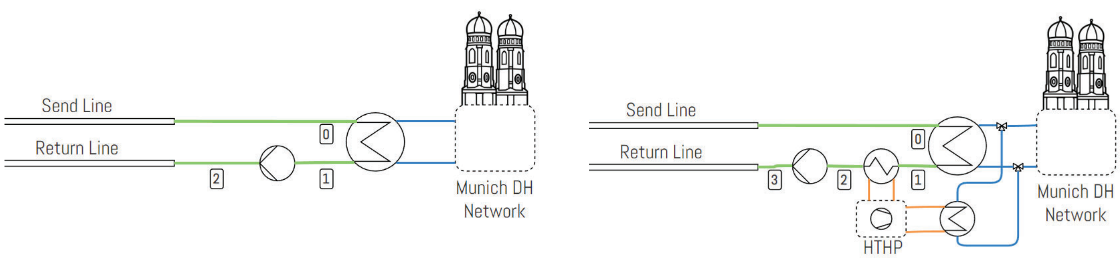
Given the high investment costs and anticipated slow transients in the pipelines, the system is expected to operate in a steady state condition, providing a constant heat flux to the Munich area DH Network throughout its lifetime. Thus, the water flow rate in the DH is evaluated based on the system's heat transport capacity rather than on the heat demand from the grid. Various configurations of the heat transfer system were analyzed for both the water-based and CO_2-based cases, as illustrated in Fig. 2 and discussed in the following section.

2.2.1. Base Case

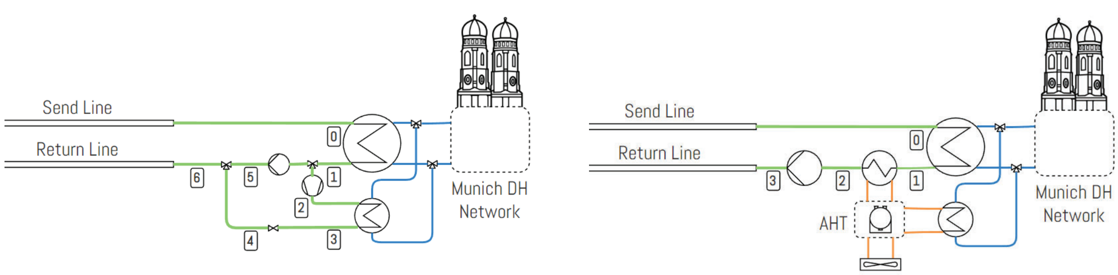
The most basic approach for long-distance heat transportation, as depicted in Fig. 2a, involves circulating the fluid via a pump placed after the DH network heat exchanger. The flow rate of the fluid is optimized to minimize the *LCOH* under specific design conditions. Additionally, for CO_2-based systems, the pipeline pressure is also optimized.

2.2.2. Heat Pump Case

The industrial requirement of fixed lowest temperature (65 °C) in standard district heating networks can limit the amount of heat that can be transported for a given flow rate, as the temperature at the outlet of the DH heat exchanger cannot go below a certain value. To overcome this limitation, a heat pump can be installed after the DH heat exchanger outlet to further cool down the working fluid before redirecting it to the geothermal field, as shown in Fig. 2b.



(a) Base Case **(b)** High Temperature Heat Pump (HTHP) Case



(c) Simplified Heat Pump for CO_2-based system **(d)** Absorption Heat Transformer (AHT) Case

Figure 2: Different configuration on the DH network side of the system

This configuration not only improves the heat transfer rate but also reduces the pumping power for CO_2-based systems as CO_2 becomes less compressible at lower temperatures. Alternatively, a compression set-up can replace the heat pump in CO_2-based systems as shown in Fig. 2c, which removes the inefficiencies associated with the heat pump evaporator.

The heat pump in Fig. 2b has been modeled with a fixed exergy efficiency of 0.4, according to experimental results from literature [17], to avoid the need for complete modeling. Knowing the exergy efficiency is possible to estimate the electrical power demand as:

$$\dot{W}_{heat\ pump} = \frac{1}{\eta_{exergy}} \left(1 - \frac{T_{low}}{T_{high}}\right) \dot{Q}_{heat\ pump} = \frac{1}{0.4} \left(1 - \frac{T_{low}}{T_{high}}\right) \dot{Q}_{heat\ pump} \tag{4}$$

 https://doi.org/10.52202/069564-0233

T_{low} and T_{high} have been evaluated considering $\Delta T_{pinch\ point} = 5$°C in the heat pump's heat exchangers.

2.2.3. Absorption Heat Transformer Case

Heat pumps can increase power extraction from the geothermal fluid, but at the expense of increased electricity consumption. To minimize the electricity consumption, heat transformers can be used instead of heat pumps. However, the heat transformer method requires the dissipation of some of the transported heat to allow for the remaining heat to reach the desired temperature, as depicted in Fig. 2d.

The heat transformer has been modelled as a black box considering a 50% exergy efficiency [18] in analysing the various configurations. The ratio between the transmitted power and the incoming one can then be determined modifying the equation for the exergy efficiency presented in [18]:

$$\frac{\dot{Q}_{out}}{\dot{Q}_{in}} = \frac{1}{\eta_{exergy}} \frac{1 - \frac{T_{amb}}{T_{in}}}{1 - \frac{T_{amb}}{T_{out}}} \tag{5}$$

2.2.4. Heat Pump Temperature Considerations

If the output temperature from the main DH heat exchanger exceeds the requirements of the DH network, the temperature at the outlet of the heat pump can be lowered resulting in a reduction of the compression power needed (Fig. 3 should clarify this point).

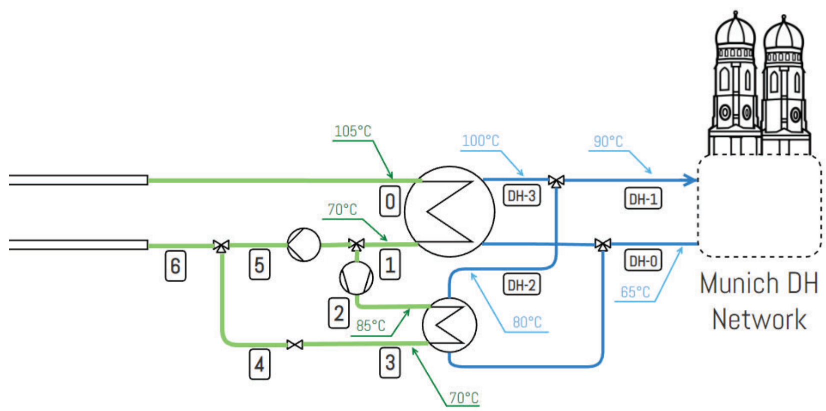


Figure 3: Example of how a lower output temperature can be set to the heat pump outlet: Temperatures of *points [DH-0]* and *[DH-1]* are fixed due to the grid design constraints (65°C and 90°C in this example). If temperature in *point [DH-2]* is higher than required, temperature in *point [DH-3]* can be lower to compensate

With reference to Fig. 3, temperature at *point [DH-3]* can be identified starting from an adimensional parameter defined as:

$$T_{ratio} = \frac{T_{DH3} - T_{DH0}}{T_{DH1} - T_{DH0}} \tag{6}$$

Notice that choosing T_{ratio} implies defining the ratio between the flow rate in *[DH-3]* and in *[DH-2]*:

$$\dot{m}_{DH_{ratio}} = \frac{\dot{m}_{DH3}}{\dot{m}_{DH2}} = \frac{h_{DH2} - h_{DH1}}{h_{DH1} - h_{DH3}} \approx \frac{T_{DH2} - T_{DH1}}{T_{DH1} - T_{DH3}} \tag{7}$$

Moreover, is interesting to notice that a heat pump scheme with $T_{ratio} = 0$ is equivalent to a base scheme (as defined in section 2.2.1.) in which the temperature in the DH network is controlled by letting some fluid by-pass the DH heat exchanger.

2.3. Economic Model

The levelized cost of heat (LCOH) has been evaluated to optimize the design parameter of the different schemes and to compare the different solutions. The LCOH is calculated as the minimum cost at which the heat must be sold in order to recover the investment after the lifetime of the plant, it can be derived by setting the NPV of the system to 0:

$$NPV = -C_{tot} + \sum_{t=1}^{L_e} CF_t\,(1+i)^{-t} = 0 \tag{8}$$

Where the annual cash flow (CF_t) is:

$$CF_t = h_y \left(LCOH\dot{Q}_{DH} - \dot{W}_{pump}c_{el} \right) - C_{om} \quad (9)$$

The LCOH can then be calculated rearranging (8) and (9) assuming a constant annual cash flow:

$$LCOH = \frac{C_{tot}\beta + \dot{W}_{pump}c_{el}}{\dot{Q}_{DH}}, \quad \beta = \frac{1 + \alpha OM_{ratio}}{\alpha h_y}, \quad \alpha = \frac{1 - (1 + i)^{-L_e}}{i} \quad (10)$$

The costs are evaluated using some specific correlations listed in Table 1.

Table 1: Cost correlation used in economic analysis

Component	**Cost Correlation**	**Notes**	**Ref.**
Overall Investment	$C_{tot} = 2C_{pipe} + \sum C_{HE} + \sum C_{other}$	*Result in [€], conversion €/$ applied if needed. Pump acquisition cost has been neglected. C_{other} represents the cost of additional components such as the heat pump or the CO_2 compressor*	-
Yearly Maintenance	$C_{om} = OM_{ratio}C_{tot}$	*5% OM_{ratio} considered*	-
Pipeline	$C_{pipe} = \left(0.6492\ d^{0.9779} + C_{ins}\right) L$	*Result in [$], pipe diameter in [m]*	[6]
Pipe Insulation	$C_{ins} = c_{ins}\left(\pi s_{ins}\left(d + s_{ins}\right)\right)$	*Result in [$/m], c_{ins} in [$/m^3]. It depends on the insulation material (see [6])*	[6]
Heat Exchangers	$C_{HE} = 49.45UA_{HE}^{0.7544}$	*Result in [$], Correlation for CO_2, UA_{HE} in [W/K], it is the product of the HE area and heat transfer coefficient*	[19]
Heat Pump	$C_{heat\ pump} = 0.33667\dot{W}_{heat\ pump}$	*Result in [M€], $\dot{W}_{heat\ pump}$ in [MW], Correlation for $\dot{W}_{heat\ pump}$ up to 10MW, Only the heat pump acquisition cost has been considered.*	[20]
Heat Transformer	$C_{heat\ transformer} = 375\dot{Q}_{in}$	*Result in [€], $\dot{Q}_{in}$ in [kW], correlation valid for $\dot{Q}_{in} \approx$10MW, correlation for absorption heat pumps used following the approach of [21]. 375 is the mean of the range (300-450) presented in [22]*	[22].

2.3.1. Remarks on the LCOH calculation

Following the approach defined in [6], the LCOH calculated in 10 refers only to the process of transporting the heat. In order to identify the real cost of heat for DH users, heat production costs (well drilling, reservoir circulation pump, etc.) must be taken into account:

$$LCOH_{tot} = \frac{(C_{tot} + C_{prod})\beta + (\dot{W}_{pump} + \dot{W}_{pump_{prod}})c_{el}}{\dot{Q}_{DH}} \quad (11)$$

In order to avoid the need for a complete economic evaluation of the production site, it is tempting to simplify the overall LCOH calculation considering a fixed price for the produced heat using values retrieved from literature:

$$LCOH_{tot} = \frac{C_{tot}\beta + \dot{W}_{pump}c_{el} + \dot{Q}_{geo}c_{heat_{prod}}}{\dot{Q}_{DH}} \quad (12)$$

It is important to consider that using equation (12) may lead to distorted results. The reason for this is that more complex system schemes, such as those described in sections 2.2.2. or 2.2.3., are chosen because they have a lower temperature in the return line and thus a higher heat extraction rate ($\dot{Q}geo$) *for the same number of wells and reservoir pumping power.* However, due to the fixed value for $c_{heat_{prod}}$ in equation (12), this behavior cannot be accurately modeled. To address this issue, the most straightforward solution is to evaluate the overall production cost of different systems using a fixed design extraction power:

$$LCOH_{tot} = \frac{C_{tot}\beta + \dot{W}_{pump}c_{el} + C_{heat_{prod}}}{\dot{Q}_{DH}}, \quad C_{heat_{prod}} = \dot{Q}_{geo_{DESIGN}}c_{heat_{prod}} \quad (13)$$

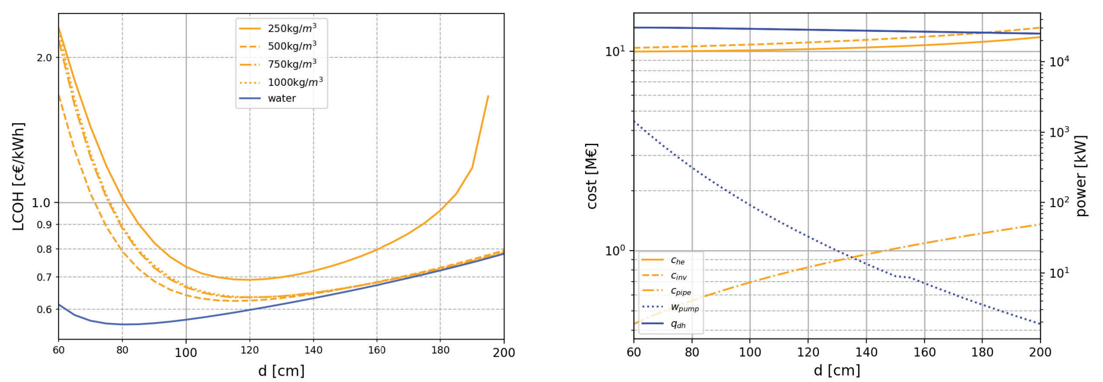
3. Results

This section presents the results for the four different investigated technological concepts visualized in Fig.2.

https://doi.org/10.52202/069564-0233

3.1. Base case

Fig.4a displays the achievable LCOH for both water and CO_2 considering different pipe diameters. The results indicate that both heat carriers have a certain optimal pipe diameter, which corresponds to the optimal trade-off between investment and operational costs. For CO_2, the optimal pipe diameter is at around 130 cm, while it is at around 85 cm for water. While the deviation between both heat carries is rather small (0.1 c€/kWh), no clear advantages for using CO_2 as heat carrier in this standard scenario can be seen. The figure also shows the effect of the minimum CO_2 density in the system, showing an optimum in the LCOH for $\rho_{min} = 500 kg/m^3$.



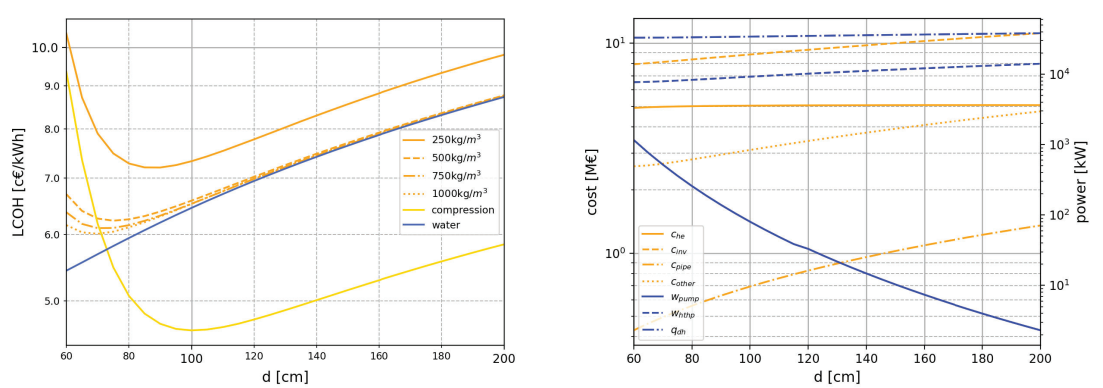
(a) LCOH with diameter **(b)** Cost Composition for CO_2 with $\rho = 450[kg/m^3]$

Figure 4: Achievable LCOH for water and CO_2 considering different densities for the CO_2

The findings presented in Fig. 4a can be understood by analyzing the information provided in Figure 4b. Heat exchangers and pipeline installation are the biggest contributors to the capital investment, costing around 10 M€ and 1 M€, respectively. The cost of the heat exchangers can be explained considering that the system is required to transport a substantial amount of power with a limited temperature difference (ΔT) between the geothermal water (115℃) and the district heating network (90℃). As a result, the two heat exchangers can only have a limited logarithmic mean temperature difference (LMTD), 12.5℃ in the best case scenario, this increase the required UA and the heat exchanger cost. Increasing the pipeline diameter results in some additional heat loss to the environment because of the increase in surface area. These losses are negligible if compared with the overall power transported by the system, but make the UA requirements even more demanding.

3.2. HTHP case

Do to the high investment cost required for the acquisition of the heat exchangers the installation of an heat pump can be useful for increasing the available ΔT and allowing the installation of smaller heat exchangers.



(a) LCOH with diameter **(b)** Cost Composition for CO_2 with $\rho = 700[kg/m^3]$

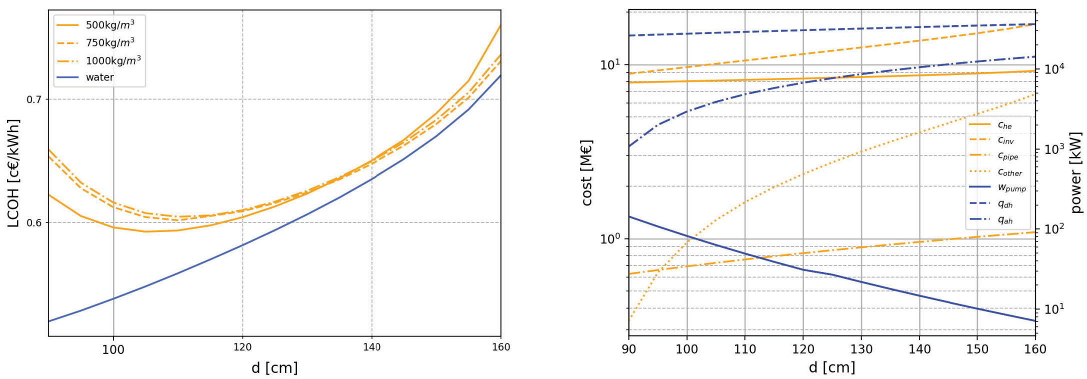
Figure 5: Achievable LCOH for water and CO_2 for the HTHP (High Temperature Heat Pump) case

In Fig. 5, it is apparent that the LCOH has substantially increased when compared to the baseline scenario, despite a decrease in the cost of heat exchangers to 4M€. This is mainly due to the increased in electrical power consumption. The high cost of electricity (the average price for Bavaria in 2022 was 22.5 cents per kilowatt-hour [23], which is more than 30 times higher than the LCOH for the baseline scenario) makes it unprofitable to extract heat from the fluid using electrical power, even with a high COP. It is critical to note that this is true for the LCOH shown in Figure 5 which only considers the cost of the transport system, ignoring the cost of heat production, depending on the cost of heat production this effect can change dramatically.

Another interesting finding shown in Fig. 5 is that the CO_2 scheme the compression system replacing the heat pump (Fig. 2c) due to its simplicity and higher COP, is capable of performing better than the water-based system in the considered scenario. Especially against the background of high heat demand periods during the winter, the additional installation of a CO_2 compressor can be favourable from an operator's perspective, since it allows to supply of additional heat without the need for additional drilling.

3.3. AHT case

An absorption heat transformer can be considered as a solution of increasing the ΔT without using additional electrical power. In fact, as can be see from Fig. 6, the LCOH has decreased for both water and CO_2.



(a) LCOH with diameter

(b) Cost Composition for CO_2 with $\rho = 450[kg/m^3]$

Figure 6: Achievable LCOH for water and CO_2 for the AHT (Absorption Heat Transformer) case

Fig. 6b, shows that the cost of the heat exchangers has decreased to 8M€. The power provided by the AHT in the optimal condition for CO_2 (d=110cm) if 4MW which is only about 10% of the overall heat transported by the network, this shows that the real advantage of installing an AHT it to increase the available ΔT in order to allow the installation of smaller heat exchangers.

4. Conclusion

The results of this work provide valuable insights into both the achievable LCOH of long-distance heat transport from geothermal sources in general and the thermo-economic comparison of water and CO_2 as potential heat carrier fluids. First, the results of the base case scenario (cf. Fig 4a) demonstrate that for both heat carrier options rather low LCOH for the transport of the heat can be achieved. The resulting additional LCHO by the long-distance heat transport of around 0.6 c€/kWh is rather small compared to the typical overall LCOH of geothermal district heating systems [24]. Considering that long-distance heat transport enables the utilization of geological attractive regions in the countryside with lower project-specific LCOH, installing the long-distance heat transport system might result in an overall lower LCOH of the whole geothermal heating system. Therefore, the findings of this work support the general conclusions by the work of Molar-Cruz et al. [5] on the theoretical advantages of geothermal heating systems with long-distance heat transport as well as the economic feasibility of the projects currently in the planning stage in the Greater Area of Munich, Germany [13].
Comparing the thermo-economic performance of water and CO_2 shows rather similar achievable LCOH, with a slight advantage for the classical concept of using water. While CO_2 reveals a lower pressure drop within the piping system, this advantage is overcompensated by the fact that the pressure increase for CO_2 is taking place at a lower density than for water, resulting in a higher power demand. Furthermore, considering the potential integration of an HTHP increases the LCOH significantly, mainly due to the currently rather high electricity prices. Nonetheless, the considered LCOH only address the installation and operation of the transportation system and the HTHP installation. However, installing an HTHP lowers also the LCOH of the geothermal project itself

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(which are rather high especially caused by the drilling cost [25]) due to a higher utilization and it reduces the need for installing and/or integrating further alternative heat sources. Thus, while the installation of an HTHP might be useful from a thermo-economic perspective, it needs to be assessed in a broader system study considering also other available potential heat sources and technologies. Regarding the potential application of an HTHP into the long-distance heat transport system, the results of this work highlight the potential advantage of CO_2 as a heat carrier (cf. Fig. 5). In the case of using CO_2, the additional temperature increase takes place directly within the CO_2 stream by just installing a compressor, while in the case of the water system, a complete HTHP system needs to be installed. Thus, the usage of CO_2 allows significantly lower investment costs as well as higher COPs.

Concerning the thermo-economic comparison of water and CO_2 for the considered use case with a rather high required DH supply temperature, CO_2 results in comparable LCOH as water, but has no further positive impact on the economic performance despite in case of an additional HTHP system for increasing the thermodynamic capacity of the heat transport system. Furthermore, the future trends towards lower DH supply temperatures as well as the use of CO_2 as a heat carrier in geothermal systems (cf. [9] might result in a thermo-economic favourability of CO_2 as a heat carrier for long-distance heat transport and might be evaluated in future studies.

Acknowledgments

For the University of Florence contribution, this research received partial support from *Italian PNRR NEST Spoke 5 "Energy Conversion"*. On the other hand, regarding the contribution of the Technical University of Munich, funding from the *Bavarian State Ministry of Science and the Arts* in the framework of the Project *Geothermal-Alliance Bavaria* is gratefully acknowledged.

Nomenclature

Acronyms

AHT	Absorption Heat Transformer
CHP	Combined Heat and Power
COP	Coefficient Of Performance
DH	District Heating
HTHP	High Temperature Heat Pump
LCOH	Levelized Cost Of Heat, *c€/kWh*
LMTD	Logarithmic Mean Temperature Difference
NVP	Net Present Value, *€*

Economics

C	Absolute cost, *€*
c	Relative cost, *€/kW*
C_{om}	Operation and maintenance cost, *€/year*
C_{tot}	Overall investment cost of the system, *€*
CF_t	Yearly cash flow, *€/year*
h_y	Yearly operational time, *hours*
i	Interest rate
L_e	System operational life, *years*
OM_{ratio}	Ratio between C_{om} and C_{tot}

Geometrics

d	Pipeline diameter, *m*
s_{ins}	Pipeline insulation thickness, *m*

Thermodynamics

$\dot{m}$	Mass flow rate, *kg/s*
$\dot{Q}$	Heat flux, *kW*
$\dot{W}$	Mechanical power, *kW*
η_{exergy}	Exergy efficiency
k	thermal conductivity, *W/(m K)*
Nu	Nusselt number
Pr	Prandtl number
r_{tot}	Total thermal resistance, *K/W*
Re	Reynolds number

References

[1] D. Romanov and B. Leiss, "Geothermal energy at different depths for district heating and cooling of existing and future building stock," *Renewable and Sustainable Energy Reviews*, vol. 167, p. 112 727, 2022.

[2] J. W. Lund and A. N. Toth, "Direct utilization of geothermal energy 2020 worldwide review," *Geothermics*, vol. 90, p. 101 915, 2021, ISSN: 03756505. DOI: `10.1016/j.geothermics.2020.101915`.

[3] J. Limberger, T. Boxem, M. Pluymaekers, *et al.*, "Geothermal energy in deep aquifers: A global assessment of the resource base for direct heat utilization," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 961–975, 2018, ISSN: 1364-0321. DOI: `10.1016/j.rser.2017.09.084`.

[4] S. Eyerer, C. Schifflechner, S. Hofbauer, W. Bauer, C. Wieland, and H. Spliethoff, “Combined heat and power from hydrothermal geothermal resources in germany: An assessment of the potential,” *renewable and sustainable energy reviews*, vol. 120, p. 109 661, 2020.

[5] A. Molar-Cruz, M. F. Keim, C. Schifflechner, *et al.*, “Techno-economic optimization of large-scale deep geothermal district heating systems with long-distance heat transport,” *Energy Conversion and Management*, vol. 267, p. 115 906, 2022, ISSN: 0196-8904. DOI: 10.1016/j.enconman.2022.115906.

[6] K. C. Kavvadias and S. Quoilin, “Exploiting waste heat potential by long distance heat transmission: Design considerations and techno-economic assessment,” *Applied Energy*, vol. 216, pp. 452–465, 2018, ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2018.02.080.

[7] S. Moser and S. Puschnigg, “Supra-regional district heating networks: A missing infrastructure for a sustainable energy system,” *Energies*, vol. 14, no. 12, p. 3380, 2021.

[8] C. Schifflechner, C. Wieland, and H. Spliethoff, “Co2 plume geothermal (cpg) systems for combined heat and power production: An evaluation of various plant configurations,” *Journal of Thermal Science*, 2022, ISSN: 1003-2169. DOI: 10.1007/s11630-022-1694-6.

[9] M. Tagliaferri, P. Gładysz, P. Ungar, *et al.*, “Techno-economic assessment of the supercritical carbon dioxide enhanced geothermal systems,” *Sustainability*, vol. 14, no. 24, p. 16 580, 2022.

[10] Y. Shi, X. Song, G. Wang, *et al.*, “Study on wellbore fluid flow and heat transfer of a multilateral-well co2 enhanced geothermal system,” *Applied energy*, vol. 249, pp. 14–27, 2019.

[11] P. Ungar, L. Milli, G. Manfrida, D. Fiaschi, and L. Talluri, “Re-designing district heating networks through innovative co2 solutions,” in *Journal of Physics: Conference Series*, IOP Publishing, vol. 2385, 2022, p. 012 125.

[12] R. Suciu, L. Girardin, and F. Maréchal, “Energy integration of co2 networks and power to gas for emerging energy autonomous cities in europe,” *Energy*, vol. 157, pp. 830–842, 2018.

[13] J. Weber, H. Born, S. Pester, C. Schifflechner, and I. Moeck, “Geothermal energy use in germany, country update 2019-2021,” in *Proceedings of the European Geothermal Congress 2022*, 2022.

[14] J. Dormand and P. Prince, “A family of embedded runge-kutta formulae,” *Journal of Computational and Applied Mathematics*, vol. 6, no. 1, pp. 19–26, 1980, ISSN: 0377-0427. DOI: https://doi.org/10.1016/0771-050X(80)90013-3.

[15] P. Virtanen, R. Gommers, T. E. Oliphant, *et al.*, “SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python,” *Nature Methods*, vol. 17, pp. 261–272, 2020. DOI: 10.1038/s41592-019-0686-2.

[16] S. W. Churchill, “Friction-factor equatin spans over all fluid-flow regimes,” *Chemical Engineering*, vol. 84, pp. 91–92, 1977.

[17] E. Bilgen and H. Takahashi, “Exergy analysis and experimental study of heat pump systems,” *Exergy, An International Journal*, vol. 2, no. 4, pp. 259–265, 2002, ISSN: 1164-0235. DOI: https://doi.org/10.1016/S1164-0235(02)00083-3.

[18] I. N. Balderas-Sánchez, J. C. Jiménez-García, and W. Rivera, “Modeling of a double effect heat transformer operating with water/lithium bromide,” *Processes*, vol. 7, no. 6, 2019, ISSN: 2227-9717. DOI: 10.3390/pr7060371. [Online]. Available: https://www.mdpi.com/2227-9717/7/6/371.

[19] N. Weiland, B. Lance, and S. Pidaparti, “Sco2 power cycle component cost correlations from doe data spanning multiple scales and applications,” Jun. 2019. DOI: 10.1115/GT2019-90493.

[20] H. Pieper, T. Ommen, F. Buhler, B. L. Paaske, B. Elmegaard, and W. B. Markussen, “Allocation of investment costs for large-scale heat pumps supplying district heating,” *Energy Procedia*, vol. 147, pp. 358–367, 2018, International Scientific Conference “Environmental and Climate Technologies”, CONECT 2018, 16-18 May 2018, Riga, Latvia, ISSN: 1876-6102. DOI: https://doi.org/10.1016/j.egypro.2018.07.104. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1876610218302613.

[21] S. Smolen and M. Budnik-Rodz, “Technical and economic aspects of waste heat utilisation,” *Thermal Science*, vol. 11, no. 3, pp. 165–172, 2007, Cited by: 6; All Open Access, Gold Open Access, Green Open Access. DOI: 10.2298/TSCI0703165S.

[22] A. Arnitz, R. Rieberer, and V. Wilk, “Industrial heat pumps, second phase, iea heat pump technology (hpt) programme annex 48, task 4: Training materials for industrial heat pumps,” IEA Heat Pump Technology (HPT), 2019.

[23] Statista, *Strompreise für gewerbe- und industriekunden in deutschland in den jahren 2012 bis 2022*, 2022. [Online]. Available: https://de.statista.com/statistik/daten/studie/154902/umfrage/strompreise-fuer-industrie-und-gewerbe-seit-2006 (visited on 03/25/2023).

 https://doi.org/10.52202/069564-0233

[24] E. D. Mattson and G. Neupane, “Lcoh estimated from existing geothermal district heating systems in the us,” Idaho National Lab.(INL), Idaho Falls, ID (United States), Tech. Rep., 2017.

[25] M. Shamoushaki, D. Fiaschi, G. Manfrida, P. H. Niknam, and L. Talluri, “Feasibility study and economic analysis of geothermal well drilling,” *International Journal of Environmental Studies*, vol. 78, no. 6, pp. 1022–1036, 2021.