IMPROVING THE ACCURACY OF HEAT PUMP FEASIBILITY ASSESSMENT

by

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This research provides techno-economic assessment of three different heat pump systems within the transition in energy markets. The assessment is carried out using a generic Microsoft EXCEL tool, which is widely applicable for cases with different scale, heat sources and output temperatures. The tool includes profitability and performance calculation for selected refrigerant conditions and components. The main objective of the tool is to calculate COP accurately from enthalpies for given demand and temperatures instead of using Carnot's efficiency. In the tool, the price of the electricity is evaluated based on few different scenarios reflecting the development of electricity prices to comprehensively assess the long-term profitability of the selected three heat pump systems. The performance and flexibility of the ground source heat pump in the same building is evaluated using the tool within three different cases: ground source heat pump, ground source heat pump and thermal energy storage, and hybrid operation combining ground source heat pump and district heating. As a conclusion thermal energy storage along with ground source heat pump improves the flexibility of the system the most and reduce the dependency between electricity prices and system profitability. Thermal energy storage along with heat pump decreased the annual heating cost up to 28% compared to using solely heat pump.

Key words: *heat pump, COP, refrigerant*

Introduction

Reducing greenhouse gas emissions and achieving the climate goals is crucial in the fight against the climate change. The energy sector is a major contributor to these emissions in Europe and in order to achieve the carbon neutrality target, these emissions must be reduced. Various strategies and initiatives are being implemented to reduce energy sector emissions, including the transition to renewable energy sources, improving energy efficiency, and implementing carbon pricing policies. Electrification is seen as a potential solution in reducing the emissions of the heating sector, especially utilizing the heat pump technology. Heat pumps can help in reducing energy consumption, but the variability of renewable energy based electricity production such as wind and solar power and the recent increase in electricity price can represent uncertainties from the economic point of view. Especially in the cold climate, where the peak heat demand takes place at the same time when electricity prices are the highest. The variability of energy prices and the target of reducing energy consumption emphasizes the importance of efficient and flexible operation of the heat pump. At the same time, environmental friendliness must be ensured by the refrigerant selection.

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It has been investigated, that limiting factors for refrigerant selection are COP and volumetric heating capacity (VHC), of which COP is associated with the thermodynamic behavior of the refrigerant at different temperatures while VHC determines the size of the heat pump [1-3]. As stated, the refrigerant has an impact on the overall efficiency, but it also has an impact on the climate. The refrigerant is expected to have good thermodynamic performance, but today also the environmental aspect is as important as physical properties and safety [4]. Earlier common refrigerants were harmful to the ozone layer and were replaced with low ozone depletion potential (ODP) refrigerants, which still have high GWP. These high GWP refrigerants will soon be phased out and replaced with new environmentally friendly options [4, 5]. This paper reports the findings of a recent study [6] in which the techno-economic assessment of different heat pump systems was carried out by creating a generic tool which considered the properties of the refrigerant. The study focused on the low GWP refrigerants and the focus on the tool was calculating COP from enthalpies instead of the common practice of using Carnot’s efficiency. The tool was then demonstrated through three different heat pump systems.

Previous studies indicates that the most promising environmentally friendly refrigerants include natural refrigerants: water, R718, ammonia, R717, CO_2, R744, hydrocarbons, HC, propane, R290, butane, R600, isobutane, R600a, and pentane, R601, and synthetic hydrofluoroolefins, HFO, R1234ze(E), R1234ze(Z), R1234yf, and R1233zd [3-5, 7-9]. Also, the selection of the refrigerant for different heat pump systems have been studied before. Jiang *et al.* [4] studied compressor and refrigerant selection for efficient heat supply considering performance and heating capacity. Resulting four refrigerant categories defined by the optimal condensing temperature as the compressor type is determined by the system size. The final decision of the refrigerant from a certain category depends on the safety and the environmental requirements. Wu *et al.* [7] analyzed low GWP refrigerants and their optimal operation conditions basing on their thermophysical properties. Wang *et al.* [10] investigated the effect of the higher lift to the COP and heating capacity under various compressor frequency waterflow rate resulting that the optimal lift mainly depends on the heat sink temprerature. Yan *et al.* [2] estimated the performance of low GWP refrigerants in the conventional heat pumps. De Paula *et al.* [8] presented a mathematical model for the vapor compression system, which was used to estimate the performance of low GWP refrigerants. Yan *et al.* [3] proposed a model for predicting the performance of low GWP refrigerants in the high temperature heat pumps which gives the COP and VHC values from only critical point as a source data. Basing on recent studies about heat pump selection for different conditions heat pump component selection is implement in the used tool.

The objective of this study is to assess the feasible operation of a heat pump system within the transition in energy markets. The fluctuation of the energy prices increase the need for more flexible heat production and more accurate calculation of the heat pump performance in general. Generic Microsoft EXCEL tool created created and presented in a recent study [6] will serve a basis for this study. The tool provides levelized costs of generated heat within its lifetime and payback time that is calcuated by comparing the total lifecycle cost to an alternative heating solution. The performance of the heat pump is calculated for selected demand profile, operation temperatures, compressor and refrigerant. The long-term feasibility assessment is implemented by calculating the total cost for the first year which serves as a reference year. The costs of the following years are calculated based on a reference year and assuming a fixed annual development on an energy prices. Three different heat pump systems are reviewed, and the purpose is to examine the impact of uncertainties and increased flexibility on profitability.

Method and approach

This study evaluates three distinct heat pump system using a generic Microsoft EXCEL tool capable of accommodating various heat pump configurations, including those utilizing air, water, or the ground as a heat source. Furthermore, the tool allows for the input of demand and temperature data, either as a constant values or time series, making it applicable to individual houses as well as larger ensembles. The tool provides a comprehensive assessment of heat pump efficiency, incorporating calculations for both profitability and performance under specific operating conditions. As an enhancement to previous research, flexibility has been incorporated into the tool, allowing for the consideration of a heat storage facility or hybrid operation with a district heat (DH) connection. The tool consists of four main steps: setting parameters, refrigerant and compressor selection to suit with the selected conditions, COP calculation for selected heat pump system from enthalpies, and economic calculation and profitability assessment. These fundamental principles and the four-step process are illustrated in fig. 1. The tool is designed to be adaptable and can accommodate a wide range of heat pump systems, utilizing detailed information to facilitate the comparison of uncertainties across different scenarios. The more accurate listing of input options can be found in *Appendix*, tab. A1 and the tool outputs are listed in *Appendix*, tab. A2.

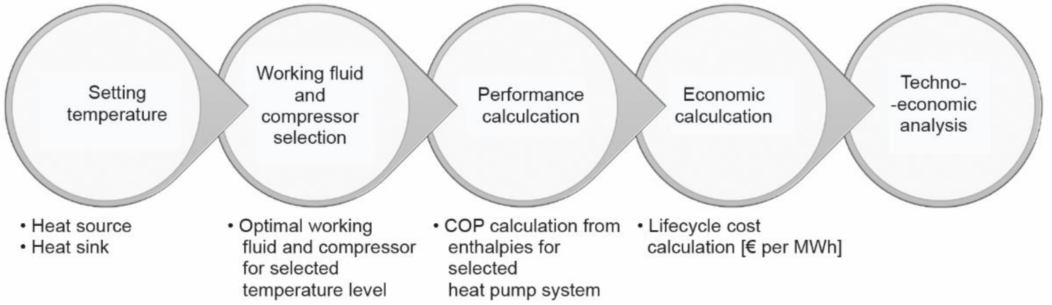

Figure 1. The basic working principle of the tool

The aim of the tool is to improve the accuracy of the performance calculation. Carnot's efficiency is convenient method to assess the performance of the heat pump but considers only the temperatures, not the properties of the refrigerant. The COP can be calculated from the enthalpy changes in the compressor and condenser. Specific enthalpy of the refrigerant at vapour and liquid phases is dependent on the temperature, thus the relation between pressure and enthalpy determines the efficiency and suitability of the refrigerant at different temperatures [5]. Generally, optimal output temperature for a refrigerant is determined by the shape of its temperature-pressure curve at saturation since the highest achievable temperature is limited by the corresponding pressure. Thus the condensing temperature also depends on the characteritics of the heat exchanger, which are not considered in this study. However, the condensing temperature is assumed to be 5 °C higher than the heat sink temperature [4, 7, 11].

The COP value is calculated from specific enthalpy values of the refrigerant, that the tool finds from the inserted tables which contains the refrigerant specific enthalpy, entropy, pressure and density at different temperatures at the saturated liquid and vapor stages up to the critical point. Evaporating and condensing processes are assumed to occur at constant pressure enabling the Microsoft EXCEL tool finding corresponding enthalpy values to the temperature levels utilizing MATCH and OFFSET functions. Compressing process occurs at superheated regions, and the enthalpy change is calculated by the First law of thermodynamics and then considering the isentropic efficiency. The compressing process is not fully isentropic meaning there is some heat transferred causing a change in enthalpy, while in the isentropic process, the enthalpy change is only caused by the work done to the system and thus the isentropic efficiency of the compressor is considered. With all specific enthalpy values are known at different states of the heat pump cycle, the COP is calculated by dividing the enthalpy change in the condenser with the enthalpy change at the compressor.

Economic feasibility calculation is implemented by assessing the investment costs and calculating the operational cost for the first year and are then discounted over 25 years. The investment cost is determined by the type and size of the heat pump. The share of the possible loan can be determined, as well as the annual interest rate. The operational cost of the first year are calculated based on the calculated performance and price of the electricity. As an output the tool gives the levelized cost of heat (LCOH) and payback time compared to alternative heating solution.

The selection of the refrigerants available in the tool is based on a literature review. According to recent studies, the most potential low GWP refrigerants for low temperature and small capacity heat pumps for substituting R134a are R290, R1234yf, R1234ze and R744 [7, 8, 12-14]. Wu *et al.* [7] investigated that these refrigerants perform best with condensing temperature below 80 °C, which can also be observed from the properties of these refrigerants. Several research indicates that correspondingly refrigerants with higher critical temperature and relatively low specific volume are more suitable for larger and high temperature applications. Especially R717, R718, R601, R600a and R1233zd have shown good performance at high condensing temperatures [1-3, 7, 15-17].

A few assumptions of the operation of the heat pumps have been made to simplify the calculations which may distort the results. All losses and leakages are neglected, and the evaporating, and condensing processes are assumed isobaric. Any other components than compressors are not considered, and the performance of the heat exchangers are assumed constant. Isentropic efficiency of the compression process is assumed for every compressor type. However, it is assumed remain constant while it decreases as the pressure ratio increases.

Case study

The objective of the study is to assess the techno-economic feasibility of implementing a heat pump system within the context of the ongoing energy transition across three different cases of heat pump systems. For this assessment a ground source heat pump (GSHP) in an apartment building got selected which serves as a Case 0. In Case 1 there is the same GSHP with a thermal energy storage (GSHP + TES) and in Case 2 GSHP combined with DH (GSHP + DH).

This research is a continuation of previous work where a GSHP in an apartment building was one of the three cases examined [6]. Additionally, statistics from Statistics Finland indicate a growing prevalence of GSHP in apartment buildings in recent years [18]. Growing popularity in apartment buildings may be due to its capability to generate heat all year round without a significant decrease in its efficiency. The GSHP is not as strongly dependent on the outdoor temperature as air source heat pumps and thus provide better performance and ensures sufficient heat production even during colder periods.

The demand data utilized in these cases aligns with the data from the previous study [6]. To account for uncertainties in future energy markets, a long-term profitability analysis is performed, starting from various years with differing weather conditions and energy prices.

The tool incorporates hourly temperature data and electricity prices for four different years along with seasonal DH prices in Helsinki. The selected years and 2019, 2020, 2021, and 2022, of which 2020 was the warmest and most windy, 2021 coldest and 2022 least windy. The average energy prices of these years are listed in tab. 1. Each of these representative years serves as the starting point, followed by an assumed fixed annual increase in energy price for future years. The feasibility assessment is conducted by comparing these costs with the total cumulative cost of DH for the same building. The DH was chosen as a benchmark, due to its prevalence as the most common heating source in Finnish apartment building according to statistic Finland [18].

Table 1. Average yearly prices of electricity and DH

	2019	2020	2021	2022
Electricity [€ per MWh]	44.04	28.00	72.34	154.03
DH [€ per MWh]	44.62	41.69	49.87	61.16

Case 0: an apartment building with a GSHP

In all the cases the same hourly heat demand profile of an apartment building with an annual heat consumption of 520 MWh and peak load of 200 kW is used. The building represents a typical residential building in Finland constructed in the 1960's. There are 48 apartments in the building and heat is supplied with radiators with design temperature of 40/70 °C. The required supply temperature for space heating is calculated hourly based on outdoor temperature. The COP for space and domestic hot water heating are calculated separately since the required temperature for space heating varies depending on the outdoor temperature while DHW temperature is required to stay constantly above 55 °C. Condensing temperature for DHW is decided to keep constant at 63 °C. The heat source temperature is set constant at 5 °C according to a recent GSHP case study in Espoo, Finland which indicates that the temperature of entering fluid to a heat pump evaporator vary between 3 °C and 9 °C [19].

The selection of the heat pump for this specific building is carried out using a methodology similar to a previous study. In both cases three identical of GSHP units are employed, each equipped with piston compressors. The piston compressors in this case are equipped with an economizer, which enables wider operation temperature envelope. The heat pumps parameters refer to Gebwell Taurus Inverter Pro GSHP which is suitable for heating large properties. Each has a capacity up to 100 kW and has reference COP values of 4.2 (0/35 °C) and 2.7 (0/55 °C) presented for a refrigerant R513A, which is a mixture of refrigerants R134A and R1234yf. According to a recent study refrigerants R134A, R1234yf, and R513A can be used under similar conditions without any changes in the system [20]. Therefore refrigerant R1234yf got selected for this case. The heat pump parameters remain consistent in all cases and the selected parameters for this building with the GSHP are listed in *Appendix*, tab. A3.

To provide a comprehensive assessment, the heating costs of the apartment building when supplied with DH are also considered. Consequently, it becomes more meaningful to evaluate the flexibility introduced by the heat pump and heat storage.

Case 1: Residential building with GSHP vs. residential building with GSHP and TES

In the first case GSHP in a residential building is compared with a system equipped with a TES. The TES is designed to store heat over short term and mitigate the impact of energy price fluctuation on a daily basis. Within the tool the charging and discharging of TES is determined based on the electricity price of the current hour relative to the daily average. The size of the storage can be selected, and it should ideally cover approximately half a day's energy demand. In this case the capacity of the storage is set at 1200 kWh, which appears sufficient to meet the daily charge and discharge requirements. The investment and maintenance cost of the heat storage are estimated based on recent review and investment cost is assumed as 2 € per kWh and annual operational cost is assumed to be 2% of the investment cost [21].

Case 2: Residential building with GSHP as a hybrid solution with DH

In the second case the same residential GSHP is compared with a hybrid solution *i.e.* a heat pump with a DH connection. In this case DH connection provide flexibility to variable electricity prices. The DH is typically seasonally priced and is not varying hourly like electricity. Now the tool selects hourly whether it is more feasible to run the pump or provide heating with DH and based on it, calculates hourly cost. Therefore, the entire demand will be met either by DH or by heat pump according to their costs. In this case the flexibility is achieved by utilizing fixed pricing for DH, however, the fixed fees of the district heat connection must be paid. The district heat energy fees correspond seasonal prices of the energy company Helen for the selected reference year.

Results

In Case 0 a comprehensive evaluation of the long-term feasibility the GSHP in the apartment building is conducted. The asses include an efficiency calculation for the heat pump and comparison its profitability to the most typical heating system in such building in Finland. The COP values are calculated separately for space and DHW heating and the range for monthly variation in COP for space heating is presented in fig. 2. Performance is calculated for all the reference years considering that the COP depends on the outdoor temperature which can differ from year to year. The calculated COP values for space heating range from 2.8 to 5.1, which seems reasonable for radiator heating system. Monthly minimum, maximum and average COP values are presented in tab. 2. Highest COP values are achieved in 2020 when the average outdoor temperature was also highest. The COP variations also seem to fit into the scope for given COP values for the heat pump.

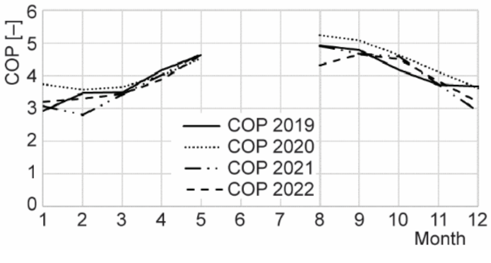

Figure 2. Variation of the monthly average COP

Table 3 provides a summary of the levelized cost of heat for the GSHP, electric heating and DH calculated with all four years as a reference year. These calculations form a basis for two additional cases. The total cost is broken down in fig. 3, where the impact of the higher price of the electricity is illustrates.

Table 2. Performance results for every reference year

	Minimal COP	Maximal COP	Average COP	Seasonal COP
2019	1.7	5.2	3.9	3.2
2020	2.3	5.2	4.1	3.4
2021	1.7	5,2	3.8	3.0
2022	1.8	5.2	3.8	3.2

Table 3. Economic feasibility of DH and GSHP

LCOH [€ per MWh]	DH	Heat pump
2019	71.56	44.28
2020	67.17	38.30
2021	76.66	56.14
2022	94.39	72.65

In Case 1, a TES is incorporated into the system to enhance flexibility and to offset the high prices during the hours of peak electricity demand hours. The feasibility assessment is implemented across all reference years and findings are summarized in tab. 4. Figure 4 provides the detailed breakdown of the overall costs. Notably, total savings remain consistent across all the reference years, but year 2022 stands out due its extremely high electricity prices.

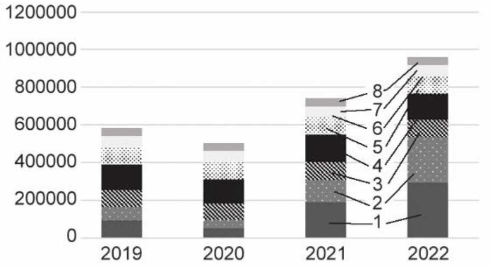

Figure 3. Comparison of cumulative cost distribution of Case 0 (GSHP) *1 – space, 2 – DHW, 3 – taxes, 4 – transmission, 5 – fixed, 6 – investment, 7 – loan, and 8 - maintenance*

Case 2 is hybrid operation incorporating both a heat pump and DH depending on cost-effectiveness. Figure 5 provides a visual representation of the annual usage of the heat pump and DH for each reference year. As there is a district heat connection, a smaller heat pump with lower investment cost seemed to be more feasible option. The maximum capacity of the heat pump is limited to 120 kW and the peak demand is supplied with DH. Notably, in years 2021 and 2022, higher electricity prices resulted in an increased utilization rate of the DH connection. Since the costs and performance assessments are conducted only for the first year, the pricing of that specific year exerts a significant influence on outcomes. The distribution of usage between the heat pump and DH is determined only by the prices of the first year, without considering operational cost in subsequent years. Findings of the Case 2 are summarized in tab. 5. Total costs are broken down in fig. 6 where it is notable that the fixed cost is high due to the fixed fees of district heat connection.

All the results from the three cases using the four reference years are summarized in tab. 6. In the case of GSHP + DH, the payback time appears to be a bit longer compared to

Table 4. Economic feasibility of GSHP + TES

	2019	2020	2021	2022
LCOH [€ per MWh]	40.5	34.1	47.0	56.2
Payback time	6	5	6	5
Savings [€ per MWh]	31.08	33.1	29.6	38.2

Table 5. Economic feasibility of ground source heat pump and DH hybrid (GSHP + DH)

	2019	2020	2021	2022
LCOH [€ per MWh]	48.3	42.3	56.1	66.9
Payback time	6	6	7	5
Savings [€ per MWh]	23.3	24.8	20.6	25.2

GSHP + TES. A comprehensive view of the total generated savings across these three cases, considering impact of baseline values on their respective profitability is repsented in *Appendix*, fig. A1. Examining tab. 6, it becomes evident that the years 2019 and 2020, featured the lowest electricity prices, have the least divergence in results among the cases. Conversely, in years with higher electricity prices, Case 1 emerges as the significantly more economically viable option than the others. Adding TES alongside with heat pump, the annual heating cost decrease by 28% with the 2022 electricity prices and 18% with 2020 prices.

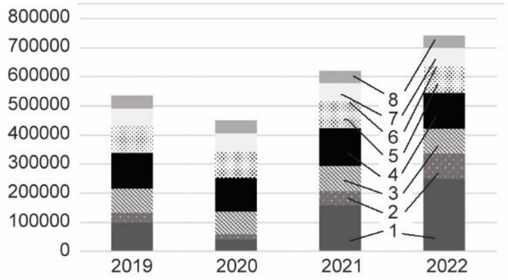

Figure 4. Comparison of cumulative cost of the Case 1 (GSHP + TES); *1 – space, 2 – DHW, 3 – taxes, 4 – transmission, 5 – fixed, 6 – investment, 7 – loan, and 8 – maintenance*

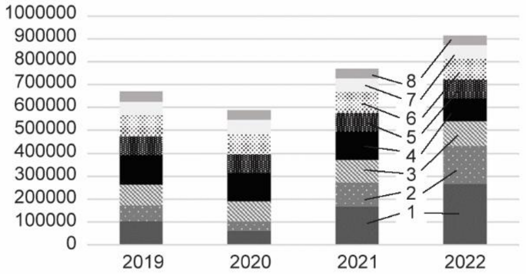

Figure 5. Distribution of cumulative costs of the Case 2 (GSHP +DH); *1 – space, 2 – DHW, 3 – taxes, 4 – transmission, 5 – fixed, 6 – investment, 7 – loan, and 8 - maintenance*

Given the energy prices in 2020 and 2021, it appears more economically viable to rely solely on the heat pump instead of hybrid solution. This observation is supported by the usage rates as depicted in fig. 5, which show a minimal utilization of the district heat connection in 2020. Correspondingly there is higher utilization rate in 2021, however the fixed fees of district heat connection are relatively high compared to the total cumulative cost as fig. 6 indicates.

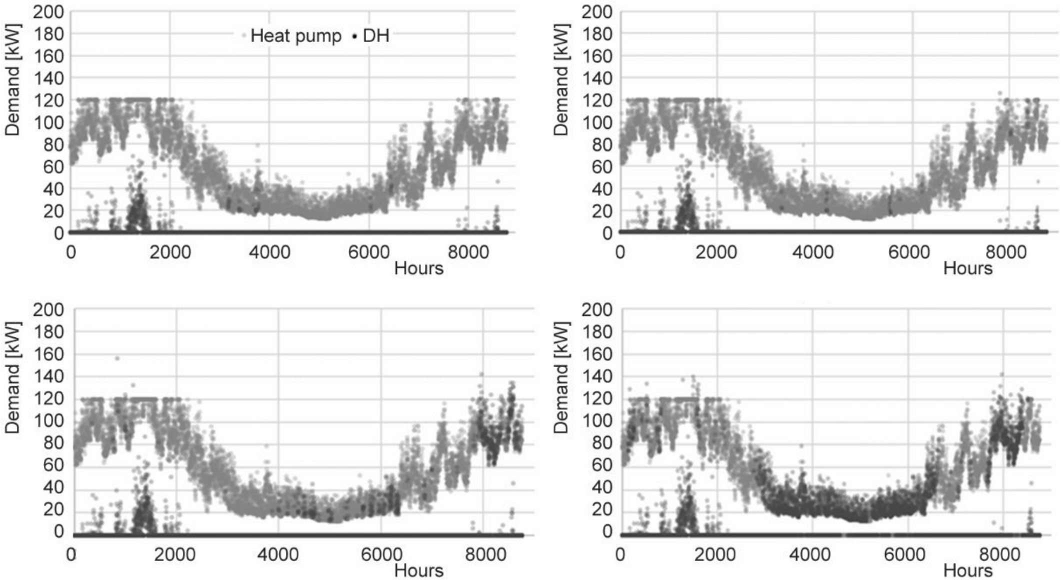

Figure 6. The annual usage of the GSHP and DH

Table 6. Results of all cases

LCOH [€ per MWh]	DH	GSHP	GSHP + TES	GSHP + DH
2019	71.65	44.28 (6)	40.78 (6)	43.00 (5)
2020	67.17	38.29 (6)	34.37 (5)	42.60 (6)
2021	76.66	56.14 (8)	47.33 (6)	58.35 (8)
2022	94.39	72.64 (8)	56.43 (5)	69.53 (6)

Discussion

Unsurprisingly, electricity price seems to be the factor which has the largest impact on the long-term feasibility. As the price of the electricity is the biggest uncertainty, the flexibility of heat pump system becomes relevant. Overall, the Case 1, GSHP with a TES, generates the most savings despite the energy prices of the first year. Especially with high energy prices of the years 2021 and 2022 the profitability stands out. Notably, in case GSHP, the payback time exhibits slight variations, highlighting how the fluctuations in electricity prices can influence overall profitability and underscore the importance of flexibility when using a heat pump. In contrast, the payback time of the case GSHP + TES does not vary across the reference years. With higher electricity prices, the advantages of thermal storage become more pronounced, but even in scenarios with stable prices it remains economically viable choice. Consequently, it can be concluded that improving the flexibility substantial reduction in electricity demand can be achieved and heat pumps can maintain the position as a profitable environmental friendly heating solution.

In the cases with TES and hybrid operation, the assessment is limited to the conditions of the reference year and does not account for potential future increases in energy prices. These cases assume that the utilization rate of TES and the DH connection will remain constant, irrespective of any changes in future profitability. More accurate results would be obtained if the future price of electricity for development assumed the profile instead of a fixed annual price increase. However, it is important to note that it is not expected that the price of electricity will increase in the future from the levels observed in 2021 and 2022. Nevertheless, for the purposes of this study the conditions are assumed same in every case because the main objective was to review long term feasibility of a heat pump system within the transition in energy markets, but it is important to emphasize that assessing overall feasibility should not solely rely on a single year's pricing data.

To analyze the effect of the assumed fixed electricity price, additional test was conducted where there was no annual development and a slight decrease in electricity price. The results for cumulative cost with different fixed annual development in the electricity price are presented in fig. 7. The results highlight that, once more, during the years of lower electricity prices in 2019 and 2020, the differences between the cases are relatively small. Moreover, even as electricity prices rise, GSHP + TES consistently delivers the most favorable outcome. On the other hand, GSHP + DH appears to be more sensitive to energy price fluctuations, yet it remains a viable option.

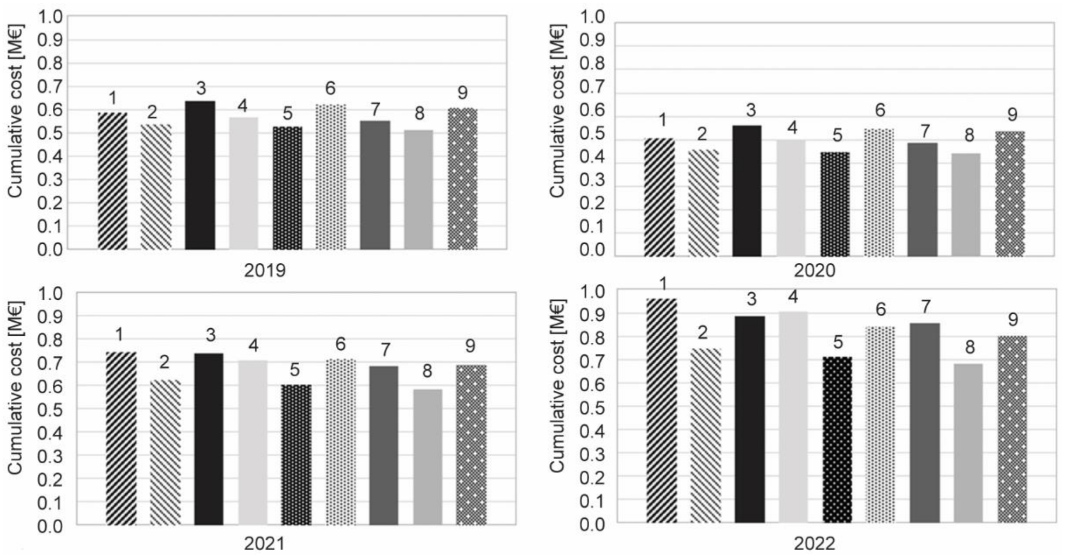

Figure 7. Cumulative cost variation with different scenarios for annual electricity price development; *1 – GSHP, 1% increase, 2 – GSHP + TES, 1% increase, 3 – GHP + DH, 1% increase, 3 – GSHP, 0% increase, 4 – GSHP + TES, 0% increase, 5 – GHP + DH, 0% increase, 6 – GSHP, 1% decrease, 7 – GSHP + TES, 1% decrease, and 8 – GHP + DH, 1% decrease*

Renaldi *et al.* [22] studied TES alongside with residential heat pump in the UK to shift the heat demand to off peak hours to generate savings. The study was carried out by linear model of heat pump with a TES which used annual heat demand, temperature and occupancy profiles as a initial informations. As a result it was found out that a heat pump is not a competive solution compared to gas boiler even with a TES, even tough TES indicated significant savings compared to using heat pump alone [22]. Arteconi *et al.* [23] investigated the role of heat pump and TES on domestic demand side management resulting that the feasibility of demand side management strongly depends on electricity tariff stricture and optimal heat supply temperatures. These studies were completed before the electricity market had changes and did not consider the future of electricity prices. However the finnish energy markets seems to be more favorable to generate revenue from varying electricity prices. Further as a competing heating source there is a DH in Finland, so the results are not entirely comparable.

Conclusions

This study analyzes the long-term feasibility of heat pump systems focusing on uncertainties in the energy markets, also considering the physical properties of the refrigerants in order to calculate the COP of the heat pumps accurately. Three different GSHP solutions are assessed through general Microsoft EXCEL tool created for a recent study. The tool was further developed to include a possibility of using a heat storage or DH together with a heat pump. The volatile nature of the electricity market is one of the biggest uncertainties when assessing the profitability of the heat pumps, which was considered by using the electricity price data from past four years as a starting point. By using various reference years with radically different electricity prices, the benefits of increased flexibility are better reflected. However, assuming fixed annual development in electricity prices distorts the results presuming a consistent need for TES and hybrid operation each year.

Comparing the result of the study to other similars, it becomes evident that the electricity market and hourly pricing is a key to generate revenue by shifting electrical loads from high peak to off peak periods. According to results, the TES brings the desired flexibility to GSHP, which is much more sensitive alone to fluctuations of the electricity prices. Even though, the economic feasibility does not give as clear benefits for the case with GSHP + DH in research, the results are strongly depended on the DH prices compared to electricity prices and high fixed cost leads to higher payback time compared to case without district heat connection. In contrast, the inclusion of TES along with the GSHP leads to consistent payback times across the reference years, making it robust choice even in scenarios with stable electricity prices. Further operation of the GSHP + HP system has more benefits when the electricity prices are high for a longer period enabling taking advantage of seasonally priced DH, while TES is more feasible solution to shift consumption within a shorter time frame.

In conclusion, this study provides insights into the long-term feasibility of heat pump systems within evolving energy markets. It emphasizes the significance of electricity prices, the benefits of TES, and the sensitivity of hybrid operation to DH costs. While assumed fixed conditions impose limitations, the tool is versatile, suitable for applications of various sizes, and can be readily adapted to incorporate uncertainties making this study a strong foundation for further analysis where accurate performance evaluation is crucial.

Acronyms

DH – district heat
GSHP – ground source heat pump
LCOH – levelized cost of heat
ODP – ozone depletion potential
TES – thermal energy storage
VHC – volumetric heating capacity

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Appendix

Table A1. Input options in the tool related to heat pump compressor and costs

Heat pump	Heat source	Ground/water/air/Constant/time series
	Heat sink	Water/air/Constant/time series
	Working fluid	R290/R600a/R601/R1234ze/zR1234yf/R717/R718/R1233zd
	Heat distribution	Radiator/floor heating
Compressor	Compressor	Scroll/piston/screw/centrifugal
	Compressor type	Inverter/double stage
	Economiser Super heating Sub cooling	yes/no [°C] [°C]
Investment and costs	Investment cost	[€ per kW]
	Maintenance	1%
	New compressor	[€]
	Share of loan	[%]
	Interest rate	[%]
	Discount	[%]
	DH index	[%]
	Electricity index	[%]

Table A2. Outputs from the tool for heat pump performance and economic feasibility

Performance	COP	Economic	LCOH [€ per MWh]
	SCOP		Payback time [years]
	VHC		Savings [€ per MWh]

Table A3. Parameters used in the tool

Heat pump	Heat source	Ground/constant 5 °C
	Heat sink	Water/time series
	Capacity	3 × 90 kW
	Refrigerant	R1234yf
	Heating system	Radiator/design 70/40 °C
	Compressor	Piston
Compressor	Displacement [m^3h^{-1}]	45
	Compressor type	Inverter
	Economiser	Yes
	Isentropic efficiency Super heating Sub cooling	0.8 5 10
Investment and costs	Investment cost [€ per kW]	750
	Maintenance [€ per year]	1150 (1% of investment)
	New compressor	1500
	Share of loan [%]	40
	Interest rate [%]	2
	Discount [%]	2
	DH index [%]	2
	Electricity index [%]	1

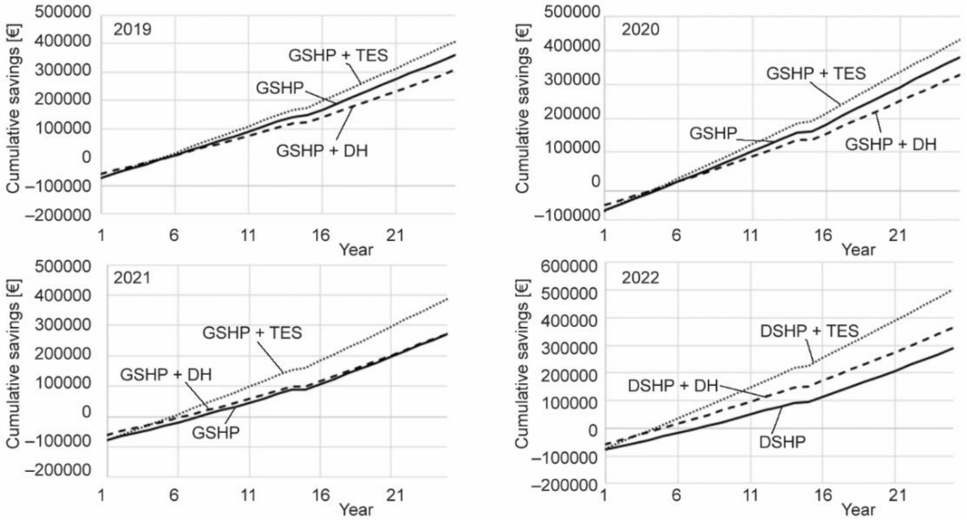

Figure A1. Comparison of total cumulative savings of the cases between different years; *1 – GSHP, 2 – GSHP + TES, and 3 – GSHP + DH*

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