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# Allocation of investment costs for large-scale heat pumps supplying district heating

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**Abstract**

Large-scale heat pumps (HPs) are proposed as a technology to efficiently utilize intermittent wind power and other renewable sources. More than 25 large-scale HPs have been installed over the past decade to supply district heating (DH) in Denmark. A continuous increase is expected in the coming years. The HP projects differ in size, configuration, components and heat source. All these have an impact on the investment costs, which poses challenges for estimating costs, e.g. when planning new HP projects. For this paper, the investment costs of existing and planned electrically driven large-scale HPs were analyzed. All analyzed HPs use natural refrigerants and supply DH in Denmark. The total investment costs were divided into different categories to identify cost correlations for each of them depending on the heat source and HP capacity. The developed cost correlations were combined and verified by comparing the resulting correlations with the total investment costs of the considered HPs. Different intervals of the specific total investment costs for HPs depending on the heat source and HP capacity were derived. They identified the most and least expensive heat sources for HP capacities between 0.5 MW and 10 MW. It was shown that a considerable amount (~50 %) of the investment costs was placed on other parts than the HP itself.



*Keywords:* district heating; energy planning; heat sources; investment costs; large-scale heat pumps

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## 1. Introduction

The Paris Agreement states that the global temperature rise shall be kept below 2 °C above pre-industrial levels by 2100 to reduce climate change caused by greenhouse gas emissions [1]. For achieving this goal, 195 members have signed the agreement and 175 parties have ratified it by April 2018 [2]. In the EU, heating and cooling is responsible for half of the final energy consumption, from which 75 % was produced by fossil fuels in 2012 [3]. Even though district heating (DH) accounts for only 12 % of the heat supplied to EU citizens, the proportion varies greatly by country. Especially countries from the northern region have a high share of DH. The proportion of DH in Denmark, Sweden, Finland, Poland and the Baltic States was above 50 % in 2013 [4].

Several reports conclude that DH, especially based on combined heat and power (CHP) plants, is an efficient way to supply heat and to use resources, e.g. [3, 5, 6]. Many studies have further shown that DH is an essential technology to reach the EU's goal of decarbonizing the energy supply. This may be reached by expanding the share of the DH heat supply, improving the current DH networks, converting DH to the $4^{th}$ generation of low-temperature DH and/or by exploiting synergies between thermal networks and electrical grids [7–11]. Methods of evaluating the current state of a DH network and determining the main improvement potentials are presented in Volkova et al. [12, 13]. Exploiting synergies between networks is explained by Lund et al. [10] and Connolly et al. [11] in order to efficiently integrate a high share of renewable energy sources in energy systems. One of these synergies is to use electricity for heating. This would allow using intermittent renewable power, such as generated from wind and photovoltaics, to produce heat. As DH in many cases includes significant storage capacity, this integrated operation may be cheaper and more efficient than electrical storages. In addition, CHP plants could be operated more flexibly and furthermore balancing power and electrical grid services could be offered [10, 11, 14]. One of the technologies that may connect the power and heating sector are large-scale heat pumps (HPs).

David et al. [15] analyzed existing large-scale HPs supplying DH in Europe. They identified 149 existing large-scale HPs with a thermal capacity above 1 MW in 2017. The HPs were analyzed in terms of size, year of construction, heat source, supply temperature, refrigerant, operating mode and coefficient of performance (COP). Many of the HPs were built until the year 2000 with an accumulated thermal capacity of 77 %. Afterwards, large-scale HPs were built in Denmark, Finland, France, Norway, Italy, Switzerland and Sweden. Many of the newly built HPs used R134a as refrigerant, which has a comparable high global warming potential (GWP) [16]. Natural refrigerants, such as Ammonia and $CO_2$, with very low GWP and no ozone depletion potential (ODP) were used for ten large-scale HPs built in Denmark, five in Switzerland, two in Norway and one in Sweden.

Considering HPs above a thermal capacity of 0.2 MW, Denmark has built more than 25 HPs using natural refrigerants over the past decade to supply DH in Denmark. This resulted in an accumulated thermal capacity of over 50 MW in 2017 [17]. A continuous increase in the installed capacity is expected in the coming years. In the context of smart energy systems and reducing greenhouse gas emissions, Denmark may be seen as a frontrunner with regards to the implementation of large-scale HPs with natural refrigerants. A great benefit is expected if the existing knowledge and conclusions can be summarized and be transferred to relevant partners inside Denmark and abroad. The HP projects differ in size, configuration, components, heat source and performance [15, 18]. All these have an impact on the investment costs, which makes it difficult for the DH industry to estimate expected costs and to plan new HP projects. In [19], it was shown for three examples that the investment costs contribute with around 30 % to the heat production costs of large-scale HPs under Danish conditions. The remaining costs result from the electricity price (20 %), tariffs (17 %), taxes (27 %) as well as operation and maintenance (6 %). Ommen et al. [20] stated similar contributions of investment costs (20 % to 37 %), electricity costs (21 % to 27 %) as well as for tariffs and taxes (41 % to 53 %) for eight different HP types used for DH. This shows that the investment costs contribute with 1/3 to the production costs of heat, which makes a good estimate of these costs important.

Cost correlations for HPs up to 0.2 MW thermal capacity were published by Wolf et al. [21] for ground-source, water-source and air-source HPs. The results were based on 254 HPs from eight different manufacturers. These correlations, however, are only valid for the HP unit itself. Grosse et al. [22] provided a correlation for large-scale HPs based on reference project information and manufacturer estimative offers. However, also this correlation is for the HP only. The Danish Energy Agency suggested in 2014 specific total investment costs for large-scale HP projects of 0.5 million €/MW to 0.8 million €/MW [23]. An updated version of this report was released by the end of 2017 and suggests costs of 0.8 million €/MW to 1.1 million €/MW [19]. Usually, a decrease in costs is expected, but the opposite was the case. In addition, the range has become quite large, which could result in very high unexpected costs. This motivated an investigation of analyzing large-scale HP projects connected to DH networks in Denmark in more detail to provide a better estimate on the investment costs and how these may vary depending on the capacity, heat source or others. The purpose of this investigation was to gain a better understanding of the economics of large-scale HPs, to use the results for energy system models and to provide this information to DH companies. This may help to increase the penetration of large-scale HPs on the market, which would result in a more efficient use and integration of renewable energy sources in smart energy systems.

## 2. Method

For this paper, the investment costs of large-scale HP projects were analyzed. The total investment costs were divided into different categories to identify cost correlations for each of them, depending on the heat source and HP capacity. The developed cost correlations from each category were combined and verified by comparing the resulting correlations with the known total investment costs of existing HPs and results from literature.

### *2.1. Selection criteria*

The criteria for selecting HPs were that they are vapor compression machines, are connected to DH, use a natural refrigerant, have a thermal capacity above 0.2 MW and were built or are planned to be built in Denmark. These criteria were chosen to align with environmental obligations [1] and power-to-heat solutions for an efficient integration of energy systems [10, 11]. Denmark was chosen as the only country, because many HPs using natural refrigerants have been installed and data was available. The installation costs for other countries may vary, which could impact and distort the developed cost correlations. Furthermore, other countries may have different incentive/subsidy-chemes, which may change the economic feasibility and complexity ratio. The mix of data with different boundary conditions was not desired.

### *2.2. Data acquisition*

Information about investment costs were collected for 26 built HP projects and three planned projects mainly from [18, 24], personal communication with a consultant firm [25] and direct communication with DH companies that have large-scale HPs installed. Additional information about twelve offers for HP units using industrial excess heat as heat source was provided by Buhler et al. [26]. The considered investment costs included both purchase and installation of equipment and consulting services. Besides investment costs, information was gathered about:

- Type of heat source;
- Installed thermal capacity;
- Inlet and outlet temperatures of heat source and heat sink;
- Inlet and outlet temperatures of COP and refrigerant.

### *2.3. Cost fraction categories*

Data about the investment costs of large-scale HP projects were collected for the categories as stated in Table 1.

Table 1. Collection of investment costs for the following cost fraction categories.

| Total | HP | Heat source | Construction (buildings, connections and piping inside the building) | Electricity (electrical installations; connection to electrical grid, control system, transformers) | Consulting | Others |
|---|---|---|---|---|---|---|

All electricity-related investment costs were summarized as one group, because it was not always clearly distinguished between the individual costs for the different HP projects. Some of these costs are fixed, while others depend on the installed capacity. In Denmark, two types of connections to the electrical grid are usually used to connect large-scale HPs. One costs between 80,000 € and 110,000 €, which gives the operator of the grid the freedom to shut down the HP for frequency control. The second option is more expensive and does not give the grid operator such possibility. The costs for the control system may also vary, which may be lower if a control system was already in place for other production plants [27]. Some projects included costs that were excluded for the analysis (others), because they were considered not to be part of a regular investment of a HP project. These were additional equipment costs, e.g. for a storage tank or a heat exchanger for direct heat exchange. Other excluded costs were related to the DH side such as DH transmission pipes, pumps and connections, which were assumed to be established before the investment of the HP or known by the DH company.

### *2.4. Development of cost correlations*

The investment costs of the different HP projects were analyzed in *Matlab* [28], to create linear relations between costs and thermal capacity of the HP. The choice of linear relationship was made to ease implementation of the correlations for later use, such as the case of linear optimization of energy plant investments. Cost correlations were developed for each cost fraction category as well as for the total investment costs. In addition, the coefficient of determination ($R^2$) and the confidence intervals with one standard deviation of the mean (68 %) were calculated. If data of sufficient quantity and quality were available, a heat source based correlation was created for the individual groups. Data was not available from all HP projects for all cost fraction categories. Therefore, only HP projects with known costs were considered for the individual categories. In addition, some outliers were excluded in some of the categories, because of very project-specific costs, which is explained in more detail below. A range of offers for only the HP unit, using industrial excess heat as heat source, were available [26]. For these it was assumed that the heat source investment costs were 16 % of the total investment costs, as it was found by Grosse et al. [22]. The heat source costs could then be determined by the HP offers and the developed cost correlations for the other cost fraction categories.

### *2.5. Estimation of investment costs for different heat sources*

The developed cost correlations of all categories were combined to estimate the total investment costs of the HP projects for different heat sources. This was done for the following heat sources: flue gas, industrial excess heat, groundwater, sewage water, air.

The resulting cost correlations of the total investment costs were then compared to the known total investment costs of HP projects. Specific cost intervals for HP projects depending on the heat source and capacity were derived. The developed cost correlation of each cost fraction category was further used to estimate the unknown costs of a HP project. This allowed an estimation of the total investment cost if only one or few of the cost fractions were known, such as the investment costs of the HP only, or when one of the cost fractions was missing. Estimating all unknown cost fractions allowed to compare the total investment costs for HPs using different heat sources for all HP projects of the investigated heat sources.

### *2.6. Breakdown of total investment costs*

The mean value of the costs of each category was determined based on all HP projects for the five mentioned heat sources. Thereby, the contribution of each cost fraction to the total investment costs were identified, which allowed to breakdown the total investment costs by each category for the different heat sources.

## 3. Results

Based on the gathered data, it was observed that large-scale HPs in Denmark have been built within the last decade from 2009 on. The HP capacities varied between 0.3 MW and 10 MW. Seven different heat sources were identified: flue gas, industrial excess heat, groundwater, sewage water, air, solar and district cooling.

The majority of the 41 heat pumps was found to utilize ammonia as the refrigerant. Few exceptions exist, where either $CO_2$ or a mixture of ammonia and water were used. The COP varied between 3.1 and 5.3 with one exception of 6.3. The mean COP of all HP projects was 4.4. The heat sink outlet temperature of the HPs varied between 60 °C and 90 °C, except for HPs using flue gas as heat source, where the heat sink outlet temperature varied between 42 °C and 52 °C. The results of the analysis are presented in separate sub-sections together with the developed cost correlations and breakdown of the total investment costs. The list of HPs may be found in the supplementary material.

### *3.1. Heat pump investment costs*

The HP investment costs for the investigated HP projects for different thermal capacity can be found in Fig. 1. The number of each data point corresponds to one HP project. If a number is not shown, no costs for this category were available. Also shown are:

- The developed cost correlations for HP projects for any heat source except flue gas and HP offers, entitled “all\gas, offer”;
- For flue gas only entitled “gas”, the corresponding $R^2$-values, the confidence interval and excluded data points.

The number in parenthesis behind the $R^2$-value gives the number of considered data points for the correlation. In addition, a cost correlation, $f_{ref}$, from Grosse et al. [22] was included, which was based on reference project information and manufacturer estimative offers. As shown, the variation of HP investment costs is large, but can be estimated by a linear correlation depending on the thermal capacity of the HP. The $R^2$-value for the correlation is quite high and based on twelve HP projects of different thermal capacity. An additional correlation was created for HPs based on flue gas, because their application differs. Specifically, the flue gas temperature after heat recovery is at 40 °C, approx. 20 °C to 30 °C higher than for the other heat sources. Furthermore, the HPs are located before the boiler with heat sink temperatures at around 50 °C, which is lower than the typical DH supply temperatures. Consequently, the temperature lift, the HP has to overcome, is much smaller resulting in the installation of single one-stage HPs that are simpler and cheaper than HPs based on other heat sources [18]. The points 2 and 3 (on top of each other) were excluded, because these HPs can be operated electrically or by a gas motor. The gas motor, the gear box and their integration result in additional costs, which make these HPs more expensive than the others. The points 4 and 5 were excluded, because these HPs are used to supply both DH and district cooling. It is expected that these HPs are more expensive, which may be due to the very low heat source temperature, which is cooled from –1 °C to –8 °C [18] and the resulting large temperature lift.

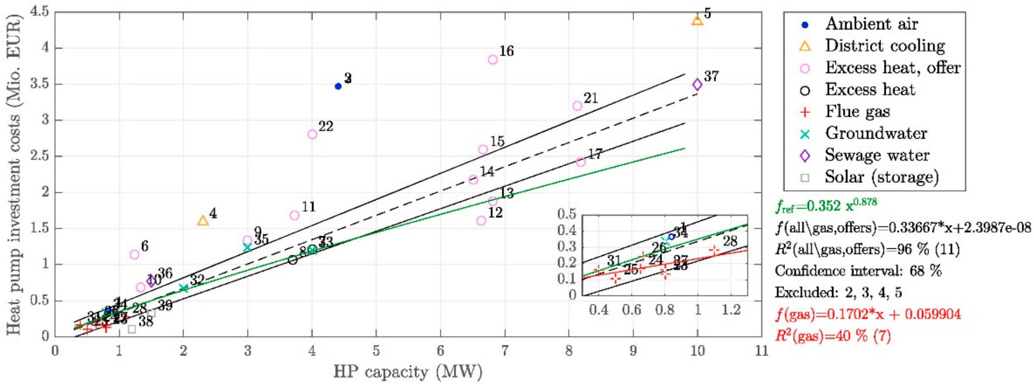


Fig. 1. HP investment costs.

### *3.2. Construction costs*

The construction costs for the investigated HP projects are shown in Fig. 2(a). Points 23, 25, 35 and 41 were excluded, because the HPs were placed in an existing building, resulting in negligible construction costs. The construction costs increased with HP capacity independent of the heat source, because the heat source should not impact the size of the building. The $R^2$-value is high and the confidence interval rather narrow. The construction costs for the HP project from point 2 were higher, because the building had to be built fast. For the same kind of HP (point 3), a building was erected much cheaper, because it was modular based and done in-house. It is further expected that the construction costs could be reduced even more, if a combination of steel beams and sandwich panels will be used for the building. This indicates a potential cost reduction for future projects [29].

### *3.3. Electricity-related investment costs*

The electricity-related investment costs for the investigated HP projects are presented in Fig. 2(b). The $R^2$-value is high, however, the confidence interval is wider than for the construction costs. The HP projects with a thermal capacity below 2 MW and for point 3 have all the cheaper connection to the electrical grid, as explained in Section 2.3. In addition, many of these HPs were built at already existing production sites, which results in few additional costs related to the control system. Furthermore, no additional transformer or changes to the transformer were required. All this indicates that HP projects below a thermal capacity of 2 MW have low costs related to electrical works. Larger HPs require their own control system and changes to the transformer or a larger transformer. Points 4 and 5 were excluded. These are HP projects based on district cooling. They are both more expensive than the remaining projects, which may be due to the more advanced control system and the more expensive connection to the electrical grid.

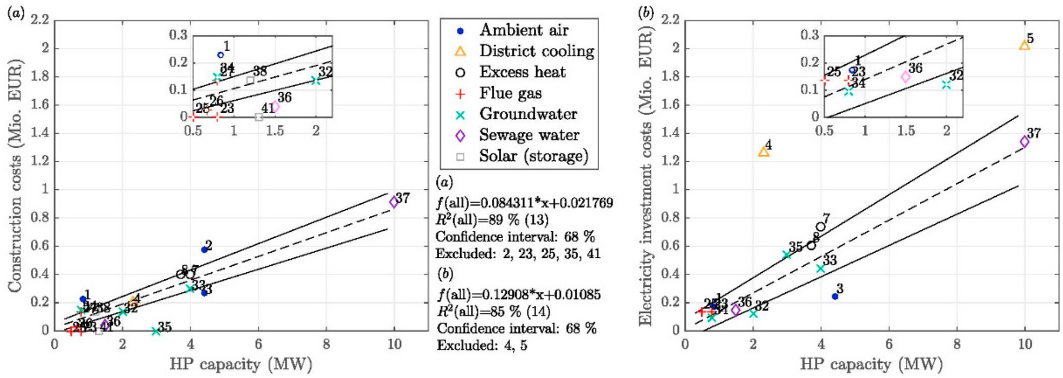


Fig. 2. (a) Construction costs for HPs; (b) electricity-related investment costs for HPs.

### *3.4. Consulting costs*

The consulting costs of twelve HP projects were known, which were very different from each other. The minimum and maximum values were 0.01 million € and 0.32 million €, respectively. A general trend was not found. Therefore, the consulting costs were assumed to be the mean, 0.15 million €. The consulting costs may depend on the consulting company hired and how their services are charged, e.g. based on a fixed price for installed HP capacity or the actual hours spent on the project. Both possibilities offer different advantages and risks. The consulting costs for air-source HPs were generally lower than for other projects. No consulting costs for HP projects based on flue gas were known, because the HP installations were often part of a main project, which included e.g. a gas engine or a gas boiler. The consulting costs were covered by the main projects [30]. Therefore, its value was assumed to be zero for flue gas.

### *3.5. Heat source investment costs*

The heat source investment costs are shown in Fig. 3. Cost correlations were created for five different heat sources. Dividing the HP projects by heat sources resulted in few HP projects for each heat source. Therefore, the cost correlations presented here may be seen as first estimates. The costs of flue gas for the different projects are in good agreement, even though the $R^2$-value is not high. The HP from point 23 utilizes flue gas from a gas motor and not from a gas boiler. This point was excluded, because an additional exhaust fan was installed before the heat exchanger at the flue gas to prevent a pressure increase in the turbocharger of the gas motor [18]. The number of HPs that use air as heat source was limited to three, from which two are of the same type. However, the investment costs were provided by the manufacturer [27] and are therefore considered to be of good quality. The cost increase is very steep, which may be because the installed heat source capacity is 25 % larger than required. This was done to ensure that one part of the evaporators can always be defrosted [27]. The costs of sewage water as a heat source are constant, based on the two HP projects. The main costs may result from the heat exchanger to utilize the sewage water and the required filters and clean-in-place (CIP) equipment to ensure smooth operation [18]. Such special equipment is required no matter which size, resulting in high costs also for small capacities. The cost correlation for groundwater was based on three HP projects. The costs of groundwater may be the most difficult to estimate, because each project may differ in the way groundwater is accessed and released. Groundwater may be excessed in different depth, such as at 30 m, 100 m or 200 m, which will have a large impact on the drilling costs. The capacity for each borehole is limited depending on the reservoir and flow, which requires establishment of several boreholes for one project. In addition, the groundwater may have to be reinjected by additional boreholes, may be dispersed in the ground just below the surface or may be released to the sea. Finally, permission for using groundwater as a heat source has to be given, too. Point 33 was excluded, because the boreholes were 250 m deep and reinjection boreholes were required, which made it very costly [18, 19]. The costs for establishing excess heat as a heat source was a fixed fraction of the total investment costs, as explained in Section 2.4. The cost correlation has a good $R^2$-value based on eleven HP projects. The costs may vary depending on the industrial process and how easily a stream can be utilized. Points 16 and 22 were excluded, because they were configured to achieve a very high COP resulting in higher costs than other HPs with similar capacity. No costs were assumed for district cooling as a heat source, because this investment was considered to be part of establishing the district cooling network.

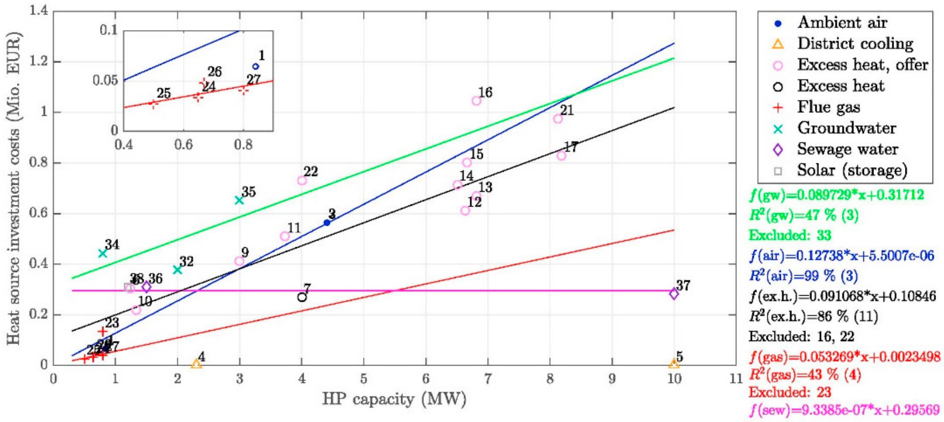


Fig. 3. Heat source investment costs for HPs using different heat sources.

### 3.6. Estimation of total investment costs

The total investment costs of only 16 of the investigated HP projects were known, assuming the consulting costs of flue gas were zero. The developed cost correlations for each cost fraction category were used to determine the unknown costs of a HP project to get an estimate of the total investment costs for all HP projects. The total investment costs for all HP projects and the correlation of the total investment costs for the following five different heat sources can be found in Fig.4: sewage water, groundwater, air, industrial excess heat, flue gas.

The project numbers in gray indicate that the total investment cost of this project is based on at least one correlation of one of the cost fraction categories. HPs 2 and 3 can be operated electrically or by gas, as explained in Section 3.1. Therefore, the HPs were more expensive. The correlation for HPs from Section 3.1 was used, instead of the actual costs, to show the total investment costs of the HP projects 2 and 3 for a regular HP. HP projects based on flue gas are cheaper than HPs based on other sources, because of less expensive HPs and heat source access. The cost correlations for the HP projects based on the four other heat sources result in a similar trend, even though different correlations were used for heat sources. This indicates that total investment costs, independent of the heat source and COP, may be below a certain threshold to be feasible. The groundwater and sewage water HP projects have high initial costs for small capacities. Sewage water HPs, however, become cheaper for larger capacities due to the constant costs for the heat source. The correlation underestimates the total investment costs compared to project 37. The HP project 33 was more expensive, because the heat source investment costs were much higher than for the other groundwater HPs.

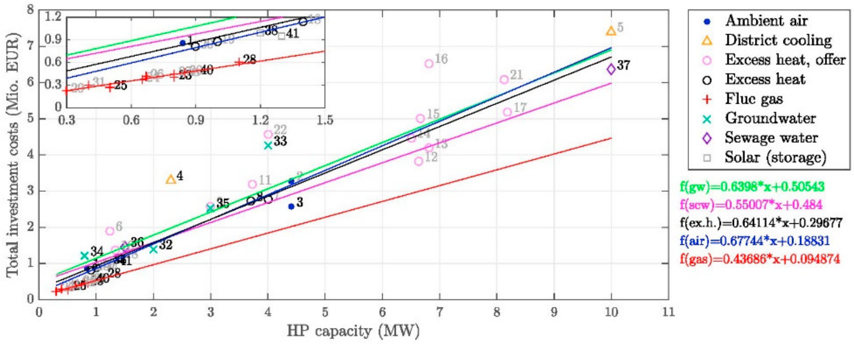


Fig. 4. Total investment costs for HPs using different heat sources.

The presented cost correlations of the total investment costs for different heat sources result in high specific total investment costs (million €/MW) for capacities below 4 MW, due to high initial project costs. The specific total costs between 4 MW and 10 MW decrease only slightly. An overview for different HP capacities is shown in Table 2.

Table 2. Specific total investment costs for HP projects depending on the heat source and HP capacity.

| Specific costs, million €/MW | Flue gas | Sewage water | Excess heat | Groundwater | Air |
|---|---|---|---|---|---|
| 0.5 MW ≤ $HP_{Capacity}$ < 1 MW | 0.63 to 0.53 | 1.91 to 1.23 | 1.30 to 0.97 | 1.72 to 1.18 | 1.12 to 0.90 |
| 1 MW ≤ $HP_{Capacity}$ < 4 MW | 0.53 to 0.46 | 1.23 to 0.72 | 0.97 to 0.72 | 1.18 to 0.77 | 0.90 to 0.73 |
| 4 MW ≤ $HP_{Capacity}$ ≤ 10 MW | 0.46 to 0.44 | 0.72 to 0.62 | 0.72 to 0.67 | 0.77 to 0.69 | 0.73 to 0.70 |

### *3.7. Breakdown of total investment costs*

The total investment costs were broken-down for five different heat sources, as shown in Fig. 5.

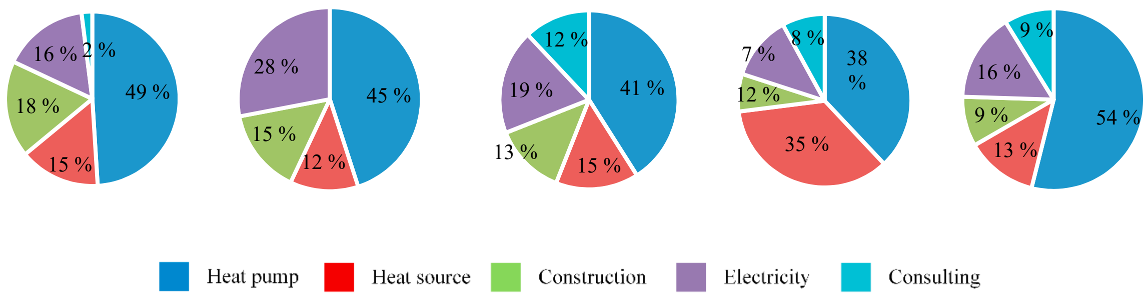


Fig. 5. Breakdown of investment costs for HPs for five different heat sources: (a) air; (b) flue gas; (c) excess heat; (d) groundwater; (e) sewage water.

The HP contributed the most to the total investment costs. The cost fraction for the HP varied between 38 % and 54 %. Sewage water HPs accounted for the highest proportion of the total investment costs. For HPs utilizing groundwater as the heat source the fraction related to HPs was only 38 %, while the heat source took an equal proportion of 35 % of the total investment costs. For the other four heat sources, the heat source investment costs varied between 12 % and 15 %. The cost fraction for construction costs differed for the heat sources. It was 7 % and 9 % for the more expensive heat source projects based on groundwater and sewage water, respectively. For the remaining heat sources, the cost fraction varied between 13 % and 18 %. Electricity-related investment costs contributed with 12 % to 19 % to the overall investment. Groundwater HPs were an exception, because other costs were relatively higher. An opposite trend was found for flue gas based HP projects, because of the minimum costs required for a connection to the electrical grid. This accounted for a higher proportion for smaller HP projects and resulted in a proportion of 28 %. Consulting costs were between 8 % and 12 % of the total investment, except for air-source HP projects with only 2 %. No consulting costs were assumed for flue gas, as explained in Section 3.4.

## 4. Discussion

The developed cost correlations were based on available data of a limited number of HP projects. Dividing the projects by heat source resulted in even fewer data points, which may impact the validity of the used statistical methods and the accuracy of the developed correlations. In addition, data points for some correlations were excluded, which may be subjective and details about some of the projects may not be known, which could influence the process of excluding data points. The Danish Energy Agency suggested a wide range of specific total investment costs from 0.5 million €/MW to 0.8 million €/MW in 2014 [23] and from 0.8 million €/MW to 1.1 million €/MW in 2017 [19]. Usually, a decrease in costs is expected, but the opposite was the case. Such unexpected development happened, because, at the time of the first release, many of the existing large-scale HPs were based on flue gas condensation. The results have shown that those projects were cheaper. However, many new HP projects were built between 2014 and 2017 that were based on natural heat sources with a larger temperature lift between heat source and heat sink [17]. The HP, accessing the heat source, consulting etc. became more expensive. Consequently, the costs for large-scale HP projects increased. The specific cost interval could be narrowed down further and differentiated between heat sources and HP capacity based on the presented results. The breakdown of the total investment costs is overall in agreement with the results published by Grosse et al. [22]. They provided cost fractions of the total investment costs for large-scale HPs based on groundwater, flue gas and industrial excess heat. Bejan et al. [31] describe and estimate the breakdown for total capital investment costs for thermal design projects in general, such as for power plants or boilers. Their estimated proportions also fit with the presented cost fractions for large-scale HP projects. The development of linear correlations for the later use of optimization may be justified by the fact that economy of scale effects for large-scale HPs are limited by 70 % to 90 % for an increase in capacity of 100 %, because of limited component capacity ranges [32]. Often, large-scale HPs are built in parallel to increase capacity [18]. The non-linear correlation for HPs presented by Grosse et al. [22] may take into account these effects. However, it was shown in Fig. 1 that the economy of scale effects were minor. Fig. 1 also showed that HP costs based on offers for similar capacity and temperature levels may vary significantly. Based on the collected data for the projects, e.g. 13 and 16 as well as for 14 and 15, the more expensive HP offers also had a higher COP. However, a general dependency on the COP and/or temperature levels was not identified for all projects. The consulting costs for HP projects based on flue gas were assumed to be zero, due to the lack of data. A constant value could be added to the developed correlation of total investment costs, if more information about the consulting costs are known. Grosse et al. [22] stated that the consulting costs for flue gas based HP projects are 5 %, which is only a small fraction of the total investment costs.

## 5. Conclusion

The total investment costs of 41 large-scale HP projects were analyzed and divided into costs related to the HP unit itself, the heat source, construction, consulting and electricity-related investments. Cost correlations for each of the cost fraction categories were created, which allowed estimation of unknown costs and the total investment costs of a HP project. As a result, cost correlations for the total investment costs were developed for five different heat sources: flue gas, air, groundwater, sewage water and industrial excess heat. The results showed that different specific total investment costs exist for large-scale HPs depending on the heat source and the HP capacity. The most and least expensive heat sources, depending on the capacity, were identified. It was shown that a considerable amount of the investment costs was placed on other parts than the HP itself, e.g. equipment to access the heat source, engineering works and others. It was further noted that the specific investment costs decrease for larger capacities, due to lower specific costs on e.g. permissions and connection to the electrical grid. The developed cost correlations may provide help during the planning process of new large-scale HP projects to decide among different available heat sources and to estimate the expected investment costs. This may align the expected and realized costs and give an indication about the feasibility of new HP projects. More large-scale HPs would ensure an efficient integration of renewable energy sources and coupling of the electricity and heating sector, which is required for future smart energy systems.

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