A collective heat and cold distribution system with decentralised booster heat pumps: a sizing study

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Abstract

A combined distribution circuit (CDC) is a collective two-pipe heating and cooling system for apartment buildings. Previous research has demonstrated the advantages of implementing a booster heat pump (BHP) in district heating. However, no detailed study is available on the influence of the BHP's sizing and low design temperatures (e.g. 40°C/33°C). Our research aims to gain more insight into the sizing of a CDC with a central ground-source HP and decentral BHPs for DHW production. This was achieved by using a dynamic simulation environment in Matlab to study the impact of various design choices. The results show that the performance of the central HP is decisive for the total system efficiency (334%) and that the sizing of the BHPs affects their performances.

Key Innovations

- In summer, booster heat pumps (BHP) are used to produce domestic hot water with indoor excess heat.
- Detailed insight in design choices of BHP.
- A central production unit is decisive for the total system efficiency, if the supply temperature is within the boundaries of the BHP.

Practical Implications

The performance of the central production unit is decisive over the performance of the decentral booster heat pumps, if they only produce domestic hot water. The BHPs should not be oversized as this leads to poor performances because of temperatures outside the boundaries.

Introduction

Centralized thermal networks, such as district heating (DH), have been in continuous development since 1877 (European Commission, 2018; Lund et al, 2018). A DH is a large circuit that consists of heat producers, heat consumers and distribution pipes. Such systems are part of the solution to secure a sustainable future. Throughout the past decades, some important trends in thermal networks have been researched in order to reduce their fossil fuel consumption.

Firstly, the distribution temperature has been lowered from over 200°C (1st generation steam networks) to <100°C (3rd generation heating grids) (European Commission, 2018; Köfinger et al., 2016). Lowering the distribution temperature facilitates the implementation of renewable and low-exergy heating sources (e.g. heat pump (HP), solar collector, combined heat and power (CHP), waste heat, etc.). The use of renewable heating and cooling sources will play an important role in achieving the climate goals of the European Union (EU) by 2050. These heat sources are mostly expensive investments for individual purpose. However, because of economies of scale and the large number of end-users in a heating network which enables efficient controlling, the payback period is reduced.

Secondly, the distribution temperature can be even lower than 70°C, e.g. a supply temperature of 40°C. In this case, a decentralised heat producer is required to provide domestic hot water (DHW) and, if needed, space heating at higher temperatures than the distribution temperature. Previous research (Ommen et al., 2017) has shown the energetic advantages of using a booster heat pump (BHP). Especially, a BHP is beneficial in combination with a central HP. When the central heat producer is a CHP and decentral BHPs are used, the total system efficiency reduces by 20% compared to a low temperature DH grid (70°C supply) heated by a central HP. Furthermore, the studies of Köfinger et al. (2016) and Østergaard and Andersen (2016) confirm the energetical efficiency of a BHP when producing domestic hot water (DHW) in ultra-low temperature district heating (ULTDH) and stored in a thermal energy storage (TES).

Thirdly, a shift in the relative heat and cold demand is taking place in the building stock in Europe. The energy-performance regulations of new buildings and the refurbishments of existing buildings led to a reduced space heating demand (Buffa et al., 2019). In comparison to the values of 2016, a reduction in the space heating demand of ca. 25% was estimated by the RHC Technology Platform as well as an increase of 300% in the space cooling demand (European Commission, 2011). The study of the Netherlands' Ministry of Economic Affairs and Climate (RON, 2018) confirms that the relative shares of DHW and cooling in the total energy demand in the building stock is rising in Europe. For these reasons, this research has taken into account the cooling demand in buildings.

Finally, collective-thermal networks on building level appear more frequently in residential buildings (De Pauw et al., 2018). Specifically, the use of a collective two-pipe distribution system that supplies heat for space heating or cooling as well as for DHW (in this paper called a "combined distribution circuit (CDC)") is increasing. The main advantage of such systems in apartment buildings is that the installed heating power can be reduced in comparison to four- or six-pipe distribution systems and individual energy systems. This is mainly because of the non-simultaneity of DHW use in the different apartments.

At the time of writing, investigations concerning BHPs have been confined primarily to the average performances of a collective heating system on a large scale (i.e. DH). However, no detailed study on the influences of design choices has been performed. As a result, no in-depth knowledge is available on the sizing, controlling and evaluation of such a system, neither on a large (i.e. district heating) nor on a small scale (i.e. in apartment buildings). Furthermore, the Belgian Energy Performance of Buildings Directive (EPBD) legislation has a major impact on system selection. However, EPBD does not provide for any appropriate evaluation framework for this type of heating and cooling systems, because of two reasons. I) A certificate of conformity (in Dutch "gelijkvormigheidsattest") is needed in order to evaluate an innovative concept in a more appropriate way. II) The framework uses a large timestep (of a month) and a myriad of correction factors for the simplifications and assumptions (Flemish government, 2010). For example, the operation times of heat pumps are fixed per year and do not depend on the storage tank volume. For these reasons, it is not known if the sizing of various components has an influence on the calculated energetic performances.

In this paper, the influence of different design choices in a CDC with BHPs is investigated. In particular, the following design parameters were studied:

- balance between decentralised and centralised heat production by varying the size of the BHPs and the decentralised storage of DHW
- central storage tank volume, connected to the central HP
- the design temperatures of the central distribution

This study is required in order to develop a code of good practices by designing such systems and to understand the different influences in a CDC with decentralised BHPs.

Method

Simulation-based

In-situ measurements would be an inefficient way to study the influences of various design choices, because it would be time-consuming and cost-inefficient to build all the studied variants. Therefore, in a previous research (Jacobs et al., 2021), a dynamic simulation environment in Matlab has been developed in order to evaluate the concept energetically. It is based on the simulation environment of Van Riet (2019), also used for the energetic evaluation of different hydraulic hybrid configurations in collective heating systems on building level. Jacobs et al. (2021) found that the innovative concept is more energy efficient than a conventional CDC with fossil boilers. Furthermore, the possible energy recuperations of the BHPs between cooling and simultaneous DHW demand during summer is demonstrated. The results show a possible energy recuperation of 27,5% during summer.

The second advantage of using a simulation environment is the possibility to keep the heat demand profiles, imposed on the production systems, identical for the different sensitivity analyses (De Pauw et al., 2018). The models used for this evaluation are created in a simulation environment with the following main characteristics:

- The dynamic behaviour of all components is taken into account by their differential equations and a small timestep of 10 seconds.
- All inputs of the models are considered constant during one timestep.
- The hydraulics (pressure drops and values) of the components are not taken into account: a perfectly controlled installation is considered. However, the time-delay in the pipes is included.
- Most of the differential equations regarding temperatures are non-homogenous linear ordinary differential equation with constant coefficients, De Pauw et al. (2018) describes these general equations. Only the storage tank model is a partial differential equation, where iteration might be required.

Main models of simulation environment

The focus of the models in the simulations is the dynamic thermal behaviour of each component. The influence of temperature changes is considered. The heat pumps' mass flows (central and decentral) are nominal, i.e. no variable mass flows are considered. In order to verify the models, energy balances are performed during post-processing for every single step. The errors of the energy balances were less than 0,00001 joules.

<u>*Zone model*</u>. 20 zones are considered and every dwelling is modelled as described. In electrical analogy a 3R2C-model of the zone is given in Figure 1.

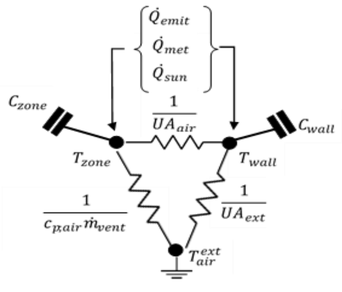

Figure 1: 3R2C model of the zone. Ventilation and transmission losses are included.

The zone is modelled as two lumped capacitances, i.e. the indoor air volume (c_{air}) and the walls (c_{wall}). Three heat transfer resistances are defined: one between the capacitances of the zone ($1/UA_{air}$), one between the walls and the outdoor temperature ($1/UA_{ext}$) and one between indoor and outdoor air ($1/c_{p;air}\dot{m}_{vent}$) , which describes the ventilation losses. The following equations describe the thermal behaviour of the zones:

$$C_{zone}\frac{d(T_{zone})}{dt} = 0{,}6\dot{Q}_{emit} + 0{,}5\dot{Q}_{sun} + 0{,}75\dot{Q}_{met} - UA_{air}(T_{zone} - T_{wall}) - c_{p;air}\dot{m}_{vent}(T_{zone} - T_{ext}) \quad (1)$$

$$C_{wall}\frac{d(T_{wall})}{dt} = 0{,}4\dot{Q}_{emit} + 0{,}5\dot{Q}_{sun} + 0{,}25\dot{Q}_{met} + UA_{air}(T_{zone} - T_{wall}) - UA_{ext}(T_{wall} - T_{ext}) \qquad (2)$$

Where $\dot{Q}_{sun}$ and $\dot{Q}_{met}$ are resp. the solar heat gains and internal heat gains and $\dot{Q}_{emit}$ the heating power of the underfloor heating (or cooling) (all in W). The outdoor temperature (T_{ext}) and $\dot{Q}_{sun}$ are based on weather data from Uccle, Belgium (SELUWM, 2014). In (1) the wall temperature (T_{wall}) [°C] is from the previous timestep. In (2) the zone temperature (T_{zone}) [°C] is calculated in (1).

The underfloor heating has also a thermal capacity ($c_{emitter}$) of which the thermal model is described in the study of Van Riet et al. (2019).

Booster heat pump. Both the evaporator and the condenser are dynamically modelled with a thermal capacitance. Jacobs et al. (2021) described the differential equations and are drawn from Figure 2. The data of the *Alpha Innotec WWB21* from *Nathan Systems* is fitted to a polynomial with a nonlinear regression model in Matlab. This polynomial (i.e. performance map) is scaled to the nominal heating power of the BHP, which facilitates the variation of the BHPs' sizing with only two equations. The minimal and maximal source temperatures are resp. 18°C and 42°C. The maximal sink temperature is 73°C.

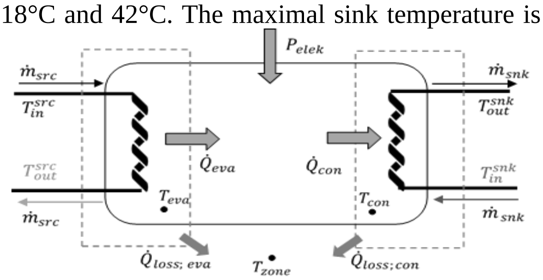

Figure 2: scheme of BHP, with mass flow and energy balances

Ground-source heat pump. The central heat pump is a brine/water heat pump, where the source temperature is considered constantly 10°C throughout the year. This is considered as a valid assumption, because the temperature fluctuations of the ground diminish by an increased depth due to the increased thermal inertia. The transient behaviour of the condenser is taken into account as in (Van Riet et al., 2018a). During the summer, the central HP has two modes: I) it can extract cold from the ground and provide cooling to the CDC. This is required when the cool load is large, but no DHW is produced by the BHPs. II) The central HP provides heat to the CDC when the BHPs produce DHW while no cooling is required in the apartments (e.g. during the evening/night). This mode will avoid too low distribution temperatures.

Distribution pipes. The models of all the pipes are based on a plug-flow method (Van Riet et al., 2018b). The CDC is modelled as a supply and return pipe without branches. A strongly ventilated ventilation shaft of the CDC is assumed, which means that the distribution losses are not considered as a heat source for the apartments.

For more detailed information on all the models, we refer to Jacobs et al. (2021).

Case description

The apartment building consists of 20 dwellings in Belgium, each inhabited by different families that are relevant for Flemish families (De Schutter et al., 2018). The "profile generator" of the Instal2020 project (WTCB, 2018) is used for the occupancy profile (internal heat gains from inhabitants and electric appliances) and DHW demand profiles. The average DHW demands at 60°C is 0,86 MWh/year/person. During winter, the set point temperature is 19°C at night or when no one is inside, otherwise it is 21°C. In summer, this set point is 25°C for space cooling. Every dwelling is directly connected to the CDC, with underfloor heating for space heating or cooling, and has a BHP with a DHW-TES. Figure 3 gives an overview of the concept with one apartment. In the substations, a connection between the underfloor heating and the BHP is available. Through these connections (blue arrows in Figure 3), energy recuperation during the summer is possible. The excessive heat of the apartments is used as a heat source for the BHP. On the other hand, the BHP's evaporator is a cooling source for the underfloor cooling. No hydraulic separations (e.g. decentral heat exchangers) are needed as it is a small building and the BHP separates the DHW from the CDC. The design temperatures of the underfloor heating is equal to the design temperatures of the central distribution (CDC). The CDC's supply temperature follows a heating curve.

The heat load by design conditions (21°C indoor and -8°C outdoor) is 2030 W. The apartments are characterised by an average energy demand for space conditioning of 20 kWh/m²/year. The central ground-source HP is dimensioned at 40,6 kW (Q_{HP}) to cover the full heat load of all 20 apartments. A storage tank is connected to the central HP and its storage volume is varied in the analyses according the loading time of the central HP:

$$V_{tank}\ [l] = Q_{HP} \cdot t \Big/ 4187[\tfrac{J}{kgK}] \cdot \Delta T_{des} \qquad (3)$$

Where ΔT_{des} is the design temperatures of the distribution system and t [s] is the time in which the central HP can thermally load the storage tank. More detailed characteristics are described in Jacobs et al. (2021).

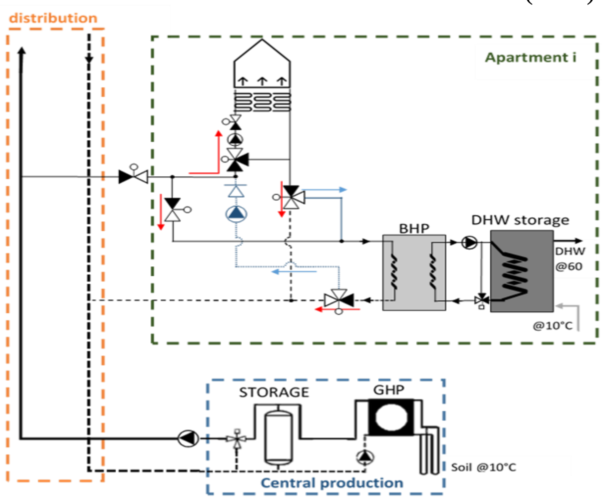

Figure 3: scheme of the heating and cooling system.

Key Performance Indicators (KPI)

The results are based on various key performance indicators (KPIs) which are shortly described below:

- *Room Temperature Lack (RTL)* and *Room Temperature Excess (RTE)*: respectively, the number of Kelvin hours below or above the set point temperature of the apartment's indoor air. The RTL is used as a discomfort parameter during winter, while the RTE is relevant during summer.
- *Sanitary Temperature Lack (STL)*: The number of Kelvin hours that the DHW is below its set point at tapping (40°C). Note that the mixing of the DHW with domestic cold water is not simulated. Thus, ideal mixing taps are considered.
- *CDC Temperature Lack (CTL)*: The number of Kelvin hours the supply temperature in the CDC is below its set point. During winter, this set point depends on the outdoor temperature.
- *Total primary energy consumption (PE)*: the electricity consumption is divided by 40%, i.e. the average efficiency of a Belgian electricity network.
- *Seasonal Performance factor (SPF)*: the total efficiency of the total system or a (booster) heat pump on a yearly basis.
- *Mean continous operation time of the BHPs (t^{cyc})*: average hours a BHP works in one start-stop cycle. A higher value effects its energetic performances and maintenance costs in a positive way.

Results and discussion

The analyses, based on sensitivity analyses, are executed on following parameters:

- The nominal heating power of the BHP at 20/50°C (Q_{nom}^{BWP}) in the range of powers which are available in the market, namely 1,5 kW, 2kW and 2,5 kW.
- The volume of the decentral DHW-TES, determined with a so-called PV-curve (WTCB, 2018) (i.e. the reference volume). This reference volume is increased and decreased by 50%.
- The central storage volume depends on the loading time of the central HP. This loading time (*t*) is varied by 2700s (0,75h), 3600s (1h) and 5400s (1,5h).
- The design temperatures of the CDC in heating mode. Those of the cooling mode are not varied (19/24 °C). The variations are listed in Table 1.

Table 1: scope of the investigated design temperatures

Heating (winter) [°C]	**Cooling (summer) [°C]**
29/22	19/24
30/23	19/24
32/25	19/24
35/28	19/24
40/33	19/24

Sizing of DHW production

The sizing of decentral DHW production consists of two parts: the nominal heating power of the BHPs and the storage volume of the decentral DHW-TES. Firstly, a higher nominal heating power (Q_{nom}^{BWP}) will require less time in order to load the DHW-TES. However, the energetic performances of an oversized BHP decrease, as the number of start-ups increases. Secondly, a larger DHW-TES will provide heat for a longer time, while increasing the envelope losses. An optimum of the sizing of decentral storage and the Q_{nom}^{BWP} needs to be found.

Figure 7 (at the end of this paper) shows that the maximum sanitary temperature lack (STL) for a DHW-TES of "-50%" is between 6 to 7 Kh per year per apartment. These Kelvin-hours are taken into account only when a DHW demand occurs. This means, for example, that per year 36 to 42 showers of 10 minutes are 1°C too cold, which is inadmissible. However, this discomfort is the maximum discomfort per apartment of all apartments. Thus, other families experience lower discomforts or even no discomfort. In this respect, it was found that an undersized ("-50%") DHW-TES might be sufficient for some families, but a smaller DHW-TES will not satisfy in every situation. Therefore, the reference volume (100%) is recommended. Furthermore, the 1,5 kW BHP consumes the least PE of all BHPs. It consumes 6% less PE than BHPs of 2 kW and even 12% less than 2,5 kW BHPs. In conclusion, the 1,5 kW BHP with the reference volume (175 liter determined with the PV-curve) gives the best results. The STL is maximum 1,05 Kh/year, which only occurs during one month in only one apartment.

The BHP can use the indoor excessive heat as a heat source during summer. For this reason, the indoor air temperature requirement is considered as an evaluation criteria for the BHP's sizing. Figure 8 (at the end of this paper) gives an pareto analysis of the PE use and the indoor air temperature comfort, both during summer. This analysis proofs that an 1,5 kW leads to a lower PE use in combination with a higher indoor air comfort (i.e. lower room temperature excess (RTE)) in comparison to larger BHPs. Furthermore, a larger storage volume, leads to an increased PE use, as a consequence of higher envelope losses. However, in this research, all envelope losses of the tanks are considered as losses and do not influence the heat and cold demand of the apartment. In this respect, it is possible that a larger storage tank will lead to an increased cooling demand and thus increases the total energy demand. On the other hand, these envelope losses are a heat source for the building during winter and might decrease the total energy demand.

Finally, an overview is given in Table 3 (at the end of this paper) of the mean operating time of all BHPs and of the mean efficiencies during winter (heating, h) and summer (cooling, c). A smaller BHP has a longer cycle time, which lowers the maintenance costs. The longer cycle time is because of not overheating its outlet temperature at the condenser, thus the BHP can heat up the DHW-TES in one cycle. However, only a fixed nominal mass flow at both sides of the BHP is considered (125 l/h and 300 l/h for the evaporator's and condenser's side, resp.). As a result of the overheating, the efficiencies (SPF) of BHPs improves when they are smaller. The difference of SPF in summer and winter is a result of the different supply temperature at the evaporator side of the BHP (from the collective distribution pipes).

Volume of central storage tank

The central storage's sizing is varied according to the central HP's thermal loading time. As described in (3) from the case description, all other parameters of the central storage tank's sizing are held constant. In this sensitivity analysis, the thermal stability of the distribution system is considered as the KPI by introducing the Combilus Temperature Lack (CTL). This KPI is important in ultralow temperature networks with BHPs, as a too low supply temperature will unintentionally switch off the BHPs. The second KPI is the heat loss of the central storage tank, because a larger tank will lead to higher envelope losses.

Figure 4 shows that a smaller tank (0,75h loading time) provides a more constant supply temperature, because the CTL is 5,15 Kh/day. A storage tank that is thermally loaded in 1h by the central HP causes a CTL of 5,62 Kh/day, while the largest storage tank (1,5h) supplies a temperature that is 5,95 Kh/day lower than the set point. On the other hand, the envelope losses are the highest for the smallest storage tank (0,75h). The reason for the higher heat losses is that the summer period is included. In summer, the water temperature in the tanks is lower than its environment (20°C) and thus the water is heated up by the environment. This leads to a negative heat loss, which is "larger" by the larger tank. With this insight, it is expected that the heat losses during winter are indeed lower for a smaller tank.

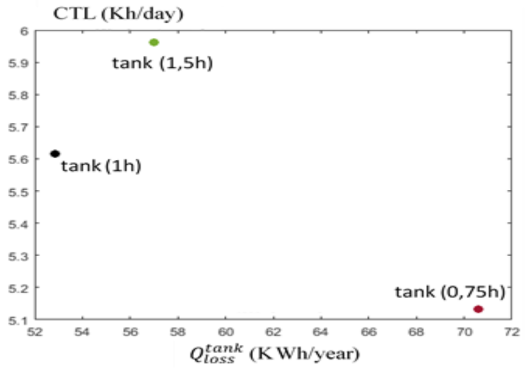

Figure 4: sensitivity analysis on the central TES. CTL in function of the envelope losses.

In this research only the CTL and the storage tank's losses are taken into account. However, the storage will have an influence on the PE use of the central HP. Furthermore, the CTL does not give a full perception of the stability. The stability depends on multiple parameters, such as pressure, mass flow, temperature excess, etc. We suggest to perform more detailed studies on this component of the system, with the insight gained from our research.

Design temperature of central distribution

In order to reduce the distribution losses, a lower distribution temperature is possible. However, this temperature has a direct impact on the efficiency of the central heat producer, as well as on that of the decentral BHPs. As a result, the total system efficiency (i.e. SPF_{system}) is affected by this design choice. In this study, the design mass flows are not varied, thus a ΔT of 7 Kelvin is maintained. The BHPs of 1,5 kW are considered with a reference DHW tank. The central storage's loading time is 1h.

Figure 5 shows the pareto analysis of the mean RTL and RTE during the heating season (winter) relative to the total PE consumption of the concept. This analysis shows that the concept has met the indoor temperature requirements during winter for all design temperatures (only a maximum mean RTL of 0,48 Kh/day/apartment), but mostly it is in fact too warm inside the apartments (a maximum mean RTE of 4,8 Kh/day/apartment). This is favourable in terms of comfort in the apartments in the heating season. However, because of the higher indoor air temperature, the transmission losses are higher compared to the set-point temperature. As the RTL is maximum 0,48 Kh/day/apartment, this KPI can be ignored. On the other hand, the results show that the PE consumption is decisive. The range is 48,15 MWh (at 29/22) to 51,57 MWh (at 40/33), which is a difference of 7%.

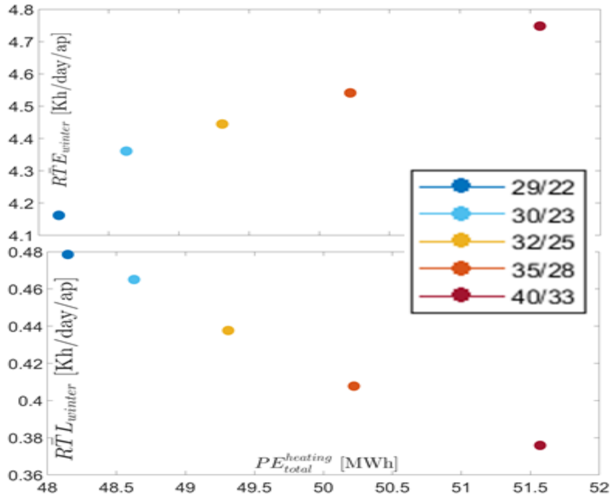

Figure 5: central distribution temperature analysis. The total PE during winter in function of the RTL and RTE.

A considerable energy saving is achieved by lowering the design temperatures, while the comfort in the apartments improves (the RTE also decreases). The explanation for the possible energy savings is shown in Figure 6,

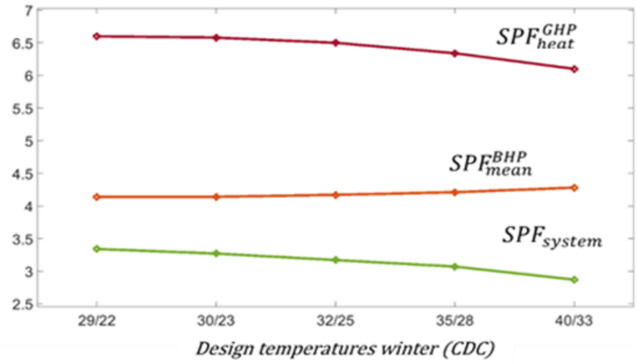

Figure 6: SPF of central HP, BHPs and total system for the different design temperatures.

which illustrates the SPF of the central producer, the average SPF of the BHPs and the total system efficiency. As the central distribution temperatures are lower, the SPF of the central ground-source heat pump (GHP) increases, while the SPF of the BHPs decreases.

Therefore, the system efficiency (i.e. SPF_{system}) increases when the central distribution temperature decreases, despite the higher electricity consumption of the 20 decentral BHPs. This statement is explained by the various components' share of heat production for the design temperatures examined, as given in Table 2. During winter, the central HP delivers all the heat for space heating as well as the heat for all the BHPs to produce DHW, i.e. the BHPs only produces DHW. All heat shares are given in MWh.

Table 2: heat shares of different HPs in the system

	29/22	30/23	32/25	35/28	40/33
Q_{heat}^{GHP}	71,8	72,7	74	75,1	76,6
Q_{DHW}^{BHPs}	49,9	49,9	49,9	49,9	49,9
Q_{eva}^{BHPs}	37,74	37,77	37,86	37,98	38,2

The BHPs deliver 49,9 MWh of DHW for every design temperature per winter season. Of this heat, between 37,74 MWh and 38,2 MWh is extracted from the CDC, i.e. supplied by the central HP. Thus, only a small share of heat is supplied by the BHPs and they therefore have a low influence on the total efficiency. However, they are an important component for increasing the total efficiency, for example in low temperature networks. With this insight, it is important to note that the SPF of the BHPs nonetheless plays an important role. If the BHP's SPF is low, the heat extraction of the BHP from the CDC will be lower, thus the relative heat generation of the central HP for DHW will decrease. In this case, it is expected that the BHPs will have a higher impact on the total system efficiency, then a lower temperature will be a disadvantage for the total system. This should be the subject of further research.

In conclusion, we found that the SPF of the central HP (or, by extension, the central heat producer at low temperatures) is decisive for the system efficiency (i.e. SPF_{system}) in case the decentral BHPs' SPF is representative of what is available on the market, hence the central HP provides the largest share of heat to the system. In this respect, a lower distribution temperature is beneficial for the energy savings of the total system. However, further research is needed to determine its boundaries.

Conclusion

This research has investigated various design choices of a ultralow temperature CDC with decentral BHPs, based on a case for Belgium. The case study consist of 20 apartments. The central production is a ground-coupled heat pump, without back-up fossil boilers. All apartments are equipped with an underfloor heating/cooling system and a BHP for DHW production with a storage tank.

The evaluation of the concept's different sizing is performed in the simulation environment of Jacobs et al. (2021). The step size is 10 seconds in order to take into account the detailed DHW profiles, the control technology and to obtain detailed results. This was needed to have a better understanding of how the BHPs should be dimensioned.

In this paper, three design choices were investigated, namely I) the nominal heating power of the decentral BHPs, II) the volume of the central storage tank and III) the central distribution temperature.

The study on the sizing of the BHPs' nominal heating power shows that the BHP may not be oversized, because this leads to an short-cycling of the BHP resulting of a too high condenser temperatures (too much heating power) or too low evaporator temperatures (too much heat extraction from the CDC). However, in this research the mass flows are kept constant. Further research has to determine what the influence of a variable mass flow would be.

The sensitivity analysis on the central storage was based on the temperature deviation of the central distribution temperature (*CDC Temperature Lack* (CTL)). In this research, three sizes of the central TES were compared. It was found that a smaller TES leads to larger envelope losses due to the (unintentional) heat gains during summer. When calculating the envelope losses over a year and the tank is used as a heat and cold storage, then the heat gains during summer should be calculated as an envelope loss. Thus, the envelope losses' summation should be an absolute instead. However, this analysis needs to be further expanded in the future.

A third influence study considered the central distribution temperatures during the heating season. It confirmed the assumption that a lower distribution temperature increases the system efficiency. In this respect, the central HP is decisive for the energy performance of the entire system, because the largest part of thermal power is provided by the central HP (between 85,5 and 86,7% during winter for the considered case studies). The performance of the individual BHPs is less influential to the system efficiency (i.e. SPF_{system}).

All the results of this concept study show that the CDC at lower temperatures with decentralised BHP is a good, sustainable system to provide heating to apartment buildings.

This research only studied one hydronic configuration of the CDC with BHPs and some analyses can be expanded. In this way, even more in-depth insight will be gained. We propose the following topics to study in future research:

- Variation in the heat pumps' mass flows.
- More in-depth analysis of the central storage sizing.
- Different control strategies, in order to optimise the energy recuperation and minimise the PE use.
- Various hydronic configurations between the central distribution and the apartments' substation. For example, use the BHP for DHW production as well as for space heating, or a hydraulic separation between the apartments' space heating system and the CDC.

Acknowledgement

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Annex: oversized figures and table

The following belongs to the results section: “*sizing of DHW production*”.

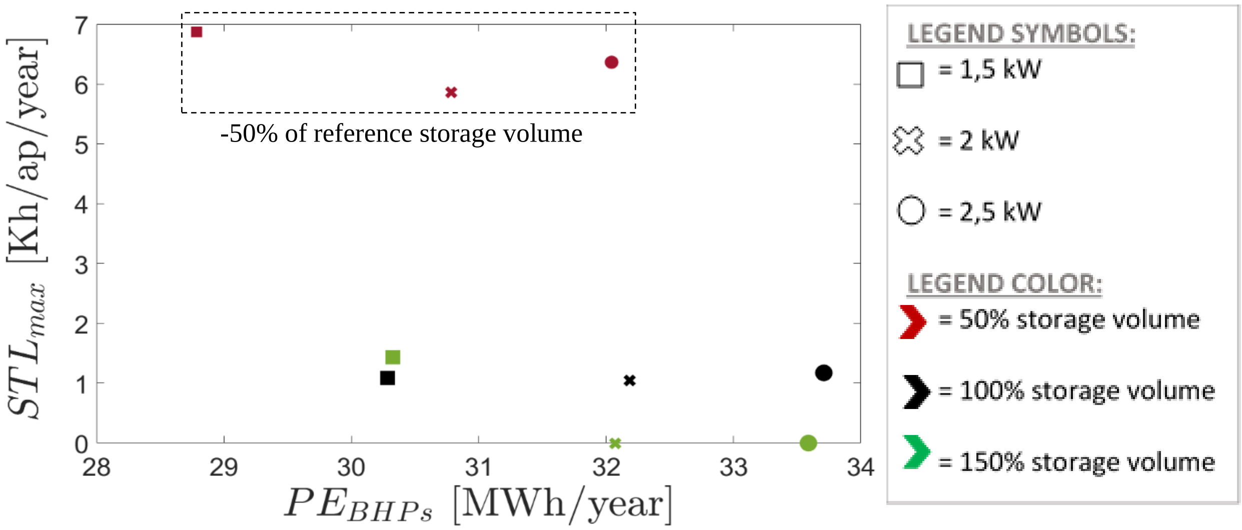

Figure 7: Pareto analysis of the sensitivity study on the BHPs' nominal heating power and their DHW-TES. STL in function of the total PE use of all BHPs.

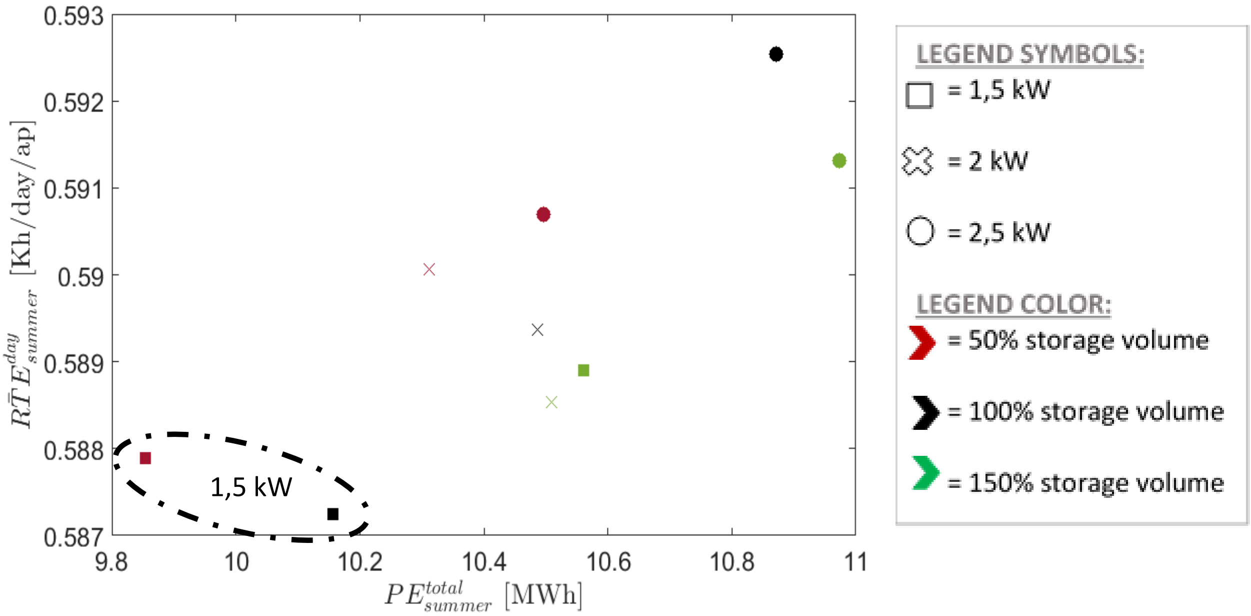

Figure 8: pareto analysis: RTE and total PE use during the summer period, as the BHPs can cool down the apartments.

Table 3: overview of the BHPs' mean operating time and their efficiencies for heating (h) and cooling (c) season.

Q^{BHP}_{nom} [W]		**50%**	**100% (ref volume)**	**150%**
1500	t^{cyc} [h]	3,91	5,48	7,45
	SPF_h | SPF_c	4,28 | 3,96	4,19 | 3,89	4,25 | 3,91
2000	t^{cyc} [h]	1,11	1,06	1,07
	SPF_h | SPF_c	4,06 | 3,76	3,98 | 3,71	4,04 | 3,73
2500	t^{cyc} [h]	0,26	0,24	0,25
	SPF_h | SPF_c	3,93 | 3,62	3,84 | 3,56	3,88 | 3,58