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# Optimized district heating system for combined operation with seasonal heat storage

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**Abstract.** This study optimizes the district heating network side of a high temperature community heating system powered by decentralized solar collectors and seasonal thermal energy storage (STES). Six network configurations are considered which have the potential to improve system performance compared to a base scenario. The base scenario consists of a 2-line network with a fixed supply temperature where the decentralised solar collectors feed in over the heating network. All alternative configurations aim to improve system performance by lowering the temperature of consumed and/or produced heat. Lowering the temperature in the heating network reduces heat losses and decreases heat pump utilization. Lowering the operational temperature of the solar collectors increases their efficiency. The strategies explored by the different configurations include variable supply temperatures, a 4-line network (where the solar collectors do not feed into the heating network), and ways to mitigate temperature constraints imposed by domestic hot water production regulations. In the neighbourhood “Karwijhof” of Nagele, 24 consumers will make the switch to a solar+storage district heating system. In order to assess their performance, all configurations and the base scenario are modelled in Matlab/Simulink. The system performance is measured in terms of levelised cost of heat (LCOH) and seasonal coefficient of performance (SCOP). They are compared to a scenario where the dwellings are fitted with individual high temperature air to water heat pumps. Making the supply temperature variable (dependent on the ambient temperature) reduces pipeline thermal losses and reduces heat pump utilization. The transition from a 2-line network to a 4-line network where the solar collectors are separately connected to the buffer was found to significantly increase solar collector efficiency. The combination of these two measures reduces the LCOH by 4.5 %. Slightly oversizing the buffer volume and solar area significantly increases the SCOP with small impact on LCOH. When comparing the improved community solar heating system with a scenario where every house is heated with an individual heat pump instead, it is found that the community solar system achieve a 15.7 % lower LCOH while having a SCOP of 4.4 compared to just 2.75 for the heat pump scenario.

**Keywords.** Energy, Renewable and smart energy solutions for buildings and sites, Design of Innovative HVAC systems for optimized operational performances.

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## 1. Introduction

In the fight against climate change, the Dutch government has vowed to replace current natural gas-based heating systems in buildings for more environmentally friendly alternatives. The need to convert hundreds of thousands of buildings annually, and its accompanying incentives, have sparked a pursuit for low carbon heating systems. A system relatively novel to the Netherlands, is one where

solar thermal energy is used to provide the built environment with its heating needs. When such a system is to provide a large portion of the total heating load, energy storage is needed in order to cope with the seasonal mismatch between supply and demand. Until recently, few of these projects were developed due to prohibitively high costs of the high temperature seasonal thermal energy storage (STES). However, the introduction of a new STES design by the company Hocosto has diminished costs

to a point where economic feasibility is achieved for a variety of projects. While Hocosto's solar-plus-storage concept has been tried and tested for several use cases such as individual houses, sport accommodations and schools, arguably the most promising application is the combination with small district heating systems (DHS). In such a system, several consumers would be connected to a central STES by a DHS. This study focuses on decentralised generation, where the consumers generate thermal energy with solar collectors on their own roofs. The concept of having a solar heating network with high temperature STES, offers the appealing benefit that the DHS could operate at a relatively high temperature, mitigating the need to convert participating buildings to be suited for low temperature heating (as is the case for many other low carbon heating concepts). However, having high temperatures in the network has three major downsides:

- Heat losses in the DHS increase
- Higher supply temperatures means more exergy needs to be generated by a heat pump (when the buffer temperature is below the supply temperature, a heat pump needs to supply exergy)
- The solar collectors have to operate at higher temperatures, decreasing their efficiency

This study aims to improve the performance of decentralised solar+storage district heating systems while maintaining the possibility to work with the existing high temperature heating systems. The performance of the system is measured in LCOH, or levelised cost of heat. LCOH takes into account all costs, discounted for the weighted average cost of capital (WACC), divided over the delivered heat. The result is an energy cost expressed in €/kWh. After careful examination of current literature, the improvements potentially leading to a lower LCOH will be sought in (partially) mitigating one or more of the three issues enumerated above. In total, seven different network configurations are considered. The general design and layout of these systems are elaborated. In order to compare the different configurations based on LCOH, they are simulated for several years in a Matlab/Simulink environment. Additionally, to compare how the systems financially hold up to alternative heating systems, they are compared to a scenario where the houses are heated by individual air-water heat pumps. A simple model of a single house and heat pump is introduced. Finally, the comparison between the systems is made. The systems are scaled based on buffer size and solar collector area for the lowest LCOH. Additionally, all systems are also sized for the lowest LCOH with the additional constraint that the seasonal coefficient of performance (SCOP) must be at least 5. This is done because it is reasonable to assume that ecological constraints will be applied in the adoption of such systems. The SCOP is defined as the ratio between the annual consumed thermal

energy by the consumers and the total electricity consumption by the entire system (including heat pump, circulation pumps, auxiliary heater and, if applied, DHW boilers). Since the network is small, the energy consumption of the circulation pumps is small (ca. 6000 kWh per year). High comfort levels are to be guaranteed to consumers, while physical space occupation and work required inside dwelling is to be minimized. This paper summarizes the work developed by Wolbert [1] in the frame of the 'Energiek Nagele' project.

## 2. System configurations

### 2.1 Alternative solutions

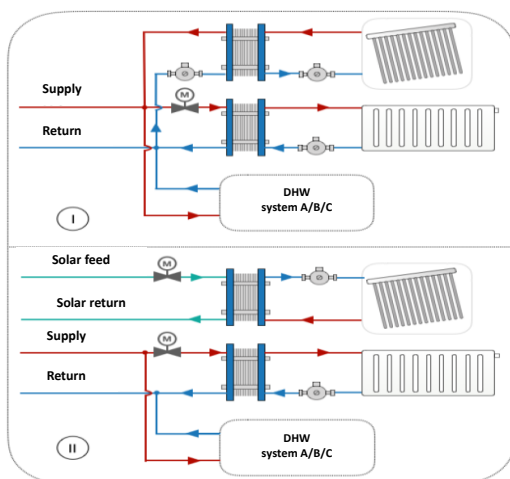
Typical district heating systems (DHS) consist of three main components: An energy source, a distribution network, and more than one end-user. This paper examines solar-based DHS with an additional component: an Underground Seasonal Thermal Energy Storage (USTES). In Nagele, 24 buildings will be connected to a small district heating network powered by decentralised solar thermal energy. The aim of this study is to optimize the district heating part of the system for operation in conjunction with solar collectors and storage. The performance of the system is measured in LCOH. Several network configurations are dynamically modelled and compared. Three main approaches are considered to improve overall system performance; Firstly, the implementation of a four-line network so that the solar collectors do not feed into the heating network, but have their own dedicated network instead; Secondly, an approach where the DHW systems of consumers are altered in order to allow lower supply temperatures; Finally, the introduction of a variable supply temperature based on the ambient temperature. In total, seven different combinations are compared:

- 0-A: Base case, fixed supply temperature, 2-line network, DHW system A
- I-A: Variable supply temperature, 2-line network, DHW system A
- I-B: Variable supply temperature, 2-line network, DHW system B
- I-C: Variable supply temperature, 2-line network, DHW system C
- II-A: Variable supply temperature, 4-line network, DHW system A
- II-B: Variable supply temperature, 4-line network, DHW system B
- II-C: Variable supply temperature, 4-line network, DHW system C

### 2.2 Two-line and four-line networks

In this study, two main pipeline configurations are considered, both of which are shown in Fig. 1. In both configurations, three heat exchangers per consumer are used to achieve hydraulic separation between the network on one side, and the solar collectors, heating system, and DHW system on the other side.

In system I, there are just two pipelines to which every consumer is connected. Through these pipelines, heat is delivered from the buffer to the consumers, but also the solar energy generated by the solar collectors is transported from the dwellings to the buffer. The biggest benefit of this system is its simplicity and the resulting reduced installation costs since only two pipelines have to be used. System II is unique in the way that it uses a separate network for the solar collectors, much like the Drake Landing solar community in Canada as described by Sibbitt et al. [2].



**Fig. 1** - Two main network configurations. In configuration II, the solar collectors feed in to their own dedicated network. In configuration I, the solar collectors feed in to the heating network, mitigating the need for this dedicated network for the solar collectors.

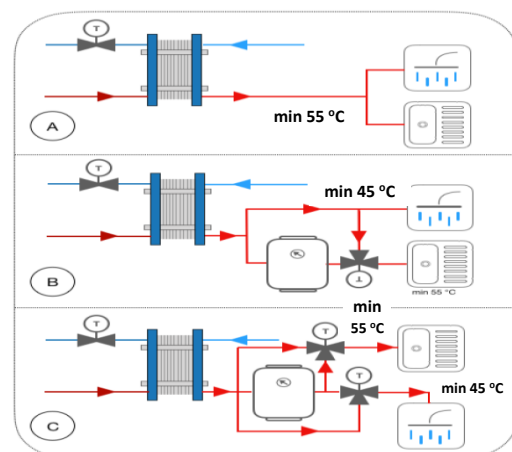
The main presumed benefit of this system is an increase in efficiency of the solar collectors since they can operate at lower temperatures. Also, it eliminates the need of one circulation pump per consumer.

## 2.3 Supply temperatures

Low supply temperatures allow for the use of a wider range of materials and it results in lower return temperatures, which lead to higher solar collector efficiencies. The supply temperature is constrained by several factors: It needs to be sufficiently high to provide enough capacity for space heating, it needs to be high enough to produce DHW according to Dutch legislation, and it is influenced by outlet temperature of the solar collectors. The houses in Nagele are suited so that a supply temperature of 70 °C is sufficiently high to provide enough space heating power year round. However, required space heating power obviously is greatly dependent on

weather conditions and is therefore not equal throughout time. Because of that, the supply temperature could be made weather dependent: For higher ambient temperatures, the supply temperature could be lower than the 70 °C needed at low outdoor temperatures. As a result, average network temperatures can be reduced, yielding the advantages listed above. The main constraint in lowering supply temperatures, is the preparation of DHW, since minimum temperatures need to be achieved in order to provide enough comfort and mitigate Legionella growth. The most common method of DHW preparation in district heating networks, is direct preparation through a plate heat exchanger. This method is described by DHW concept A below. Two other concepts (B and C) are conceived which aim to reduce the minimum network supply temperature.

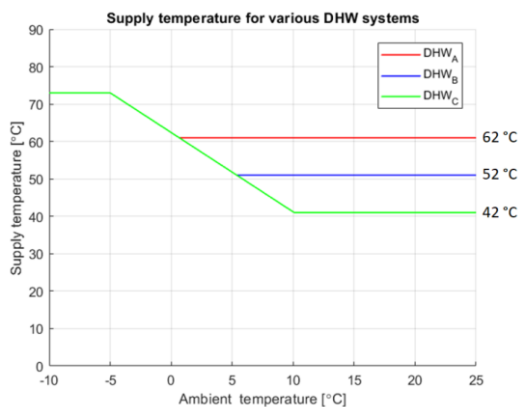
**DHW concept A:** A single heat exchanger provides all hot water using the heating network as the sole energy source. The minimum DHW supply temperature at tapping locations is 55 °C for non-sanitary purposes, while DHW for sanitary purposes can have temperatures below that. A mean temperature difference over the heat exchanger of 5 K is assumed (based on research by Yang & Svendsen [3]). Also, there will be (small) thermal losses in the pipelines between the heat exchanger and tapping location. The minimum network temperature at the heat exchanger is 61 °C.



**Fig. 2** - Three DHW preparation concepts. Concept A uses only a heat exchanger, requiring the outlet temperature of the heat exchanger to be at least 55 °C. Concept B uses an electric heater to reheat the DHW for kitchen use, reducing the required temperature at the outlet of the heat exchanger to 45 °C. Concept C uses an electric heater to reheat the DHW for all purposes, further reducing the required temperature at the outlet of the heat exchanger. Thermostatic valves are added to limit the outlet DHW temperature to the required level.

**DHW concept B.** Most of the time, ambient temperatures would allow the minimum supply temperature to be lower than 62 °C. Since this constraint is set by the minimum DHW temperatures, methods are explored to break this constraint. The temperature of DHW for sanitary purposes (which makes up 87.4% of total DHW

demand) is allowed to be below 55 °C in residential environments. Concept B, shown in Fig. 2, makes use of this exception by using an in-line heater to heat non-sanitary water to the 55 °C level. The minimum temperature for sanitary DHW is chosen to be 45 °C, as this seems to be the highest temperature at which consumers shower/bathe. One important component of this concept, is the thermostatic mixing valve after the electric boiler. This allows the hot water tapping temperature to remain constant also for higher boiler temperatures. This is important in Nagele, since space comes at a premium. By using the mixing valve, the boiler temperature can be higher, which increases the stored energy. The advantage is that network temperatures can decrease for relatively high ambient temperatures. The network supply temperature (at consumer level) can vary between 52 and 73 °C. The additional costs compared to DHW concept A are low, since only a small boiler (in the order of 10-15 L) is needed.

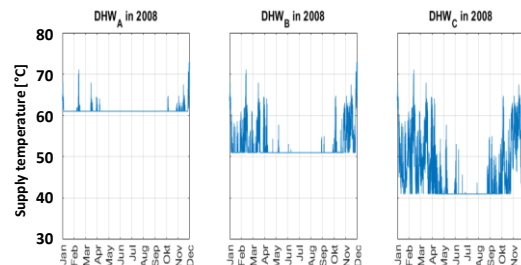


**Fig. 3** - Supply temperatures for all DHW concepts as a function of ambient temperatures.

**DHW concept C.** Concept B is constrained by the 45 °C temperature needed for sanitary purposes. This is resolved in concept C (shown in Fig. 2), where the sanitary water is also heated by the boiler to reach the minimum service level. While theoretically there is no minimum network temperature for this concept since all DHW energy can be supplied by the boiler, this would incur high electricity consumption. Also, there is not enough physical space available at the consumers in Nagele to place sufficiently large boilers. Therefore, the minimum DHW exit temperature of the heat exchanger is chosen to be 35 °C. The reason being that, in combination with a relatively small 40 L boiler at 85 °C, 200 L of 45 °C DHW can be produced, which is assumed to be a very comfortable amount for the consumers. This concept goes further than concept B in achieving lower network temperatures at the cost of higher electrical energy consumption at the consumer level and slightly higher costs of installation. Electrical consumption will be higher when network temperatures are low, but lower average network temperatures have their benefits. In such a configuration, the network supply temperature (at consumer level) can vary between 42 and 73 °C.

**Supply temperatures of all systems.** DHW systems B and C are conceived in order to reach lower network temperatures than system A allows. In Fig. 3, the supply

temperatures of all three concepts are shown. It is clear that for concepts B and C, the system can operate at lower supply temperatures.



**Fig. 4** - Simulated supply temperatures for all DHW concepts for the year 2008.

In Fig. 4, the simulated supply temperatures for the year 2008 is shown for all three concepts. Ambient temperature data from the KNMI [4] for the location Marknesse is used. Marknesse is roughly 13 km from Nagele. When looking at the graph, it can clearly be seen that the peak supply temperature of 73 °C is rarely reached. While it appears that network B and C operate at much lower temperatures most of the time, note that the temperatures displayed are the supply temperatures assumed necessary to properly heat the buildings and provide their DHW. It is the minimum temperature needed in the supply lines of the network at the consumers. Therefore, in the two-line network where the solar collectors feed in over the same pipelines, the actual supply temperatures will be higher at times. Especially at the end of summer when buffer temperatures (and thus solar inlet temperatures) are high, the outlet temperatures of the solar collectors will be significantly higher than the service level temperatures.

### 3. DHN

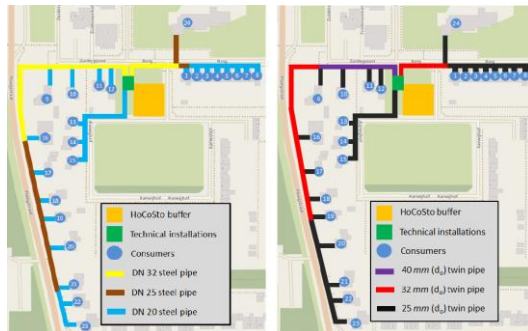
The pipelines are sized by imposing a limit on the fluid velocity. In picking an appropriate maximum fluid velocity, it is important to understand that peak power (and thus peak fluid velocity) only rarely occurs in the network. The average power is much lower. Therefore, the economic optimum peak fluid velocity will be relatively high. The pipelines are sized so that this peak fluid velocity does not exceed 2.5 m/s. Two different network configurations are considered in this study: A steel 2-line heating network where the solar collectors feed in to the heating network, and a 4-line network consisting of 2 PE heating pipes and 2 steel solar pipes.

#### 3.1 Two-line network (configuration I)

The two-line network consists of two steel pipelines. The total required pipe length is 691 m. The peak power at every section is determined by either the maximum heating load (space heating + DHW) during cold days, or by the maximum solar yield during hot sunny days, since the solar collectors feed in over the network. The  $\Delta T$  between supply and return for space heating is assumed to be 20 K, while the  $\Delta T$  for DHW preparation is assumed to be 50 K. The pump of every solar array is chosen so that it can



provide enough flow to keep the  $\Delta T$  at a maximum of 30 K during peak power. The DHW peak demand is assumed to be 25% of the absolute peak, since not all consumers will consume DHW simultaneously. In Fig. 5, the resulting pipeline topology and dimensions of network I are shown. In total, 185 m of DN32, 165 m of DN25 and 341 m of DN20 are needed. The peak solar power is leading in diameter selection on every section.



**Fig. 5** – LHS: Layout of the steel pipe network which shows pipe diameters for every section. RHS: Layout of the flexible twin pipe network which shows pipe diameters for every section.

### 3.2 Four-line network (configuration II)

The 4-line network consists of a PE heating network to satisfy space heating and DHW loads, and a steel pipeline network to transport the thermal energy generated by the solar collectors to the buffer. Since the solar yield was leading for diameter selection of the steel pipelines in the 2-line network, the steel network in the 4-line configuration will be equally sized. The PE pipelines are scaled using the peak power in the network: 75 m of DN40, 200 m of DN32, and 416 m of DN25.

## 4. Seasonal thermal energy storage (STES)

The seasonal thermal energy storage (STES) to be used in the project in Nagele, is one supplied by the company Hocosto. It is an underground seasonal thermal energy storage (USTES) pit type, with water as a heat carrier medium. A patented aluminium frame allows Hocosto to install buffers quickly, and cheaper than any other thermal storage solution. Since the frame can carry large loads, the space above the buffer can be used effectively, for example as a parking lot. Further details of the USTES can be found in a companion paper by ter Meulen et al. [5]. Discharging the buffer is done by extracting fluid from the top of the buffer and returning it to the bottom of the buffer. Charging is done the other way around. The buffer system will be insulated on all sides using XPS (extruded Polystyrene).

## 5. System model

The model uses KNMI weather data for the 5-year period from 01-01-2008 till 31-12-2012. Because it

is important to have realistic buffer temperatures at the start of the simulation, the first year is not used in the results.

### 5.1 Consumers

In order to simplify the model and reduce simulation times, the 24 consumers in the network have been aggregated in 6 clusters, taking type and size of the dwellings, as well as their locations into account. For every cluster, all heat flows (space heating, hot water demand and solar generation) are simulated (see [5] to see how the model has been calibrated). As a result, the mass flow and inlet/outlet temperatures at every consumer level are calculated. Since the network is branched and bidirectional, fluid flows will occur directly between the solar collectors and the space heating and DHW heat exchangers. Therefore, it cannot simply be assumed that the inlet temperatures of the DHW and space heating heat exchangers are equal to the network supply temperature, and neither can it be assumed that the inlet temperature of the solar collectors is equal to the network return temperature. For that reason, the fluid temperatures at the consumer level are calculated for each time step depending on the fluid flows (and their inlet/outlet temperatures) through each of the three heat exchangers at the consumers, and the flow to or from the network. For example, when the supply temperature of the network is 60 °C, the solar collectors operate at an outlet temperature of 80 °C and 5 L/min, the DHW heat exchanger would have an inlet temperature of 70 °C at 10 L/min. This is especially relevant for the solar collector efficiency, since it is very dependent on its inlet temperature.

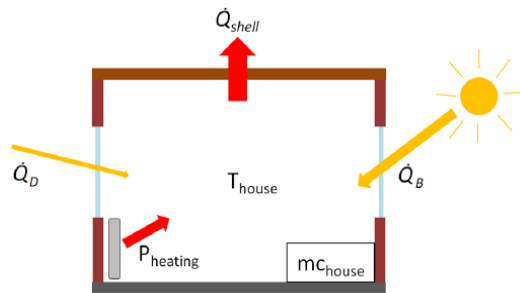
**DHW:** The heating load consists not only of space heating, but also of the production of domestic hot water (DHW). Based on Fuentes et al. [6], demand profiles are generated for all consumer clusters. The demand is separated into three different categories: Showers, baths and tapping (kitchen etc.). The flow rates expressed in L/min of 45 °C for showers and baths, and 55 °C for tapping. Variations are given between households in time of occurrence, longevity, and flow rate. The means are based on DIN 1988-300 [6]. The average drawn volume per household per day is 80, 20 and 28 L/day for showers, baths and sinks, respectively. The heat exchangers for DHW production are scaled so that at maximum power, the temperature difference over the exchanger is 5 K. The mean temperature difference over the heat exchanger for every time step is obtained by assuming a constant UA-value of 500 W/K for the heat exchanger.

One of the most important differences between DHW concepts, will be the boiler electricity consumption. The energy consumption of the electric boilers consists of both energy delivered and heat losses. Since the boilers are kept at a constant temperature, the heat losses of the boiler are introduced as a fixed loss. The loss equals 20 W for the small boilers, and

35 W for the larger boilers.

## 5.2 Space heating

For the space heating requirement, it is not only important to know the power required by the consumers, but also the mass flows and temperatures of these mass flows. Therefore, a heating system is modelled for every cluster. Fig. 6 shows the energy balance which is made for the clusters.



**Fig. 6** - Energy balance of a consumer, with the beam (B) and diffuse (D) solar gains, heat losses through the shell (shell) and heating gains (heating + heat capacity).

For each time step, the room temperature is updated using the heat flows in and out of the building. Ventilation and infiltration have been aggregated with the shell losses. The UA-value of each cluster has been calibrated with the measured energy consumption of the cluster.

## 5.3 Solar collectors

The solar collector output is modelled per time step, depending on the solar irradiance and the solar collector efficiency. The position of the sun and the angles and power of beam radiation on the inclined surfaces have been modelled using methods described by Duffie & Beckman [7].

## 5.4 Pipelines

The two-line system will use two steel-PUR-PE pipelines, while the 4-line system will use two steel-PUR-PE lines for the solar loop, and PE-twin pipelines for the heating network. The heat losses have been calculated as proposed by Miltenburg [8]. Additionally, considering the discussion by Wallenten [9], when pipes are laid in the ground close to each other their heat losses cannot be calculated independently. The problem of two pipes close to each other in the ground can be divided into two problems: A symmetrical and asymmetrical problem, where the symmetrical problem represents heat loss from the pipes to the surroundings and the asymmetrical problem heat transfer from one to another pipe. While the resulting equations can easily be used to calculate steady state heat losses, implementation in the model is slightly more difficult since both soil surface and fluid temperature are not constant. To overcome the varying soil temperatures, the soil temperature at a larger depth of 0.2 m is

taken instead of the surface temperature. The result is that the new environmental temperature is much more stable with just a gradual seasonal variation. Since the resistance over the insulation dominates over the heat resistance of the soil, the assumption that the soil temperature at a depth of 0.2 m is undisturbed seems reasonable. The effects of the variable fluid temperature are ignored, since the thermal resistance of the insulation is much higher than that of the soil. This results in minimal temperature differences of the soil.

## 5.5 Heat pump

This heat pump has been assumed to achieve a system efficiency equal to 40% of Carnot efficiency. The 40% system efficiency includes the temperature differences over the heat exchangers at both sides of the heat pump.

## 5.6 Component costs

Table 1 provides a summary of the costs.

**Tab. 1** - Cost overview of the system components.

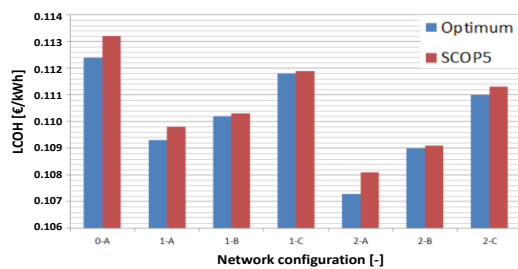
Component	Cost [€]	Capacity
USTES	150	m <sup>3</sup>
w-w Heat Pump	500	kW
Delivery kit	1000	consumer
Evacuated tube collectors	450	m <sup>2</sup>
Central installations	35000	-
2-line DHN	180	m
4-line DHN	255	m
Electricity 0-10000 kWh	0.178	kWh
Electricity 10000-2500000 kWh	0.150	kWh
Maintenance	1.2%	CAPEX

# 6. Results

## 6.1 Comparison of optimum designs

Fig. 7 shows the LCOH for the optimum design of all configurations for both the absolute economic optimum as well as for the situation where an SCOP of 5 has to be met. The economically most attractive system is configuration 2-A with 1100 m<sup>3</sup> of buffer and 900 m<sup>2</sup> of solar collectors. The cost benefit however, is just 0.5 cents per kWh, or 4.5% compared to the base scenario 0-A with 1275 m<sup>3</sup> of buffer and 1100 m<sup>2</sup> of solar collectors. Sizing the buffer volume and solar area slightly larger does not increase LCOH considerably, but does increase SCOP profoundly. This is also seen in Fig. 7, where the systems with a minimum SCOP of 5 are only slightly more expensive than systems without this

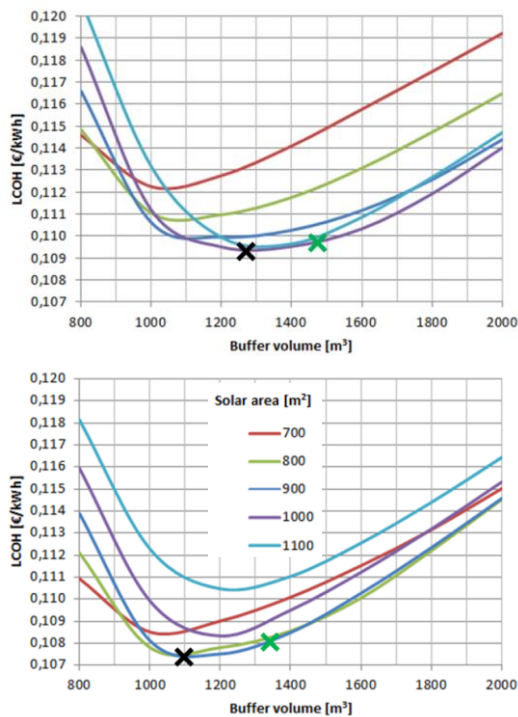
constraint.



**Fig. 7** - Lowest LCOH and LCOH for a minimum SCOP of 5 for every system configuration.

## 6.2 LCOH of best 2 and 4 line systems

Fig. 8 shows how the LCOH varies with buffer size and solar collector area for the best 2 (TOP) and 4 (BOTTOM) line systems.



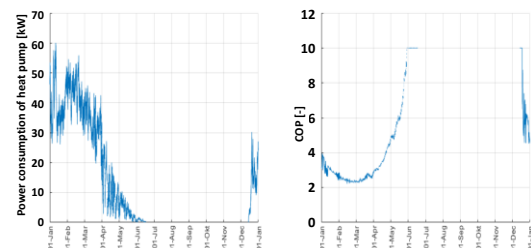
**Fig. 8** - TOP: LCOH for configuration 1-A at various buffer volumes and solar areas. BOTTOM: same for configuration 2-A.

Configuration 1-A (Fig. 8 - TOP) is a 2-line network which aims to improve system performance by implementing a variable supply temperature. The minimum supply temperature is restricted to 62 °C due to constraints in the DHW system. This lower supply temperature results in slightly lower pipeline losses, lower heat pump electricity consumption and higher solar collector efficiency. At the absolute economic optimum (1000 m² solar collector area and 1275 m³ buffer), the LCOH is 0.109 €/kWh. Fig. 8 also displays the required design values to reach an SCOP of 5 (1000 m² solar collector area and 1475 m³ buffer). The LCOH is then 0.110 €/kWh.

Configuration 2-A (Fig. 8 - BOTTOM) is a 4-line network where the solar collectors supply heat to the buffer through a separate network. It aims to increase solar collector efficiency by allowing them to operate at lower mean temperatures. The supply temperature of the heating network is variable, but limited to a minimum of 62 °C due to DHW production constraints. Fig. 8 shows the LCOH for various buffer volumes and solar collector areas. The LCOH of 0.107 €/kWh is the lowest attained. When the constraint of having to achieve a SCOP of 5 is to be met, the LCOH increases to 0.108 €/kWh.

## 6.3 Power consumption and COP of heat pump

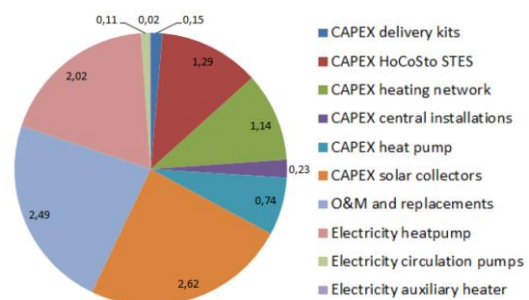
Fig. 9 shows the electric power consumption of the heat pump and its corresponding COP for the year 2009. The heat pump is mainly active in late winter and spring. This was expected since these are the periods where the buffer temperatures are low. Correspondingly, it is at these times when buffer temperatures are low that the COP is also lower. Note that the COP is capped at 10, since it is not realistic that higher COP's can be achieved. The impact of this on the results is extremely limited since the heat pump is barely operational when higher COP's could be achieved, as can be seen in Fig. 9.



**Fig. 9** - Electric power consumption and COP of heat pump in 2009. Configuration 2-A, scaled to have a SCOP of at least 5. 900 m² of solar collectors, 1325 m³ of buffer.

## 6.4 Performance of configuration 2-A

Configuration 2-A achieves the lowest LCOH for both the absolute cost optimum, as well as for the scenario where a SCOP of at least 5 has to be met.

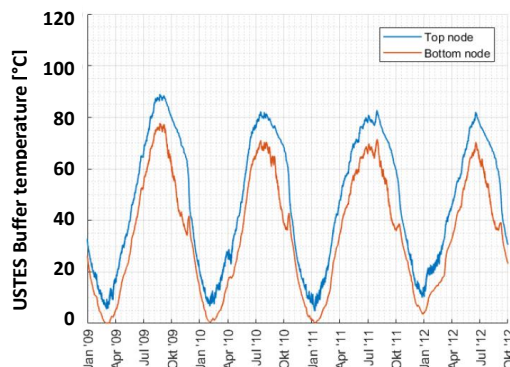


**Fig. 10** - Cost breakdown for configuration 2-A in €/cent/kWh with scaling for SCOP of 5.

Fig. 10 shows a cost breakdown for configuration 2-A sized to reach a SCOP of 5. Slightly oversizing the buffer reduces the electricity consumption from the



auxiliary heater, but increases buffer CAPEX and O&M. The lower auxiliary heater electricity consumption follows from the lowest buffer temperatures which are higher when the buffer is scaled slightly larger, see Fig. 11..



**Fig. 11** - Buffer temperatures for configurations 2-A, sized to have a SCOP of at least 5.

### 6.5 Comparison with individual air-water heat pumps and conventional gas heating

If every participating building is outfitted with an individual high temperature air-water heat pump, the model predicts an average LCOH of 0.127 €/kWh, consisting of 0.87 cents in O&M, 6.87 cents in electricity costs, and 4.99 cents resulting from CAPEX. The SCOP over the 5 simulated years is 2.75, which roughly aligns with claims from air-water heat pump manufacturers. Comparing this scenario with configuration 2-A of the DHS, configuration 2-A achieves an SCOP of 4.4 for a cost of 0.107 €/kWh, the individual heat pump scenario is 18.6 % more expensive, and consumes 63.6 % more electricity. Based on a price of 0.67 €/m<sup>3</sup> of natural gas, a boiler efficiency of 90 %, annual maintenance costs of 100 €, initial CAPEX of 1500 € and 20 year boiler life, the LCOH of heating with natural gas is estimated as 0.082 €/kWh. This is significantly lower than the lowest achieved LCOH of 0.107 €/kWh by the proposed DHS. However, the extra costs related to the damage of the environment are not incorporated into the natural gas heating LCOH.

## 7. Conclusions

The LCOH decreases when a variable supply temperature is adopted instead of a fixed supply temperature of 73 °C. Best option is when a single heat exchanger provides all hot water using the heating network as the sole energy source and the supply temperature is environmental temperature dependent. Decoupling the solar collectors from the heating network by implementing a 4-line network reduces the LCOH. The decrease of the LCOH results from the significant increase in solar collector efficiency which results from the lower operating temperatures. The advantage is larger for a 4-line network where the operating temperature of the solar collectors can be optimized.

Slightly oversizing the solar collector area and buffer volume greatly reduces the electricity consumption of a system (and so increases the SCOP), without significantly adding to the costs keeping a similar LCOH. A 30 % lower electricity consumption can be achieved when a 1 % higher heating cost is accepted compared to the cheapest sizing. Solutions with supply temperatures requiring additional electrical heating of the DHW in buffers are not cost efficient. The cost increases due to higher CAPEX, increase in thermal losses, and a shift in electricity consumption from the centralised location to decentralised locations (where the electricity tariff is higher). While the proposed DHS can reach LCOH values of 0.107 €/kWh, individual air-water heat pumps in each building results in an LCOH of 0.127 €/kWh.

### Data access statement

The datasets generated during and/or analysed during the current study are not publicly available because MSc thesis [1] is under embargo but will be available at the end of embargo period.

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