INTEGRATION OF HEAT AND ELECTRICITY SECTORS WITH HEAT PUMP FURNISHED VARIABLE TEMPERATURE DISTRICT HEATING

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Abstract - In this work, the novel concept of non-uniform temperature district heating system with decentralized heat pumps and stand-alone heat storage units is proposed. In this system, the temperature within the transmission pipeline is always at the ultra-low level and the heat pumps will increase the temperature to 70^{o}C during a short period a day to provide the domestic hot water need of the consumers. Heat pumps are sized in neighborhood scale, and each heat pump is assigned for a few neighborhoods. By such a design, a strong synergy between the heat and electricity sectors is made, the rate of heat loss is minimal, a high potential for employing low-grade renewable sources is made, and the legionella risk is absolutely zero. These features are all the important characteristics of the smart energy systems. The system is designed and analyzed for a case study. It is demonstrated that the proposed system shows the best performance compared to any other district heating solution.

Keywords - District heating; Non-uniform supply temperature; Decentralized heat pump, Stratified storage tank.

I. INTRODUCTION

According to [1], in a Smart Energy System (SES), there must be concrete synergies between the district heating (DH) system and the other energy sectors, especially electricity. As such, DH is a high capacity sector for utilization of renewable sources, which is a further feature of the SES [2].

Today, lower-temperature DH (LTDH) systems are emerging.The two main objectives of decreasing the supply temperature in a DH system is decreasing the rate of loss and increasing the potential for utilization of more renewable sources [3]. The risk of legionella generation and the inability for domestic hot water (DHW) preparation are two of the main challenges of such systems. Yang et al. [4]an energy, exergy and economic analysis of various solutions for DHW supply with LTDH systems. Olsen et al. [5] presented a sort of propositions for facilitating the development of a 50 °C-LTDH system. Wang et al. [6] proposed and analyzed the combination of high- and low-temperature DH systems for energy-efficient buildings. The use of heat pumps in the substations was another solution offered for DHW preparation in a ULTDH system [7].

Ommen et al. [8]. Investigated several different configurations of substations with an individualheat pump. Kamal [9] discussed the practical methods of integrating the existing DH systems with the future DH systems. Ziemele et al. [10] analyzed the feasibility of a smartDH system in Latvia and assessed various policies. Paiho and Reda[11] did the same for Finland and discussed the challenges on the way of transition for the current DH system to the future system.

In this work, the new scheme of non-uniform temperature DH system with decentralized heat pumps and stand-alone heat storage tanks (NUTDH-HPHS) is proposed and analyzed. In this system, the transmission pipeline of the DH network is always at the low temperature of 40 ^{o}C. Decentralized neighborhood-scale heat pumps increase the temperature of each neighborhood to 70 ^{o}C for a short time every day. Each heat pump may supply a few neighborhoods in turn. The substations are equipped with heat storage units. In order to assess the proficiency of the proposed system, it is designed and analyzed for a case study in Denmark and its performance is compared with the other popular DH schemes.

II. NUTDH-HPHS VS. OTHERS

In this section, the main features of the NUTDH-HPHS system together with some of the most popular DH schemes are discussed.

A. LTDH System

In an LTDH system, the supply and return temperatures are 50-55 ^{o}C and 25-30 ^{o}C, respectively [5]. The rest of the system characteristics, e.g. the piping system, heat suppliers, etc., are just similar to the currently in operation DH system worldwide. The LTDH scheme is much appropriate for Denmark, as this supply temperature range is enough for DHW preparation in this country with DHW comfort temperature of 45 ^{o}C, while this cannot be appropriate for locations with higher comfort temperatures.The best configuration of the substation for this DH system is an instantaneous heat exchange unit (IHEU). Figure 1 shows the schematic of this type of substation for this DH scheme with marked temperature values on it.

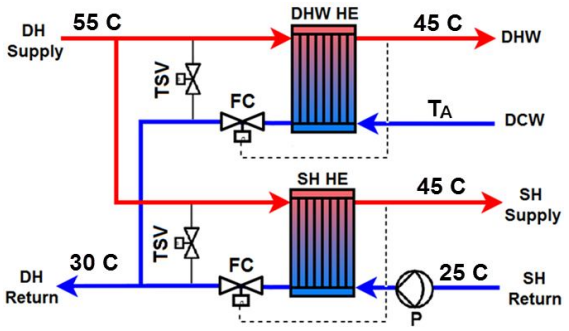


Figure 1 Schematic of an IHEU Substation in an LTDH system; SH: space heating, HE: heat exchanger, P: pump, DCW: domestic cold water, FC: flow controller, TSV: thermos static valve.

B. Ultra-LTDH System

In an ultra-LTDH (ULTDH) system, with the same main characteristics as the LTDH system, the supply and the return temperature ranges are 35-45 ^{o}C of 25-30 ^{o}C. As this supply temperature range is not sufficient for direct DHW supply, there should be an auxiliary system for boosting the temperature to the comfort level.One of the most popular substation types for this DH scheme is individual heat pump furnished units (IHPFU). Figure 2 illustrates the schematic of an IHPFU substation, in which the hot water supplied by the DH is used for space heating and the DHW demand is provided by a heat pump. A thorough explanation of various HPF substation designs may be found in [8].

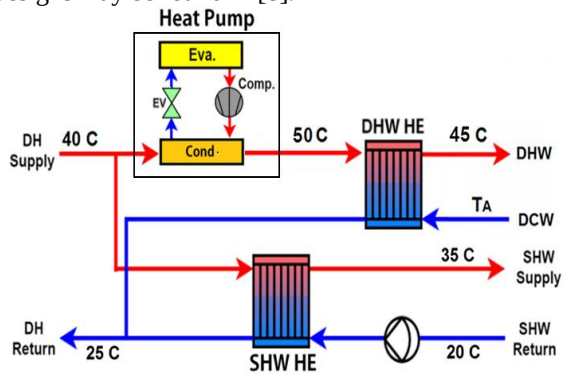


Figure 2 Schematic of an IHPFU Substation in a ULTDH system.

C. NUTDH-HPHS System

The proposed NUTDH-HPHS system works based on an ultra-low temperature in transmission pipeline all the time, and through the distribution pipes over a major time of the day. The decentralized neighborhood-scale heat pumps will increase the temperature of supply for each neighborhood from the ultra-low level to a moderate level during a few hours a day for each neighborhood. The substations in this scheme are equipped with a storage tank to store heat for DHW use when heat pump is supporting the given neighborhood. In addition, the heat pumps offer thermal disinfection for the entire piping in the system so that the legionella risk is totally prevented. Based on the operation strategies designed for this DH scheme:

a) The space heating demand is supplied by the ultra-low temperature level of 40 ^{o}C, while the temperature 70 ^{o}C is applied for a short period a day for DHW preparation.

b) The upper and lower design temperatures are chosen based on the comfort standard temperatures, the temperature drop along the pipeline, and the expected efficiency of the heat exchangers effectiveness factor.

c) Decentralized heat pumps, in neighborhood scale and each heat pump for supporting a few neighborhoods, are employed for increasing the ultra-low supply temperature to the desired medium temperature.

d) As high-temperature supply is only available a few hours a day, heat storage tanks are required at the substations. Helically coiled heat storage units are the best choice among all heat storage options. Overall, the substation comes with the configuration shown in Figure 3.

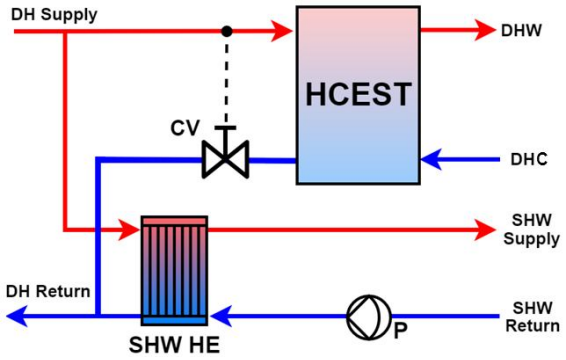


Figure 3 The schematic of the substation of a NUTDH-HPHS system; HCEST: helically coiled energy storage tank.

III. MATHEMATICAL MODEL

The first step in modeling a DH system is calculating the rate of heat demand in the network and sizing the pipeline based on the maximum load of the system. The rate of heat loss from a piece of pipe, with x m length, can be calculated by:

$$\dot{Q}_l(x) = UA_l(x)(T_{in} - T_s) \qquad (1)$$

in which, T_{in} is the temperature of the fluid within the pipe, T_s is the temperature of the surrounding andUA_l is the overall heat loss coefficient. Dividing the pipe into several small divisions with x m length each and constant temperature, assuming a constant surface temperature internal flow, the temperature of water through the next divisions is calculated as:

$$T_e = (T_i - T_s)\exp\left(\frac{UA_l x}{\dot{m}c}\right) + T_s \qquad (2)$$

where,T_e is the outlet temperature of the fluid in the previous pipe division (the inlet of the next division), T_i is the inlet temperature of the previous division. $\dot{m}$is the mass flow rate, and c is the thermal capacity of water.

For calculating the rate of pressure drop along the pipeline, two sources of pressure reduction should be considered. These are pressure losses because of

friction (major) and the minor losses due to the other factors. It is recommended to consider the minor losses as 20% of the major losses in a water pipeline. Therefore, the total pressure loss in a DH pipeline with x m length could be calculated by:

$$\Delta P_t = 1.2\,\frac{f x \rho u^2}{2 d_{in}} \qquad (3)$$

in which, u is velocity and f is Darcy friction factor. Having the value of the pressure losses, and the specific volume of water (v), the work of the booster pumps for compensating the pressure losses is calculated by [12]:

$$\dot{W}_p(x) = \dot{m} v \Delta P_t = \frac{0.6 f \dot{m} x u^2}{d_{in}} \qquad (4)$$

For the plate heat exchanger in the substations, considering counter-flow heat exchangers and the effectiveness factor of 0.8 for each, the heat transferred from the DH water to the secondary side of the heat exchanger is given by [13]:

$$\dot{Q}_{hx} = UA_{hx}\Delta T_{lm} \qquad (5)$$

where,UA_{hx} is the overall heat transfer coefficient of the heat exchanger and $\Delta T_{lm}$is the logarithmic mean temperature difference.

In addition to the common components employed in various DH schemes, there are two components that are specifically only for the NUTDH-HPHS system, i.e. the heat pump and the individual heat storage tanks. Regarding the heat pumps, the heating duty of the heat pumps could be calculated by:

$$\dot{Q}_{hp} = \dot{m}_{dh,n} c_p \left(T_{high} - T_{low}\right) = \dot{Q}_{l,n}\left(\frac{\beta_{hp}}{\beta_{hp} - 1}\right) \qquad (6)$$

in which, $\dot{m}_{dh,n}$ is the mass flow rate of DH water required for the n'th neighborhood/street, T_{high} is the desired temperature after the heat pump (70 ^{o}C) and T_{low} is the temperature of DH water before the heat pump which is supposed to be at the ultra-low level. Also, β_{hp} is the heat pump coefficient of factor (considered as 4 here), and $\dot{Q}_{l,n}$ is the rate of heat that should be rejected from the heat pump working fluid to the low-temperature heat source of heat pump, which can be an air source or a ground source heat pump. The electricity required to derive the heat pump for producing this amount of heat is also calculated by:

$$E_{hp} = \dot{Q}_{hp} - \dot{Q}_{l,dh} = \dot{Q}_{hp}\left(\frac{1}{\beta_{hp}}\right) \qquad (7)$$

As mentioned, helically coiled heat storage tanks are going to be used for NUTDH-HPHS system. Such a storage tank will operate with significant degrees of stratification so that the upper layers of the tank are hotter than the lower layers. For modeling a stratified tank, the tank is divided into Γ nodes and the energy balance equation is written for each of the nodes. The result will be a set of differential equations that should be solved to calculate the temperature of the nodes.The energy balance on the node j can be written as [33]:

$$\dot{Q}^{\lambda}_{st,j} = \dot{Q}^{\lambda}_{sup,j} + \dot{Q}^{\lambda}_{ld,j} + \dot{Q}^{\lambda}_{mix,j} + \dot{Q}^{\lambda}_{l,j} + \dot{Q}^{\lambda}_{aux,j} \qquad (8)$$

in which, the superscription λ counts the time steps, and $\dot{Q}^{\lambda}_{st,j}$ is the rate of storage of heat into each node which may be explicitly calculable by:

$$\dot{Q}^{\lambda}_{st,j} = \rho c_p V_j \frac{T^{\lambda}_j - T^{\lambda-1}_j}{\Delta t} \qquad (9)$$

where, $V_j$is the volume of water in each node, and Δt is the duration of each time step (1 min in this work). The rate of heat extracted from each node to provide the DHW demand is calculated by:

$$\dot{Q}^{\lambda}_{ld,j} = \dot{m}^{\lambda}_{ld,j} c_p \left(T^{\lambda}_j - T^{\lambda}_{j+1}\right) \qquad (10)$$

where, $\dot{m}^{\lambda}_{ld,j}$ is the mass flow rate of the water extracted from the node j at each time step. The heat transfer from/into the j'th node due to the heat conductivity with the neighbor nodes is given by:

$$\dot{Q}^{\lambda}_{mix,j} = \frac{k}{\Delta y} A_j \left(2T^{\lambda}_j - T^{\lambda}_{j+1} - T^{\lambda}_{j-1}\right) \qquad (11)$$

in which, Δy is the height of each node in the tank, k is the thermal conductivity of water, and A_j refers to the cross-section area of water in the tank.

$\dot{Q}^{\lambda}_{l,j}$is the rate of heat losses from each node to the ambient during each time step and is calculated as:

$$\dot{Q}^{\lambda}_{l,j} = UA^{\lambda}_{l,j}\left(T^{\lambda}_j - T^{\lambda}_a\right) \qquad (12)$$

$\dot{Q}^{\lambda}_{sup,j}$is the heat supplied to each node through the helical coil, calculated by:

$$\dot{Q}^{\lambda}_{sup,j} = \sum_{m=r}^{R} UA^{\lambda}_m \left(\overline{T}^{\lambda}_m - T^{\lambda}_{m,ext}\right) \qquad (13)$$

where,R-r is the number of coil nodes (m) lying in each node of the storage tank (j). Note that by applying the formulation given above for the stratified tank nodes, a set of non-linear algebraic nonlinear equations is obtained, for solving which numerical methods should be employed[14].

IV. RESULTS AND DISCUSSIONS

In this section, the results of the simulations and analysis carried out on the NUTDH-HPHS system for the Danish case study is presented. Figure 4 presents information about the ambient temperature and the solar energy availability in the case study which are the two effective environmental parameters.

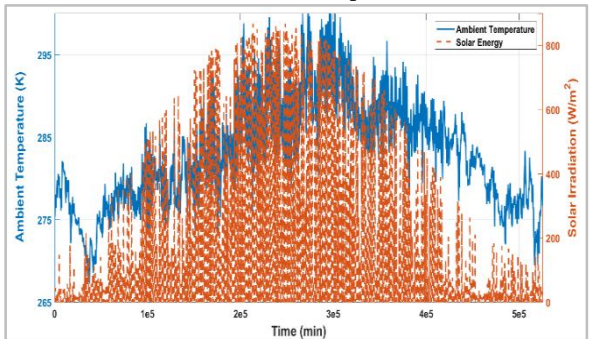


Figure4 Solar irradiation and ambient temperature in the case study over an entire year.

A randomized version of the standard Danish DHW draw-off profile is considered for the buildings of the DH network. As such, having the ambient temperature, the comfort indoor temperature, the solar energy availability, the buildings' characteristics, etc. one could make the calculation of the buildings heat demand for space heating. Figure 5 gives this information .

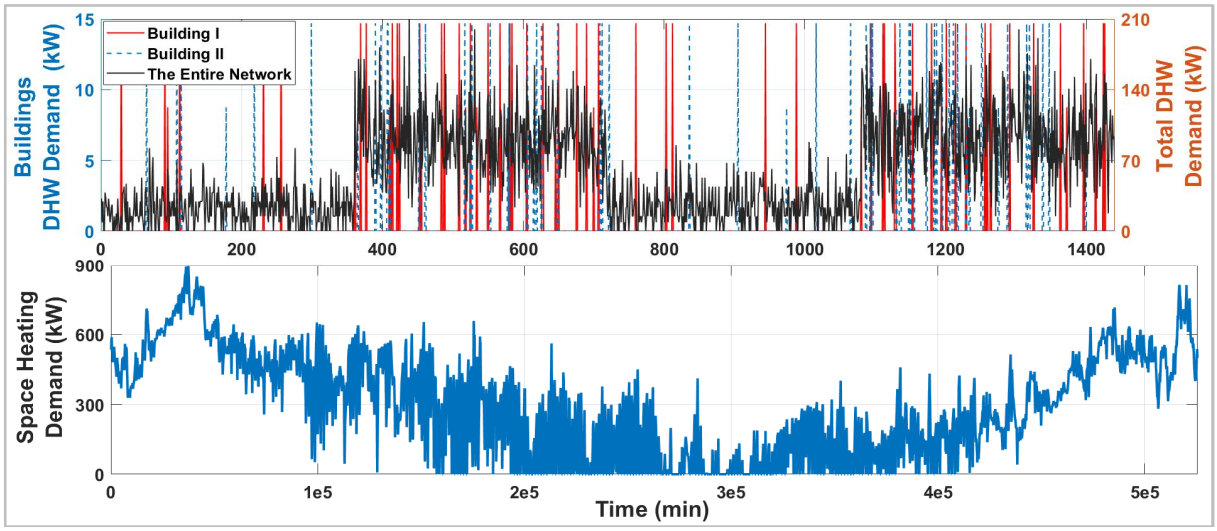


Figure5 Space heating and DHW demand profiles of the case study.

Figure 6 presents information about the total mass flow rate of the DH systems in the different cases for three consecutive winter and summer days with extreme low and high temperatures over the year. As seen, the NUTDH-HPHS case gives the higher mass flow rate with a few peak periods every day for charging the storage tanks.

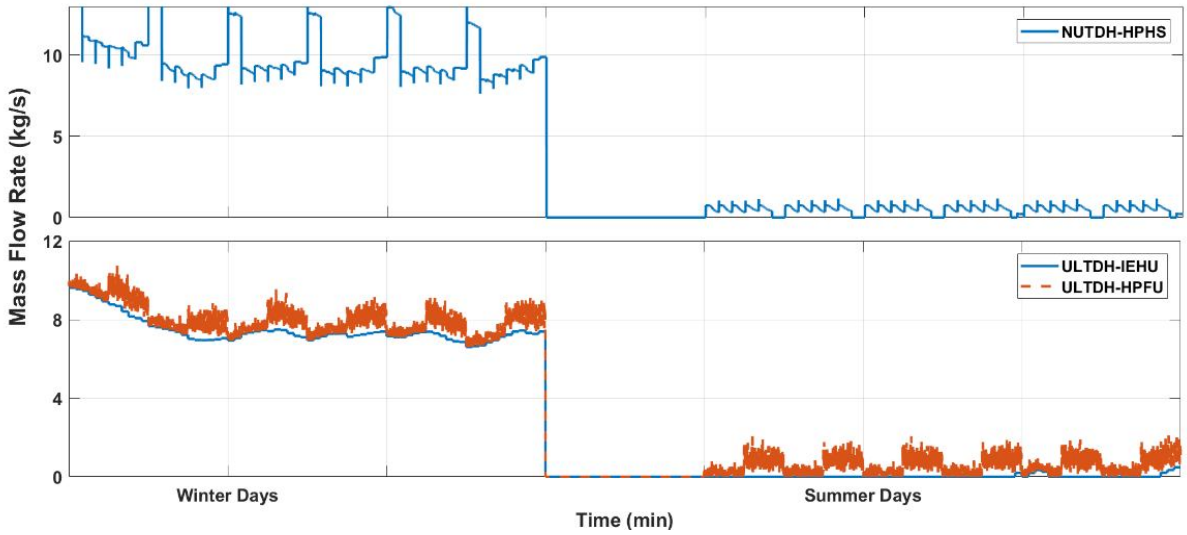


Figure6 The mass flow rate of the DH system in various scenarios.

Having the mass flow rate of the water required and the supply and return temperature in each scheme, one could size the transmission and distribution pipelines. Knowing the dimensions of the pipes, one could calculate the amounts of electricity required to run the pumps in each scheme. The investigations show that the total annual electricity consumption of the booster pumps in the NUTDH-HPHS, ULTDH-IEHU and ULTDH-HPFU systems are respectively 10.1 MWh, 15.2 MWh and 14.1 MWh. Figure 7 illustrates the rate of heat loss in different DH schemes considered in this work over the typical winter and summer days. Expectedly, because of the low supply temperature and lower load (not covering the DHW demand), the ULTDH-IEHU system offers the lowest rate of losses among all of the systems. As such, the ULTDH-HPFU presents a very interesting rate of loss. However, these two cases are not that much of interest because the former lacks from not covering the DHW demand of the network, and the former suffers from the very high cost of the substation that makes it not be cost-effective.

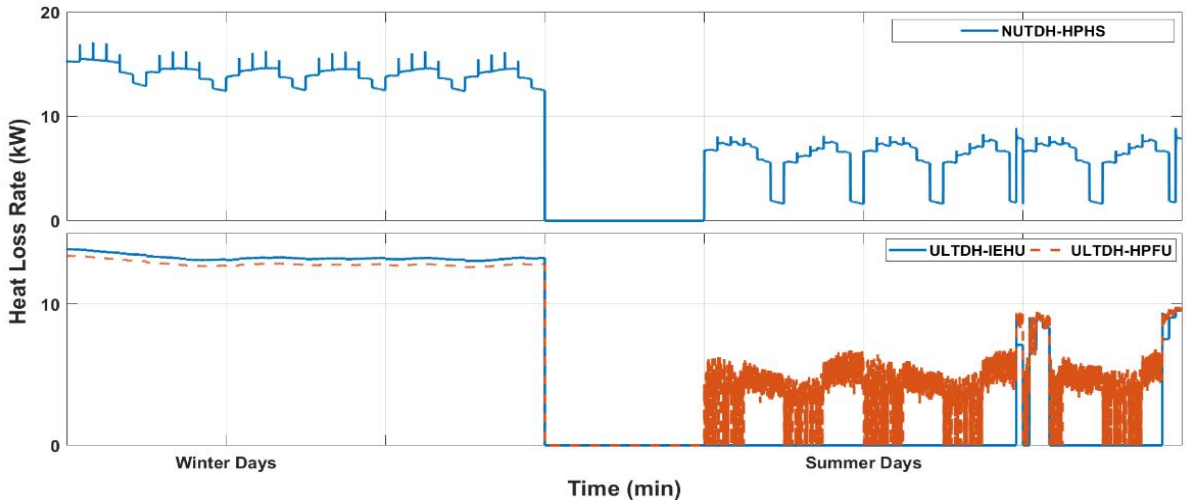


Figure7 The rate of heat losses in the entire pipeline of the considered scenarios for an entire year.

In addition, both of these cases depend on the end-users' electricity. On the other hand, the NUTDH-HPHS performs very well and shows quite efficient in terms of heat loss. Scaling the small case study to a realistic large-scale DH system, the investigations show thatthe annual heat loss of the ULTDH-IEHU system will be 10.1%. For the ULTDH-HPFU system, this value is 11.3% while the NUTDH-HPHS system shows the approximate loss rate of 13.6%.

Figure 8 presents information about the rate of electricity consumption in each of the schemes. As mentioned before, dependency on electricity cannot be considered as an advantage, especially when it is in the small-scale like buildings. However, when this dependency is in the form of a synergy between the sectors, it is a strong benefit because it will create a huge potential for cost-effective management of energy and for moving toward a smart energy system. According to the figure, the synergy of the NUTDH-HPHS system with the electricity network is extremely higher than the other cases as the heat pumps should periodically supply high-temperature water for both DHW and space heating uses while the other two cases only provide energy for DHW use.

Taking into account the presented results,it can be concluded that the NUTDH-HPHS system outperforms the other competitor DH systems in an overall techno-economic point of view. A summary of the main points in this comparison assessment is:

a) The ULTDH-IEHU is very efficient and offers a low rate of heat loss, however, firstly, it needs large pipes that is evidently costly and it does not cover the DHW demand. In addition, it will consume electricity at the substation point, which is costly and inefficient.

b) The ULTDH-HPFU unit offers a very good rate of loss and efficiency but it seriously suffers from the economic point of view where the individual heat pumps make the substation be far cost-inefficient [7].

c) The NUTDH-HPHS is the best choice as it covers both DHW and space heating loads and offers a low rate of loss. In addition, the further advantages of this system areits high potential for integration and utilization of any low-grade heat source, such as waste heat flows and low-grade renewable energy sources, and the reliable synergy that it makes with the electricity sector through the heat pumps. In large-scale applications, the synergy with the electricity grid can be highly advantageous, bringing a huge energy-economy saving and resulting in an excellent cost-effectiveness.

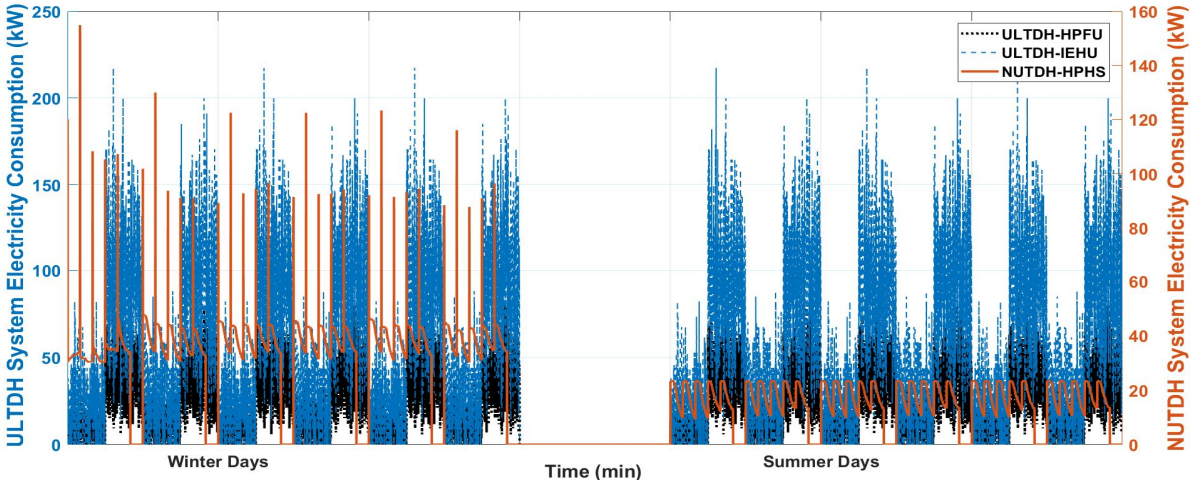


Figure8 Electricity consumption in each of the three electricity dependent DH schemes.

An important factor in the NUTDH-HPHS system is the size of the storage thank required for the substations. The main criteria for sizing the storage tanks is that none of the buildings in the network should run out of hot water, with top node temperature of at least 45 ^{o}C, at any point during the year. The assessment of the results shows that a storage tank with 265 lit volume can satisfy this condition. Figure 9 shows the variation of the temperature of the storage tanks (at three levels of the bottom, the middle and the top) over the sample chosen typical seasonal days for three of the buildings in the network located in the first, the third and the last streets. This figure shows how the storage tank is charged during the charging time and how it is discharged when the system is in low-temperature mode. As seen, the entire of the tanks approach the maximum possible level in the charging phase and never run fully out of hot water with the least temperature of 45 ^{o}C on the top in discharging phase.

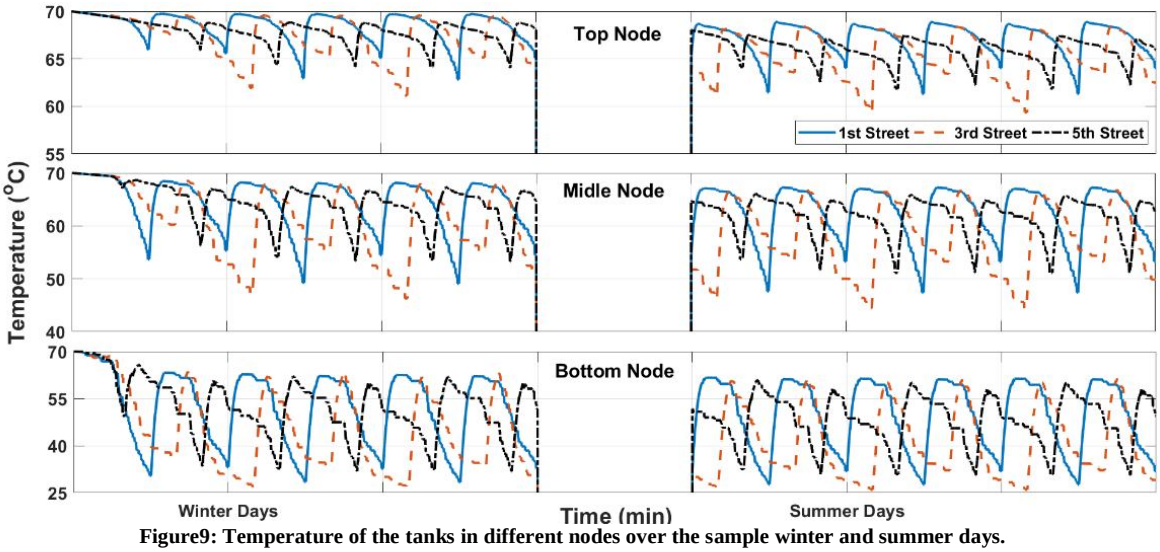


Figure9: Temperature of the tanks in different nodes over the sample winter and summer days.

CONCLUSION

This study presents a thermodynamic analysis of an innovative DH concept, so-called NUTDH-HPHS. This system operates based on an ultra-low temperature supply most of the time and a medium-level supply temperature during a short period of time a day. The high-temperature supply is provided through decentralized heat pumps and the DHW demand of the end-users if provided through standalone helically coiled heat storage tanks. The results of the investigations prove that the proposed system is highly competent, offering a very low rate of loss, a high possibility for integrating low-grade renewable energy systems and providing a concrete synergy with the electricity grid.

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