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Triple function substation and high-efficiency micro booster heat pump for Ultra Low Temperature District Heating

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Abstract. District-Heating (DH) covers around the 9% of the total heat demand in the EU, with a proven high-performance levels and low operational costs. DH may suffer adaptations in order to maintain competitiveness with individual heating systems. The most important one is the reduction of supply temperatures up to 50ºC, emerging the concept of Ultra Low Temperature (ULT) DH. ULT DH allows the transmission and distribution heat losses minimization, since heat losses are proportional to the temperature-gradient between supply line the ambient, increasing overall system performance. Furthermore, enables the integration of low-grade energy sources with low marginal costs, such as solar thermal energy or waste heat from industrial and commercial buildings. This study presents the combination of a novel 3 function-scheme (3FS) substation and a micro booster heat pump for domestic hot water. The novel design of the substation allows different operation modes between the grid and the building according to the temperature level and demand range every moment. Regarding the microbooster, this unit is used directly to lift the temperature of the domestic hot water (DHW), so that risk of legionella is avoided and that the required comfort temperature is reached. Preliminary test for the energy performance of the booster heat pump was measured on serially produced units according to tapping profiles and methodologies of standard EN16147. DHW coefficients of performance of 5.2 and 8.5 were measured for heat source supply temperatures respectively of 25 and 40 °C and return temperatures of 22 and 30 °C. This paper explores the possible operational modes of a 3FS in combination with a Building Integrated Solar Thermal System (BISTS) and a Microbooster heat pump.

1. Introduction

Energy development comprised three main routes for achieving energy decarbonisation. Regarding the production side, the main challenges are, replacing the actual generation mix based on fossil fuels by Renewable Energy Sources (RES)-based energy mix and the improvement of energy efficiency in the production systems. On the consumption side, the main challenge is to reduce the energy demand by using different techniques [1].

Regarding the consumption side, buildings are responsible for around 40% of the total energy consumption in the EU [2]. Buildings energy performance are the key for achieving the goals set by the [h2020] and the EC, by means of directives such as [3] & [4], control and regulate the situation of constructive characteristics of new buildings.

Traditional District Heating (DH) networks distribute energy from a centralized heat generation plant to a number of customers. This kind of heat generation and distribution system have resulted to be a very efficient system, especially in high urban density areas, where the heat demand is concentrated in a small area.

Actually, DH networks cover 13% of the total heat loads in buildings [5]. However, DH actually are still totally dependent on fossil fuels, with about 90% of the heat generated worldwide in these networks comes from non-renewable sources [5]. In the EU, this percentage is a bit lower in comparison with the worldwide share, but it is still a very high percentage, with around 70% of the heat from non-renewable source [5]. The opportunity to reduce the heat losses and to enhance the efficiency of supply plants – typically Combined Heat & Power (CHP) plants – has driven many DH utilities to lower network operating temperatures, thus leading to the 4th generation DH (4GDH) grids. Several studies [6-8] conclude that DH networks plays an important role in the implementation of future sustainable energy systems

1.1 4th Generation District Heating concept (4GDH)

According to [9], 4th Generation DH networks are considered those that supply temperatures are below 60ºC, arriving to 70ºC in very cold periods. Within 4GDH, depending on the supply temperature they are divided into Very Low Temperature (VLT) DH – with supply/return temperature around 60/30ºC – and Ultra Low Temperature (ULT) DH – with supply/return temperatures around 45/30ºC.

The study [5] concludes that the role of DH in area of reduced SH demand with high renewable share is significant, but that DH technologies must be further developed to decrease grid heat losses, exploit synergies and thereby increase the efficiencies of low-grade energy production units. In this way, 4GDH networks will have to meet the following challenges in order to be competitive.

Firstly, 4GDH has to be able to supply low temperature heating for new building with reduced demand space heating. nZEB (nearly Zero Energy Buildings) will have a very reduced space-heating demand by increasing the thermal performance of the walls. It is possible to reduce the total SH demand up to the demand for DHW. In the same way, it will also be necessary to incorporate a LT DHW supply system.

The use of large heat storage system is minimised in 4GDH, so that the possibility to have problems with the legionella bacteria is also minimised. When the supply temperatures from the DH are reduced, a microbooster heat pump could be used as an alternative to traditional electric heater, boosting DHW up to 55ºC reducing the legionella risk.

4GDH networks aims to be a smart thermal network, similar to the one that exists for electricity distribution. The concept for the smart thermal network is based on connecting buildings to the same grid can be served by centralised plants and distributed heating units along the network. This way prosumer concept is defined, where a prosumer could be an active building with a distributed heat source installed e.g. on its roof, so that in moments of high DH demand the building consumes heat from the grid and in moments of high heat production, the building becomes another distributed heat source for the grid. The low supply temperatures of the 4GDH networks, in combination with specific pipelines with improved insulation makes possible to reduce heat grid losses. These specific pipes are formed by twin pipes with the supply pipe in the centre and the return pipe located at the isotherm equal to the return temperature. Other advantage of the reduced operating temperatures is the ability to use low-grade RES and waste heat from low-temperatures sources. Waste heat streams are usually low-grade heat stream which are very useful for DH networks because they supply heat all year round and on an ongoing basis. As for RES, the most used are the Building Integrated Solar Thermal Systems (BISTS), which has its own chapter. Other benefits from reduced operating temperatures are: higher power-to-heat ratios in CHP plants, higher COP (Coefficient of Performance) in Heat-Pumps etc.

Heat pumps are thermal devices that uses electricity to produce high-grade heat from a lower grade heat source. Heat pumps are important elements in decarbonisation process in the buildings, as the electricity grid also decarbonises. As the study [12] concludes, HP can be installed so that heat is delivered to the network, or from the network, or both. The heat pumps that make all functioning schemes available are named as reversible heat pumps and in case that one of the thermal sources is the DH itself, the heat pumps are denominated as District Heating Reversible Heat Pumps (DHRHP). In case that HP operates as a distributed source for the DH grid, heat source may use different sources
Each of the installation scheme can be made more economically favourable if cooling demand is also present. In broad terms, the efficiency of heat pumps is determined by the temperature gradient between the cold source and the hot temperature. When the temperature gradient is relatively high (above 40ºC), different challenges are found in existing technology, such as high electricity consumption.

The application of this technology into DH networks varies depending on the temperature range of the DH. For high temperature DH (T_{supply} > 70ºC), HP system consists of a central installation retrofitted into an existing network. Heat is supplied by the HP to the DH at high temperatures and in consequence the sub-optimal values for the COPs. These are usually the HP with highest capacity and one of the main applications is connecting them to the flue of a CHP to carry out heat recovery, boosting heat, for example, from 50ºC to 90ºC. In low temperature networks, the heat flow direction is from the network to the consumption points, this way, the heat from the VLT/ULT is used as the heat source, and it is boosted until the consumption requirement.

1.2 Booster & Micro-Booster Heat Pumps in DH

The micro-booster (MB) is a particular case of HP water heater. In new building with low-temperature radiators or flor-heating, the supply temperature of ULT is enough for covering the load for SH, in terms of temperature grade. However, temperature range is not enough for the final state of the DHW and usually a micro-booster is needed for the preparation of the DHW. The required typical temperature for DHW is 40-45ºC depending on the tapping place (kitchen or bathroom). When storing hot tap water, there is always a risk of bacterium "Legionella", which can be avoided by increasing the temperature of the DHW to around 55ºC. Legionella disinfection functionalities can periodically increase DHW temperature up 65ºC to avoid Legionella.

[14] studied the feasibility of DH networks with 40ºC supply temperature and booster heat pumps for DHW preparation and compared its thermodynamic and economic performance with those obtained by distributed electric water heaters. This study concluded that MB has the highest annualised investment cost but performs with lowest operating expenditure.

2. Technologies description: ULTDH with Triple Function Substation (3FS), Building Integrated Solar Thermal System (BISTS) and Microbooster Heat Pump (MBHP).

This paragraph is aimed to present the connection from a ULT DH subnetwork to a specific multi-rising dwelling by means of the proposed 3FS. Figure 1 shows the position of each subsystem in the connection overall system.

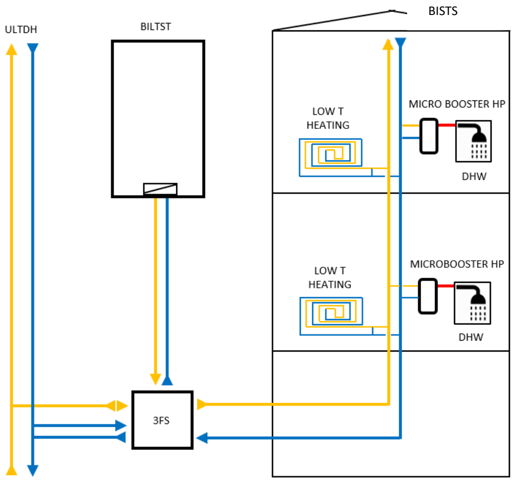

Figure 1. Scheme of heat exchange concept by 3FS and localization of MBHP

2.1 BISTS (Building Integrated Solar Thermal Systems)

One of the most promising RES that may be integrated into the 4th GDH is solar thermal technology integrated into different envelopes of the building. Most ST systems have been incorporated on the roofs. However, roofs have limited surface, and, in most cases, it is not enough to meet all the heat demand of the dwelling. Whereas the maximum solar radiation is received directly on the roof (with a specific inclination depending on the location), the south façade of a building receives around 70% of the maximum in whole year. Responding to an increasingly higher requirement for higher renewable share in 4GDH, solar installations into building envelopes results to be a very promising solution that is being analysed by different studies [10] & [11].

2.2 Triple function substation in ULTDH (3FS)

A new triple function substation (3FS) design concept is proposed. The unit is thought for the operation with ULTDH at supply temperatures of 35-45 ºC. The 3FS allows for an easier integration of solar thermal in district heating introducing the following functionalities:

1) Extraction of heat from the district heating network (conventional). ULTDH can be used to supply space heating to the buildings and it can be utilized by the DHW microbooster unit to produce domestic hot water. Additional heat can be supplied by the BILTST to the building if the demand is higher than the available solar heat production.
2) Injection of heat at high temperature to the supply line of the DH grid. When solar heat production increases above the space heating and DHW demand, then heat can be supplied back to the district heating flow line if the supply line temperature is reached.
3) Injection of heat at low temperature to the return line of the DH grid. In case the minimum supply line temperature is not reached due to low solar radiation, the heat produced by the solar system can be injected in the return line. This allows for an increase of the heat generation efficiency of the solar heating panels.

When the 3FS is placed in locations with nZEB buildings supplied by ULTDH the following design is proposed.

2.3 Operational mode 3FS in ULTDH and nZEB with boosters.

In Figure 2 different functioning modes included in the design of the 3FS are shown.

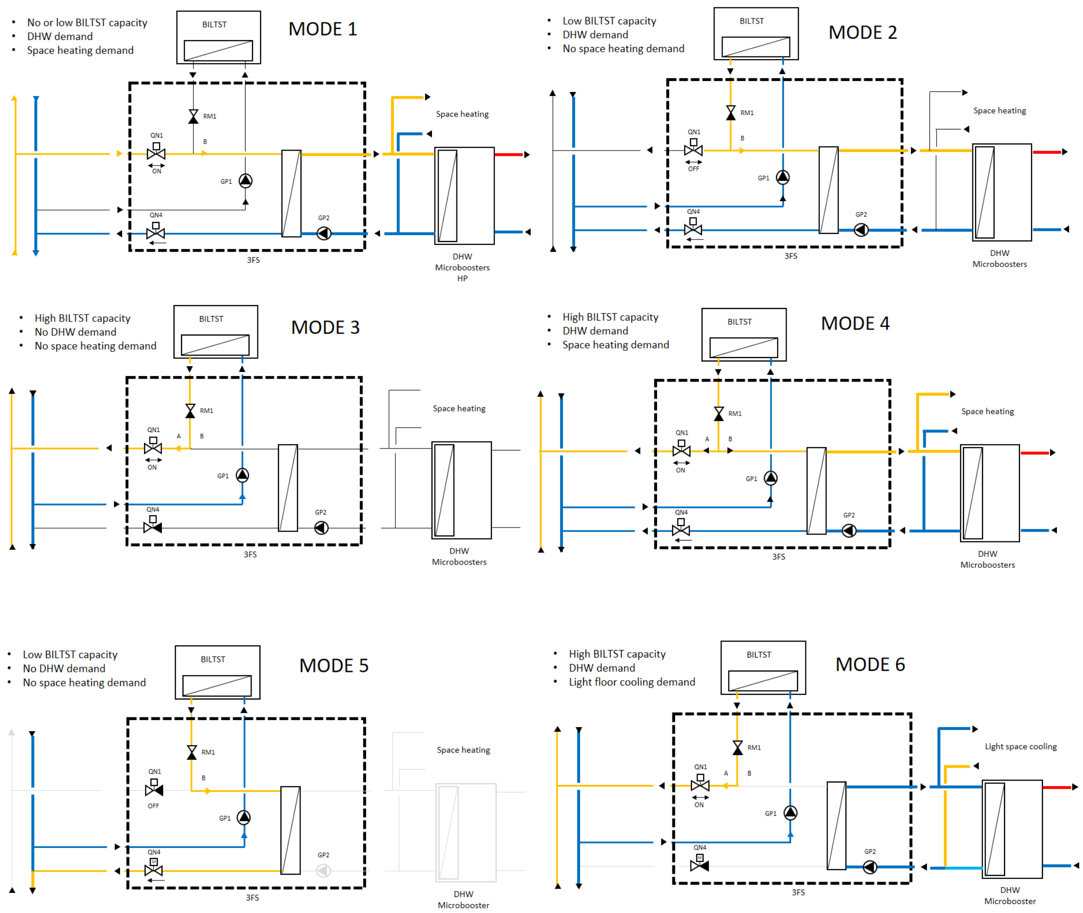

Figure 2. Operational mode 3FS in ULTDH and nZEB with boosters.

1) Mode 1: Heat from DH is used for DHW (Microbooster) and SH.
2) Mode 2: Heat from DH, in combination with BISTS is used for DHW load (and/or SH).
3) Mode 3: Heat from BISTS is injected in the supply line. No demand for SH or DHW
4) Mode 4: The two heat sources (BISTS and ULT DH supply line) are combined for satisfying DHW & DH demand
5) Mode 5: Heat from BISTS (high-grade heat) is injected to the return line of the DH.
6) Mode 6: Heat from BISTS (high-grade heat) is injected to the supply line of the DH. The booster supplies DHW and space cooling simultaneously. Minimum floor temperature can be controlled by the 3FS valve QN4.

2.4 Microbooster Heat Pump for DHW in ULTDH
The last subsystem is the discussed Microbooster. It is a unit that extracts heat from a liquid heat source through a vapour compression cycle in order to produce hot domestic tap water at higher temperature than the heat source. The technology was introduced to allow the utilization of ultra-low temperatures heating networks and to reach the needed domestic hot water temperatures while minimizing energy consumption. The unit is composed of a built-in hot water storage tank, a heat source circuit, a heat pump circuit and a controller. The Microbooster can operate in different operating modes according to the heat source, DHW conditions and type of installations.
The booster heat pump can be connected in parallel or in serial connection to a heating system.

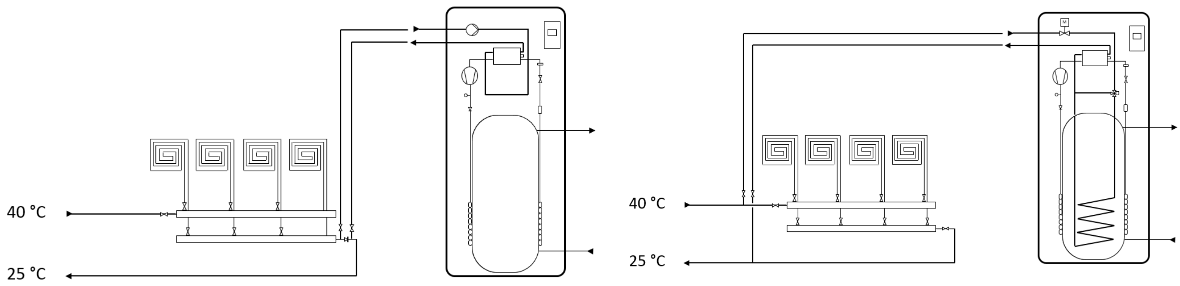

Figure 3. Operation schemes of the MBHP

When connected in serial connection to the heating system, the Microbooster allow for minimal return heat source water temperature. On the other hand, when the unit is connected in parallel connection the booster unit allow for minimum electricity consumption. In this case, the Microbooster can be equipped with a coil which allows for pre-heating of domestic hot water inside the tank, by directly using DH and without the use of the heat pump cycle. When no more heat can be extracted from the heat source, the heat pump is activated to further increase the domestic hot water temperature up to 65ºC.
The Energy performance of the booster heat pump was measured on a working prototype and on field test units according to tapping profiles and methodologies of standard EN16147. Domestic hot water coefficients of performance of 4.8 and 8.0 were measured for heat source supply temp. Further tests on serially produced units have shown significant performance improvements, with COP of 5.2 and 8.5 at heat source of 25ºC and 40ºC respectively. The unit is currently under test at a recognized third-party test institute for its the performance assessment.

3. Conclusion
This paper has presented the technical feasibility of the combi-system which clusters ULT DH, BISTS, 3-FS substation and microbooster. Different connection schemes have been analysed in function of the climatic & operational situation of the location. Regarding the microbooster, it allows the viability of the ULT DH networks, by preparation of the DHW. Since the thermal gradient from the input source and the output source is relatively low (±10ºC), the COP reached by this system is higher than traditional heat-pumps, achieving values up to 8.5. The presented overall system shows great flexibility to adapt for different situations, increasing RES share of the network and reducing dependency of large heat

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production plants. This paper presents a new concept which will further investigated and analysed in future research.

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