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# Individual Heat Substations Integrated with Heat Pumps for District Heating Systems in Ukraine

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Energy systems around the world require a sustainable way for energy supply that does not add carbon to the atmosphere and thus does not enlarge the greenhouse effect, which is seen nowadays as the main cause of climate change. Urban housing consumes the most energy in European countries accounting for up to 43 % of final energy, while 65 % of it is spent on house heating and hot tap water supply. The reduction of carbon dioxide emissions and increasing of energy efficiency of power plants in Ukrainian cities, where district heating systems are centralised, and heat carriers are supplied from central combined heat and power stations based on fossil fuels, can be performed by modifying the existing district heating systems. One of the promising ways is the transition to low-temperature heat carriers from combined heat and power stations, which suppose the use of renewable energy sources, which can be integrated with individual heat substations of houses, and should satisfy the needs of residents in heating and hot water, with the possibility of air conditioning. In the present work, the possible implementation of individual heat substations integrated with heat pumps for low-temperature district heating systems is discussed. The analysis of the possibilities to increase the energy efficiency of the dormitory building with old construction is provided. The method for the design of individual heat substations for heating and hot water supply systems is discussed, including the recommendations for the building renovation.

## 1. Introduction

Energy systems around the world require a sustainable way for energy supply that does not add carbon to the atmosphere and does not enlarge the greenhouse effect, which is seen nowadays as the main cause of climate change (IEA 2019). To fulfil the world's energy needs in universal energy access and cleaner air require changes of all parts of the energy systems with no simple or single solutions. The emission cuts can be achieved due to multiple fuels and technologies providing efficient and cost-effective energy services. And to keep the lower temperature rise, more measures are needed. As the year 2030 targets, renewables and energy efficiency are the primary mechanisms for the low-carbon and reduced pollutant emissions as stated in the Sustainable Development agenda. The COVID-19 pandemic revealed the importance of our homes for a living. The need for their renovation offers a unique opportunity to redesign and modernise the buildings themselves and their heating systems, making them more environmentally friendly and more digital, which will ensure economic recovery. But only 1 % of buildings undergo energy-efficient renovation every year, so effective action is crucial to making Europe climate-neutral by 2050. The existing publications on district heating (DH) systems show that each system has its particular specifics, and its further development or renovation is challenging. The high population in China with dense housing and the use of coal-fired cogeneration discovered the potential to implement absorption heat pumps for the DH systems and to solve the problem of the remote location of heat sources by proposing the technologies for long-distance heat transportation (Li et al. 2019). Low-temperature DH concepts for space heating and domestic hot water in Austria are presented in (Köfinger et al. 2016). For some countries as Germany and Switzerland, the moving

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to the 5th Generation DH has already started (Buffa et al. 2019). For the integration of renewables and efficient heat recovery in DH systems, the Pinch Integration (PI) method is widely used. In the paper of Jørgensen et al. (2018), the PI method was used to estimate the highest coefficient of performance for the heat exchanger network of district heating ammonia heat pumps. The possibility of waste heat utilisation from the cooling process of a supermarket by the heat pump is examined by (Boldyryev et al. 2013). In the presented work, the possible implementation of individual heat substations (IHS) integrated with heat pumps for low-temperature district heating systems is discussed. The typical schemes of heat pumps integration in existing district heating systems, where they are booster heat pumps to the DH heat carrier, are presented. The approach for the selection of optimal heat transfer equipment for the IHS is described, focusing on the optimal selection of heat transfer equipment.

## 2. Methodology

The methodology used in the present work includes the analysis of the present state of the DHS in Ukraine, the possibilities for implementation of efficient heat substations for buildings, the methods to determine the heat loads for heating and hot water supply systems, and optimal design of PHEs for IHS.

### 2.1 District Heating systems in Ukraine

Ukraine has a quite developed district heating (DH) infrastructure in all major urban settlements. In urban areas, where buildings of a different kind are closely situated, the supply of utilities is done from a centralised distribution network in the form of pressurised hot water what comprise the DH System. In Ukraine, as for now, DH covers 40 % of the population, which is approximately 5.5 M households, and it covers about half of the energy demand for heating purposes. Natural gas still remains the dominant fuel for the district heating sector, while the use of biomass for heating is growing. In 2018 the volume of heat energy supply to final consumers constituted 42 TWh, and natural gas has been used as the major fuel. The estimation of the technical condition of Ukrainian DH systems (Geletukha et al. 2019), especially thermal networks, revealed its deterioration. In recent years, the length of heating networks has decreased by 8,000 km due to the decrease of DH consumers. 38 % of the remaining 20,000 km of heating networks are in poor and emergency technical condition. The average heat loss in heating networks is 19 %. As an approach, the authors propose to use the bio-fuel for DH systems and to move to more efficient heat generation technologies, such as CHP; only a limited number of buildings are equipped with automated IHS substations.

The successful transition toward efficient DH in Ukraine requires smart modernisation of DHS facilities. The straight replacement of outdated with modern equipment having the same capacity does not look like a reasonable option in many cases, as DHS heat generation and transportation infrastructure do not match the existing heat demand. Low-temperature DH ensures the efficiency of the energy supply. The well-insulated building, tending to zero losses, lowers the limits on energy consumption for heating, considerably increasing the energy efficiency on the consumer side. At the same time, better energy performance of buildings makes low-temperature DH supply possible. And DH supply losses can be reduced with reduced network temperatures. This increases the supply-side efficiency and competitiveness of DHS to supply heat. The possibilities of retrofitting of existing Ukrainian DHS to the modern district heating of the 4th Generation are discussed in (Fialko et al. 2020). One of the main limitations, in this case, is the high cost of required investments. The high energy efficiency and a high share of renewable energy of low-temperature district heating systems make them the future of district heating for the sustainable development of Ukraine.

The present paper is discussed the promising way of the step-by-step transition to low-temperature heat carriers from combined heat and power plants (CHPs) with the use of renewable energy sources, which can be integrated into individual heat substations of houses. It should satisfy the needs of residents in space heating and hot water, with the possibility of air conditioning.

### 2.2 Individual heat substations for DHS

The renovation of the existing DH networks can be done with an application of individual heating substations with the possibility to upgrade to 4th Generation DH systems by the implementation of heat pump technologies. At the same time, the use of low-temperature heating systems requires well-insulated buildings, which still causes problems in Ukraine, where most of the multi-stored buildings are of old construction with high heat losses. The modernisation should be made in two steps: (i) the energy audit for the building should be carried out, proposing the proper measures for increasing the energy efficiency for the building itself; and (ii) the IHS to cover the new heat demand should be designed with the flexible design of IHS (Król and Ocłoń, 2018). The IHS design should meet a load of heating and hot water supply. Based on the known value of heat load, it is possible to create the IHS that best meets the heating needs with a minimal capital cost of equipment. The analysis of existing units determines the ways of increasing the energy efficiency of the heating system of the whole building. When designing a heating system for a building, the design outside temperature is taken as the winter temperature equal to the average temperature of the coldest five-day period. The heat exchanger of the IHS is calculated according to the hourly heat load of the heating system, which is determined at the average temperature of the coldest five days and therefore is the maximum heat load of the heating.

It is possible to use individual heat substations with heat pumps for heating separate multi-storey houses presented in Fig. 1 to achieve the maximal effect. The heat pump is integrated into the 2-staged mixed flowsheet heating system to heat the water in the heat exchanger – storage tank circuit to 60 – 65 °C, and the evaporator uses the water from the heating system. In the summertime, the heating system can be used for hot water supply independently from central district heating system and can be used for cooling purposes also.

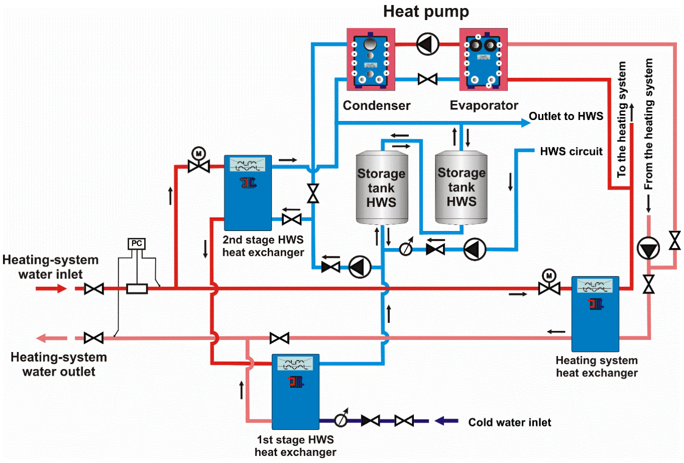


*Figure 1: The individual heat substation with heat pump*

The purpose of the heating system is to ensure a comfortable temperature in the apartments, where a balance between the heat loss of the building and the heat supplied should be satisfied:

$$Q = Q_w + Q_{\inf} = Q_{heat} + Q_{hg} \tag{1}$$

where $Q_w$ are the heat losses by heat transfer through the external walls, W; $Q_{inf}$ are heat losses by infiltration through leaks of external fences, W; $Q_{heat}$ is heat input into the building by the heating system, W; $Q_{hg}$ is internal (household) heat input, W.

Maximum hourly heat consumption for heating is defined by the type of building. The building heat losses through the walls can be estimated as follows:

$$Q_w = qV_{out}\left(t_{in} - t_{out}\right) \tag{2}$$

where the value $q$, W/(m$^3$·°C), determines the average heat loss of 1 m$^3$ of the building, referred to as the calculated temperature difference of 1 °C. This value is calculated from the relation: $q = q_0\beta_t$, where $\beta$ is the temperature coefficient, which accounts for the deviation of the actual temperature difference from the calculated $\beta_t = 0.54 + 22/(t_{in} - t_{out})$.

The reference quantity of specific thermal parameters is determined by the relation:

$$q_0 = \frac{1}{R_0 V_{out}}\left[A_{out}\eta_{win} + S_{out}\left(\eta_{ceil} + \eta_{floor}\right)\right] \tag{3}$$

where $R_0$ is the heat transfer resistance of the outer wall, (m$^2$·K)/W; $\eta_{win}$ is a coefficient that takes into account the increase in heat losses through the windows in comparison with the outer walls; $\eta_{ceil}, \eta_{floor}$ are coefficients that take into account the reduction in comparison with external walls of heat losses through the ceiling and floor; $A_{out}$ and $S_{out}$ are the surface area of external walls and building correspondingly, m$^2$.

The average indoor air temperature in the building is calculated from the ratio:

$$t_{in}^{av} = \sum_{i=1}^{n}(S_b^i \cdot t_{in}^i) / \sum_{i=1}^{n} S_b^i \tag{4}$$

where $S_b$, $t_b$ are the area, m$^2$ and internal temperature, °C, of individual apartments; $n$ is the total number of apartments.

The amount of input heat $Q_{hg}$, W, and heat losses in the whole building $Q_{heat}$, W, are determined as:

$$Q_{hg} = q_{hg}(F_{live}^{b} + F_{kit}^{b}); \quad Q_{heat} = \sum_{j=1}^{J}\left\{\sum_{i=1}^{I}\left[\sum_{m=1}^{M}\left(K_m F_{m,i,j} n_m\right)\left(t_{in,j} - t_{in}\right)\right]\right\} \tag{5}$$

where $q_{hg}$ is the amount of heat input, set at a minimum value corresponding to the share of these heat inputs in an apartment with a corner room, 15 W/m$^2$; $F_{live}^{b}$, $F_{kit}^{b}$ are total floor area of heated rooms of the building (living rooms and kitchens correspondingly), m$^2$;$K$ is the heat transfer coefficient of the fencing, W/(m$^2$ K); $K$ is the area of the outside fencing, m$^2$; $n$ is coefficient taking into account the protection of the fencing from the influence of the outside air; $I$, J is the number of rooms in the building that have the same and different design temperatures of the internal air, respectively; $M$ is the number of outside fencing in the room.
The total consumption of hot water during the day $G_{dl}$, m$^3$/s, and the average hourly flow rate for the two-stage connection scheme for HWS heat exchangers $G_{HwS}^{mean}$, m$^3$/s, are calculated as:

$$G_{all} = \int_{0}^{24} G_{HWS}^{i}(t)dt = G_{HWS}^{mean} \cdot 24; \quad G_{HWS}^{mean} = \frac{3,600 \cdot Q_{HWS}^{mean}}{c_h \cdot (t_d^{'} - t_a^{'})}\left(\frac{55 - t_p}{55 - t_c} + 0.2\right) \tag{6}$$

where $G_{HWS}^{mean}$ is the average consumption of hot water, m$^3$/s; $t_p$ is the outlet temperature of the heated media for the heat exchanger of the first stage, which is the inlet temperature for the second heat exchanger, ºC; $t_c$ is the temperature of cold water in the winter, ºC; $t_d$ is the temperature of the network heat carrier in the supply pipeline, ºC; $t_a$ is return water temperature after the HWS heat exchanger, ºC; $c_h$ is the mean specific heat of the return water, J/(kg·K); $Q_{HWS}^{mean}$ is average hourly heat load of HWS system, W.
Besides the heat loads, the implementation of PHEs for IHS presented in Fig. 1 imposes additional requirements for the design: (i) Operating temperatures are 50 - 69 °C for the supply and 30 – 35 °C for the return; (ii) A high-efficiency PHEs need to be applied, due to the low operating temperature differences, with a logarithmic temperature difference in the range from 6 °C to 8 °C; (iii) The total pressure loss of the unit below 0.3 bar. The design of PHEs for the IHS was done based on the previous research. The description of the heat exchangers and estimation of heat transfer and pressure drop is described in (Klemeš et al., 2015).

## 3. Case study

The 4th Generation District Heating and cooling technology require the improvement of both the performance of the buildings and the district heating system in order to improve the energy efficiency of the total system. The reduction of heating demands of existing buildings may be achieved by the higher insulation of the existing buildings, which will increase comfort while lowering the supply temperatures. It will also reduce DHS losses and increase the recycling of heat as well as the efficiencies of the production units.
The energy analysis of one of the universities dormitories was carried out. The building is located in the living suburb with two supermarkets nearby, which makes it possible to examine the application of waste heat from refrigerators, which can also be used in summer for the HWS system. The building is connected to the centralised DH system with a direct connection for HWS. The temperature inside the building in the living apartments varied from 12 to 18 °C at in different rooms, and the required value is 20 °C. The inspection of the building was done at an average outdoor temperature equal to -1 °C. The heating period is equal to 179 d. The initial and calculated building parameters for heat loads are listed in Table 1.
The building is connected to the existing centralised DH network. The heating system in the building is old and in poor technical condition. It consists mainly of old iron radiators without thermostatic valves. The building has a direct connection to the DHS without any automatic control system. There are only manual control valves that are used to increase or decrease the heat supply to the building. The system is not balanced with uneven temperature distribution in the building. The results of the building examination detected the good potential for an energy-saving measure in the building with proposing different stages for the renovation: 1st stage – Minor measures to increase the building efficiency to satisfy Ukrainian standards; 2nd stage – The measures for high-efficient energy renovation of the building; 3rd stage – Installation of IHS with PHE for hot water; 4th stage – Installation of 2-staged mixed HIS for heating and HWS systems; 5th stage – Installation of IHS for heating and HWS systems with heat pump utilising waste heat from the nearby supermarket.
As the building energy efficiency is very low, at the 1st stage, it should be increased to lower the heat energy consumption. The two possible solutions were proposed for building efficiency, which differs in materials and measures. Both 1st and 2nd stages require the insulation of the building with changing the doors and windows, insulation of the roof and basement. The reconstruction of the building supposes the modernisation of all heating systems of the building with insulated pipes and new radiators, renovation of pipes for hot water for both cases.

*Table 1: Main data of the observed building*

| Parameter | Value |
|---|---|
| Year of construction | 1967 |
| Type of construction | ISO 6 with white and clay bricks |
| Number of floors | 5 |
| Total area, $m^2$ | 5,967 |
| Heating area, $m^2$ | 5,029 |
| Heat load for heating, kW | 361 |
| Heat load for HWS for maximal load, kW | 110 |
| Total heat load, kW | 471 |

Stage 2 also includes the implementation of a new ventilation system with 65 % heat recuperation. The installation of the new heat substation is required, which can include the installation of IHS with PHE for the HWS system (3rd stage) or installation of the IHS for heating and HWS applying the 2-staged mixed flowsheet of connection to the DHS (4th stage). As a possibility for further energy efficiency, Stage 5 is proposed, which examines the possibility to implement waste heat from a nearby supermarket for hot water heating in summer and residential heating when the outdoor temperature is higher than 5 °C. The building energy balances for 1st and 2nd stages based on monitoring building heat performance are presented in Table 2. For stage 1, the heat load for heating will be more than two times less and come to 161 kW, decreasing the total heat load to 271 kW.

*Table 2: The energy balances of the building before and after proposed measures*

| Parameter | Before renovation | After 1st stage | After 2nd stage |
|---|---|---|---|
| Total heat consumption, (MWh/) | 1,177.3 | 767.4 | 601.3 |
| Heat consumption for heating per year (MWh/y) | 675.1 | 348.9 | 182.8 |
| Heat consumption for HWS per year, (MWh/y) | 502.2 | 418.5 | 418.5 |

The estimated cost of proposed renovations for 1st stage needs 352.6 k€ investments and for 2nd stage equals to 480,500 Euro. The savings will come to 19.975 k€/y for the 1st and 28.069 k€/y for the 2nd stages. The payback period with the existing prices for natural gas is 17.7 y for the 1st and 17.1 y for the 2nd stage.

*Table 3: PHEs design for the 3rd and 4th stage*

| Heat exchanger | Type of heat exchanger | Heat transfer area, $m^2$ |
|---|---|---|
| 3rd stage | | |
| PHE for HWS system | M6 | 1.95 |
| | CB60 | 1.74 |
| 4th stage | | |
| PHE for heating | M3 | 1.7 |
| 1st stage HWS PHE | M6 | 2.25 |
| 2nd stage HWS PHE | M3 | 0.67 |

The other three scenarios suppose the installation of IHS. The 3rd stage requires the installation of the IHS with PHE for hot water heating using the DHS heat carrier. The calculation of the PHE for hot water heating was done for two types of PHEs, which are possible to apply for IHS. The heat exchanger was calculated according to the following operating conditions: heat load is 110 kW, the temperature program for the hot side (DH supply and return) was taken with 85 ºC inlet temperature, and 50 ºC outlet temperature, the temperature program for the cold side is 40 ºC for inlet and 70 ºC for an outlet. The 4th stage supposes the implementation of 2-staged mixed IHS for heating and HWS systems requires the installation of the IHS with all equipment and PHE for hot water heating using the DHS heat carrier. The temperatures for the DH supply and return were taken, as for the 3rd stage, inlet and outlet temperatures as for the HWS system. The heat load for heating was taken as for the case with renovations, and equal to 161 kW with a total heat load of 171 kW. The supply and return temperatures were taken as 60 °C and 30 °C. The results of the PHEs design are presented in Table 3. The type of the heat exchanger, as well as operating parameters, affect the HIS design. The possibility of PHEs changing the heat transfer area by adding or removing the plates makes the transition from the 3rd to 4th stage less costly. The gasketed PHE were calculated for IHS, and the total cost of three heat exchangers is equal 2.997 k€ and the price of IHS equal 7.548 k€. The savings will come to 29.627 k€/y for the 3rd stage and 34.132 k€/y for the 4th stage, as we can use M6 PHE with an additional heat transfer area. The further improvement is the installation of the IHS for heating and HWS systems with a heat pump with the utilisation of waste heat from the nearby supermarket. The 2-staged mixed IHS for heating and HWS systems with heat pumps can be implemented when moving to low-temperature DHS of the 4th Generation DH. It would need to add the additional two PHEs, the condenser and evaporator, to the 4th stage. In the present work, the general possibility was considered, as the energy efficiency of the examined building should be increased to near-zero losses, which is preferred for the implementation of such systems.

## 4. Conclusions

The existing DH system in Ukraine needs modernisation of all its components, including DH pipelines and the equipment of central heat stations and individual heat substations in multi-story houses, assembling it with individual measuring devices. The case study of a dormitory house constructed 50 y ago is an example of a possible approach to renovations of such buildings. The improvement of the energy efficiency of the building can decrease the total heat consumption by 40 % for the simplest case. The installation of IHS on the base of PHEs can further decrease the heat consumption by an additional 7 % for IHS only for the HWS system and by 15 % when using 2-staged mixed IHS for area heating and HWS. The possibilities of implementation of low-temperature DH for reforming the housing and utilities sector in Ukraine revealed its limitations for the old houses with bad insulation. The introduction of low-temperature DH in Ukraine should be carried out by gradually adding its elements to existing heating supply systems through measures such as increasing the share of renewable energy sources and integration of an individual heat substation with heat pumps. The optimal selection of heat transfer equipment ensures the reliable operation of individual heat substation and their minimal price. The discussed approach can be applicable for centralised DH systems of Central and Eastern Europe.

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