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Dynamic investigation of centralized and decentralized storage systems for a district heating network

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ABSTRACT

District heating is an efficient and promising way to cover the residential space-heating and domestic hot water needs, resulting in economic and environmental benefits, especially if operated by renewable power stations, when compared to fossil fuels. In this direction, the present study investigates in detail a district heating network with novel decentralized storage for domestic hot water (enerboxx scenario), over centralized storage systems, applying a specific schedule-based approach for the coordinated hot water tank charging. The goal of this design is to properly control the system by charging it at predetermined time periods during the day aiming at i) diminishing the thermal losses and ii) reducing the thermal demand from the grid, over the period of a day. The simulation is conducted with a newly developed component-based tool, called INTEMA, which is based on the Modelica language. This encompasses the ability to discretize with high temporal resolution and adjustable time steps the overall grid configuration, with the support of customizable level of detail models for simulating key system components such as the storage tanks, the piping and the dwelling needs, as well as the application of an advanced control system over the district heating network and the dwellings. More specifically, a combined control system that controls both operating parameters in the network and inside the dwellings is applied. The developed system model is verified against available data for a standard centralized storage system (reference scenario) and afterwards, the novel decentralized design is compared against corresponding results of the standard system, as concerns key operational parameters; indicatively the temperature levels of the hot water and the heat load demand. The analysis is conducted for a heating network of 9 dwellings in Austria, which have an underfloor heating system, a system for covering the domestic hot water demand, considering also that each of these 9 dwellings is characterized by a unique demand profile. It was found that the decentralized approach leads to lower demand and there are energy savings of 18 % compared to the reference scenario, while the thermal losses are reduced by about 22 %. Moreover, a parametric study regarding the storage tank volume and the heat exchanger thermal transmittance in the tank is conducted, in order to examine the impact of these design parameters on the system dynamic behavior.

1. Introduction

District heating is a promising choice for delivering space heating and domestic hot water (DHW) by exploiting various renewable energy sources or waste heat streams. Biomass, solar thermal energy, geothermal energy and waste heat recovery can be used in order to produce significant amounts of heat for exploitation in the building sector [1]. This fact leads to significant fossil fuel savings of up to 20 % [2,3] and to the reduction of CO_2 emissions by up to 33 % [3]. The aforementioned expected reductions are relatively high because they refer to the building sector, which is one of the most energy-consuming sectors with a percentage of about 36 % in the EU [4]. There are countries that rely heavily on district heating systems and Denmark is the most representative example by covering 2/3 of their heating needs

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with district heating [5]. Moreover, several studies have been conducted in order to evaluate the cost-effectiveness of district heating in Europe. These studies assist the decision-making process for the optimum district heating design and propose market models to widely spread their use, aiming at accelerating the decarbonization of societies [6–8].

The sustainability of the district heating systems is dependent on the proper design, engineering and installation of necessary thermal storage systems, if possible, except from the overall system configuration, including piping, power plant providing the heat and other key parameters, in order to increase the overall system efficiency, rendering the system more resilient, while also increasing its flexibility potential [9]. The installation of properly sized storage tanks (centralized or decentralized) can ensure the storage of available excess thermal energy at specific time periods, improving the overall system performance [10]. Moreover, district heating systems require appropriate control strategies to operate within the required range of temperature levels (defined by the dwelling residents), and the proper mass flow rates to charge the storage devices in an optimal way [11,12]. The suitable control strategy, which is usually implemented with advanced control algorithms [13], is able to save significant amounts of thermal energy, up to 20 % in cold climates [12], and in the last years a lot of interest is being paid towards this direction. Moreover, it is very important to use secondary control in the dwellings in order to optimize the storage strategy according to the profile demand of every user separately. This technique renders possible i) the overall energy consumption reduction, ii) the reduction of the peak loads, iii) the quicker response time of the system and iv) the avoidance of the system's oversizing towards the development of a sustainable thermal energy grid [14,15]. Practically, the goal of the district heating systems of the 4th generation is to operate with a low source temperature of around 45–55 °C for reducing exergy losses, minimizing also the thermal losses during the transfer, storing of high amounts of thermal energy and couple the district heating systems with renewable systems [16]. In the last years, the 5th generation district heating systems gain great attention as they are capable of operating with even lower temperatures than those of the 4th generation, close to 35 °C, and they feed water-source heat pumps for upgrading the low stored temperature into the desired temperature levels [17]. It is critical to add that the design of the buildings, the load profile of the consumers and the thermal losses of the piping are important parameters that influence, in a great percentage, the final system behavior [18].

According to the available open literature, there are important studies in the field of district heating systems that examine different aspects of these networks and suggest various ideas for their improvements. One very important aspect is the goal of reducing the operating temperature levels in the district heating network aiming at the reduction of thermal losses. In this direction, Castro Flores et al. [19] conducted a techno-economic study regarding the use of low-temperature district heating networks and they found that the examined configurations lead to a 7 % thermal losses reduction compared to conventional systems. Another critical aspect is the exploitation of renewable energy sources for district heating aiming at fossil fuel or/and electricity savings for the cases that heat pumps are incorporated into the network. Soltero et al. [20] examined numerically the use of biomass for feeding district heating, including technical and non-technical parameters in order to evaluate properly the sustainability of the examined configurations. Their model is an important one for utilization by decision-makers in the energy sector. Moreover, there are studies that try to exploit properly the low-temperature waste heat in the district heating networks by upgrading it through the use of heat pumps. Wang et al. [21] examined a complex multi-heat source district heating system with low-temperature waste heat coupled with heat pumps for upgrading the heat inputs. Based on the conducted optimization studies, they concluded that the proposed optimized configuration leads to a total energy input reduction of about 70 %. Another option is the combination of the district heating network with concentrating solar parabolic trough collector for feeding an absorption heat pump aiming at heating/cooling production. Sadi and Arabkoohsar [22] studied a configuration like this and they concluded to a payback period of 7.5 years and to significant CO_2 emissions reduction. Moreover, Arabkoohsar et al. [23] examined the use of an absorption chiller powered by evacuated tube solar collectors in the district heating network aiming to i) produce both heating and cooling, ii) ensure a safe operation of the system during the summer and ii) exploit the waste energy during the summer. A multi-objective optimization analysis was applied and they concluded that their configuration can properly operate during summer, while the levelized cost of the cooling product can be decreased by around 10 %.

The next critical aspect under research in the domain of district heating networks regards thermal storage. The use of thermal energy storage is a way of enhancing district heating performance and cost-effectiveness, as has been highlighted by Bott et al. [24]. Moreover, it is reported in the literature, that the use of a thermal storage system reduces running costs and leads to energy savings [25]. Guo et al. [26] examined the use of a centralized thermal storage system in a district heating network with three different types of users' thermal profiles. They stated that the use of the centralized storage system was important in order to satisfy the different heat demand profiles, as well as to achieve energy savings. Another idea is the use of geothermal boreholes for storing thermal energy. In this direction, Saloux and Candanedo [27] investigated a solar-driven district heating system with a thermal storage unit based on geothermal boreholes. They emphasized the proper sizing of the system and the suitable control of thermal storage. They concluded that the energy savings after the control optimization can reach up to 30 %. Seasonal thermal storage is another important aspect that can aid the district heating networks. Salvestroni et al. [28] examined in TRNSYS a solar-fed district heating system with seasonal storage using a conical-shaped water storage tank, by applying a proper control strategy based on differential controllers. They achieved a 44 % solar coverage with a collecting area of 1000 m^2 coupled to a storage tank of 3800 m^3. Moreover, the literature includes studies that combine both thermal and electrical storage systems. Moser et al. [29] examined the use of a modular energy management system in multi-energy systems with centralized thermal storage with tanks and batteries for electricity storage. They concluded that the use of a such system can lead to cost savings of up to 6 %.

On the other hand, there are also studies that investigate district heating networks with decentralized storage tanks in the buildings. Aste et al. [30] studied a district heating system with a biomass boiler, solar photovoltaics and a geothermal heat source, to achieve a nearly full green electricity consumption for feeding the heat pumps of the district heating system. They also used decentralized storage tanks for storing energy when space heating needs are low in summer. According to their results, the renewable energy fraction was found at 83 % during winter and 100 % during summer by taking into account the sold energy to the grid. Schmidt et al. [31] presented results regarding the use of different low-temperature district units with decentralized storage solutions. They indicated that the use of renewable energy sources and the use of low-exergy sources in general in these systems is of great advantage, contributing to the sustainability of this technology. Moreover, the literature includes studies regarding the comparison of different centralized and decentralized storage solutions for district heating networks. Jebamalai et al. [32] conducted a comparative economical study and concluded that decentralized storage inside buildings leads to a 7 % cost reduction, while centralized storage leads to a 4 % cost reduction compared to the cases without storage. Rehman et al. [33] conducted a comparative study of different storage configurations in a solar district heating network powered by solar energy. More specifically, they compared the central storage system with a system with both central storage and decentralized small storage units, referred to as a semi-decentralized system. They found that both systems can lead to a solar fraction of around 90 % and they concluded that the centralized system presents higher thermal losses to the ambient, while the decentralized system presents a reduction of about 35 % in life cycle costs.

The aforementioned literature review indicates that one of the most critical issues regarding the design of district heating systems concerns the inclusion of a storage system (centralized or decentralized) configuration, along with its design and the associated control strategy. The present work examines the case of decentralized storage tanks for DHW with a specific charging strategy aiming to reduce i) mean operating temperatures in the local network, ii) thermal losses to the environment iii) energy demand from the main district heating grid and iv) to restrict the peak demand period only during the charging periods. The proposed system charges the decentralized tanks located at each dwelling at specific periods during the day, avoiding simultaneous charging of both heating and DHW. As a result, for the greatest duration of the day, the network manages to operate with a relatively low temperature (around 39 °C) for only feeding the underfloor heating system, resulting in a lower mean operating temperature level in the network and consequently lower thermal losses. Also, the system is proposed to be designed in a way that it charges the different tanks with proper grouping, in order to avoid high peak loads; a critical aspect for the sustainability of the suggested design. Moreover, it is important to highlight that the proposed system introduces a hybrid control strategy, which includes a high-level control in the central system, supported by a secondary control on the level of the individual buildings, in line with recent recommendations, according to the literature [15]. Furthermore, the present work has an extra novelty by investigating a heating network with different demand profiles among the consumers, something very important for estimating suitable system behavior and the ability of the system configuration to account for variable thermal demand profiles to an acceptable degree. Also, this study is conducted with a tool developed in the Modelica language, within the Dymola environment [34], which is called INTEMA. The present tool is able to conduct dynamic studies with high temporal and spatial accuracy by using adjustable time steps (compared to most of the available tools in the open literature), capturing properly the fluctuations of the system behavior. Also, an extra advantage of the developed tool is the detailed investigation of the heating and the DHW systems inside every dwelling separately, as well as the detailed investigation of the transfer station. This fact enables the detailed monitoring of quantities such as temperature, temperature drop and energy demand with a small time-step (~ 1 min) in order to capture the intermittency character of the heating and DHW demand. Moreover, the consideration of the storage tanks' temperature distribution, within their volume; thus including the stratification effects, instead of assuming that a reduced-order model (i.e. a single node of the energy system) increases the accuracy of the results since thermal inertia phenomena are captured with high granularity. Regarding the present simulation study case, 9 dwellings in Austria are considered, with the district heating network providing both heating and DHW on an annual basis. The novel decentralized storage system is compared against a centralized one (reference scenario) and calculations are made to quantify the expected energy benefits of the suggested idea. The reference scenario involves a central tank of 1500 L, while the suggested scenario, called as enerboxx scenario, includes 9 separate storage tanks of 140 L each. Finally, on top of the energy savings calculated for the enerboxx, interesting results regarding the dynamic behavior of the system are presented for the temperature and thermal losses distribution throughout the day.

2. Case study description and methods

2.1. Description of the examined internal supply heating network

The examined system includes a district heating network of 9 dwellings designed to cover both heating and DHW demands. The dwellings layout is presented in Fig. 1 along with the heat source and the primary heat exchanger (HEX), which is used to feed the system with hot water. The heat source, i.e., the external heating network, provides hot water with a mass flow rate of 0.52 kg/s at a temperature of 65 °C to the primary inlet of the heat exchanger, with the secondary HEX stream (working medium: water) circulating the heat with the use of pumps through the pipe network, as depicted in Fig. 1. The nominal heating power of the primary heat exchanger is set to 18 kW_{th}.

The individual thermal loads of every dwelling were sourced by the 'LoadProfileGenerator' (LPG) tool [35]; a dedicated application that generates electrical and heating/cooling time series data, based on several characteristics, such as the i) area of the dwelling, ii) the number of inhabitants, iii) their behavior including their work schedule and other influencing parameters. It is important to state that the loads are inputs in the present study and they are completely satisfied in all the studied cases. The main annual values and attributes considered for each of the nine (9) dwellings are presented in Table 1. The considered time series are of high resolution (minute-based) since this is an important requirement to capture the intermittent character of heating and DHW demand, especially for the latter one e.g., when the user washes the hands for 1 min. Moreover, Table 2 includes the data about the daily

Table 1
Heating and domestic hot water load data description.

Dwelling ID	Description	Heating demand [kWh/a]	DHW demand [l/a]	Floor area [m^2]
1	1 Person: employed	2325	32,192	93
2	1 Person: retired	2325	53,888	93
3	1 Person: retired	1875	47,957	75
4	2 Persons: both employed	2775	38,245	111
5	2 Persons: one employed	2775	76,636	111
6	1 Person: employed	1875	46,382	75
7	3 Persons (2 adults, 1 child): one employed	3075	94,997	123
8	4 Persons (2 adults, 2 children): one employed	2950	148,926	118
9	3 Persons (2 adults, 1 child): one employed	2650	77,843	105
Sum		22,625	617,066	904

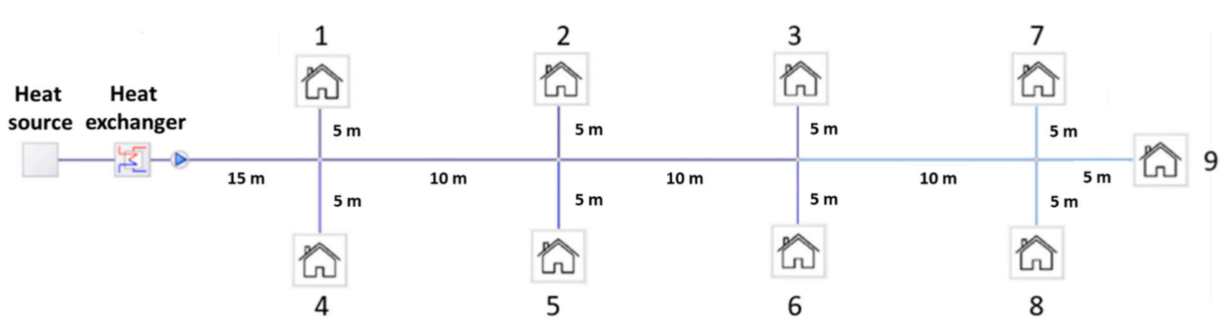

Fig. 1. District heating network topology under examination with piping details.

Table 2
Daily domestic hot water demand in the examined dwellings.

Demand (L/day)	DW1	DW2	DW3	DW4	DW5	DW6	DW7	DW8	DW9
Average	88	147	131	104	209	127	260	407	213
Maximum	99	149	167	103	248	155	189	302	177
Minimum	10	15	15	10	20	16	17	20	15

DHW demand for all the dwellings [35]. The present analysis, compared to other ones in the literature, takes into consideration different demand profiles for every end-user with a small time-step resolution of 1 min; thus accounting for stochasticity parameters on the demand side, while revealing the capability of the model to consider various demand profiles, each one representing different residents behavior, i.e. quite realistic when compared to actual conditions.

Fig. 2 depicts the ambient temperature distribution in Austria that has been utilized in the simulations, on an annual basis, while Fig. 3 presents indicatively the considered DHW load profile of dwelling 1.

Two variations of the above basic district heating connected system are considered, namely i) the reference scenario and ii) the enerboxx scenario, which corresponds to central and distributed energy storage systems respectively. The examined scenarios aim to illustrate the benefits of distributed thermal storage over centralized ones, particularly in covering DHW needs. The simulations of the two scenarios, one with a central storage tank (reference scenario) and one with tanks in every dwelling (enerboxx scenario) are investigated with system models developed in Dymola [34] using the Modelica language [36]. Several component models have been utilized or properly modified from the open-source Buildings [37] and BuildingSystems [38] libraries.

2.2. Reference scenario

The reference scenario regards a common configuration, involving a centralized water storage tank of 1500 L capacity located just downstream of the primary heat exchanger (HEX). Fig. 4 depicts the developed model in the Dymola environment for the reference scenario. Every dwelling was modeled with a separate component block, which encapsulates both heating and DHW subsystems, as it is depicted in Fig. 5. The term "component block" indicates that the building components are developed by combining other sub-components together in order to build it. The space heating is provided to the dwelling through an underfloor heating system, while the DHW is produced through a properly sized heat exchanger. There is a hybrid control system that controls i) the charging/discharging of the central storage tank, and ii) the space heating and DHW systems inside every dwelling in order to cover properly the demands. In other words, there are two different control systems, one central and one local, aiming to regulate properly the temperature levels in all the streams.

2.2.1. Control of the central storage tank in the reference scenario

A suitable control loop is applied to the central storage tank in order to charge and discharge properly taking also into account the temperature stratification inside it. Specifically, the temperature stratification indicates that the upper part of the tank has a higher temperature level compared to the lower part of the tank. Regarding the charging process, the operation of the pump on the hot side of the tank is properly controlled with a hysteresis control component which activates the pump once the temperature at the tank's middle layer falls below the threshold of 58 °C and stops when the temperature exceeds the upper limit of 63 °C. The discharging process of the central storage tank is performed at a constant temperature of 56 °C which is implemented with a PI controller and a three-way mixing valve on the return water stream from the dwellings. The controller dictates the required opening of the valve that recirculates the colder return water from the dwellings, which is then mixed with the hotter supply stream from the central tank. The result is the operation with a constant feed temperature in the district heating aiming to avoid superheating in the grid piping and consequently reduce thermal losses.

2.2.2. Control of the systems inside the dwellings in the reference scenario

Every dwelling has its own local control system in order to exploit properly the district heating and cover its space heating and DHW needs. Also, the loads are completely covered in all the cases because there are inputs in the present model and the model has been suitable designed, as it will be obvious through the validation process which is given in Subsection 3.1.

Every dwelling has an underfloor heating system; thus, the temperature level at the dwelling inlet has to be up to 45 °C maximum for safety reasons. To achieve that, the incoming high-temperature water is partially mixed with the lower temperature return water from the same dwelling, using a hydronic control circuit with a PID-controlled valve (see Fig. 5), which regulates properly the mixing of the two streams (hot and cold) in order to avoid the entrance of very hot water in the underfloor heating piping system. Moreover, the PID controller makes possible the smooth variation in the system in order to satisfy the thermal loads. This is accomplished by steering the three-way mixing valve to regulate the inlet temperature at a specific setpoint, which is a function of the ambient temperature and is described by the eq. (1). This empirical equation was provided by PINK [39], an experienced company in thermal applications, and indicates that the higher ambient temperature reduces the heating demands of the dwellings thus a lower heat

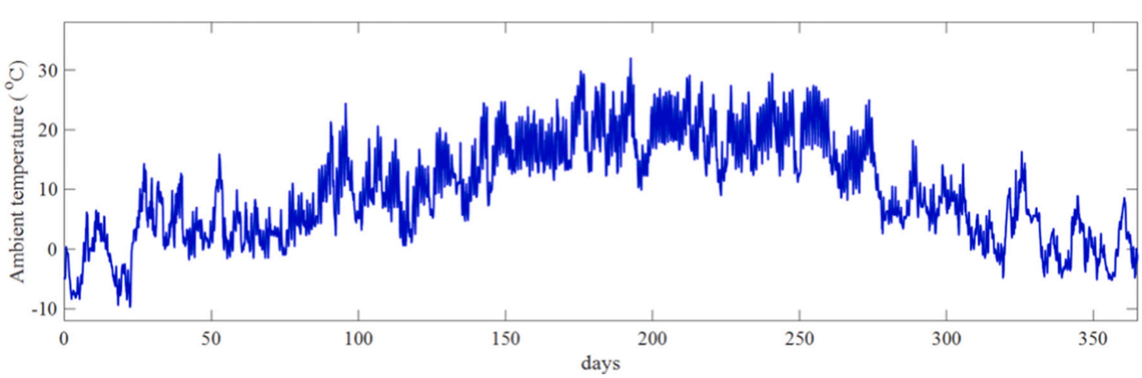

Fig. 2. Ambient temperature variation for a typical Austrian town.

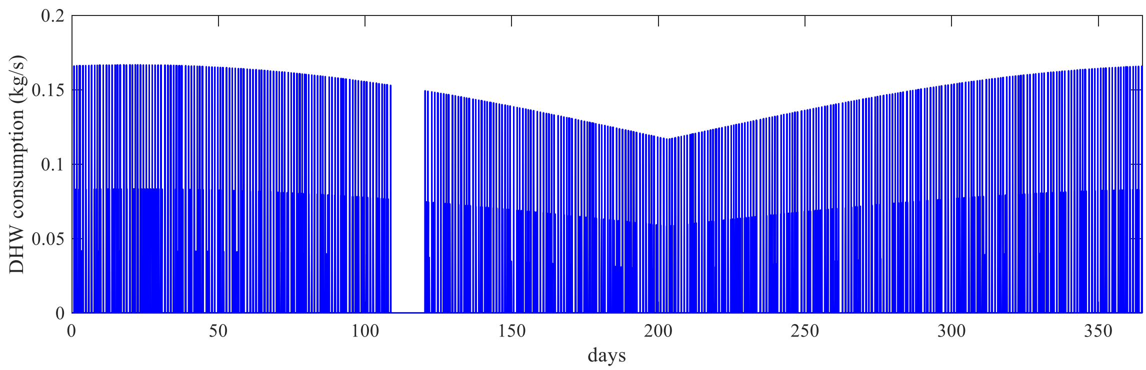

Fig. 3. Domestic hot water demand of dwelling #1.

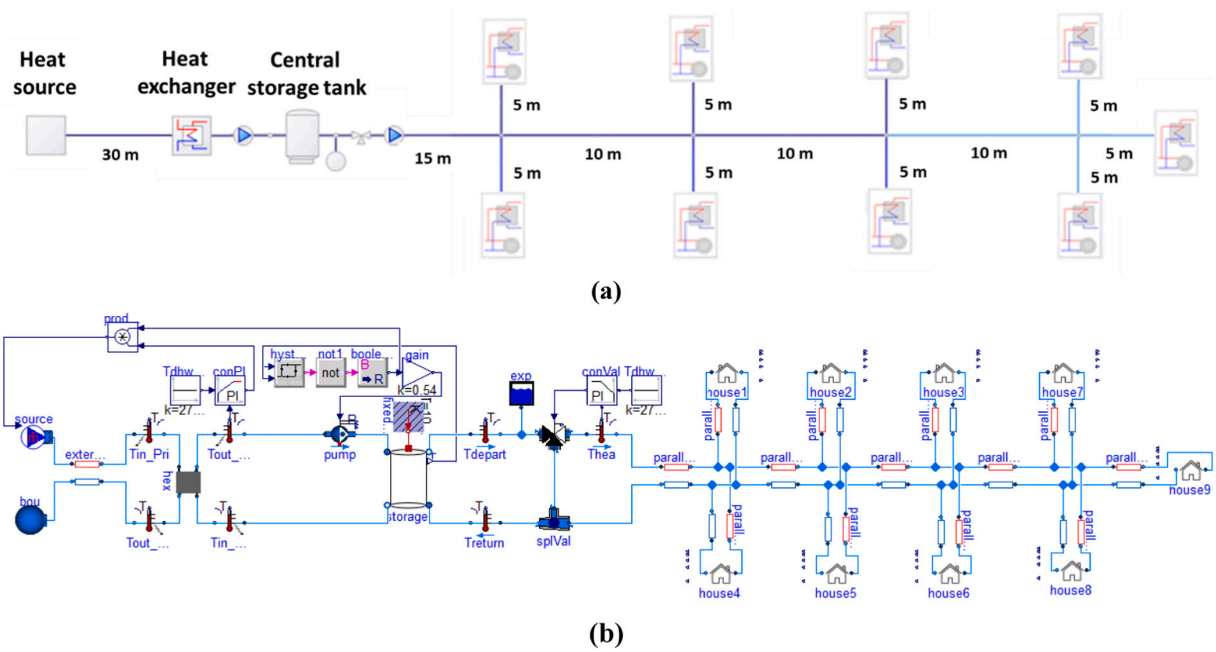

Fig. 4. The developed model of the reference scenario a) in the schematic diagram and b) in the INTEMA, depicting each of the key components with their controllers, accounted for heat exchanger, central storage tank, piping network and dwellings (see Appendix A for the detailed explanation of the components).

source temperature is needed in the underfloor heating system:

$$T_{heat,SP}\ [^{\circ}C] = -0.2 \cdot T_{Amb}\ [^{\circ}C] + 37 \quad (1)$$

The circuit of the DHW has a different control system that aims to provide water at 40 °C while the temperature of the grid water is around 15 °C. Thus, the proper control process is performed with the inclusion of a PI-controller which regulates the mass flow rate of the district hot water in order to achieve the desired DHW temperature level at the heat exchanger outlet. In every dwelling, the mass flow rate of the inlet hot water (m_{flow}) is a function of the dwelling floor area (A) and it is selected according to the next empirical mathematical formulation provided also by PINK [39], which assumes proportional thermal needs with the floor area:

$$\dot{m}_{flow}\left[\frac{kg}{s}\right] = 0.0013 \cdot A\ \left[m^2\right] \quad (2)$$

The previous formula indicates the constant mass flow rate that enters the underfloor heating system by taking into consideration the mixing process for achieving the desired temperature level according to the ambient conditions.

2.3. Enerboxx scenario

In the enerboxx scenario, the central water storage unit is omitted, and instead, for each dwelling, a distributed storage solution is proposed. Each of the 9 dwellings includes a water tank of 140 L, dedicated to the DHW needs. In this decentralized storage scenario, there is also a highly-effective heat exchanger, which is fed with hot water at 65 °C from a heat source (similar to the reference scenario) and provides hot water close to 62 °C on its other side, for the charging of the storage tanks. More specifically, the heat transfer fluid is driven through an insulated pipe network into the decentralized storage tanks inside the dwellings, as Fig. 6 indicates, at a temperature level over 60 °C. The thermal and hydraulic losses are also taken into consideration in this study. The use of a charging temperature over 60 °C renders it possible to avoid the danger of the development of Legionella bacteria [40]. Fig. 7 shows the detailed model of every separate dwelling for the enerboxx scenario, which includes the circuit for the heating and the DHW. For this operation, there is a separate tank for the DHW in every dwelling which is charged two times per day, one in the morning and one in the afternoon as will be described below in detail.

It is useful to comment that the main idea of the present system lies in avoiding the simultaneous charging of both DHW and underfloor

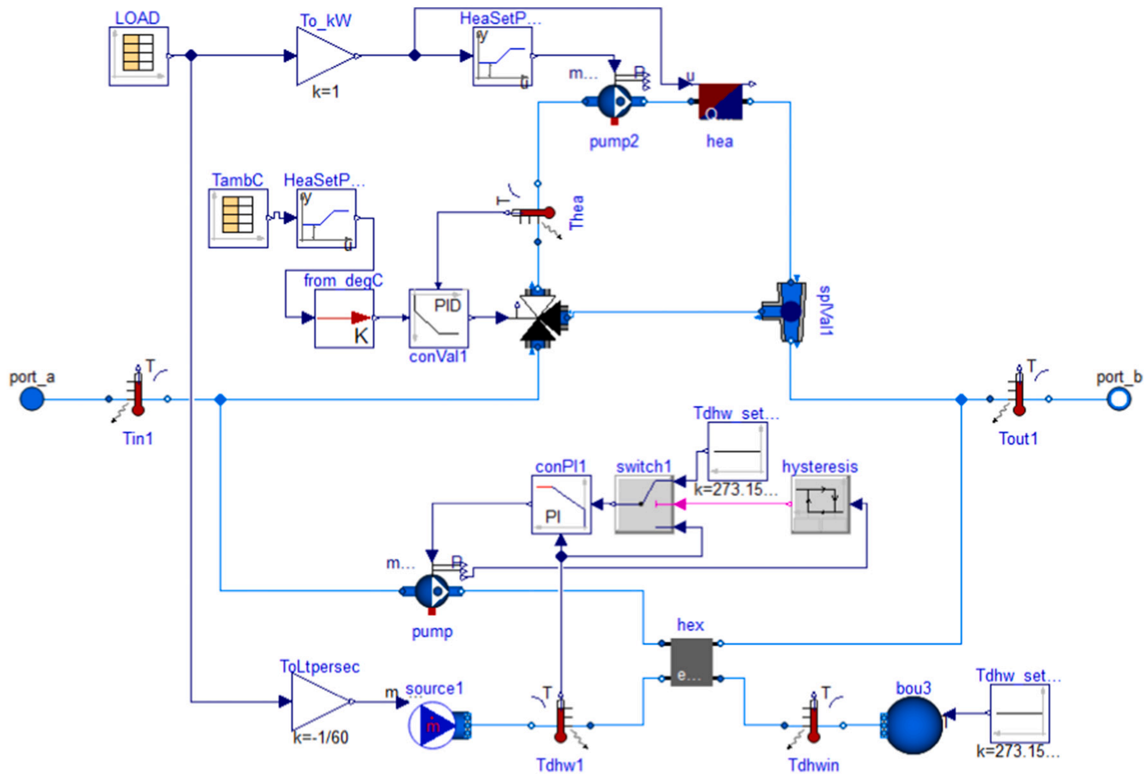

Fig. 5. Model of a single dwelling for the reference scenario in INTEMA environment, including their controllers for the heating circuit and the DHW circuit (see Appendix A for the detailed explanation of the components).

heating systems, allowing the peak load to be reduced, while also permitting the operation of the system with a relatively low temperature of around 39 °C for the majority of the day. In other words, except for the DHW charging periods, the system is designed to operate at low-temperature levels, rendering it in a position to operate in a way to cover solely the heating demand, as the charged storage tanks cover the DHW needs. Such a configuration is not possible to be applied for district heating systems integrated with a single storage tank, especially when considering that each dwelling differs in its thermal demand profile.

The enerboxx configuration is controlled on the basis of a hybrid configuration, by both i) controlling the mass flow rate through the central heat exchanger that feeds all the dwellings with a specific operating program and ii) controlling the subsystems inside every dwelling for covering both the space heating and the DHW needs. More details regarding the control and the system operation are given below.

2.3.1. Control of the central heat exchanger and operating schedule in the enerboxx scenario

Fig. 6 shows the general system that includes the central heat exchanger, the piping and the 9 dwellings. The heat absorption from the grid heat exchanger is conducted by controlling the mass flow rate of the heat source pump on the “hot” side of the central heat exchanger with the use of a PI controller. The goal of the control system is to adjust properly the temperature in the “cold” side of the central heat exchanger that feeds with heat input to the dwellings. More specifically, when there is a need to charge the storage tanks, then the temperature of the dwellings is set at 62 °C, while the rest of the time that there are only heating needs the temperature is set at 39 °C.

Practically, the storage tanks are charged two times over the day for covering solely the DHW needs, in order to avoid the continuous high flow of the heating medium (water); thus minimizing the associated thermal losses and restricting the peak demand from the district network only during the two per day charging periods. This coordinated control is schematically depicted in Fig. 8 and it is one of the main advantages arising from the enerboxx proposed configuration, over that of centralized storage. This approach guarantees the constant availability of hot water, whereby a simultaneous operation of the supply network is avoided. For the scope of simulating this operational strategy, the district-connected dwellings are classified according to three groups, based on their size and aiming to have similar aggregated load demand profiles for each group. More specifically, this classification is conducted in order for every group to have similar charging needs and thus achieve balanced charging times among the groups. Also, the number of residents in every dwelling was taken into consideration for conducting a proper classification. Below the definition of the groups is given:

- **Group #1:** dwellings #1, #4 and #7,
- **Group #2:** dwellings #2, #5 and #8,
- **Group #3:** dwellings #3, #6 and #9.

The tank grouping avoids the simultaneous charging for all the dwellings and correspondingly limits the peak demand from the network, something very important for the sustainability of the suggested concept.

The district central controller coordinates the heating and DHW charging procedure, following a selected schedule for the specific study. More specifically, the storage tanks are successively charged twice a day (at around 05:00 and 17:00) based on the defined grouping in order to charge the tanks, every early morning and early noon, when the occupants’ needs most likely begin. After the end of the successive preliminary charges of the three groups, all the storage tanks are additionally charged simultaneously for an hour as Fig. 8 shows by the ‘DHW Top’ module. During the rest of the operating hours, the space heating loads are served directly from the primary heat exchanger since they are less variable than the DHW loads. The result is the avoidance of simultaneously serving both heating and DHW needs, which in turn reduces the charging peak load. Another advantage occurs when utilizing a low-temperature heating system such as underfloor heating in

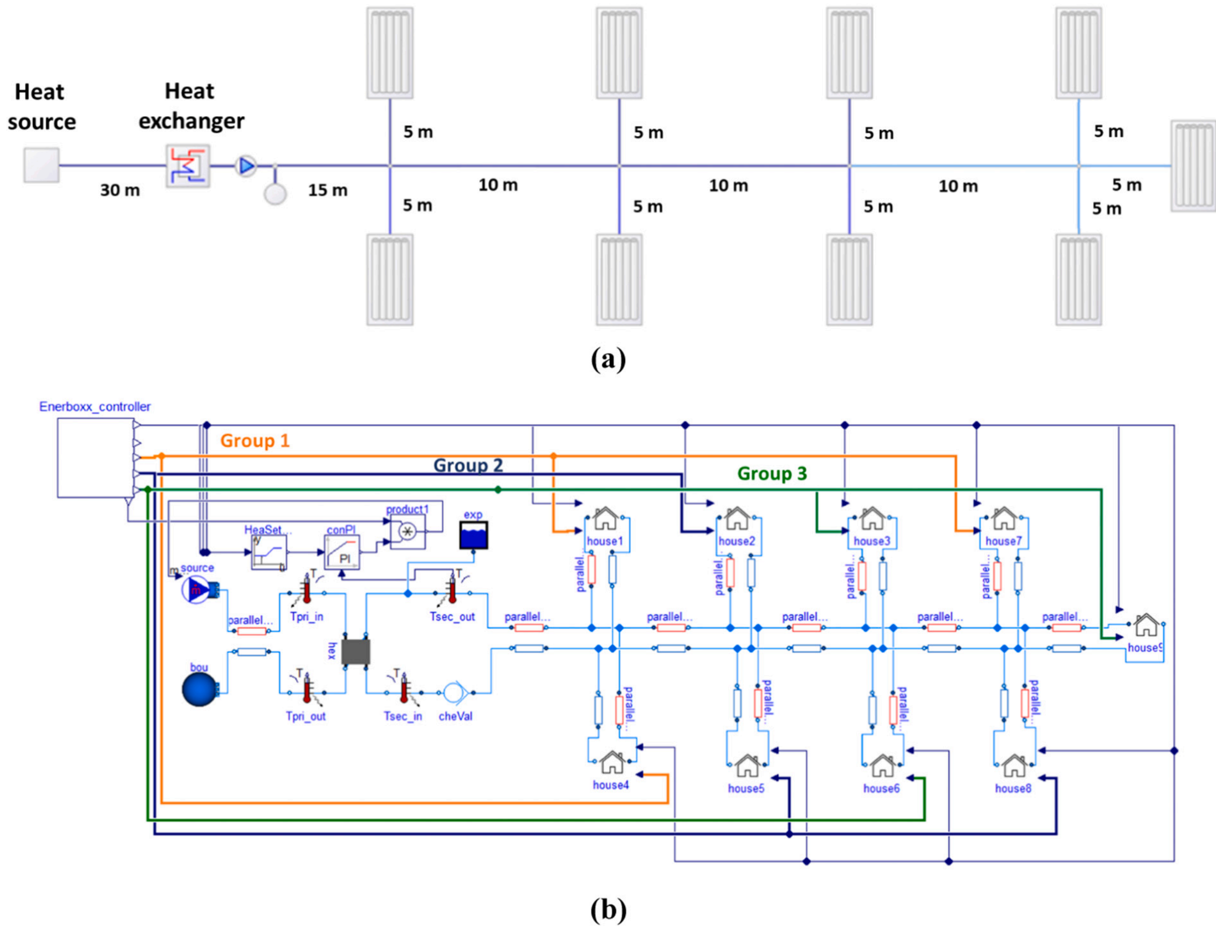

Fig. 6. Developed model of the enerboxx scenario a) in the schematic diagram and b) in the INTEMA including heat exchanger, decentralized storage tanks, piping network and dwellings (see Appendix A for the detailed explanation of the components).

the dwellings. Such systems can be operated at relatively low temperatures (~40 °C), which can further reduce losses in the pipelines. Furthermore, high feeding temperatures of ~60 °C are only required during the periods of the domestic hot water preparation, which is only twice a day for a period of 2–3 h each, while the rest of the day the system can be served with temperatures of ~40 °C. The aforementioned aspects result in an enhanced operation having also direct benefits on both design (avoidance of assets oversizing) and operation (reduction of marginal costs) phases.

2.3.2. Control of the systems inside the dwellings in the enerboxx scenario

Every dwelling has its own control system in order to utilize suitably the district heating input for covering its space heating needs and also for storing heat properly in the decentralized tank. The space heating demands are inputs in the present simulation and thus they are completely covered, as well as the suggested DHW design is found to be a suitable idea for covering the needs for DHW without any mismatch between supply and demand.

Regarding the space-heating system, there is an underfloor heating system that needs a temperature level of around 39 °C for covering the suitable demand. There is a PI-controller that makes possible the control of a three-way mixing valve that regulates the inlet temperature at a specific setpoint, according to eq. 1. Moreover, the water pump is activated when there is demand according to the given operating program.

The DHW circuit includes the decentralized storage tank which is fed twice per day with a predetermined charging program at a temperature level of 62 °C. The discharging of the tank in order to cover the demand is conducted by applying a suitable control strategy. In particular, there is a PI-controller that controls the mixing process in a three-way mixing valve in order to provide the DHW at 40 °C to the occupants. The controller takes as input the temperature level in the upper layer of the tank and determines the mixing process with the cold grid water. The extraction of the hot water from the uppermost part of the tank is a common design choice in thermal applications that has also been followed in the present analysis.

2.4. Followed methodology

The described district heating networks of Subsections 2.2 and 2.3 are simulated in Dymola [34]. The results are compared against results provided by PINK [39] and the models were verified. Moreover, the current analysis included thermal and hydraulic losses and the time step was variable and adjustable in order to take into account the sharp thermal demand variations, mainly due to the DHW demand profile. The developed models use as inputs i) the DHW loads of every dwelling, ii) the heating loads of every dwelling, and iii) the thermodynamic characteristics of the heat source from the general district heating network that feeds the heat exchanger of the local network. More specifically, the mass flow rate of the heat source that feeds the local heat exchanger of the networks has been set to 0.52 kg/s and its temperature at 65 °C, while the nominal charging heat input is 18 kW_{th}. The total length of pipes downstream of the heat exchanger (see Fig. 1) is 90 m with typical insulation of 3 cm thickness and 0.035 W/mK thermal conductivity. For reasons of direct comparison between the two cases, the aforementioned values are the same in the reference and enerboxx scenarios. The different parameters between the two scenarios are presented in Table 3

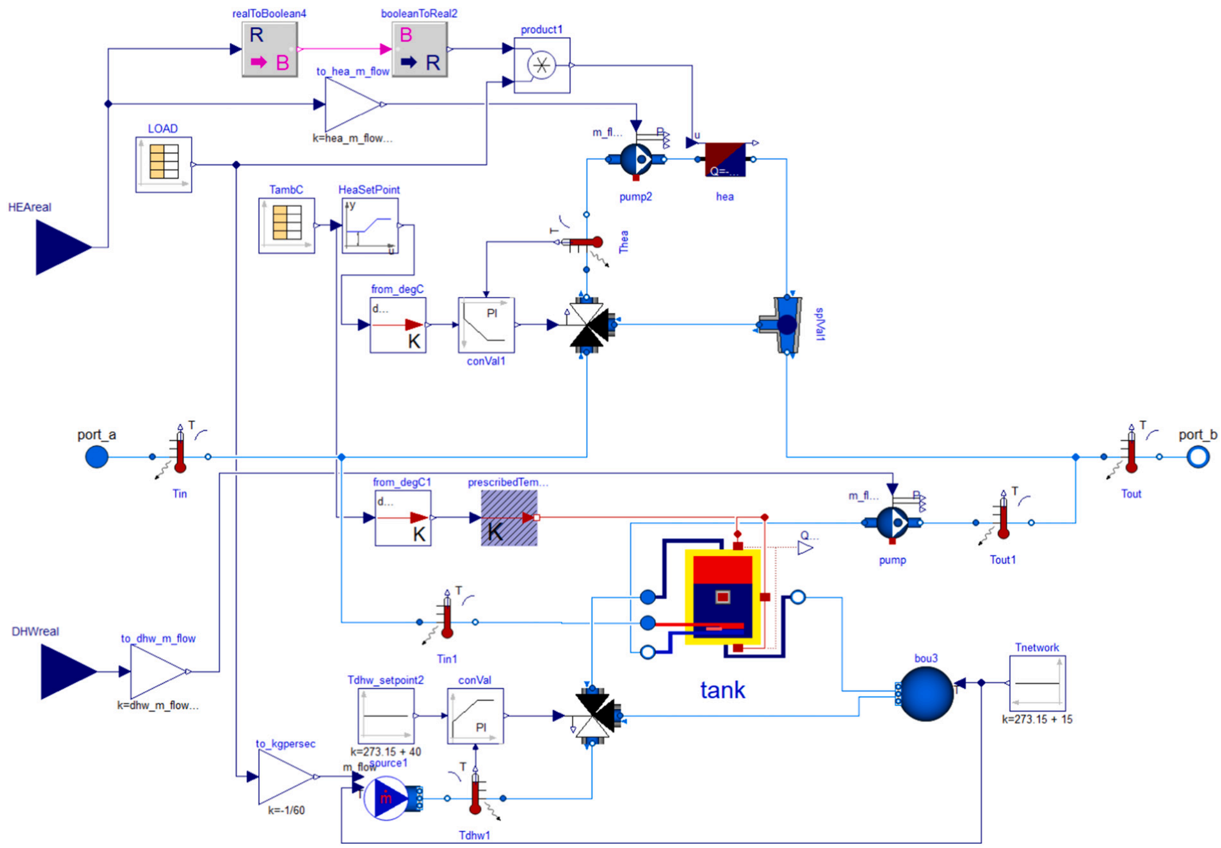

Fig. 7. Model of a single dwelling for the enerboxx scenario in the INTEMA, including key components controllers for the heating circuit and the DHW circuit (see Appendix A for the detailed explanation of the components).

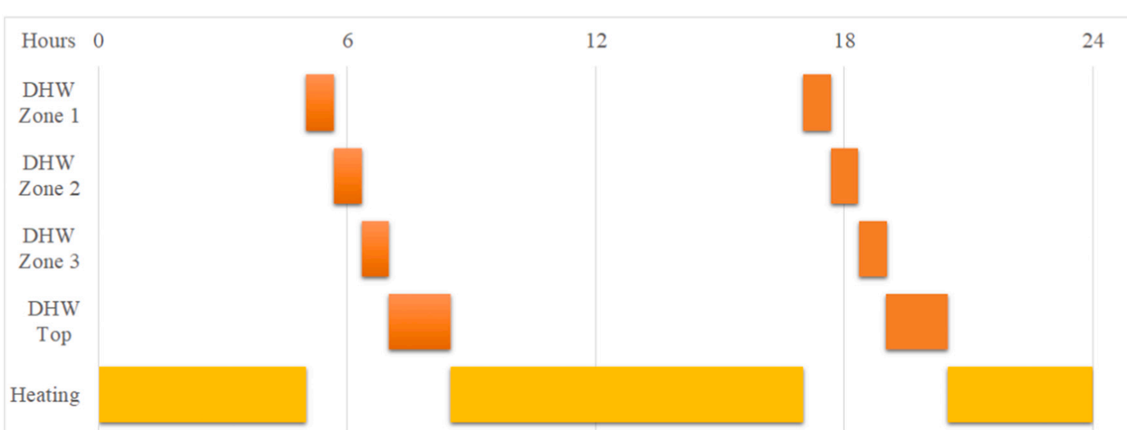

Fig. 8. Daily enerboxx coordinated control.

Table 3
Critical inputs that differentiate reference and enerboxx scenarios.

Parameters	Reference	Enerboxx
Total thermal transmittance of the heat exchanger	100 W/K	200 W/K
Volume of storage tank(s)	1500 L	9 × 140 L
Inlet temperature at dwellings for heating	56 °C	39 °C
Inlet temperature at dwellings for DHW	56 °C	62 °C

analytically.

The advantages of the enerboxx scenario are highlighted and expressed in terms of heat demand reduction from the district network. Also, results regarding the temperature variations of the water streams during the day and the temperature drops during the heat exchange, are provided and compared for both scenarios. Moreover, the present work includes a parametric analysis for the enerboxx scenarios by examining different storage tank volumes and different heat exchanger effectiveness values. This parametric work reveals important results regarding the dynamic behavior of the system and indicates useful directions for the design of the decentralized tanks for DHW in a district heating network.

3. Results and discussion

This section includes the results of the present study starting with the verification analysis of the developed model. The next step is the presentation of the dynamic behavior of the suggested enerboxx scenario as well as its comparison with the reference scenario. The last step is the inclusion of the parametric analysis results regarding the characteristics of the suggested storage tank.

3.1. Model verification

The results of the developed model are validated against provided corresponding data by PINK [39], for the same operating conditions, for the reference scenario. The provided data include temperature levels in the water streams and energy loads/demands. Results for the conducted simulations are presented for several days over the year, aiming at presenting both the overall dynamic behavior of the examined system and also demonstrating the verification procedure against the provided data.

The temperature of the working medium at the inlets and the outlets of dwelling 1 and the primary heat exchanger comparatively, are presented in Fig. 9 and Fig. 10 respectively for i) a cold day (January 1st), ii) an average temperature day (October 15th) and iii) a hot day (July 1st) indicatively. The obtained results with the INTEMA tool are quite similar to the PINK results.

Fig. 9a and Fig. 9b present the temperature of the working medium at the inlet and at the outlet of dwelling 1 during the cold day. The working medium temperature is always set to 56 °C when entering the dwelling, with its temperature at the outlet dropping down to 43–44 °C during most of the day, due to the space heating load. The observed sharp drops in the outlet temperature are due to the simultaneous demand for DHW during these short time periods. The mass flow rates of the hot water are variable during the year and depended on the buildings' thermal needs and the DHW demand. Specifically, the utilization of the DHW makes the abrupt increase in the mass flow rate demand for small time periods during the day and this fact leads to a flow rate of high variation. The obtained temperature curves for the dwelling are almost identical to the corresponding ones from PINK. Fig. 9c and Fig. 9d, depict the temperature variation of the water streams at the inlet and at the outlet of dwelling 1 for the average temperature day. It is obvious that both models, INTEMA and PINK lead to approximately the same profile for the temperature. Furthermore, it is important to highlight that the temperature drop of the working fluid in dwelling 1 during the space heating periods is about half of the respective one on the cold day of January. This is a reasonable result since on a cold day, the served heating load is lower than that of the typical examined day. Also, these results prove that the present model takes into account a variable demand profile during the day, and also for different months of the year. The results for the working medium at the inlet and at the outlet of dwelling 1 for the summer day are depicted in Fig. 9e and Fig. 9f for both model approaches, respectively. The absence of space heating demand renders the temperature of the working fluid at the outlet of dwelling 1 almost equal to its inlet temperature apart from the moments that there

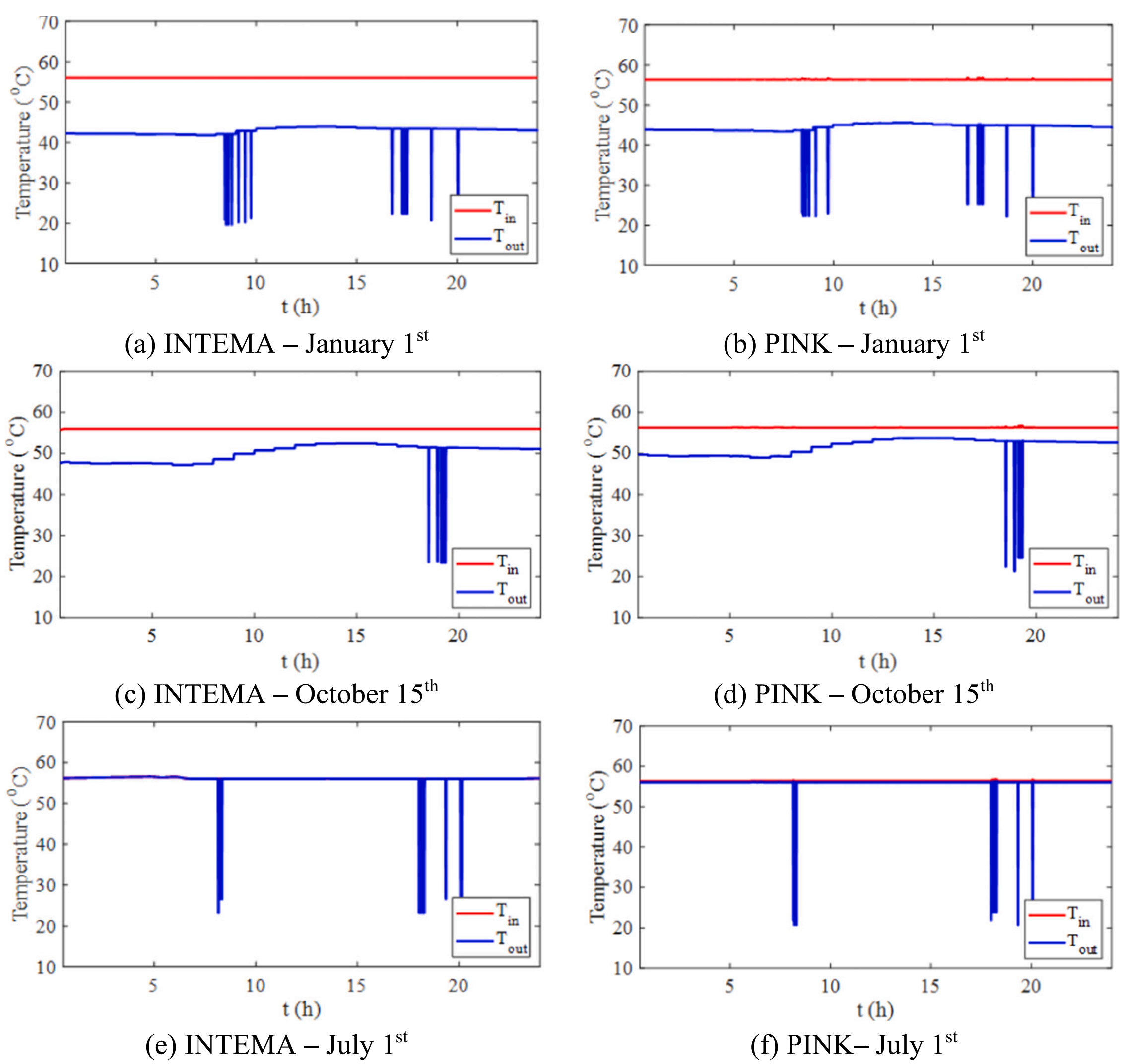

Fig. 9. Dwelling 1: Comparison of the INTEMA results with the PINK results for the reference scenario on different typical days during the year.

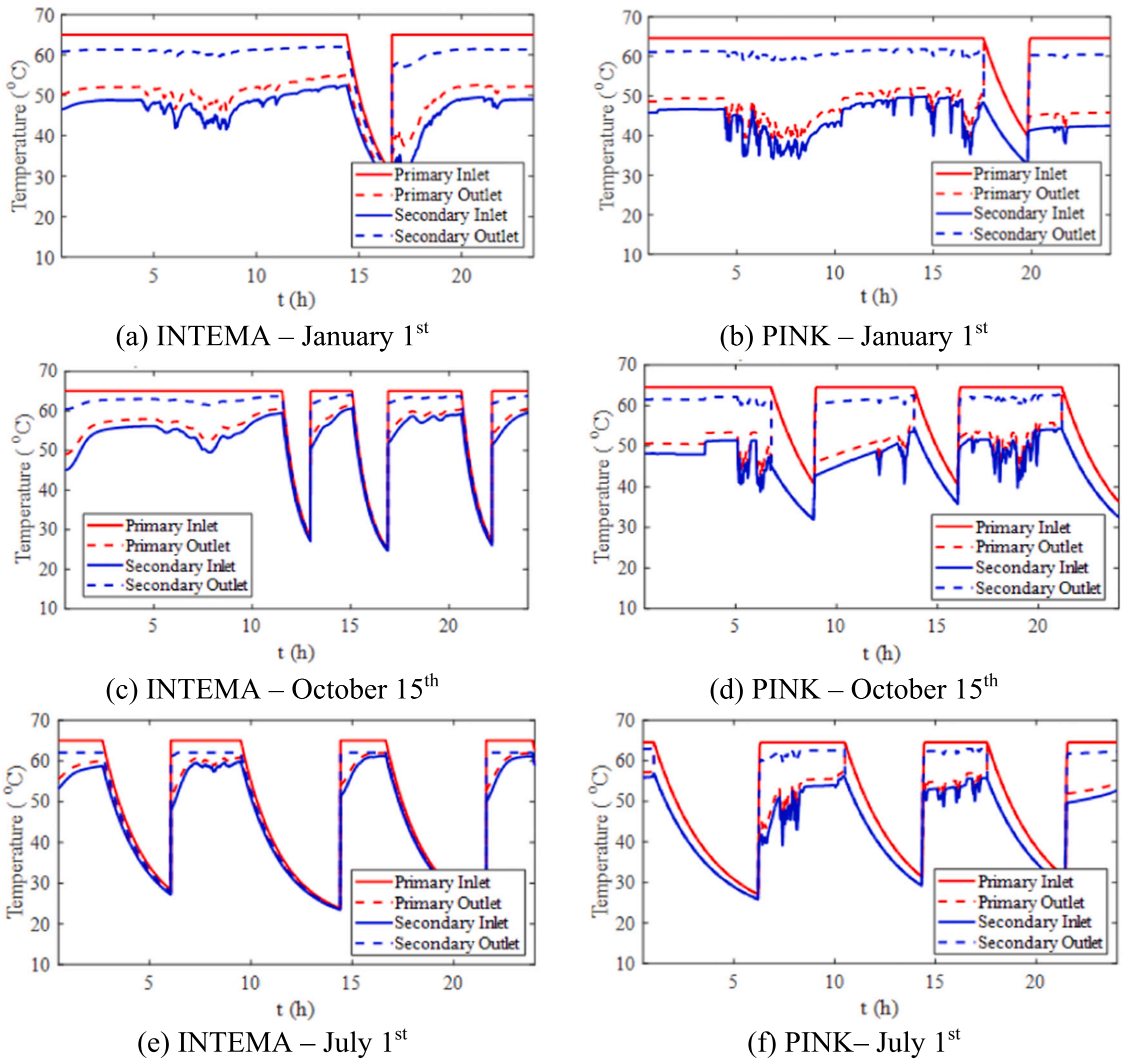

Fig. 10. Transfer Station: Comparison of the INTEMA results with the PINK results for the reference scenario on different typical days during the year.

is DHW consumption. Again, there is an agreement between the results of INTEMA and PINK.

The next step in the validation procedure lies in the comparison of the results for the transfer station, which are illustrated in Fig. 10. The aim of this analysis is to examine the aggregated system load, in comparison with the individual one that was analyzed above. More specifically, the results of this figure concern the temperature levels of both sides of the heat exchanger. The red-colored curves regard the primary stream of the heat exchanger which takes the heat from the outer grid, while the blue-colored curves regard the secondary stream, which transfers the heat to the dwellings. In all subfigures, the maximum primary side inlet temperature is equal to 65 °C.

For the winter day, Fig. 10a and Fig. 10b show that in both simulation models, the streams of the secondary side have around 5 °C lower temperatures compared to the respective streams of the primary side. This is a reasonable result that ensures proper heat transfer from the primary side to the secondary side. Also, this agreement entails that the design of the heat exchanger in INTEMA is in accordance with that of PINK. For the examined day, there is a sharp phenomenon during the afternoon. Both tools face this variation in a similar way and the small deviations are justified by the different control strategies between the tools. However, in both cases, the deviations are not very significant since the charging of the storage tank stops at around the same time with a similar duration. During that period, there is no mass flow rate through the heat exchanger and its temperature gradually decreases. For the average temperature day, Fig. 10c and Fig. 10d depict the dynamic behavior of the system. Again, there is an agreement between the results with the temperature deviations in the heat exchanger to be generally similar for the two model simulations. Also, the charging processes occur in the early morning and in the afternoon. For the summer day, Fig. 10e and Fig. 10f depict the dynamic behavior of the transfer station of the system. During this day, the load is reduced compared to the other days and this fact is based on the lack of heating demand, while only that of the DHW demand exists. Thus, there are periods without heat transfer in the heat exchanger that can be identified in the Figures in the cases where the inlet and the outlet temperatures of the primary stream are approximately the same. At this point, it is remarkable to refer that for the day of October, the non-load periods are greater compared to the cold day, while the summer day has greater periods of non-load. This is a generic result, which is also variable from day to day, but generally, it reveals that the present tools take into consideration the load variation during the year in a proper and reasonable way.

The final step of the validation procedure regards the comparison of the INTEMA total heat loads in (kWh_{th}) with the corresponding results from PINK. More specifically, the annual total thermal consumptions of the reference scenario are presented in Fig. 11 in comparison with the results provided by PINK. It can be observed that the INTEMA and PINK models present only small differences in their heat loads due to different thermal losses. According to Fig. 11, the annual deviation for the reference scenario was found at 5 %, while the seasonal is 7 % for winter,

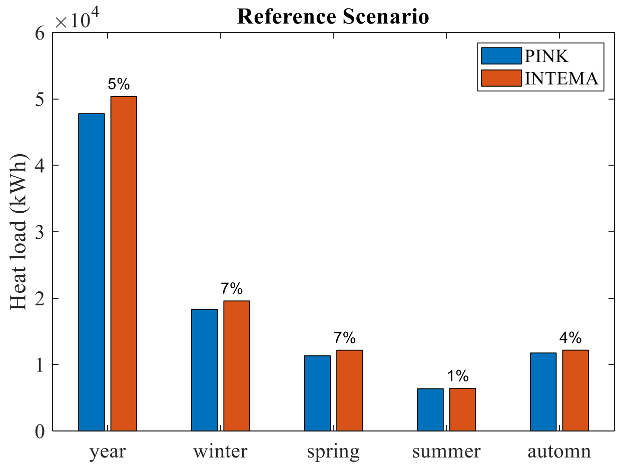

Fig. 11. Comparison of INTEMA and PINK models' annual total heat load at reference scenario (the deviations between INTEMA to PINK consumption are displayed in the chart).

7 % for spring, 1 % for summer and 4 % for autumn. The aforementioned deviations are relatively low and this fact indicates that the developed tool (INTEMA) can be considered reliable for the calculation of the energy demand of a district heating system. Additionally, the detailed comparative analysis of Fig. 9 and Fig. 10 shows that the INTEMA tool gives also reasonable and correct results regarding the temperature levels of the water streams and the temperature drop during the day for all the seasons of the year. Consequently, the developed tool is verified both in terms of dynamic time operation and in terms of energy performance seasonally and yearly.

3.2. Analysis of the enerboxx scenario

This section aims to present the results of the proposed decentralized design called enerboxx scenario. Recalling that in this scenario there is a separate storage tank in every dwelling for storing DHW at two times during the day; one in the morning and one in the afternoon. The thermal load profiles for heating and DHW are the same in both scenarios. In addition, the external heat exchanger and pipes have exactly the same insulation and geometric specifications resulting in equal pressure drop; allowing the same pumps to be used. The thermal losses from pipes to the environment are taken into consideration and play a significant role in the results because they contribute to the overall system performance. The first step in the present analysis is the presentation of the results for the dynamic operation of both systems for three typical days, one in winter, one in autumn and one in the summer.

Fig. 12 depicts the comparative results for dwelling 1 on January 1st, October 15th and July 1st. It is obvious that the temperature profiles of

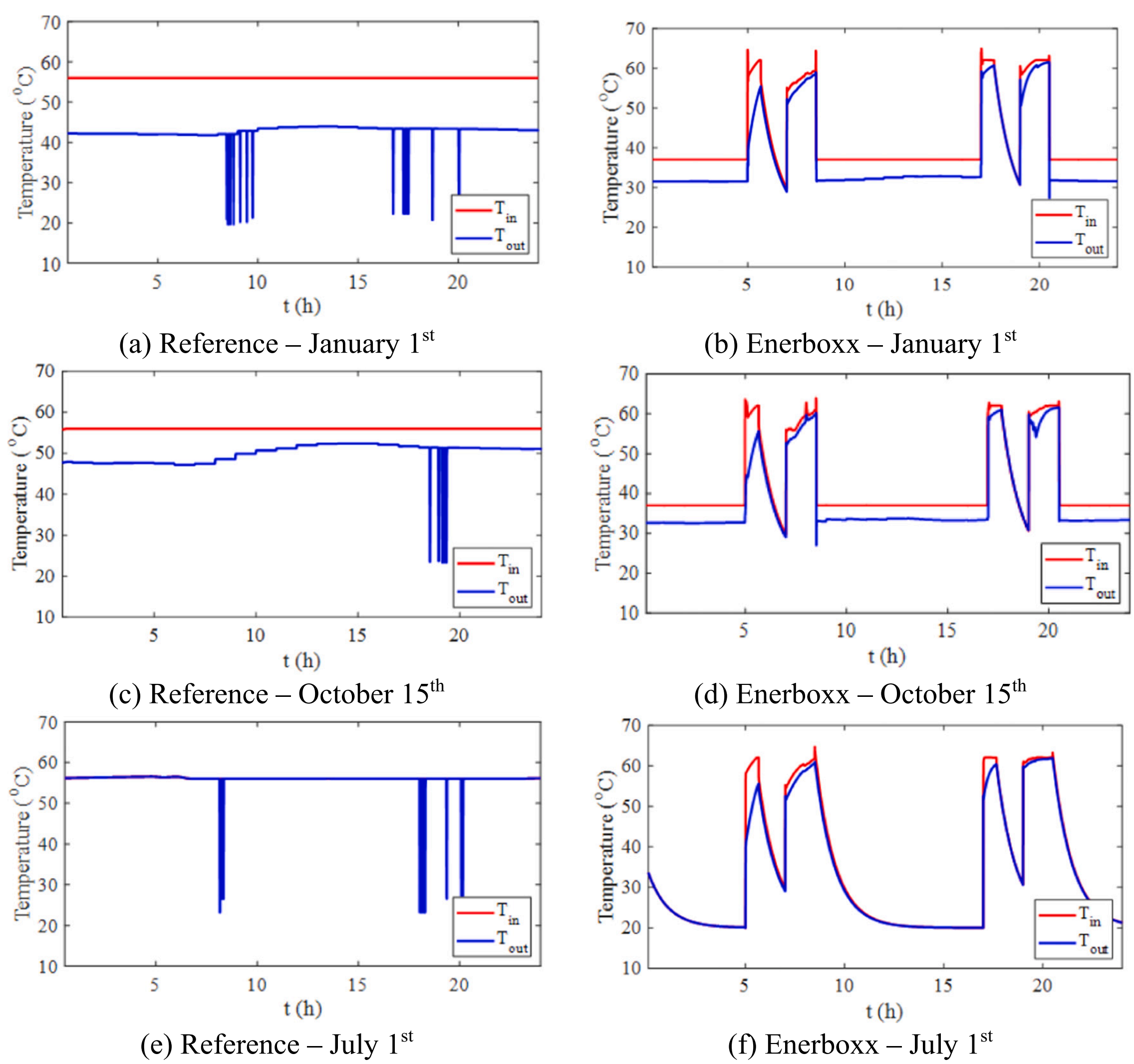

Fig. 12. Dwelling 1: Comparison of the reference and the enerboxx scenarios for different days during the year with the INTEMA tool.

the subfigures (a, c and e) for the reference scenario on the left are totally different from the subfigures (b, d and f) calculated for the enerboxx scenario, on the right. In the reference scenario, there is practically a continuous heat supply in the dwellings, which is conducted at relatively high temperatures because it is designed to cover both the heating and DHW needs. On the other hand, the enerboxx scenario charges the DHW tanks only twice a day and during the rest period, only the heating demand is present, which has a relatively low temperature for feeding the underfloor heating system. Therefore, the thermal losses during the heat transfer to the dwellings are greater in the case of the reference scenario, while for the enerboxx scenario there are energy savings which are presented in the following figures of the present subsection. The energy savings are variable over the year and range from 11 % in the summer up to 21 % during the winter period.

It is notable that in the reference scenario, the working medium enters the dwelling system at 56 °C, while the enerboxx scenario enters at 39 °C during the space heating periods (the majority of the day period) and at 62 °C only for charging the tanks (two periods each day). Therefore, these temperature values validate the aforementioned analysis regarding the reduced operating temperature in the enerboxx scenario. In this direction, Fig. 13 displays the thermal losses in (kW_{th}) during the winter day, i.e., when there are higher thermal losses. It is obvious that the thermal losses are approximately steady in the reference scenario and close to 1.3 kW_{th}, while they are variable for the enerboxx scenario. More specifically, for the majority of the day with only heating demand, the thermal losses are about 0.6 kW_{th} and only during the charging hours they are up to 1.37 kW_{th} and they exceed a bit the reference scenario losses. However, it is clear that the daily thermal losses in the reference scenario are significantly higher compared to the enerboxx scenario.

The next step in this analysis is the presentation of the energy flow diagrams (Sankey) for both systems in order to make a detailed energetic comparative investigation for a typical year day. In Fig. 14, the Sankey diagram of the reference scenario illustrates the distribution of thermal power consumption. It can be observed that 33.8 % of the total power consumption is spent to serve the needs of the DHW, 43.4 % on heating needs and 22.8 % are owed to thermal losses in the network. In the Sankey diagrams, the percentage of the power for every system according to the total power provided by the primary heat exchanger is displayed. Thermal losses in the storage tank and in the piping are illustrated together aiming to simplify the present depiction. In addition, the mean temperature of the working fluid is displayed in every subsystem.

Fig. 15 depicts the Sankey diagram for the enerboxx scenario which shows that 36.4 % of the energy input is given in the space-heating system, while the DHW demands the 40.5 %. The total thermal losses of this scenario were calculated at 23.1 % which is a similar percentage as the thermal losses in the reference scenario (22.8 %). However, the heat input in the enerboxx scenario is 82 % of the reference's scenario heat inputs, given in green color in Fig. 15. Specifically, the green colors in this figure indicate the relative energy flow percentages normalized to the total energy demand of the reference scenario. Consequently, it can be extracted that there is an 18 % decrease in energy demand in the enerboxx scenario which is a significant energy demand reduction. Moreover, it would be valuable to state that the total thermal losses of the enerboxx scenario are 22 % lower compared to the reference scenario in absolute numbers, due to the optimum charging technique and the reduced operating temperature on the network.

The next step in the present analysis is the quantification of the energy demands and savings during the different seasons, as well as during the year. Fig. 16 presents the annual heat load at the reference and enerboxx scenario and its distribution at every season of the year. It can be observed that in both scenarios the total thermal consumption is significantly lower during the summer because in this period there is only a need for DHW. The highest demand is reasonably observed during the winter period. It is obvious that the enerboxx scenario presents decreased thermal demand due to the lower thermal losses to the environment because the circulating working medium in the enerboxx scenario has a reduced temperature level (around 39 °C) for the majority of the day.

The total heat loads of reference and enerboxx scenarios are presented comparatively in Fig. 17. The annual consumption in the enerboxx scenario is decreased by 18 % proving that the decentralized approach is more efficient. The reduction of the heat load is higher during the winter and it is 21 % compared to the summer which is 11 %, while it is 18 % during the spring and autumn. The yearly mean heat load reduction is about 18 % which is a value that indicates significant energy performance enhancement. Also, at this point, it has to be commented that the space heating and DHW demands are properly covered in both examined scenarios, something that makes possible the comparison of the examined configurations.

3.3. Parametric study of the enerboxx scenario

The presented results about the enerboxx scenario in the previous sections were acquired considering enerboxx with a volume of 140 L,

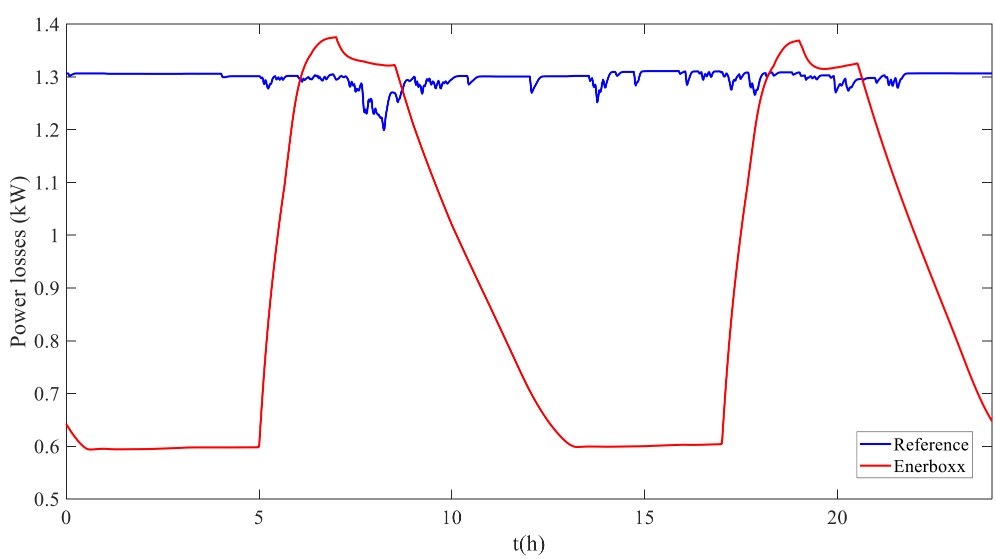

Fig. 13. Network thermal losses on a typical winter day.

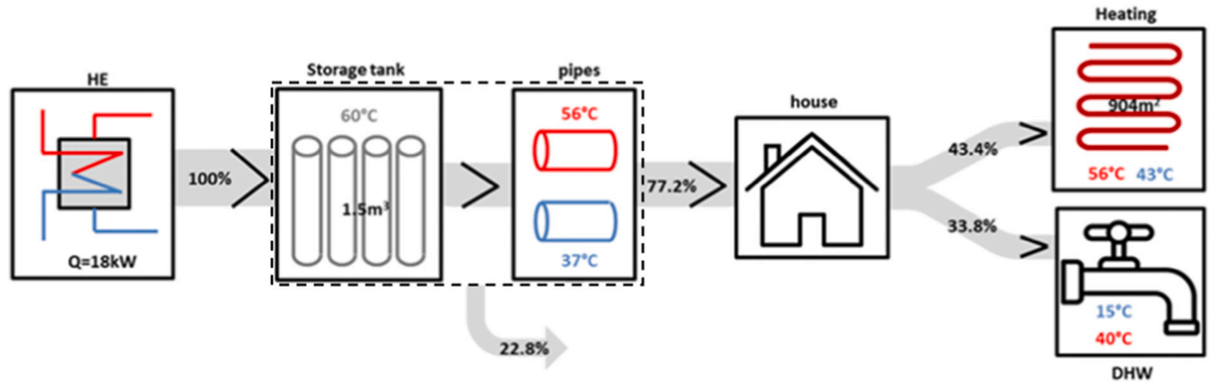

Fig. 14. Sankey diagram of the reference scenario for the dwelling.

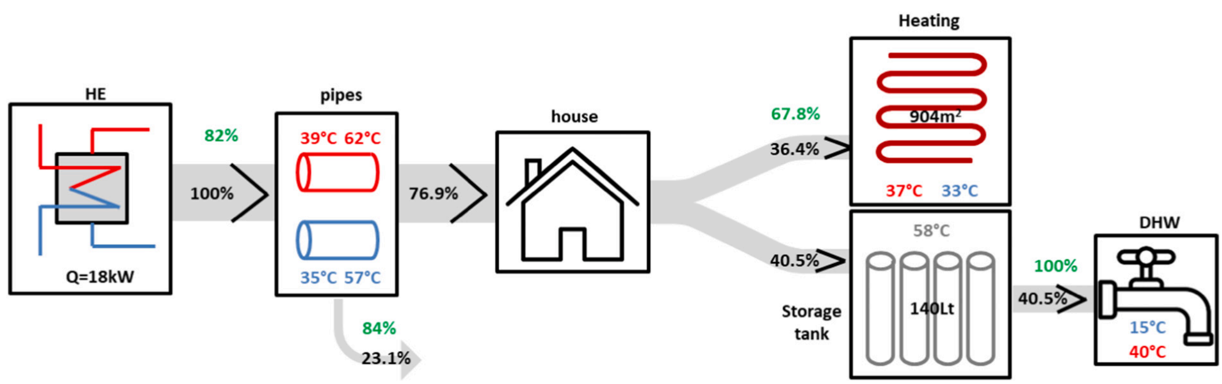

Fig. 15. Sankey diagram of enerboxx scenario for the dwelling (with green values are depicted the thermal consumptions in relation to the corresponding ones of the reference scenario). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

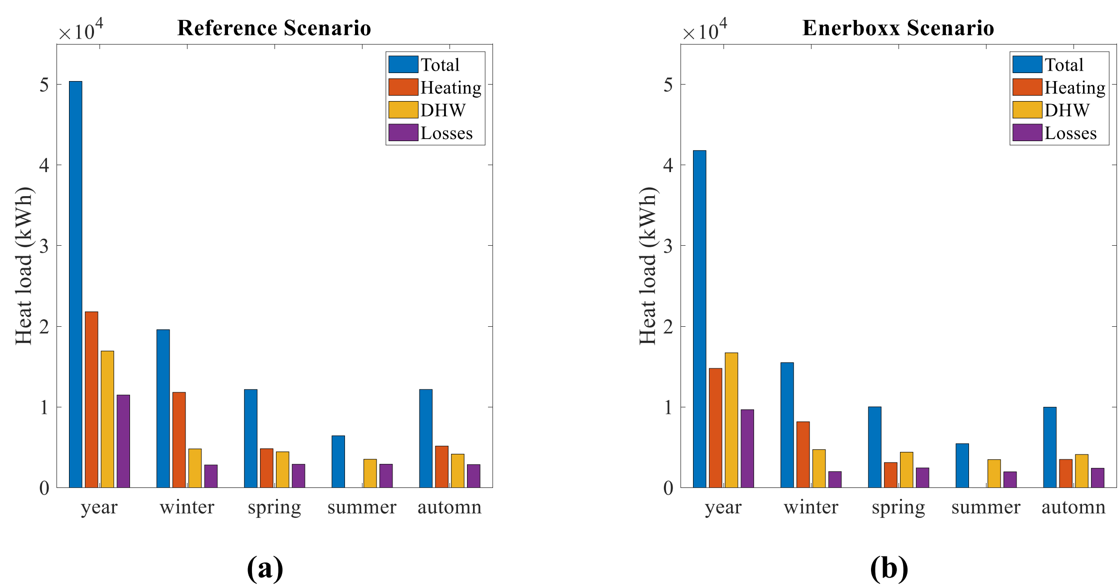

Fig. 16. Thermal consumption due to heating, DHW and thermal losses at a) reference and b) enerboxx scenarios.

and with a heat exchanger with total thermal transmittance of 200 W/K. However, these design parameters are critical and thus a parametric study is conducted in order to check their impact on the system performance.

3.3.1. Impact of the tank volume on the results

Firstly, the effect of the enerboxx volume on the thermal response of the system was investigated by simulating enerboxx with 100 L volume and comparing it with the tank of 140 L, keeping the thermal conductance of the heat exchanger at 200 W/K. The temperatures inside the 140 L enerboxx are presented in Fig. 18a, while the temperatures during the same day for the enerboxx with 100 L volume are displayed in Fig. 18b. Due to the stratification inside the tanks, the water temperature is higher as the height increases. In Fig. 18 the temperature is presented

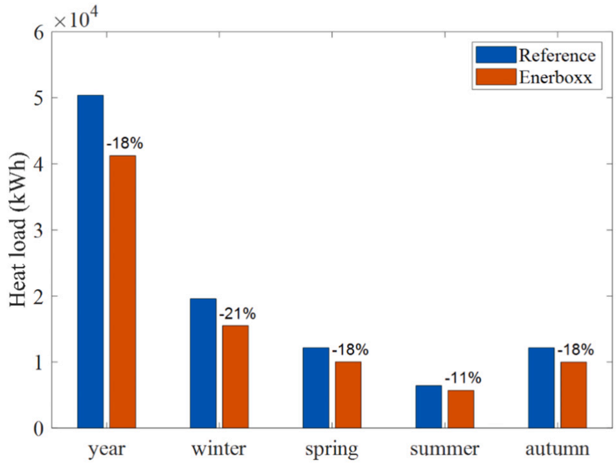

Fig. 17. Total thermal consumptions of enerboxx scenario compared to the reference. (the deviations are shown in the chart).

at 10 %, 30 %, 50 %, 70 % and 90 % of the height of the tank and it can be observed that the water temperature at the bottom of the tank is significantly lower compared to the top (~10 K). This effect is more dominant at the smaller enerboxx, where storage capacity is smaller. The temperature increases rapidly during the charging periods of the day. More specifically, the temperature increase can be observed in Fig. 18 at the 'DHW Zone 1' charging periods (see Fig. 8), which are highlighted in yellow color, and at the 'DHW Top' charging periods (see Fig. 8), which are highlighted with pink color. However, since both cases cover the total heat load of the system, the thermal energy consumptions do not differ much as Fig. 19 presents.

3.3.2. *Impact of the heat exchanger thermal transmittance on the results*

The impact of the heat exchanger inside the enerboxx was investigated for tanks with 140 L volume performing dynamic simulations with total thermal transmittance of the tank's heat exchanger at 200 W/K and 100 W/K. The temperature distribution inside the enerboxx highlights the significance of the heat exchanger to the temperature increase as Fig. 20 presents. Since in both cases the heat demand of the system is covered the total thermal consumption is approximately equal (see Fig. 21). However, it is interesting that in the system with the higher heat exchanger effectiveness, the operating temperature levels are higher and closer to the heat source temperature level. More specifically, the high heat exchanger effectiveness reduces the temperature difference between the exchanger streams and thus it gives the possibility for operation with low-temperature sources (e.g., solar thermal systems, geothermal boreholes, etc.).

4. Conclusions

The present study aims to present and investigate a novel configuration of a district heating network based on decentralized storage units for DHW needs (enerboxx). The simulation analysis is conducted with a custom tool (INTEMA) developed in the Dymola environment by using the Modelica modeling language. INTEMA is an advanced fully house-built tool that simulates in detail the district heating network using adjustable small-time steps, able to take into account any sensitive fluctuations of key operational variables, considering in detail both the general heating network and each of the dwellings separately. Also, a hybrid control strategy is applied over the whole system operation, in order to control both the district heating network behavior and the individual thermal systems inside the dwellings. The examined study cases regard a heating network with 9 dwellings in Austria with an underfloor heating system and DHW demand. This system (enerboxx scenario) achieves to reduce the mean operating temperature of the network by controlling properly the charging of the tanks, resulting in significant energy savings of around 18 % annually, due to the reduced thermal losses. The novel configuration is compared with a conventional one with a centralized storage system (reference scenario) in order to extract useful conclusions for the new suggested design. According to the present annual comparative analysis, the following conclusions can be extracted:

- The proposed system is able to deliver properly the heating and DHW demand based on a suitable control strategy, taking benefit of the advantages a decentralized storage system offers, resulting in energy savings in the range of 11 % to 21 %, by reducing the network operating temperature to 39 °C for the majority of the day and avoiding the simultaneous charging of the system for both heating and DHW

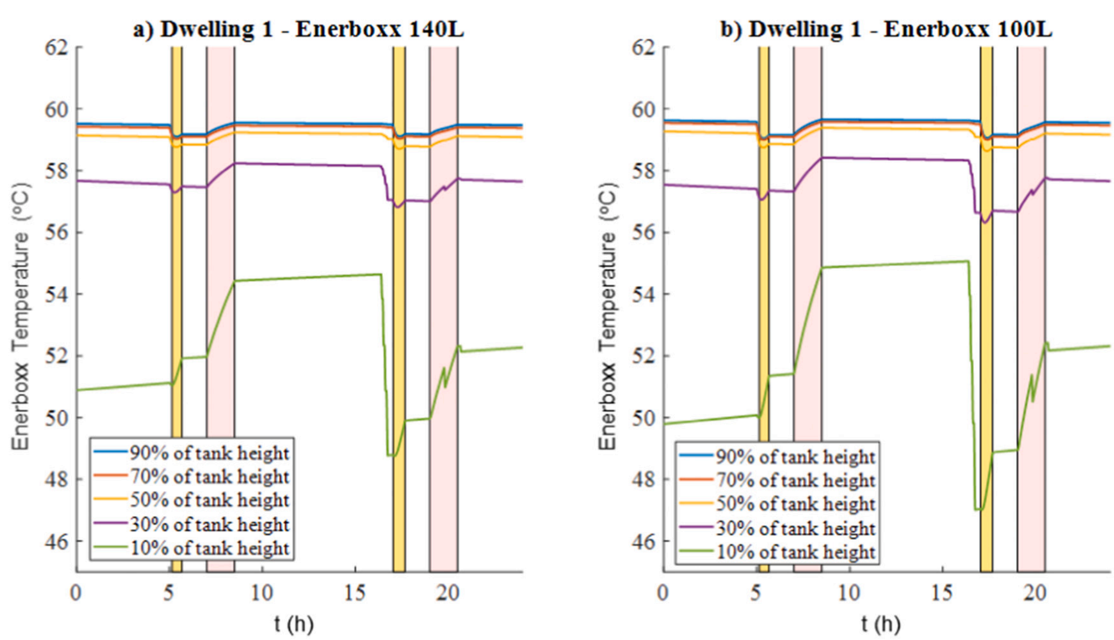

Fig. 18. Spatial distribution of water tank temperature during the time period of a typical winter day at five heights of a) 140 L enerboxx and b) 100 L enerboxx, with 200 W/K total thermal transmittance of the tank's heat exchanger.

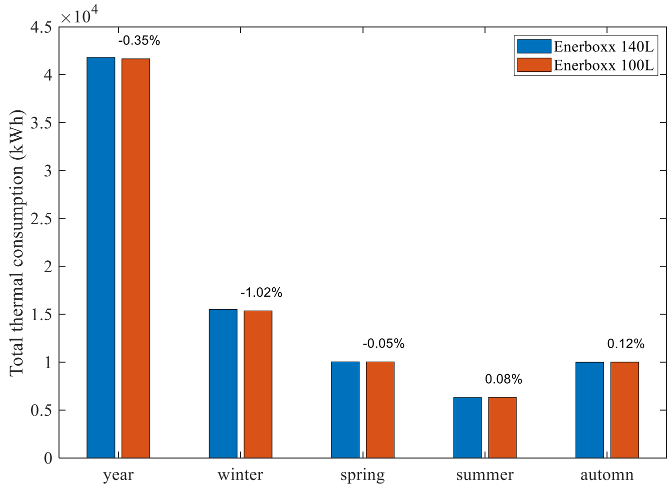

Fig. 19. Total thermal consumptions of enerboxx scenario with 140 L and 100 L tanks. (the deviations are shown in the chart).

demands. Moreover, the proposed charging strategy avoids the high peaks due to the charging of the tank at different periods while the high thermal demand is restricted only during the charging periods in the morning and the afternoon charging periods.

- The temperature level in the dwelling entrance is around 56 °C for the reference scenario, while for the enerboxx scenario is close to 39 °C for the majority of the day and only for the charging periods it is about 62 °C. Thus, the operating temperature levels are lower with the enerboxx scenario and this fact is a critical one for achieving energy savings; while also rendering this system configuration more scalable to the case of varying district heating network generations.

- The enerboxx scenario proved to be more efficient than the reference one since it presented 22 % lower thermal losses and 18 % lower demand, compared to the reference scenario with centralized storage, from the general grid on an annual basis. Practically, the proper control strategy and the lower mean operating temperature level of the network are the factors that lead to the aforementioned enhancements.

- The seasonal analysis proved that the enerboxx scenario leads to higher energy savings during the winter period (21 %) compared to the summer period (11 %), while for the rest of the year intermediate savings of around 18 % were found. These results are reasonable and are explained by the thermal enhancement margin which is lower during the summer because of the lower demand.

The proposed system enhances the operation of low-temperature district heating networks that cover also DHW needs. Possible next steps involve the consideration of renewable energies for feeding the system and more specifically the use of geothermal and solar energy. Also, heat pumps can be considered for upgrading the heat input or for providing the heat demand on the system. Furthermore, the DHW storage tank can be connected with phase change materials aiming to reduce further thermal losses and develop a more compact design. Last but not least, the system operation can be further optimized by taking into consideration economic and environmental criteria.

Nomenclature

A	Dwelling floor area, m^2
m_{flow}	Mass flow rate, kg/s
T_{amb}	Ambient temperature, °C
$T_{heat,SP}$	Set point temperature for heating, °C
T_{in}	Inlet temperature, °C
T_{out}	Outlet temperature, °C

Abbreviations

DHW	Domestic hot water
DW	Dwelling
HE	Heat exchanger

CRediT authorship contribution statement

Evangelos Bellos: Conceptualization, Formal analysis, Investigation, Validation, Writing – original draft, Writing – review & editing. **Petros Iliadis:** Conceptualization, Formal analysis, Investigation, Software, Writing – original draft, Writing – review & editing. **Christos Papalexis:** Data curation, Formal analysis, Investigation, Software, Validation, Writing – original draft, Writing – review & editing. **Renos**

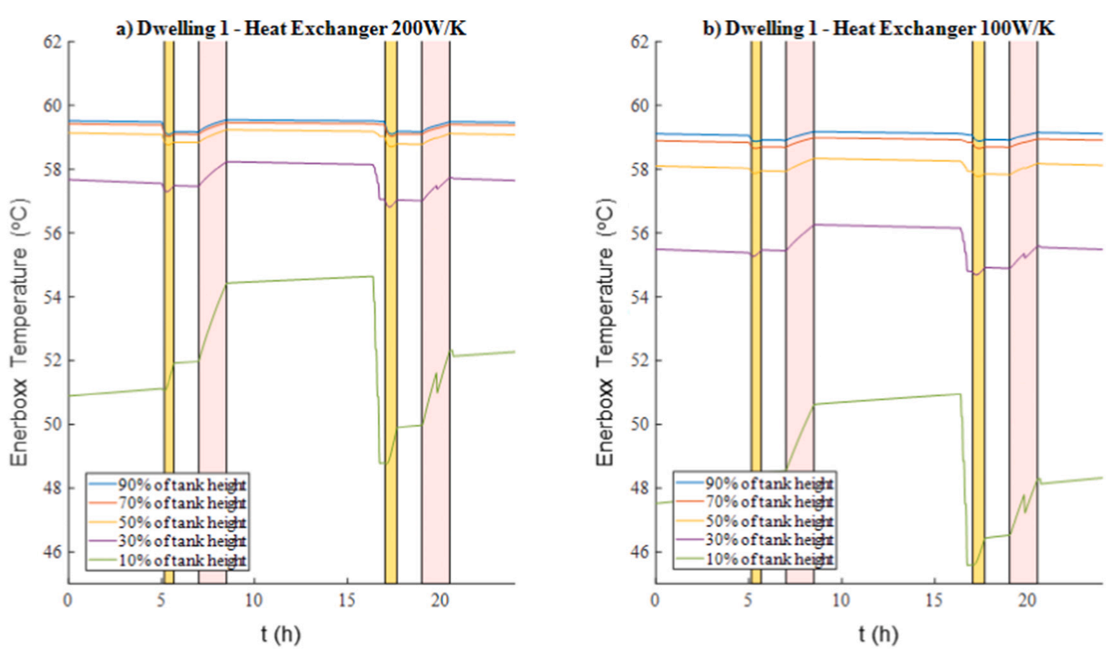

Fig. 20. Spatial distribution of water tank temperature during the time period of a typical winter day at five heights of 140 L tanks with total thermal transmittance of the tank's heat exchanger at a) 200 W/K and b) 100 W/K.

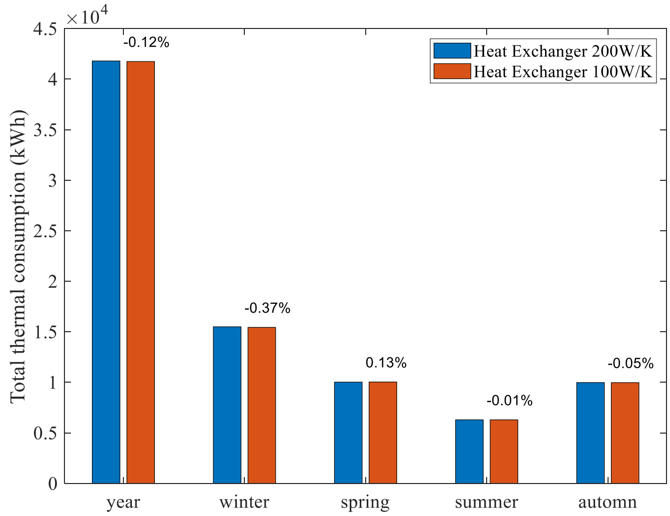

Fig. 21. Total thermal consumptions of enerboxx scenario with 200 W/K and 100 W/K total thermal transmittance of the tank's heat exchanger. (the deviations are shown in the chart).

Rotas: Formal analysis, Software, Writing – original draft, Writing – review & editing. **Nikos Nikolopoulos:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision. **Elias Kosmatopoulos:** Conceptualization, Writing – original draft, Supervision. **Christian Halmdienst:** Data curation, Supervision.

Declaration of competing interest

There is not any conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Explanation of the component symbols

The present modeling has been developed in the Modelica language and it was solved in the Dymola environment. This appendix provides a brief presentation of the component symbols that are used in the figures of the present work. The most usual and important components are explained in order to describe the figures of this work in a detailed way.

Table A1
Explanation of the component symbols of the Modelica interface.

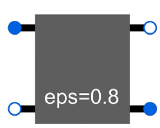
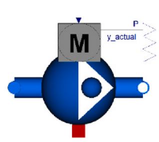
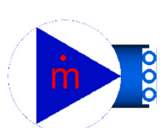
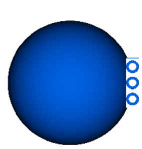
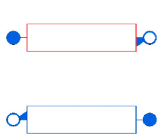
	Heat exchanger with constant effectiveness (e.g., 80 %)
	Water pump for controlling properly the mass flow rate
	Fluid source of prescribed mass flow rate
	Fluid sink/boundary
	Water tubes for connecting the building with the district heating network

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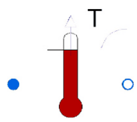
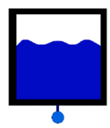
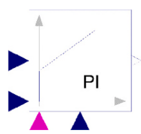
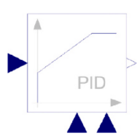
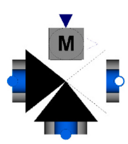
Table A1 (*continued*)

	Component of the dwelling with the DHW and space-heating systems included
	Thermometer
	Expansion tank
	PI controller
	PID controller
	Three-way valve for controlling the mixing process

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