Energetic Optimisation of the Domestic Hot Water System in a Residential Building by Means of Dynamic Simulations

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Abstract

The present study deals with the energetic optimisation of Domestic Hot Water (DHW) system in a residential building located in Catania, Italy. Each dwelling is equipped with a specific decentralised tank with an internal heat exchanger which is connected to a 2-pipe hot water network system for tank charging. The technical water is produced by an Electrical Heat Pump (EHP) coupled to a central storage tank. The energy performance analysis of the DHW model is evaluated by means of dynamic simulations under three different scenarios of charging the decentralised storage tanks by circulating pump unit: Pump activated during daytime, activated twice a day, and activated three times per day. The results obtained allow an evaluation of the DHW consumption profile, temperature variation in central storage and decentralised tanks, and the annual electrical/thermal energy analysis. The results indicate that the activation of the circulating pump during the day leads to an achievement of the highest amount of thermal energy, as well as having minimum temperature oscillation in both central storage and decentralised tanks. However, these advantages are at the cost of consuming much more electrical energy by the heat pump and up to 29 % higher emissions of CO_2. The best scenario in terms of energy-saving and CO_2 emission is the case in which the circulating pump works twice a day, consuming annually 5,832 kWh less electrical energy, compared to the case of an activated pump during the day.

1. Introduction

In recent years, research on the reduction of energy use in buildings has focused primarily on the reduction of space heating/cooling and ventilation needs. At the same time, present knowledge and understanding of energy use for Domestic Hot Water (DHW) production seem to be insufficient. The energy used for DHW production currently accounts for approximately 15–40% of the total energy needed in dwellings, and this proportion is likely to be augmented as the energy used for space heating keeps decreasing. Studies available in the literature indicate that the energy efficiency of DHW systems is surprisingly low and that a significant amount of heat is lost from the hot water before it reaches the draw-off points (Pomianowski et al., 2020). The efficiency of the DHW production and distribution varies to a significant extent from case to case due to the large scattering of key parameters in the system, such as plumbing layout, insulation level of pipework, pipe dimension and location, size of storage tank, and time-dependency of DHW consumption profile (Lutz, 2005; Marini et al., 2015; Valdiserri, 2018).

Space heating and DHW production in existing buildings require water at high temperatures (50-70 °C). Traditional 1st generation gas boilers or district heating networks generally have low efficiency and require high primary energy consumption. Furthermore, a higher thermal loss occurs in traditional DHW centralised systems of large buildings where, typically, a recirculating network from the central storage tank to individual dwellings works at high temperatures 24 hours/day. Nowadays, heat pumps are widely used for space heating purposes in buildings thanks to the high Coefficient of Performance (COP), and for the possibility of utilising renewable energy sources. Meanwhile, storage systems play an important role in order to reduce peak energy demand and increase the efficiency of whole production systems.

For these reasons, the concept developed in the e-

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SAFE project (Evola et al., 2021) appoints a central role to heat storage systems, in order to develop innovative technologies that enable effective integration and communication in heating/cooling as well as domestic hot water production. The e-SAFE project defines a control strategy that ensures the supply of hot water produced by the heat pump to individual apartments, optimising the direct use of the electricity produced by the on-site PV system during daytime periods.

In this context, the present study aims to evaluate the energy performance of the proposed model for DHW in the e-SAFE project under three different scenarios of charging the decentralised tanks by circulating pump unit: activated pump during daytime, activated twice a day, and activated three times per day. In order to find the best strategy, by means of dynamic simulations, the DHW consumption profile, technical water flow rate, and annual thermal and electrical energy consumptions are analyzed within three different charging periods. The findings of the present study are expected to provide an insight for the energetic optimisation of DHW systems.

2. DHW System Description

In the e-SAFE project, a specific system for producing DHW was designed for a residential building of 10 dwellings (5 floors) with 32 persons, located in Catania, Italy. As shown in Fig.1, each dwelling is equipped with a specific decentralised wall-mounted tank with an internal heating coil (heat exchanger) which is connected to a 2-pipe hot water network system for tank charging. The technical water is produced by an Electrical Heat Pump (EHP) coupled to a central storage tank. The technical water is supplied to decentralised tanks via the circulating pump unit.

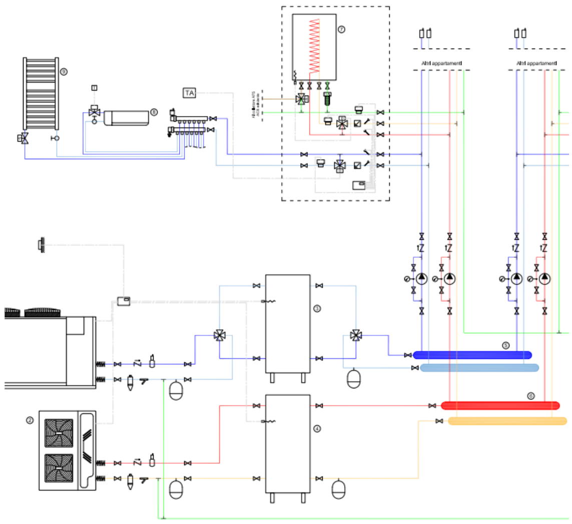

Fig. 1 – Layout of the proposed model for DHW system (the heating/cooling system is not considered in this paper)

The distribution network can be used only for the charging of DHW storage tanks or, in some contexts, can work at low temperature for heating purposes. In both cases, the network (2-pipe water loop) works at high temperature only during charging periods for few hours a day, resulting in lower heat losses in the piping network compared with traditional centralised DHW production, where a recirculating loop at high temperature works 24 hours/day.

3. Dynamic Simulation Model

The energy performance of DHW network is investigated by means of a dynamic simulation model implemented through TRNSYS software. The central storage tank (Type 60g) has a volume of 1500 l, height of 2.4 m and loss coefficient of 0.7 W/(m^{2}K), with a temperature set point of 65 °C. Each apartment was equipped with a plug-and-play decentralised hot water storage system (wall-mounted) with a volume of 140 l. The decentralised tank (Type 534-coiled) consisted of two inlet and two outlet flow ports; on one side, an inlet port for the aqueduct and an outlet port for the DHW; on the other side, an inlet and outlet for the technical water flowing through the heat exchanger. The coiled heat exchanger inside the tank with tube diameter of 0.025 m and loss coefficient of 1.4 W/(m^{2}K) had a total length of 17.8 m with coil diameter and coil pitch equal to 0.145 m and 0.35

m, respectively. The temperature setpoint for the decentralised tank was equal to 55 °C. An ON/OFF controller (Type 2) was employed for both central storage and decentralised tanks in order to regulate the setpoint temperatures in the range of ± 2.5 °C.
The technical water is supplied to the decentralised tanks by two circulating pumps (Type 743), i.e., each pump for five apartments, with the power of 200 W and a constant mass flow rate of 300 kg/h. The energy performance of the DHW model was evaluated under three different scenarios for charging the decentralised tank by circulating pump unit, namely activated pump during the daytime, activated twice a day, and activated three times per day. Table 1 reports the time slots in which the circulating pump is activated.

Table 1 – Operational time slots of the circulating pump

	1 Slot (Continuous)	2 Slots	3 Slots
Operational time slots of pump	06 – 22	08 – 10 & 15 – 18	06 – 08 & 15 – 17 & 20 – 22

The domestic hot water needs were regulated on the basis of the number of people in each apartment, the mean seasonal consumption, and the daily (hourly) consumption profile. In order to model the DHW consumption, a MATLAB code was developed and linked to the TRNSYS model by introducing a NORMRND function, i.e., random samples from a normal (Gaussian) distribution, in order to simulate the daily DHW consumption similar to the real condition.
The MATLAB code reads the number of residents in each apartment from the TRNSYS, and then, at each time step, returns a value as a consumption, simulated on the basis of seasonal and daily (hourly) profile. According to the literature data, the mean daily DHW consumption for each person was considered equal to 45 l, varying slightly in each season. Furthermore, in the daily consumption profile, it was assumed that peaks of the daily consumption profile occur in the early morning between 06 and 10 (45 % of total daily consumption) as well as in the evening between 18 and 22 (25 % of total daily consumption).

4. Results and Discussion

The profile of hot water consumption during a day for three different apartments is illustrated in Fig. 2. The selected apartments are those with the minimum, intermediate and maximum number of residents, namely 1, 3, and 5 persons. It is evident from the figure that peak consumption in each apartment is in the early morning and evening, as described in the previous section. While the peak consumption rate in the apartment with 5 persons reaches 53.9 kg/h, it hardly exceeds 9.5 kg/h in the apartment with 1 person. The trend of DHW request shows the role of virtual user, namely the MATLAB code, in random consumption of DHW in predefined ranges, on the basis of number of persons and daily profile slots. Elaboration of the annual consumption for each apartment implies that the mean daily consumption of hot water for apartments with 1, 3 and 5 person(s) is equal to 43.9, 135.7 and 217.4 l (kg), respectively.

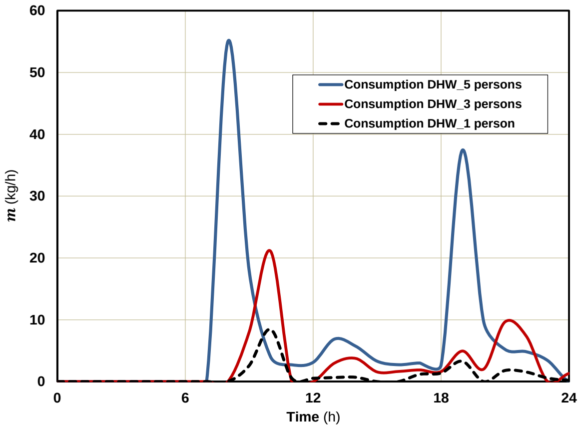

Fig. 2 – The profile of daily hot water consumption in three apartments with 1, 3 and 5 residents

The daily variation in temperature of the central storage and decentralised tank triggered by consuming hot water for different operational time slots is demonstrated in Fig. 3. The considered decentralised tank here is that of the apartment with intermediate number of residents, namely 3 persons. The figure shows that the temperature of decentralised tank increases versus set-point (57.5 °C) in defined working hours of the circulating pump, which feeds the hot water from central storage into the heat exchanger of decentralised tank, and as soon as it discharges the hot water by users (see Fig. 2), its temperature starts to decrease.

It is evident from the figure that reducing the working hours of the circulating pump results in more drastic oscillating in temperature of both central storage and decentralised tank. However, this variation in central storage is less significant compared with the internal tank. While the tank temperature in daytime activated mode (1 slot) does not drop below 37 °C, it reaches 20 °C and 29 °C in 2 and 3 operational time slots, respectively.

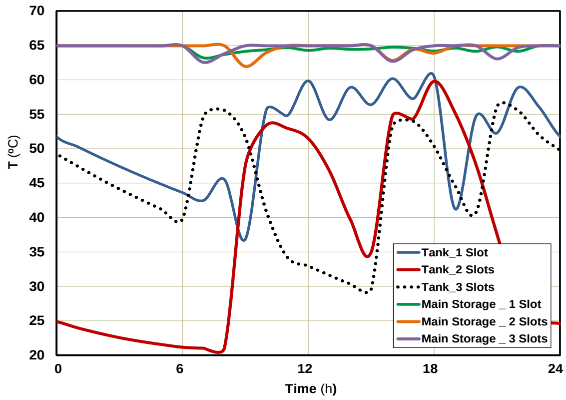

Fig. 3 – The temperature variation in central (main) storage and decentralised tank (of a dwelling with 3 persons) for different activation times of the circulating pump

A comparison between the results of Figs. 2 and 3 allows two points to be concluded. A short activation time of the circulating pump causes the risk of having a low-temperature DHW when there is a request out of operational time slots, particularly for apartments with larger number of residents. Another issue to be addressed is the advantage of matching the activation time of the circulating pump with hours in which there is the peak of DHW consumption, according to the profiles in Fig. 2.

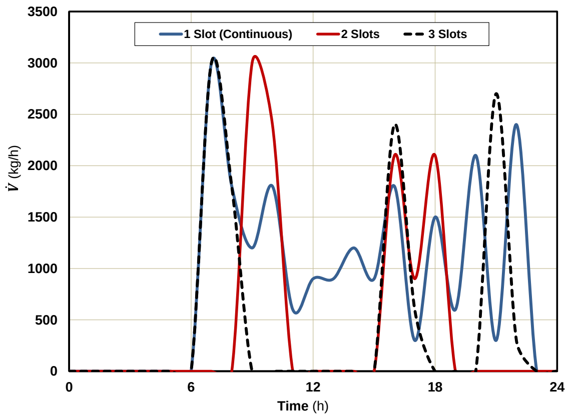

Fig. 4 – Daily total mass flow rate of technical water for different activation times of the circulating pump

Fig. 4 shows the daily total mass flow rate of technical water circulating from the central storage to each apartment's tank, for different working time slots. The figure shows that the flow rate of technical water during the early morning period reaches the highest rate, namely 3000 kg/h, in all operational time slots, implying the hot water demand by all apartments (Fig. 2). Moreover, the figure indicates that, when the circulating pump is in daily activated mode, namely available on request between 06 and 22 h, the flow rate of technical water does not reach zero during the day, due to receiving the hot water request by at least an apartment. On the other hand, the mass flow rate of technical water for 2 and 3 slots daily charging is mostly equal to zero, except for predefined working hours. A comparison between results shows that the total daily mass flow rate of technical water in continuous mode (1 slot) is up to two times higher than that in 2 times activated per day. Indeed, the possibility of charging tanks during the day (1 slot) leads to maintaining the temperature of tanks and, consequently, the DHW as high as possible. Nonetheless, it is shown in the following that this higher temperature will be at the cost of consuming much higher electrical energy, as well as the emission of CO_2.

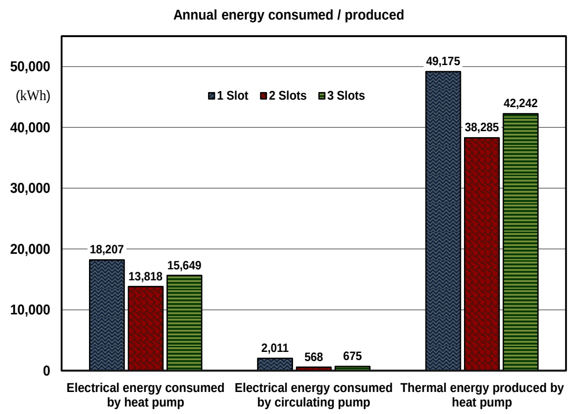

Fig. 5 – A comparison between annual energy consumed/ produced in various activation time slots of the circulating pump

The charts in Fig. 5 compare the annual amount of electrical energy consumed by the heat pump and circulating pump, as well as the thermal energy produced by the heat pump for different operational time slots of the pump. The figure shows that employing a continuous daytime operation of circulating pump (1 slot) leads to much higher electrical energy consumption of both the heat pump and circulating pump, compared with 2 and 3 slot operations; the total electrical energy consumed by the continuous operation is 5,832 and 3,894 kWh higher than that in 2 and 3 time slot operations, respectively. On the other hand, when the circulating pump is activated during the day (1 slot), the heat pump produces annually about 50,000 kWh thermal energy for DHW production, which is far higher than other scenarios.

Table 2 – A comparison between annual electrical consumption, mean COP of heat pump and CO_2 emission for different activation time slots of the circulating pump

	1 Slot	2 Slots	3 Slots
Total electrical energy consumed (kWh)	20218	14386	16324
Mean annual COP	2.69	2.77	2.71
CO_2 emission (kg)	9098.1	6473.5	7345.7

Table 2 reports values of the total electrical energy consumed, mean annual COP of heat pump, and amount of CO_2 emission by different scenarios considered for charging the tanks. The table shows that the mean annual COP of the heat pump is slightly improved when the internal tanks charge only two times per day. Considering the mean value of 0.45 kg emission of CO_2 for producing 1 kW of electricity, according to the literature data, the continuous charging of tanks (1 slot) causes 9098 kg emission of CO_2, which is 29 % and 19 % larger than 2- and 3-times charging modes.

5. Conclusions

In the present study, the energetic optimisation of the Domestic Hot Water (DHW) in a residential building was investigated by means of a dynamic simulation model developed in TRNSYS software linked to a MATLAB code. In the proposed model for the DHW system, the technical water was produced by an Electrical Heat Pump (EHP) coupled to a central storage tank. Each dwelling was equipped with a specific decentralised tank with an internal heat exchanger, which was connected to a 2-pipe hot water network system for tank charging. The energy performance of the DHW model was evaluated under three different scenarios for charging internal tanks by circulating pump unit, namely activated pump during daytime, twice a day, and three times per day.

The results obtained by dynamic simulations allowed an evaluation of the DHW consumption, temperature variation in central storage and internal tanks, the flow rate of technical water, and annual electrical/thermal energy consumption analysis. The results showed that employing the daily activated circulating pump has the advantage of achieving the highest amount of thermal energy, as well as having minimum temperature oscillation in both central storage and decentralised tanks. However, these advantages were at the cost of consuming much more electrical energy and up to 29 % higher emission of CO_2. The best scenario in terms of energy saving and CO_2 emission was when the circulating pump was working twice a day consuming annually 5,832 kWh less electrical energy compared to when the pump was activated during the day.

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