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ENERGY PERFORMANCE AND ECONOMIC EVALUATION OF HEAT PUMP/ORGANIC RANKINE CYCLE SYSTEM WITH SENSIBLE THERMAL STORAGE

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Abstract:
The interaction between electrical and thermal energy demands represent a potential area for balancing supply and demand that could contribute to the integration of intermittent renewables in energy systems. To enable the interaction between thermal and electric energy, an innovative concept that consists of a ground-source heat pump with possibility of reversing operation as an ORC power cycle combined with solar heating in a single-family building is introduced. The ORC mode enables the use of solar energy in periods of no heat energy demand and reverses the heat pump cycle to supply electrical power.

This paper combines a dynamic model based on empirical data of the HP/ORC system with lessons learned from 140 heat pump installations operating in real-life conditions in a cold climate. These installations were monitored for a period up to 5 years.

Based on the aforementioned model and real-life conditions knowledge, the paper considers two different sensible energy storage (TES) configurations for the reversible heat pump/organic Rankine cycle (HP/ORC) system: a buffer tank for both space heating and domestic hot water and a hot water storage tank used exclusively for domestic hot water. The results with the two different configurations are simulated in the Modelica language and compared in terms of energy shift potential in order to optimize RES integration, as well as the economic feasibility of the system in a cold climate.

Keywords: Reversible Heat Pump/Organic Rankine Cycle, real-life operation, sensible thermal storage, energy efficiency, economic feasibility**.**

1. Introduction

According to the European climate and energy targets set in 2007, known as "20-20-20" commitments, by 2020 the levels of EU greenhouse emissions should be reduced by 20% from the levels in 1990; the energy supply based on renewable resources (RES) should be raised to 20% and the energy efficiency should increase by 20% [1]. These targets include strategies to reduce energy consumption and implementation of highly efficient energy supply systems based on renewable energy in buildings, which account for 40% of the total energy consumption in the European Union.

Detailed data on the breakdown of end energy use in dwellings in EU-27 indicates that space heating represents on average 68% of the total energy use, while water heating, electricity for lighting and appliances and electricity for cooking represent 12%, 14% and 4%, respectively [2]. Within this context, an innovative concept of a reversible heat pump/organic Rankine cycle (HP/ORC) system is

suggested as a solution to improve the energy efficiency and the integration of renewable sources in the energy consumption of domestic buildings. The HP and flat solar collector use energy from the sun and wind to cover the heat demand and the ORC uses solar energy to supply electricity in periods of no thermal energy demand. Consequently, the HP/ORC system is a potential energy supply system providing heat and power from renewable energy resources at high energy efficiency level [3]. The components of the system and its three operation modes to cover domestic thermal and electricity demand are shown in Figure 1. First, the direct heating mode uses the flat solar collector on the roof to absorb solar energy when available and deliver it to the thermal energy storage (TES) to cover the space heating (SH) and domestic hot water (DHW) demand. Second, when solar energy is not available the heat pump (HP) mode is enabled to cover the SH and/or DHW demand. Finally, in periods of excess solar energy and no thermal demand the ORC mode is activated to produce electricity.
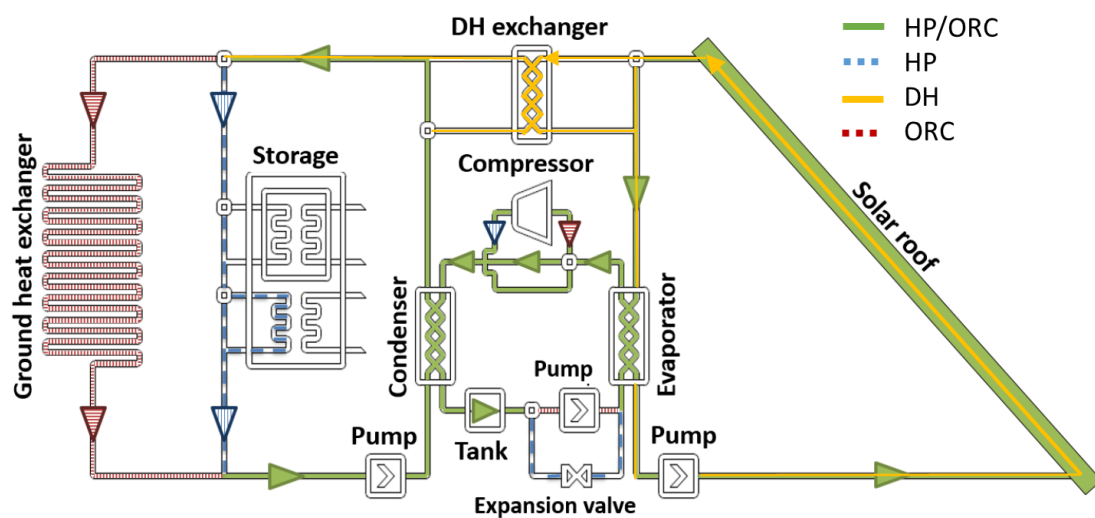

Figure 1 HP/ORC system diagram showing its components and three operation modes: direct heating (DH), heat pump (HP) and organic Rankine cycle (ORC)

For small solar heating systems the hot water storage is the most important component of the system, with regard to both thermal performance and the price of the solar heating system [4]. Thermal energy storage (TES) also offers the opportunity for thermal energy to be accumulated from several heating technologies and to store the energy for later use when required. Experience has shown that in order to increase the performance of solar combi systems with higher energy savings, it is paramount that the interplay between the solar collector and the auxiliary energy supply system is good [5].

Solar stores marketed for small solar domestic hot water systems in Europe, Canada and US are designed in different ways due to different regulatory issues concerning hot water tanks between countries. They are either based on inexpensive standard hot water tanks (in Canada, Netherlands and USA, for example) or relatively expensive specially designed tanks suitable for solar domestic hot water systems (case in Denmark, Germany and Switzerland) [6]. The solar heat can be transferred to a solar tank by means of a built-in heat exchanger spiral covering most of the tank height, by means of a mantle welded around the lower part of the tank or by means of an external heat exchanger and other advanced designs of the heat transfer loop used to transfer solar heat from the heat exchanger to the solar tank (see more in section 2.1). Investigations have shown that the mantle tank is a very attractive solar tank for small solar domestic hot water systems [5]. However, in 1996, IEA [7] investigated different tank configurations to show that only at low solar fractions there are significant

differences in thermal performance within the different configurations. Thus, cost rather than performance configurations are likely to influence decisions on the heat storage design.

The HP/ORC concept itself has been presented previously in [3, 8, 9], however none of these studies focus on the sensible water storage, which is considered essential to promote the integration of RES. Thus, the purpose of the present analysis is to compare two different low-cost hot water thermal storages configurations coupled with the HP/ORC unit. Particularly, the performance of the energy supply system, the operation costs and potential to integrate renewable energy is investigated.

2. Methods

An annual simulation was implemented to assess the dynamic behaviour of the HP/ORC system coupled with two different TES, i.e. two low flow hot water thermal storages of 250 litres under the same SH and DHW demands.

The entire energy supply system is based on a 5° tilted flat solar collector with 138,8m^2, a modified scroll compressor ground source heat pump with a heat capacity of 13kW$_{th}$ which may also be operated in ORC power mode with a capacity of 5,3kW$_e$. The unit is installed in a passive single-family house with a floor area of 140 m^2 located in Copenhagen. The annual electricity demand for lighting and appliances is 1491kWh and total heat demand for SH and DHW 4420kWh. The daily lighting and appliances and the DHW hourly profile are computed according to Georges et al. [10]. These profiles were generated according to probability density functions of the time of energy use of lighting and appliances of 1300 households across Europe and their specific energy use in EU-countries.

A model of the entire system was developed in Modelica language, in Dymola environment using CoolProp and Thermocycle libraries as presented in [11]. The model consists of a distributed building model, a model of the solar heat input, a model of the HP/ORC unit, the heat storage, and the ground pipes used as heat sink for the ORC and source for the heat pump. Figure 2 shows the entire system schematic in Dymola environment.
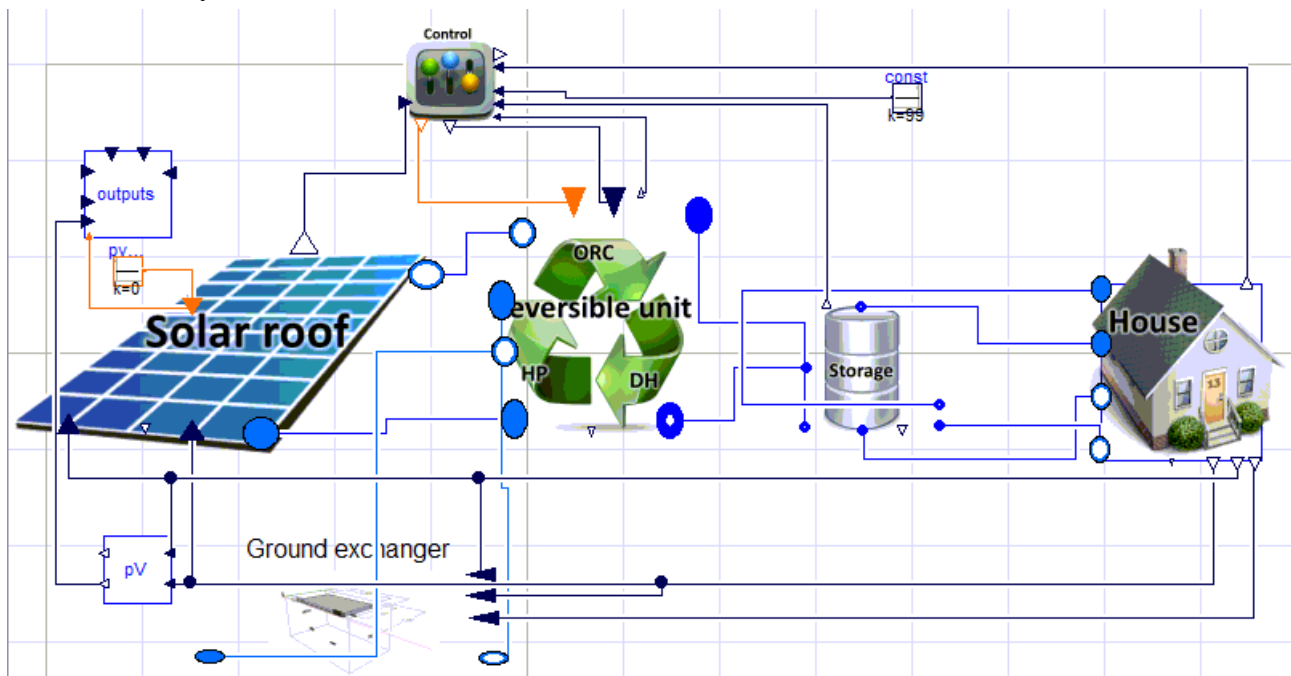

Figure 2 Entire system diagram in Dymola environment. From the left to the right: the flat plate solar collector model, the ground source heat exchanger model, the control unit, the HP/ORC, the stratified hot water storage and the house model

2.1. Hot water thermal storage configurations

The selection of the hot water storage was made from the currently marketed standard storage systems suitable for solar domestic hot water systems in Denmark and according to the most common tanks in a heat pump performance monitoring programme running in Denmark over the last 6 years [12]. Two crucial considerations were also made from the thermal performance point of view. First, a tank volume matching the daily DHW consumption in Danish single-family houses is typically ranging from 60 l/day to 160 l/day [13] plus 100 l/day for space heating. The use of a larger tank will result in a decrease of the net utilized solar energy and increase the system cost [4, 14]. Second, maintenance of thermal stratification is required. In order to maintain stratification the following criteria was taken in consideration in the design process:

- Geometrical considerations: tall water-storage tanks are preferable to best build up and keep the thermal stratification [6] - thus, a tank with a height-diameter (H/D) ratio, also known as aspect ratio, of 3.2 was chosen. In addition, the inlet and outlet were installed in the bottom and top, respectively, to avoid mixing and dead water volume.
- Operating conditions: To maintain the large temperature difference between the bottom and the top (minimum 5 °C to 10 °C) the water flow velocities should be very low less than 0.03 m/s are recommended [14]. Investigations in 1970s and 1980s show that 10% to 25% higher thermal performance and smaller amounts of lime deposits.

In addition, the DHW is maybe the most variable and therefore most critical part of the whole system; thus, the following characteristics have been taken into account for the two designs:

- The heat must be supplied at high rate when hot water is tapped;
- Legionella security must be ensured according to standard DS/CEN/TR16355-2012 [15].

In principle, four solutions are available and typically used to prepare DHW: 1.Separate domestic hot water tank; 2. Tank in tank system; 3. Internal heat exchanger for domestic hot water preparation; and 4. External flat plate heat exchanger unit. The first and last solution, 1 and 4, present crucial disadvantages in the domestic context, they represent larger space requirements and higher costs when compared to the other solutions. On the other hand, the tank in tank solution presents higher legionella risks – some volume in the lower part is at the temperature level for legionella growth and higher costs than an immersed heat exchanger [6, 16].

Based on the principles discussed above, the two stratified storage concepts depicted in Figure 3 were selected. Their characteristics can be found in *Table 1*. The first system – on the left - consists of a hot water tank with two built-in spiral heat exchangers (HXs) – one going from mid-height to bottom of the tank and another going from bottom to the top of the tank. Solar collector fluid is circulated through the mid-height helical heat exchanger, while the cold water from the grid is circulated through the all-through heat exchanger to supply DHW. The second system – on the right of Figure 3 - consists of a hot water tank with one built-in spiral heat exchanger going from the bottom to mid-height of the tank. The solar loop fluid is circulated through the heat exchanger.

What makes interesting to study these configurations is that they are both two standard low cost tanks readily available in the market. However, they both have advantages and disadvantages that affect the HP/ORC system performance. The advantages of configuration 1 is that it presents higher security against legionella due to the small volume of water in spiral HX that is heated for DHW use, but this represents higher heat losses and higher temperature set point. In addition, the disturbance of the stratification of the thermal storage is little due to the low flow (<0.2l/min) of the floor heating loop. Configuration 2, on the other hand, presents the advantage of having very little losses due to the DHW preparation because there is no internal heat exchange between the transfer fluid and the storage medium, thus avoiding temperature losses. Plus, it presents no disturbances from the floor heating loop which is typically the larger energy demand over the year in a building. However, the high flow (9.6 l/min) at DHW supply times causes turbulence that might affect the thermal stratification of the tank, crucial for a better solar system and heat pump performance.

Finally, if the solar tank is a DHW tank- as is the case of configuration 2 - due to the risk of lime problems the controller is set to switch off the solar pump at 60°C (see more in section 2.2). For configuration 1, the only limitation is the boiling temperature and the maximum temperature the material of the tank and its insulation can tolerate.
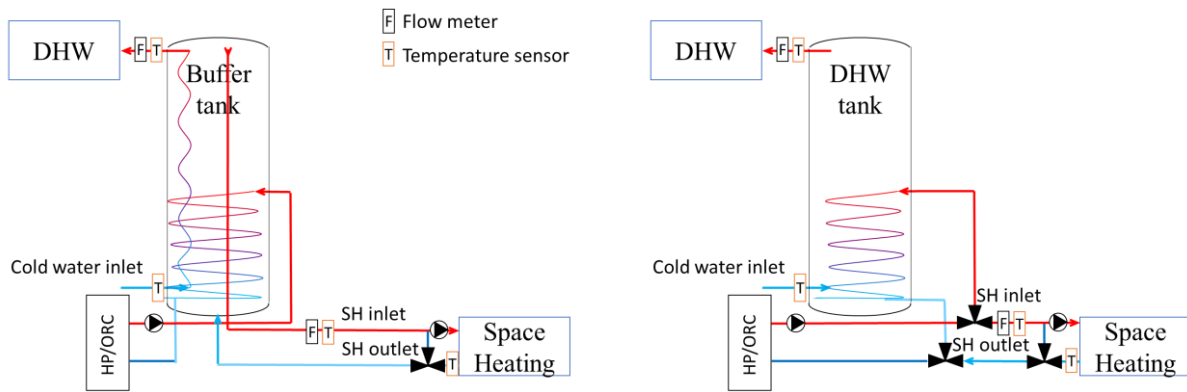

Figure 3 Hydraulic scheme of the hot water tanks configurations studied. Configuration 1 (left) and configuration 2 (right).

Table 1 Characteristics of the two tanks studied [17]

Tank type	Amb. losses [W/m²K]	Volume [m³]	Height/ Diameter	Unit Heat Exchanger				DHW Heat Exchanger			
				U-value [W/m²K]	Volume [m³]	Height inlet [m]	Height outlet [m]	U-value [W/m²K]	Volume [m³]	Height inlet [m]	Height outlet [m]
Buffer	2.7	0.25	3.2	1150	0.011	0.03	0.61	1150	0.025	0.1	1.4
DHW	2.7	0.25	3.2	1150	0.011	0.03	0.61	-	-	-	-

2.2. System control

Apart from the water tank temperatures set-point referred above, the control unit for the HP/ORC system includes features that will maximize and optimise the performance of the heating source. Three operation modes can occur: direct heating (DH) mode, the heat pump (HP) mode and the reversible cycle, organic Rankine cycle (ORC) mode. The state diagram represented in Figure 4 shows the control variables set-points for the process of mode selection. The operation of a solar thermal collector – yellow arrow - is relatively straightforward and it ensures that useful solar thermal energy, when available ($T_{roof}>T_{storage}$) is transferred into the thermal storage. In mid-season and summer periods the solar thermal energy generates a large quantity of heat on the roof which is converted into electricity by the ORC, whenever the thermal demand is covered – green arrow. Finally, in periods of heat demand, but no solar thermal energy available and no thermal energy stored, the control contains additional features to enable the HP mode – red arrow. The prioritization is based upon current demands of SH and DHW, prevailing weather conditions and current temperatures of the thermal energy storage.
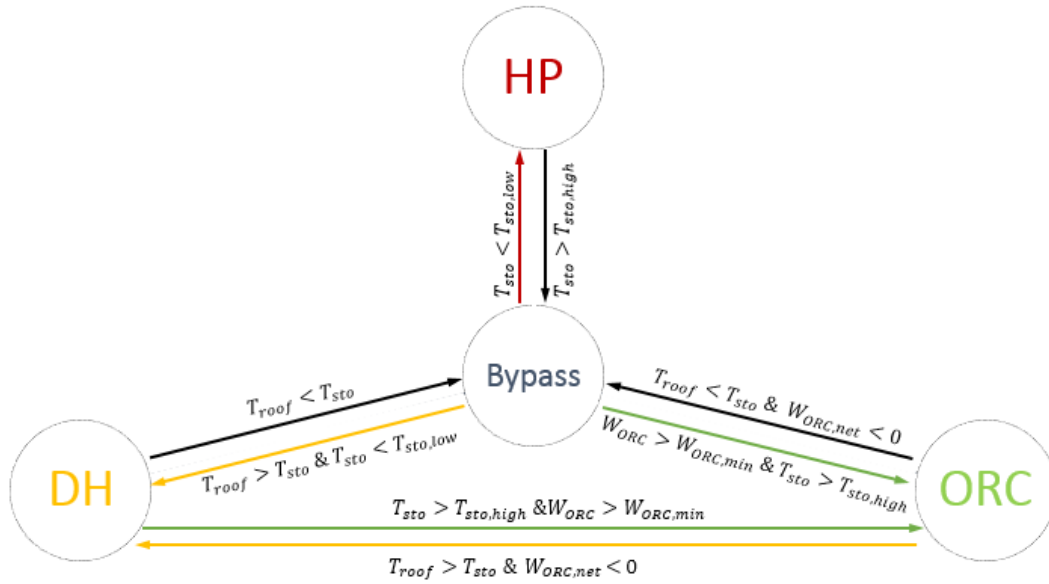
Figure 4 State diagram representing the control of the HP/ORC unit. T_{roof} is the roof temperature in the outlet, T_{sto} is the hot water tank control temperature at height 0.6m – middle of the tank -, $T_{sto,low}$ is the lower limit of temperature allow in the tank (35°C), $T_{sto,high}$ is the higher limit of temperature allow in the tank (60°C), $W_{ORC,min}$ is the lower limit of the power to start the ORC (1 W) Note: $W_{ORC,min}$ is used to avoid chattering issues during simulation. A value lower than 1 W induces a large number of mode changes.

On the space heating side of the system, room thermostats are used to monitor the air temperature in the rooms. These thermostats are used to operate zone valves that can be used to open or close the supply of heat to the rooms. A proportional-integral (PI) controller regulates the temperature of a designated room to a set point, 20°C, using a pump to adjust the hot water flow in the floor heating loop. The flow varies from 0.0 l/s to 0.4 l/s.

2.3. Performance indicators

Once the heating and power supply and demand were known, the following could be calculated: the unit seasonal performance factor (SPF_{unit}), HP seasonal performance factor (SPF$_{HP}$), renewable energy integration potential by means of demand cover factor (γ_d) [18], and annual running costs (*RC*). These are the parameters used to assess the system performance with the two tank configurations.

The SPF_{unit}, includes both the heating production by the HP and DH (Equation 1) while the SPF$_{HP}$ is defined in (2).

$$\text{SPF}_{unit} = \frac{Q_{unit}}{W_{HP}} \tag{1}$$

$$\text{SPF}_{HP} = \frac{Q_{HP}}{W_{HP}} \tag{2}$$

where Q_{HP}, is the heat supplied by the heat pump annually and W_{HP}, the heat pump power consumption.

The demand cover factor (γ_d), indicates the ratio of electricity demand (W_{prod}) that has been produced by the building's energy supply system, in this case by the ORC ($W_{cons.}$) (Equation 3).

$$\gamma_D = \frac{\int_0^t min\left(W_{cons}, W_{prod}\right)}{\int_0^t W_{cons}} \tag{3}$$

The annual running costs, RC, are defined in equation (4).

$$RC = \int_0^t \left(p_{bb} \max(\dot{W}_{net}, 0) + p_r \min(\dot{W}_{net}, 0)\right). dt \tag{4}$$

where $\dot{W}_{net}$, is the net electrical power, including HP and lights and appliances consumption and power production from the power system, p_r [€/kWh], is the retail buy price considered when the net electrical power is negative, i.e., consumed from the grid and p_{bb}, the buy-back tariff [€/kWh] considered when the net electrical power is positive, meaning sold (1). To calculate the annual operation costs two different electricity tariffs are investigated based on real tariffs in Denmark. Thus, the average retail buy and feed-in fixed tariffs are estimated to be 0.28€/kWh and 0.17€/kWh, respectively [19].

3. Results

The simulation results are summed up in Table 2.

Table 2 Energy performance and economic results of operating the system with the tank configurations

Configuration	SPF_{HP}	SPF_{unit}	RC [€]	W_{HP} [kWh]	W_{ORC} [kWh]	Q_{DH} [kWh]	Q_{unit} [kWh]	γ_D
Buffer	2.4	2.8	204	-1512	3377	578	4271	8.1
DHW	1.6	2.0	198	-1492	3371	678	3003	9.3

They showed that the SPF of the HP/ORC system in HP mode with the DWH tank, configuration 2 is 35% smaller than SPF_{HP} of the configuration 1. However, the HP power consumption and as a consequence, the running costs are 1% and 3%, respectively, lower than with configuration 1. In addition, the demand cover factor is 15% higher with configuration 2 than configuration 1. This means that with a DHW tank the HP/ORC power production matches the electricity demand 15% more times in a year than with a buffer tank.

To better understand the impact of the different hot water tank configurations in terms of the SPF, RC and W_{HP}, *Figure 5* and *Figure 6*, show the operational conditions in the system on a typical winter day with the two configurations. (a) The condenser temperature of the HP/ORC unit ($T_{cd,for}$ and $T_{cd,ret}$), the indoor temperature (T_{in}) and the tank temperature (T_{tank}) are shown as well as (b) the flow in the DHW ($\dot{m}_{DHW}$) and floor heating ($\dot{m}_{FH}$) loop, and (c) the heat production ($\dot{Q}_{unit}$) and power consumption ($\dot{W}_{unit,cons}$) and production ($\dot{W}_{unit,prod}$) of the HP/ORC unit. It can be seen that for the same demand conditions the buffer tank, configuration 1, has higher on-off cycles than configuration 2, DHW tank. However, the temperature lift of the latter is higher, due to the mix of the cold water returning from the DHW loop characteristic of this configuration. This affects the performance of the unit in terms of power consumption during the HP mode, leading lower energy efficiency the higher the temperature lift is, in the DHW tank case (Fig. 6 (c)). In addition, it can be seen that at around 11h the DH mode is activated in DHW tank case, this is due to the higher temperatures on the roof in comparison with the temperatures in tank. The temperatures are lower in DHW case (fig.6 (a)) than in the buffer case (fig.5 (a)), due to the mixing induced by DHW tapping in the morning.
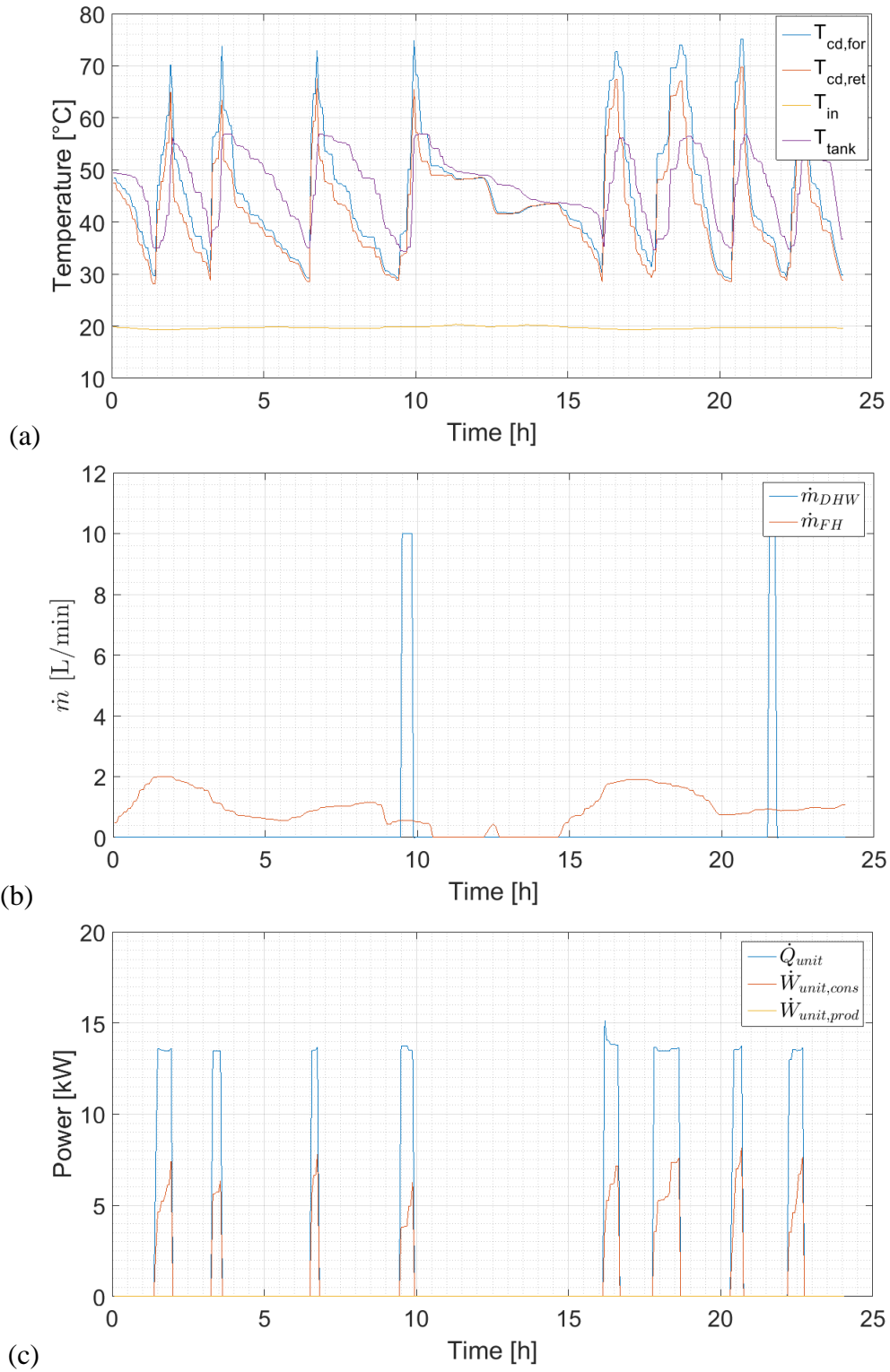
(a)

(b)

(c)

Figure 5 Typical operational conditions of the HP/ORC unit coupled with a buffer tank. $T_{cd,for}$ is HP condenser forward temperature, $T_{cd,ret}$ is the HP condenser return temperature, T_{in} is the indoor temperature in the house and T_{tank} is the temperature inside the tank at a 0.6m height.
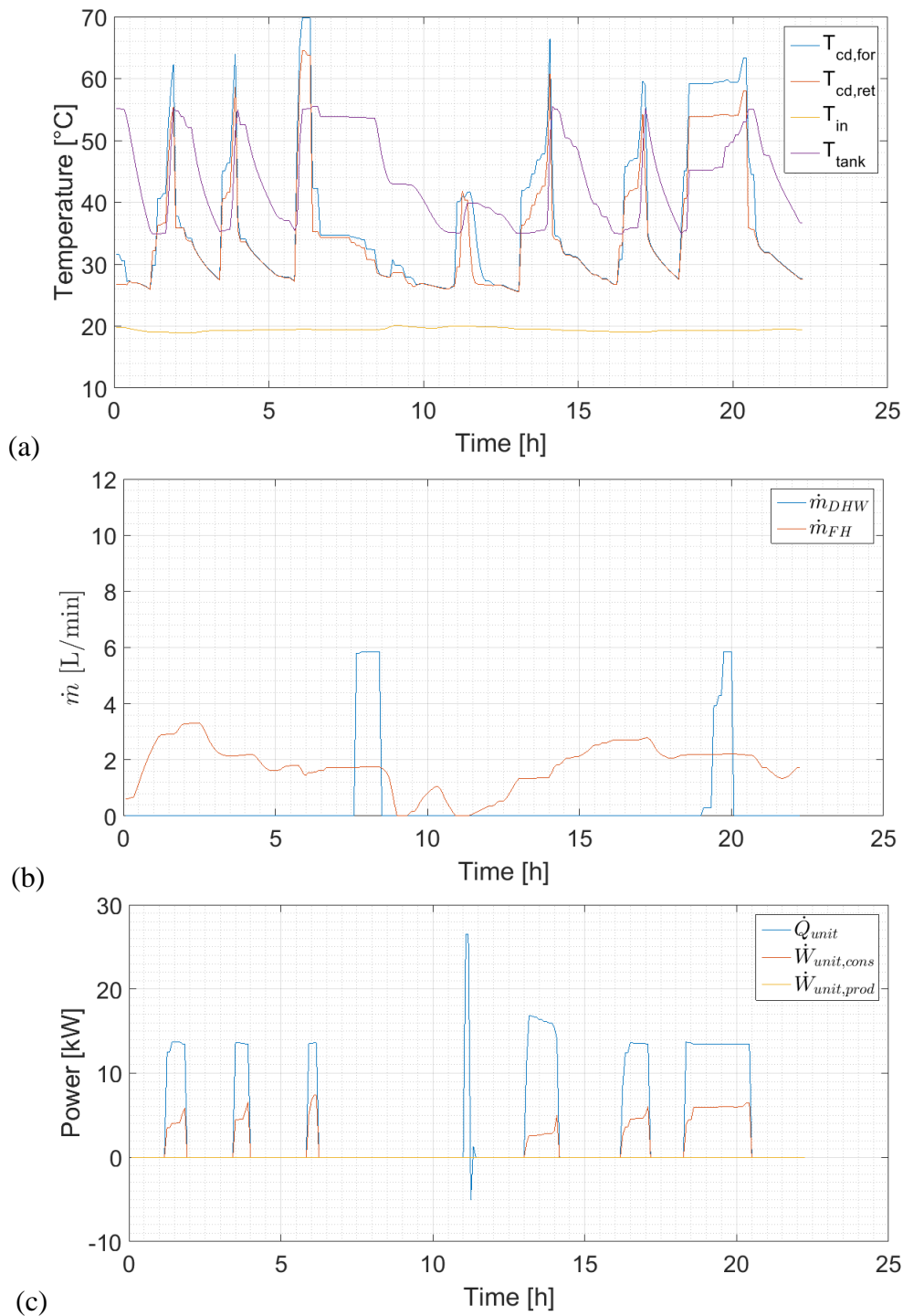
(a)

(b)

(c)

Figure 6 Typical operational conditions of the HP/ORC unit coupled with a DHW tank. $T_{cd,for}$ is HP condenser forward temperature, $T_{cd,ret}$ is the HP condenser return temperature, T_{in} is the indoor temperature inside the house and T_{tank} is the temperature inside the tank at a 0.6m height.

4. Discussion

The results in this work show that for the HP/ORC unit, i.e. HP coupled with solar collectors the DHW tank configurations are preferred against buffer tank configurations. From the HP mode point of view similar results were drawn from the monitoring programme [12] mentioned in section 2.1. During the 5 years of monitoring, residential heat pump systems conjugated with DHW tanks -

together with mantle tanks configurations - demonstrated to perform better than other configurations in terms of energy consumption.

The authors consider that further investigations with mantle tank configuration should be performed in the future. This configuration fulfils small space requirement for residential applications and has shown promising results when integrated in solar based heating systems as way to improve the thermal performance. In addition, a sensitivity analysis of different tank volumes depending on the actual daily domestic hot water consumption to further improve the overall HP/ORC system performance could also be considered.

5. Conclusions

The goal of this paper was to determine the effects of different water tank configurations on the performance of the energy supply system, a HP/ORC energy supply system coupled with TES serving SH and DHW, in terms of operation costs and renewable energy integration. Two different hot water tank configurations are integrated in HP/ORC system in a low energy single-family house. A buffer tank which stores both space heating and domestic hot water, and another, called DHW tank, exclusively dedicated to domestic hot water preparation and storage. Results from annual simulations of the entire system showed that the domestic hot water tank configuration induces a 35% lower seasonal performance factor when the HP/ORC unit, however allow 3% lower running costs and 15% higher renewable energy integration in the house electricity use. In conclusion, the results indicate that the DHW tank is preferred for the HP/ORC unit installed in a single-family house in a cold climate location, like Copenhagen.

Nomenclature

DHW	Domestic hot water	**Subscripts**	
m	Mass flow rate [L/min]	bb	Buy-back
Q	Heat power [kWh]	$Cons$	Consumption
W	Electrical power [kWh]	D	Demand
γ_D	Demand-cover factor	DH	Direct Heating
p	Electricity price [€/kWh]	HP	Heat pump
RC	Running costs [€]	net	Net power
RES	Renewable energy sources	ORC	Organic Rankine cycle
SH	Space heating	$Prod$	Production
SPF	Seasonal Performance Factor	r	Retail
TES	Thermal Energy Storage	unit	Overall HP/ORC system

Bibliography

[1] COM, "20 20 by 2020 Europe´s climate change opportunity," 2008. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52008DC0030&from=EN.

[2] E. E. A. (EEA), May 2012. [Online]. Available: http://www.eea.europa.eu/data-and-maps/figures/households-energy-consumption-by-end-uses-5. [Accessed 12 January 2016].

[3] Dumont et al., "Experimental investigation of Renewable Heat Pump/Organic Rankine Cycle unit designed to perform in a Net Zero Energy Building," *Inter. Journal Refrigeration,* vol. 54, no. ISSN 0140-7007, pp. 190-203, June 2015.

[4] Parra et al. , "Are batteries the optimum PV- coupled energy storage for dwellings? Techno-economic comparison with hot water tanks in UK," *Energy and Buildings,* Vols. Available online 29-01-16, 2016.

[5] L.Cabeza, Advances in Thermal Energy Storage Systems - Methods and Applications, Woodhead Publishing, 2014.

[6] W. Duff, " A report of the Task 14 Advanced Solar Domestic Hot Water Systems Working Group," IEA International, Energy Agency Solar Heating and Cooling Programme, 1996.

[7] W.Duff, "Task 14 Advanced solar domestic hot water systems," IEA, 1996.

[8] Dumont et al., "Design, modelling and experimentation of a reversible HP/ORC prototype,," in *Proceedigns of the 11th Int. Energy Agency Heat Pump Conference*, 2014.

[9] Dumont O. et al., "Simulation of a passive house coupled with a heat pump/organic Rankine cycle reversible unit," in *Proceedings of the 9th International Conference on System Simulation in Buildings, SSB 2014*.

[10] Georges E. et al., "Modeling and simulation of the domestic energy use in Belgium," in *Proceedings of CLIMA 2013 11th REHVA World Congress & 8th International Conference on IAQVEC*, Praha, Czech Republic., June 16-19 2013.

[11] Quoilin S. et al., "ThermoCycle: A Modelica library for the simulation of thermodynamic systems," in *Proceedings of the 10th International Modelica Conference 2014*, Lund, Sweden.

[12] Carmo et al., "Empirical platform data analysis to investigate how heat pumps operate in real-life conditions," in *ICR2015*, Yokohama, Japan, 2016.

[13] S. Furbo, "Smart solar tanks for small solar domestic hot water systems," *Solar Energy,* vol. 78, pp. 269-279, 2005.

[14] S. Furbo, "Hot Water Tanks for Solar Heating Systems Report No. R - 100," Byg.DTU, Denmark, 2004.

[15] DS/CEN/TR16355, "Recomendations for prevention of Legionella growth in installations inside buildings conveying water for human consumption," CEN, Copenhagen, 2012.

[16] A.Arteconi et al., "State of the art of thermal storage for demand-side management," *Applied Energy,* vol. 93, pp. 371-389, 2012.

[17] Austria Email, "Technical Data Combi Stratified Tank Id.Nr.: 242094-1".

[18] Baetens R. et al., "Assessing electrical bottlenecks at feeder level for residential net zero-energy buildings by integrated system simulation," *Applied Energy,* vol. 96, pp. 74-83, 2012.

[19] Energinet.dk. [Online]. Available: http://energinet.dk/DA/El/Solceller/Har-du-solceller/Sider/Pristillaeg.aspx.

[20] van Koppen et al., "The actual benefits of thermally stratified storage in a small and medium size solar system.," in *Proceedings ISES Biennal Meeting*, Atlanta, USA, 1979.

[21] G. Morrison, "Task 14: Advanced Active Solar Energy Systems. Workshop on Solar Water Heater Tank Design and Rating.," International Energy Agency Solar Heating and Cooling Programme, Working papers, San Diego, USA, 1995.

[22] A. Thür, "Compact Solar Combisystem - High effic. by minimizing temp.," DTU- PhD thesis, 2007.