Performance Evaluation of a HP/ORC (Heat Pump/Organic Rankine Cycle) System with Optimal Control of Sensible Thermal Storage

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ABSTRACT

In energy systems with high share of renewable energy sources, like wind and solar power, it is paramount to deal with their intrinsic variability. The interaction between electric and thermal energy (heating and cooling) demands represent a potential area for balancing supply and demand that could come to contribute to the integration of intermittent renewables. This paper describes an innovative concept that consists of the addition of an Organic Rankine Cycle (ORC) to a combined solar system coupled to a ground-source heat pump (HP) in a single-family building. The ORC enables the use of solar energy in periods of no thermal energy demand and reverses the heat pump cycle to supply electrical power. A dynamic model based on empirical data of this system is used to determine the annual performance. Furthermore, this work assesses the benefits of different control strategies that address the critical concern that thermal supply should always operate considering the actual load conditions in the overall system performance. The performance is assessed in terms of energy efficiency of the system, the integration of renewable energy in the energy supply of the system and the level of comfort of the users. Results show that real load control logic can lessen the adverse effects of cycling in the compressor of the system as well as increase the thermal demand covered by renewable energy. However, the extension of these improvements is highly dependent on the thermal mass of the building and the volume of the sensible storage.

1. INTRODUCTION

In the future energy systems scenery, with high share of intermittent renewable sources, both energy efficiency and the time of energy use are considered imperative to ensure security of supply. In order to achieve these objectives, new control strategies have been assessed over the last couple of decades to operate HVAC systems in buildings, as they represent 40% of the world's energy use.

Recently, Shaikh et al. (2014) presented a comprehensive and extensive review on the state-of-the-art of, so-called, *intelligent control systems* in residential, commercial and office buildings. Perspectives for the future of building automation were given based on 21 different controllers, which objective parameters include running cost reduction, increase of flexibility and thermal comfort represented by humidity, air quality and indoor temperature. Overall, it is considered that buildings occupants' behaviour, activities and preferences are the most important feedbacks for the success of building automation.

In the same study it is shown that Model-based Predictive Control (MPC), multi-agent system technology (MAST), Fuzzy and ON/OFF control methods are the most studied and promising approaches reaching up to 40% energy savings. However, the efforts needed to implement MPC, MAST and Fuzzy - such as lengthy model development and challenges to obtain reliable information for each case- are significant and often considered prohibitive. Yet, other studies have proven it is possible to achieve comparable energy savings with controllers based on traditional reactive control (ON/OFF) methods if enhanced by adaptive setbacks using occupancy presence and domestic hot water consumption (DHW) information (Tammmaro & et al., 2016; Rosiek & et al., 2013). In practice, this information is easily accessed through real-time occupancy sensors.

In this work, we intend to study the effects of enhanced reactive controllers in a residential building equipped with an innovative co-generation technology based on solar energy, known as HP/ORC unit. The novel control logics intend to minimize the total energy use by optimizing the energy use schedules according to fluctuating occupant presence while maintaining the comfort at suitable levels. The three novel operation strategies investigated are described below:

1. **Occupancy setback (OccSB):** this control minds occupancy information to adapt the indoor comfort temperatures from 20 °C, when occupied to 16.5 °C, when non-occupied.
2. **DHW priority (DHWp):** in this case the space heating distribution pump is turned off when the HP/ORC unit is supplying DHW. This control logic intends to ensure higher energy efficiency by minimizing the mixing inside the storage water tank when it delivers high temperature water for domestic end-uses.
3. **Combined Occupancy setback and DHW priority (OccSB+DHWp):** this variant terminates the space heating supply both when people are not at home or in case they are taking a shower.

These operation strategies are compared with an unbounded control strategy based exclusively on the variation of temperature in a certain height of the tank (0.6 m). A deadband (*db*) of 20K is used, so that the unit turns OFF when the temperature in tank at 0.6 m exceeds a T_{set} 60°C and then back ON when the temperature is equal to T_{set} - *db*. This large *db* is used to ensure the hot water is delivered at suitable temperatures to the user ($T_{shower} \geq 38$°C)(Kordana & et al., 2014) adjusted by a tempering valve and to protect the compressor from adverse cycling effects (Green, 2012).

2. METHODS

The annual performance of a simulated ground source based HP/ORC system integrated in a house subject to four different control strategies - previously introduced - is assessed. Conclusions are made based on a comparison of the annual performance between the new control logics and the reference case. All the simulation results presented were performed in Modelica with simulation time steps of maximum 5 minutes, using the boundary conditions for a passive house with 2 residents under Danish climate conditions. The space heating load and the domestic hot water are summarized in table 1 for the reference scenario.

In figure 1 a simplified hydraulic scheme of the simulated system is shown. The basic principle of this innovative concept is the modification of the compressor to operate as an ORC (Dumont, Quoilin, & Lemort, 2015). Combined with a thermal solar collector the system supplies a single-family residential building. The HP and direct heating from the solar collector (DH) modes cover the thermal demand. The ORC enables the use of solar energy in periods of no thermal energy demand and reverses the heat pump cycle to supply electrical power.

Figure 2 illustrates the reference control strategy that is then enhanced with the three different control logics. 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 (40°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 (2 kW) Note: $W_{ORC,min}$ is used to avoid chattering issues during simulation. A value lower than 2 kW induces a large number of mode changes. If the storage control temperature (T_{sto}) is below a fixed low temperature threshold ($T_{sto,low}$) and the temperature in the roof solar collector (T_{roof}) , the heat pump mode is activated to guarantee the space heating (SH) and the domestic hot water (DHW). The

Table 1: Space heating (SH), domestic hot water(DHW) and light and appliances(L & App) demand for reference scenario

SH [kWh]	DHW[kWh]	L & App[kWh]
3951	845	1570

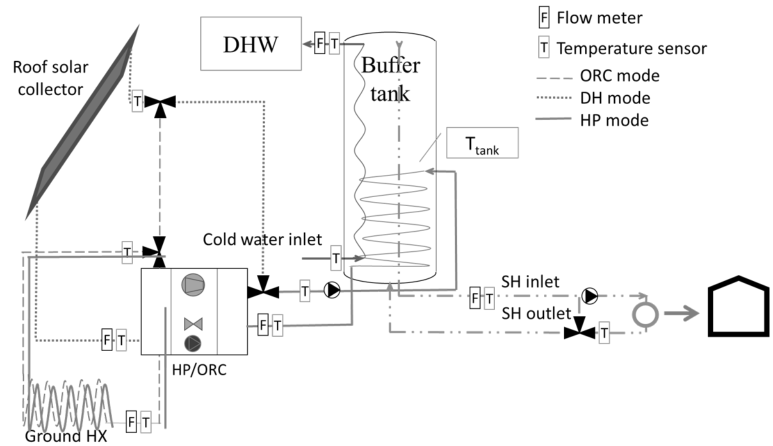

Figure 1: Simplified hydraulic schematic of the HP/ORC system

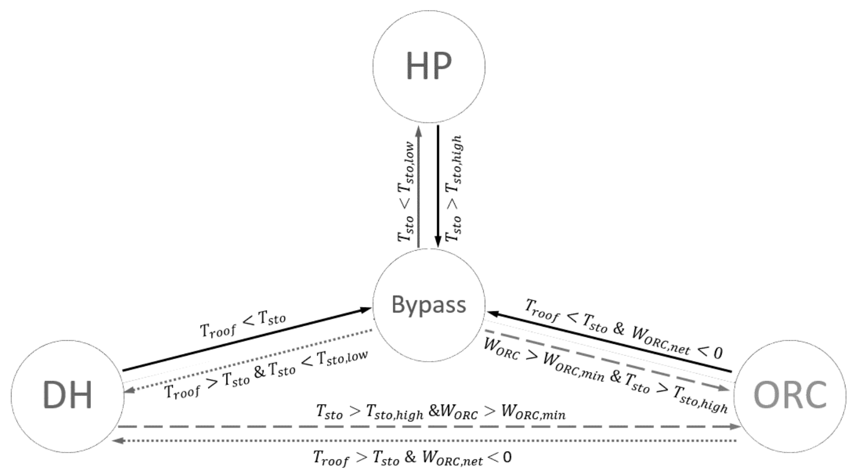

Figure 2: State diagram representing the reference case control of the HP/ORC unit.

heat pump cold source is the ground heat exchanger or the solar roof depending on which one is the warmest. If the storage control temperature is above the high temperature threshold ($T_{sto,high}$), the ORC mode is activated if the roof temperature is above the minimum power to get a net electrical production ($W_{ORC,min}$). If the storage control temperature lies between the high and low threshold, the former mode is kept to avoid excessive chattering between modes reducing performance and reliability in practice. Finally, the by-pass mode is used if the storage temperature cannot be increased and if the ORC mode is not able to produce a positive net electricity production. In the by-pass mode, only the roof pump is running to homogenize the roof temperature. This control strategy is relatively simple.

2.1 Residential buildings and users behaviour

The building model is based on the geometry and the construction characteristics of a real building 140m^2 located in Herning, Denmark.

The building model is split into 5 zones, according to its orientation, air volume and use: dining room, kitchen, main bedroom, bathroom and guest rooms. The boundary conditions of each zone are given by solar irradiance, ambient temperature, heat exchange with adjacent zones, lighting and appliances load, and occupancy state.

The walls and roof of each zone are modelled using a simplified lumped-capacitance methods introduced in Masy(2007). They are modelled with two thermal resistances and heat capacity. The simplicity of this model is appropriate for annual performance assessment. The air volume and floor slab of each zone is modelled with basic components from

Buildings library (Wetter, Zuo, & Nouidui, 2014). Due to the negligible thermal inertia of the windows, they are considered as pure thermal resistances. These components are standard models available in basic Modelica library. An extra heat capacity is included to model the thermal inertia of the furniture as well as dissimilarity in the indoor temperature of each zone. Furthermore, to control the solar heat absorbed through the windows an artificial shadow factor is included to resemble the effect of louvers.

Finally, the users load profile corresponds to hourly lighting and appliances and the DHW consumption according to probability density functions of the time of energy use of lighting and appliances in 1300 households across Europe and their specific energy use in EU-countries (Georges, 2013).

2.2 Ground source HP/ORC system

The energy supply system consists of a modified scroll compressor ground source heat pump with a thermal capacity of 13 kW_{th}, which in reversed mode operates as a ORC (5.3 kW_{el}). The different components of the HP/ORC unit are simulated with parametric curves based on an experimental campaign at different operational conditions (Dumont et al., 2015).

The model of the ground source horizontal heat exchanger consists in a 1D finite-volume model with three layers. Each heat exchanger layer is modelled with a heat capacity and two thermal resistances. These represent the pipe and the soil thermal resistance, respectively.

2.3 Solar collector

The building is equipped with a thermal collector incorporated in the whole roof (138.8 m^2) which is and is modelled using Klein's equation (Klein, 1975).

2.4 Stratified storage tank

The water tank (250 *l*) consists of a stainless steel cylinder with two built-in spiral heat exchangers (HXs), 3 *l* and 9.6 *l* respectively – one going from mid-height to bottom of the tank and another going from bottom to the top of the tank. When charging the store, the working fluid in the HP/ORC unit is circulated through the mid-height helical heat exchanger. During discharging, the cold water from the grid is circulated through the all-through heat exchanger to supply DHW. Furthermore, a direct inlet (bottom) and outlet (top) to the tank form part of the space heating loop. In periods of space heating demand the water from the house floor slab enters the inlet and supplies hot water from the outlet in the top.

In the current work, this stratified sensible thermal storage is modelled by a one-dimensional finite-volume discretization comprising i=20 isothermal segments with equal volume. The dynamic temperature profile of the tank is represented by a set of i ordinary differential equations that approximately represent the energy balance of the tank:

$$A_i \Delta x_{seg} \rho_i c_p \frac{dT_i}{dt} = \dot{m}(h_{ex,i} - h_{su,i}) + A_{hx,unit,i}\dot{q}_{hx,unit} + A_{hx,DHW,i}\dot{q}_{hx,DHW} + \alpha_i A_{i+1}\dot{q}_{i+1} + \beta_i A_{i-1}\dot{q}_{i-1} - UA_{amb,i}(T_i - T_{amb}) \quad (1)$$

where

$$\dot{q}_{hx,unit,i} = U_{hx}(T_{i,hx} - T_i) \quad (2)$$

and

$$\dot{q}_{i-1} = \sigma \frac{(T_{i-1} - T_i)}{\Delta x_{seg}} \quad (3)$$

In Eq. (1) α is 0 if the i-th node is the top of the tank and 1 otherwise and β is 0 if the i-th node is the bottom node and 1 otherwise. In addition, the model (Eq. 3) includes the mixing parameter (σ, with units of thermal conductivity) in order to represent the combined effect of the three modes of heat transfer that can occur between tank nodes (conduction, diffusion or axial mixing due to turbulent flow) as well as the mixing that occurs due to temperature inversion. This parameter is issued whenever there is temperature inversion in the tank. This parameter is estimated by minization of errors between simulated and measured temperatures in the tank from experimental tests at operation conditions identical to the conditions in which the storage tank is operated in HP/ORC system (Carmo, Dumont, Elmegaard, Nielsen, & Detlefsen, 2015). In practice, a much higher mixing parameter is used when this situation arises.

3. RESULTS AND DISCUSSION

The HP/ORC system coupled with a passive house($U_{walls} = 0.09W/m^2K$ and $U_{windows} = 0.63W/m^2K$) model results are presented under three different control strategies in comparison with the reference control. The influence of controls on a building which envelope characteristics ($U_{walls} = 0.258W/m^2K$ and $U_{windows} = 1.2W/m^2K$) are similar to current building stock is also assessed. Additionally, a case with a larger water tank (500 l) is considered. The purpose of the study is to evaluate the performance of the system in terms of energy performance, renewable energy integration and comfort levels and how the different controls can enhance its performance. The ratio of heating demand covered by HP(Q_{HP}/Q_{dem}), the annual electricity demand of the HP/ORC unit($W_{dem,HP/ORC}$**)** and production(W_{ORC}**)**, the number of HP cycles (# cycles), the average duty cycle (***adc***), the seasonal performance factor (**SPF**), the demand cover factor (γ_d), the level of discomfort in DHW (DL_{DHW}) and indoor temperature (DL_{in}) are considered to evaluate the performance of the system.

The average duration of an ON period of the HP or average duty cycle, *adc* in minutes, is defined in eq.4.

$$adc = \frac{1}{N}\sum_{1}^{N}\int_{t=1}^{t=8760*60} t_{ON} \tag{4}$$

The **SPF** is calculated as shown in eq. 5.

$$SPF = \frac{Q_{unit}}{W_{unit}} \tag{5}$$

The demand cover factor (γ_d), indicates the ratio of electricity demand ($W_{unit+L\&App}$) and the supply that has been produced by the building's energy supply system, in this case by the ORC (W_{ORC}) and is here used as an indicator of renewable energy integration (Equation 6).

$$\gamma_d = \frac{\int_1^N min(W_{dem,unit+L\&App}, W_{ORC})}{\int_1^N W_{dem,unit+L\&App}} \tag{6}$$

Finally, other two parameters are considered to quantify the level of comfort,DL_{DHW} and DL_{in}. These are measured by the percentage of time of DHW (t_{DHW}) or SH demand (t_{SH}) when the DHW or room temperatures are not delivered at the minimum desired levels, 40°C(Kordana & et al., 2014) and 19°C (ISO7730, 2004).

$$DL_{DHW} = 100\frac{\int_1^N t_{T_{DHW}<40}}{\int_1^N t_{DHW}} \tag{7}$$

$$DL_{in} = 100\frac{\int_1^N t_{T_{in}<19}}{\int_1^N t_{SH}} \tag{8}$$

3.1 Annual performance results

The results of the simulations are summarized in table 2. The table is divided horizontally in three main cases : original passive house with 250 *l*, poorly insulated house with 250 *l* and passive house equipped with a 500 *l* tank, each presenting the results with the four control logics, except the 500*l* case which only presents the results for the two most relevant cases for compactness.

From the results summarized it can be noted how the consumption of the compressor of the HP/ORC unit($W_{dem,HP/ORC}$) is not reduced with any of the controls in the passive house case, per contra $W_{dem,HP/ORC}$ increases up to 4.3% compared

Table 2: Results for the control comparison

Case	Q_{HP}/Q_{dem} [%]	$W_{dem,HP/ORC}$ [kWh]	W_{ORC} [kWh]	***adc*** [min]	**# cycles**	**SPF**	γ_d	DL_{DHW} [%]	DL_{in} [%]
Ref.	75	1975.5	3105.8	19.8	861	2.7	6.7	1.6	0.0
OccSB	76	2061.4	3111.7	46.3	377	2.6	6.5	1.0	5.5
DHW_p	75	1975.9	3105.8	19.8	862	2.7	6.7	0.8	0.0
$OccSB + DHW_p$	76	2052.9	3112.2	46.5	375	2.6	6.5	0.3	5.7
Ref.poor	85	3959.9	3100.5	22.2	1544	2	4.3	0.7	0.0
OccSBpoor	84	3775.7	3105.0	49.2	661	2	4.4	1.0	10.0
DHW_ppoor	85	3963.4	3099.9	22.0	1553	2	4.3	0.3	0.0
$OccSB + DHW_p$poor	84	3759.0	3101.8	49.9	651	2	4.4	0.9	10.4
$Ref.500l$	67	1511.3	3186.3	37.6	450	3.9	8.2	0.0	0.0
$OccSB + DHW_p 500l$	69	1464.1	3190.9	72.5	240	4.1	8.4	0.0	5.2

to the reference case. None of the controls promotes significantly the power production in ORC mode (W_{ORC}) and the demand cover factor (γ_d). The maximum improvement (0.2%) of W_{ORC} in comparison with the ref. case occurs when $OccSB + DHW_p$ is implemented. Also, when OccSB controls *adc* and #cycles are doubled and halved, respectively. Yet, this does not seems to affect the SPF. This is mainly due to the fact that *adc* is higher than the critical duty cycle time (<18 min), where the compressor efficiency is lessen (see figure 3).

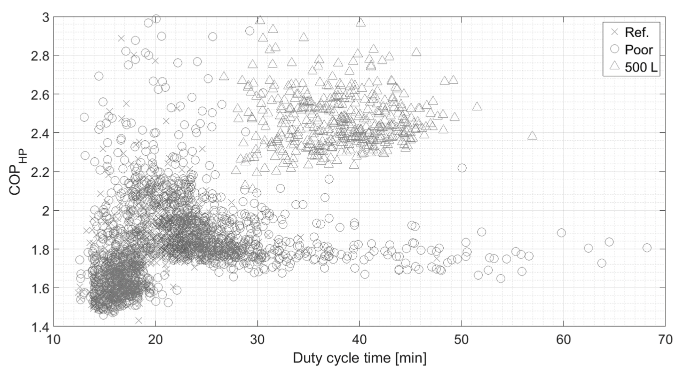

Figure 3: Results showing the effect of short duty cycle on the coefficient of performance (COP) of the compressor for the ref., poor insulation and 500 l cases in HP mode

Furthermore, it should be noted that the discomforts levels of DHW temperatures are reduced up to 80%, $OccSB$+DHW_p case.

On the other hand, in the case of house with poor insulation - $W_{dem,HP/ORC}$ of the Ref.poor is two times higher than the value of Ref.case - the new control logics achieve up to 5.1% reduction of the unit power consumption when compared to the ref. poor case, except the $DHW_p poor$. However, this is not reflected in an improvement of the SPF, the reason is the lower thermal mass of the building. While in the reference case, the large thermal mass of the building enables higher integration of renewable energy expressed by smaller values of Q_{HP}/Q_{dem}(75%), in poorly insulated buildings 85% of the Q_{dem} is covered by the HP. The comfort levels are also influenced considerably with the new control logics. The DL_{in}, for example, reaches values of 10%, which trespasses the tolerable value (5%).

Finally, the case including a larger water storage tank is considered. It is shown that the introduction of a larger sensible storage in a passive house enables a large integration of renewable sources both in the thermal demand(Q_{HP}/Q_{dem}) and power (γ_d) when compared to the reference case (Ref.) with a tank of 250 l. Additionally, new control strategies, $OccSB + DHW_p$, improve in all remaining performance parameters. The $W_{dem,HP/ORC}$ reduces 3%, the #cycles is halved and the SPF improved 5% in comparision with Ref.500L. These values increase to 25%, 72% and 50% when compared to Ref. case.

3.2 Control strategies effects: one-week operation

Figures 4-8 present the weekly (from Sunday to Saturday) profiles of (1) Temperatures in the storage($T_{sto,top}$,$T_{sto,h=0.6m}$, $T_{sto,bottom}$), outdoor(T_{out}) and indoor(T_{in}) (2) Mass flow rates in floor heating loop ($\dot{m}_{FH}$) and DHW($\dot{m}_{DHW}$) and occupancy state (3) Heating supply ($\dot{q}_{HP/ORC}$), power demand ($\dot{W}_{HP}$ and $\dot{W}_{L\&App}$) and supply($\dot{W}_{ORC}$) under different control strategies.

It can be seen how the space heating demand is modulated (fig.5) in comparison with the reference case (fig.4). In the first 60 hours the number of HP cycles is reduced from 7 to 2. The $\dot{m}_{FH}$ controlled by a PI reaches values three times higher than in the Ref. case due to the larger heat demand after a long unoccupied period where T_{in} reaches a value of 17°C. This induces a large drop and mixing of the temperatures in the storage, which leads to a longer duty cycle (fig. 5 Time=32h). Thus, no major power savings are achieved. The operation under DHW_p (fig. 6) is similar to the Ref. case. Likewise, is the operation with $OccSB + DHW_p$ (fig.7) in comparison with $OccSB$. The space heating demand is only slightly (order of seconds) delayed. Finally, the profiles with 500 l storage tank case are presented in fig. 8 showing the advantages. Lower power demand from the HP is required. Only one cycle (fig. 7) compared to the same house with same control (fig.4) and larger amount of heating demand covered by the solar collector (DH mode) at hours 58, 80 and 128.

Furthermore, the figures 4-8 (sub-figure 2) show that the occupancy schedule, in the cases studied, does not match the availability of power supply from the ORC. Ultimately, this limits the increase of renewable power integration since the energy system studied does not include an electric battery.

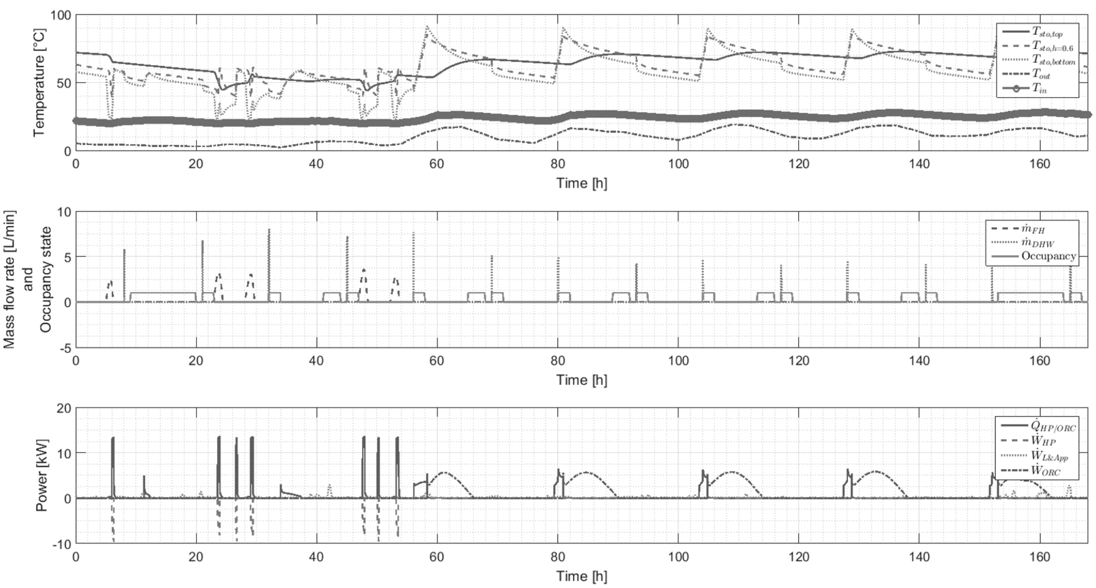

Figure 4: Ref. case operation variables as function of time during a week in May on a ref. year in danish climate

4. CONCLUSIONS

In the present study, the effect of four different control strategies in the performance of an innovative co-generation unit, known as HP/ORC unit, are presented based on simulation results. These control logics take into account real

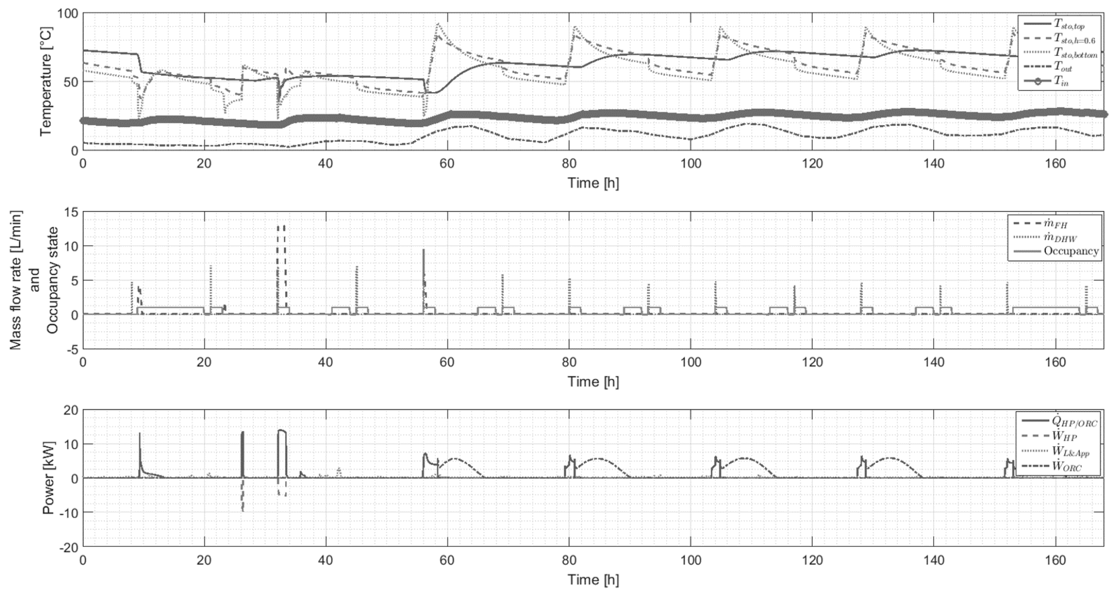

Figure 5: OccSB case operation variables as function of time during a week in May on a ref. year in danish climate

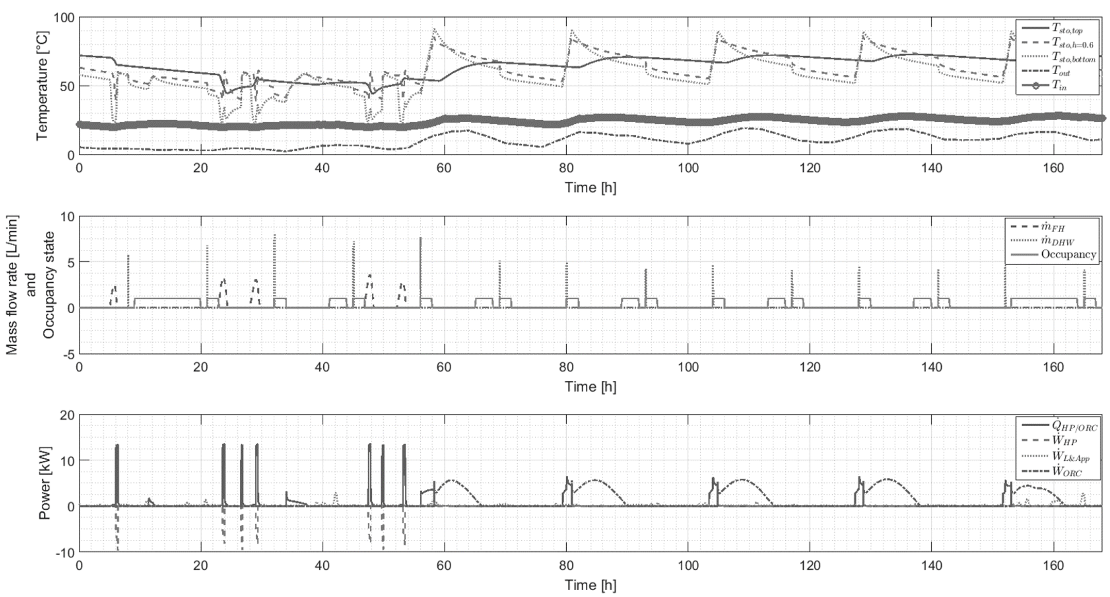

Figure 6: DHWp case operation variables as function of time during a week in May on a ref. year in danish climate

load information from occupancy and thermal energy end-use.

- It is shown that, in all cases studied, occupancy driven control logics can avoid adverse cycling effects in terms of compressor lifetime.
- The effects of these controls in improving the performance of the HP/ORC system performance depend both on the thermal mass of the building and the sensible storage volume as well as the occupancy schedule match with renewable energy availability.
- The controls do not increase the power demand covered by renewable sources but can improve the thermal demand covered by renewable energy.
- In the current building stock, occupancy controls should be implemented with deference as they might disturb the indoor comfort levels significantly.

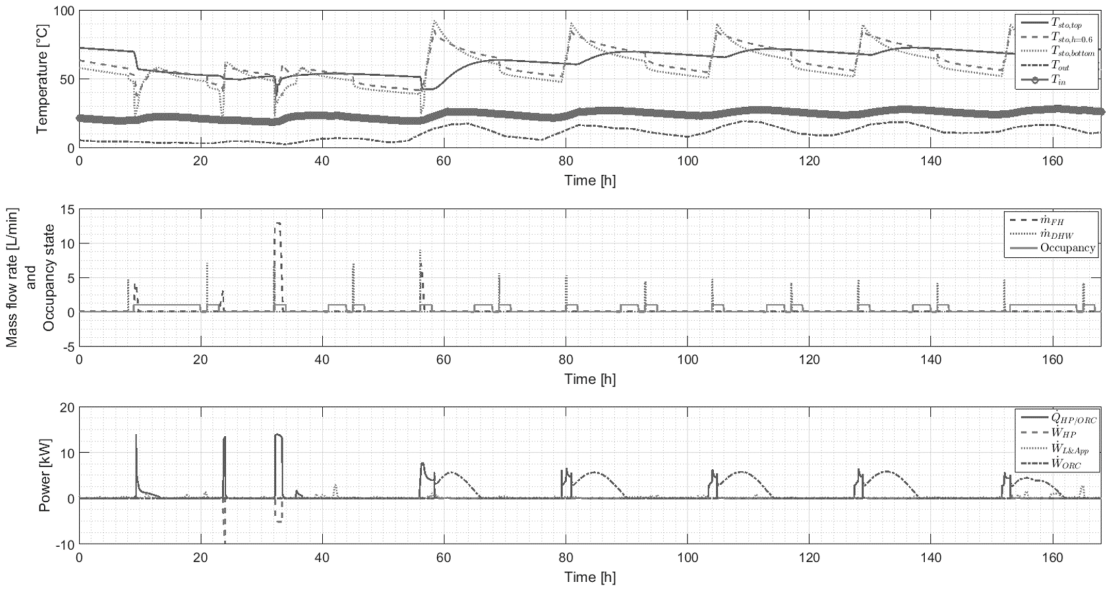

Figure 7: OccSB+DHWp case operation variables as function of time during a week in May on a ref. year in danish climate

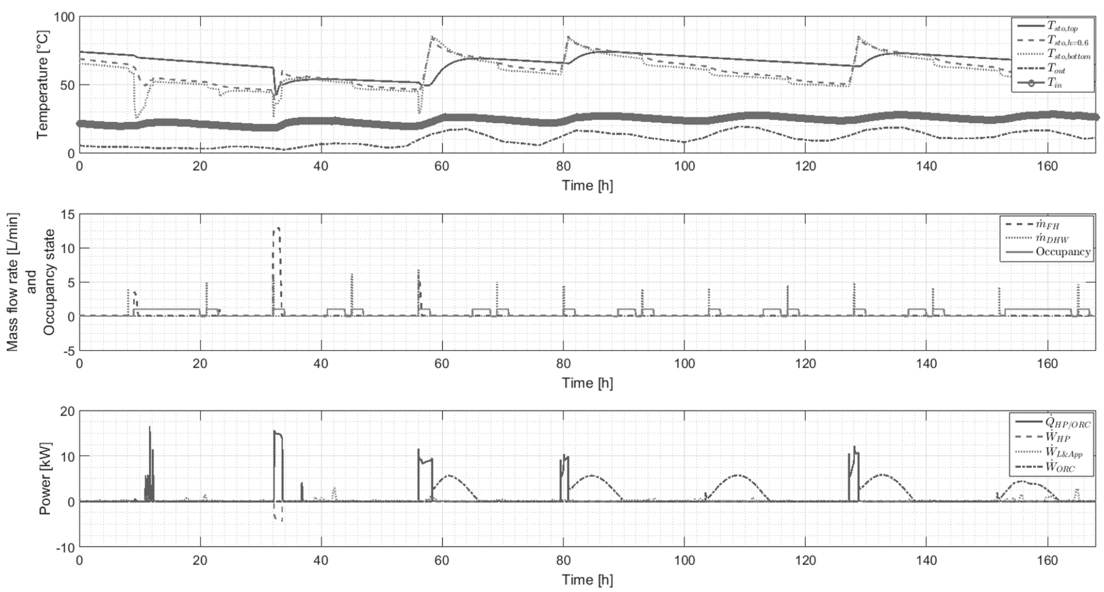

Figure 8: $OccSB + DHW_p500l$ **case operation variables as function of time during a week in May on a ref. year in danish climate**

NOMENCLATURE

A	area	m^2	C_p	specific heat	J/gK
Δx	height segment	m	h	specific entalphy	J/kg
$\dot{m}$	mass flow rate	kg/s	t	time	s
Q	heat demand	kWh	$\dot{q}$	heat flow	W

T	Temperature	°C	t	time	s
U	heat transfer coef.	W/m^2K	Q	heat	kWh
W	Power	kWh			
Greek letters					
α	binary paramater	(-)	β	binary paramater	(-)
σ	artificial mixing term	W/mK			

Subscript

amb	ambient	*seg*	tank segment
dem	demand	*el*	electrical
ex	exhaust	*hx*	heat exchanger
i	tank segment number	*in*	indoor
min	minimum	*p*	priority
out	outdoor	*ORC*	Organic Rankine Cycle
su	supply	*sto*	storage
th	thermal	*unit*	HP/ORC unit

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