Hybrid heat pump scenarios as a transition towards more flexible buildings

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ABSTRACT

The potential of heat pumps (HP) to contribute to a cost-efficient and environmentally-friendly operation of the electric power system is widely acknowledged. Nevertheless, a large-scale implementation of heat pumps in Belgium is lacking today, with applications restricted to new or deeply retrofitted houses. This paper investigates the potential of a more accessible transition scenario, where heat pumps are used to assist, rather than replace, the original heating system in place. The reference heating system considered is a gas boiler (GB) connected to radiators (RAD). To analyse the behaviour of the hybrid system, a model predictive control (MPC) approach is used. Main interests are the achievable heat pump utilisation, as well as the detailed behaviour of the system. Also the impact of the introduction of the heat pump on primary energy use and operational cost for space heating (SH) is illustrated. To ensure a profound analysis, different scenarios are investigated, where the dwelling characteristics, heating system, objective function and energy prices are varied. The results illustrate that under current price conditions in Belgium, minimisation of the primary energy use is the only beneficial scenario leading to a considerable heat pump utilisation. When minimising operational costs, a lower electricity-to-gas price ratio (EGR) is needed to tip the balance.

Keywords: hybrid heat pump, air-to-water heat pump, air-to-air heat pump, thermal energy storage, smart grid, flexibility

1. INTRODUCTION

The potential of heat pumps to contribute to a more cost-efficient and environmentally-friendly operation of the electric power system is widely acknowledged (Forsén, 2005). A first key characteristic is their high energy efficiency. Moreover, they embody a great potential for demand response (DR) when combined with thermal energy storage (TES) (Six, Desmedt, Vanhoudt, & Van Bael, 2011; Arteconi, Hewitt, & Polonara, 2013; Patteeuw, 2016). The TES, which can be provided by, among others, the thermal inertia of the building mass, unlocks the flexibility to shift heat production in time while maintaining thermal comfort of the residents. If the building is heated by a heat pump, the electricity use can hence be shifted to periods of low electricity prices or high shares of renewable energy sources (Arteconi, et al., 2013; Sweetnam, Fell, Oikonomou, & Oreszczyn, 2018).

Considering that buildings account for over 30% of the global final energy use, of which the majority is used for space heating (SH) and domestic hot water (DHW), heat pumps can be a true game changer in the built environment (IEA & IPEEC, 2015). However, in Belgium, a large-scale implementation of heat pumps is still lacking today (Jespers, Al Koussa, Dams, Renders, & Vingerhoets, 2017). The current implementation of residential heat pumps is mostly restricted to new or deeply retrofitted houses characterised by a high-quality building envelope; in these houses, a heat pump is a logic choice for the main heating system, mostly assisted by a back-up electrical resistance heater (Patteeuw, 2016). With this in mind, the question arises whether it might be possible to enhance a widespread use of heat pumps in the future energy system by implementing a more accessible transition scenario. One possible roadmap is the implementation of heat pumps in existing buildings as a supplementary space heating system, assisting – rather than completely replacing – an existing gas boiler coupled to radiators.

The goal of this paper is to determine which objectives, and, along with that, which signals can increase heat pump utilisation in a hybrid configuration. Furthermore, the impact of the unlocked flexibility on primary energy use and operational costs related to space heating is investigated. This study analyses two alternative hybrid configurations, containing either an air-to-water heat pump (AWHP) or an air-to-air heat pump (AAHP) as supplementary space heating technology. The space heating system is coupled with TES, provided (uniquely) in a passive way by the thermal inertia of the building mass; no additional active buffer tank is present. In order to fully delineate the potential of both transition scenarios, their implementation is investigated in different building types, of different age classes, with different renovation levels. Also different time-varying price profiles for both electricity and gas are considered.

The paper is structured as follows. Section 2 explains the modelling framework, used to mimic the behaviour of the system. Here, all required equations, boundary conditions and assumptions are further elaborated on. This is followed by an in-depth analysis and discussion of the results in Section 3, leading to final conclusions in Section 4.

2. METHODOLOGY

This section describes the research method. First, Section 2.1 elaborates on the investigated systems. Section 2.2 describes the set-up of the modelling framework and the controller, with the imposed objective functions, the constraints, and the additional boundary conditions.

2.1 System description

Generally, hybrid heat pump (HHP) systems are defined as the combination of a 'conventional' space heating technology and a heat pump. Consequently, a lot of different combinations are possible. The specific configurations that are studied in this paper are shown in Figure 1. The conventional scenario, where a gas boiler coupled to radiators supplies heat to the building, serves as a reference. In the first hybrid set-up (A), an air-to-water heat pump is installed in series with the conventional set-up, serving as an upstream preheating step; both heat supply systems are hydronic systems in this case. In the second hybrid set-up (B), an air-to-air heat pump is placed in parallel with the gas boiler, serving as an alternative heat supply system; here, water-based and air-based systems are combined. For both hybrid configurations (A and B) the gas boiler is also responsible for covering the full domestic hot water demand. This is however not further addressed in this paper, since this has no impact on the comparison between the different cases.

To be able to translate these theoretical concepts into practical case studies, their implementation has to be coupled to a specific building. Based on the nominal heat demand for the dwelling considered, a heat pump can then be selected within the constraints of the currently available heat pumps on the market. Note that, where the heat pump selection is a rather meticulous task, the gas boiler selection is not so stringent, since these devices tend to be largely oversized, thereby relaxing their case-specificity.

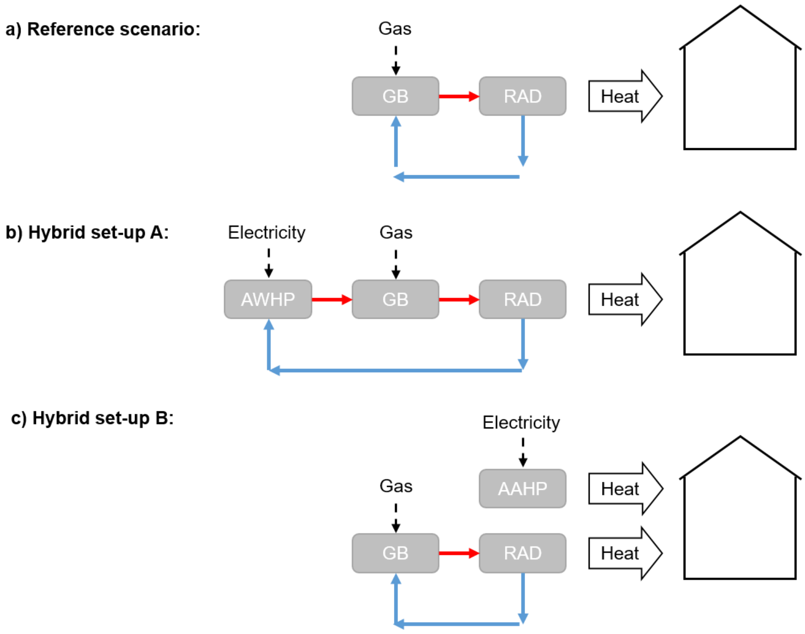

Figure 1 The investigated configurations:(a) reference scenario, where the heat demand is covered by a gas boiler coupled to radiators; (b) hybrid set-up A, where an air-to-water heat pump serves as an upstream preheating step for the gas boiler; (c) hybrid set-up B, where an air-to-air heat pump assists the gas boiler to cover the space heating demand.

Two different dwelling types are studied in this paper, being an old, mildly renovated, detached, single family house, and its new-built, low-energy equivalent. They mainly differ in thermal inertia because of different insulation levels, and in supply temperature of the radiator system, which can have a considerable impact on the heat pump utilisation and its behaviour (in case of the AWHP). The specific characteristics of both dwelling types, summarised in Table 1, are based on the Belgian building stock description developed in the European TABULA project (Cyx, Renders, & Van Holm, 2011), and the work of Reynders (2015) elaborating thereupon.

A heat loss calculation leads to the design heat demand of the space heating technology and the radiators. In general, autonomous heat pump systems are sized to meet 80% of the design heat demand at a design indoor temperature for the day zone of 20°C, for the night zone of 18°C, a ground temperature of 12°C, and an ambient temperature of -10°C (Code van goede praktijk voor de toepassing van warmtepompsystemen in de woningbouw, 2004). Since a hybrid heat pump does not have to be able to cover the full heat demand, in this case, the sizing is based on 100% of the design heat demand at the same design indoor temperatures and ground temperature, but at a higher ambient temperature of 5°C, called 'modified design heat demand'. The ambient temperature of 5°C is chosen as a reference, since this is the tipping point below which the heat pump operation is deteriorating due to the lower ambient temperature as such, and, more important, due to defrosting. At temperatures around 0°C, the relative humidity of the ambient air is rather high, and due to the low air temperature, ice is formed on the outdoor unit. This ice is removed by reverse cycle operation, thereby negatively affecting the performance in this specific temperature window (Daikin Europe N.V., 2018).

Table 2 summarises the resulting design heat demand for both case studies, together with the appropriate heat pumps resulting from a selection process in consultation with Daikin. Note that in all cases, a supplementary gas boiler is still required, since the heat pumps can only cover the heat demand at mild weather conditions.

Table 1 Dwelling characteristics of the considered building types (Reynders, 2015).

	Dwelling type 1	**Dwelling type 2**
Description	Old, mildly renovated, detached, single family house	New-built, low-energy, detached, single family house
Age class	1971-1990	Post 2005
Energy performance measures	- Double glazing - Improved air-tightness - Insulated roof - High temperature radiator (90°C/70°C)	- Double glazing - High air-tightness - Insulated roof - Insulated outer walls - Insulated floor - Heat recuperation on ventilation - Low temperature radiator (45°C/35°C)
Area	238 m²	270 m²
Main U-value (external wall)	0.990 $^{W}/_{m^2K}$	0.403 $^{W}/_{m^2K}$

Table 2 Heat pump selection process, based on the design heat demand of the considered dwellings (Daikin Europe N.V., 2018).

	Dwelling type 1	**Dwelling type 2**
Modified design heat demand	6.4 kW	3.7 kW
Heat pump selection	**AWHP:** Daikin Altherma hybrid with outdoor unit EVLQ08-CV3 **AAHP:** Daikin outdoor unit 4MXS80E (multisplit, coupled to four indoor units: 15/15/15/35)	**AWHP:** Daikin Altherma hybrid with outdoor unit EVLQ05-CV3 **AAHP:** Daikin outdoor unit FTXM35M + RXM25M (split, coupled to one indoor unit)

2.2 Modelling framework

To be able to optimise the operation of the heating system, while taking into account the system behaviour and relevant boundary conditions (such as occupant behaviour, thermal comfort requirements, weather predictions, forecasted electricity prices) a model predictive control framework has to be set up. At each control time step, an optimal control problem (OCP) is solved for a chosen prediction horizon, deciding when/how the gas boiler and/or the heat pump are/is used to cover the heat demand. Solving the OCP allows exploiting the flexibility as good as possible to reach the goal set by the minimum of the objective function, subject to (in)equality constraints describing the system behaviour and other environmental factors. In the remainder of this section, all equations needed to build up the optimal control problem formulation are discussed in detail. In the equations, j always represents the time index and Δt the corresponding time step, equal to one hour.

2.2.1 *Objective function*

In this paper, two different objective functions are considered, as shown by Equations (1) and (2). In the first case, the controller aims at minimising the operational cost of the heating system by searching for an optimal heating profile for both the heat pump and the gas boiler. In this case, the electricity and gas consumption need to be multiplied by the corresponding price profiles. In a second case, emphasis is on primary energy use. Since electricity is not primary energy, the electricity consumption of the heat pumps needs to be multiplied by the primary energy factor (PEF), representing (the inverse of) the average efficiency of the electricity generation mix.

Note that in the framework developed also other objective functions are possible, such as minimisation of CO_2 emissions, maximisation of use of electricity originating from renewable energy sources (RES), etc. However, these are not considered further here, since emphasis is on the impact of unlocking flexibility on operational cost and primary energy use.

$$\min\left(\sum_{j=1}^{n}(cost_j^{el}\cdot P_j^{HP}+cost_j^{gas}\cdot P_j^{GB})\right) \tag{1}$$

$$\min\left(\sum_{j=1}^{n}(PEF\ \cdot P_j^{HP}+P_j^{GB})\right) \tag{2}$$

With	n	Time horizon of optimal control problem	$[h]$
	$cost_j^{el}$	Electricity cost as perceived by consumer	$\left[\frac{EUR}{kWh_{el}}\right]$
	P_j^{HP}	Electrical energy used by heat pump[1]	$[kWh_{el}]$
	$cost_j^{gas}$	Gas cost as perceived by consumer	$\left[\frac{EUR}{kWh_{gas}}\right]$
	P_j^{GB}	Primary energy used by gas boiler[1,2]	$[kWh_{prim}]$
	PEF	Primary energy factor	$\left[\frac{kWh_{prim}}{kWh_{el}}\right]$

2.2.2 *Constraints*

The MPC framework needs a model of the system, being the heating system and building, to predict its behaviour over the prediction horizon. These models are described in Section 2.2.2.1 and 2.2.2.2. Furthermore, the boundary conditions, i.e., the occupant behaviour, thermal comfort requirements, weather conditions, energy prices and primary energy factor are needed. These are elaborated on in Section 2.2.2.3.

2.2.2.1 Heating system model

As already explained in Section 2.1, the buildings are equipped with a heating system combining a gas boiler and a heat pump as heat production units, and radiators as heat emission system. The behaviour of these components, as well as their interaction, are described by underlying equations. Part of these equations is based on the work of Patteeuw (2016).

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[1] Since a time step of 1 hour is used, we consider $[kWh/h]$.
[2] Since gas is a primary energy source, $[kWh_{gas}] = [kWh_{prim}]$.

Gas boiler:

$$\forall j: \dot{P}_j^{GB,sh} \leq \dot{P}^{GB,sh,max} \tag{3}$$

$$\forall j: \dot{P}_j^{GB,sh} \geq 0 \tag{4}$$

$$\forall j: \eta^{GB,sh} \cdot \dot{P}_j^{GB,sh} \leq \dot{Q}_j^{GB\to RAD,max} \tag{5}$$

With	$\dot{P}_j^{GB,sh}$	Power required by gas boiler for space heating	$[kW_{gas}]$
	$\dot{P}_j^{GB,sh,max}$	Maximum power that can be used by gas boiler	$[kW_{gas}]$
	$\eta^{GB,sh}$	Efficiency of gas boiler for space heating	$\left[\frac{kW_{heat}}{kW_{gas}}\right]$
	$\dot{Q}_j^{GB\to RAD,max}$	Maximum deliverable heat power by gas boiler to considered radiator system	$[kW_{heat}]$

The maximum power that can be used by the gas boiler for space heating, and the efficiency of the gas boiler, are derived from manufacturer data. For the old, partially renovated house, a conventional gas boiler is considered, whereas for the new-built low-energy dwelling – where the radiators operate at lower water temperatures – a more efficient condensing gas boiler is chosen.

The maximum heat power that the radiators can transfer, is defined by the design conditions of the radiator system, and the maximum attainable supply temperature by the gas boiler.

Air-to-water heat pump:

$$\forall j: \dot{P}_j^{AWHP,sh} \leq \dot{P}^{AWHP,sh,max} \tag{6}$$

$$\forall j: \dot{P}_j^{AWHP,sh} \geq 0 \tag{7}$$

$$\forall j: COP_j^{AWHP,sh} \cdot \dot{P}_j^{AWHP,sh} \leq \dot{Q}_j^{AWHP\to RAD,max} \tag{8}$$

With	$\dot{P}_j^{AWHP,sh}$	Power required by AWHP for space heating	$[kW_{el}]$
	$\dot{P}_j^{AWHP,sh,max}$	Maximum power that can be used by AWHP	$[kW_{el}]$
	$COP_j^{AWHP,sh}$	Coefficient of performance of AWHP for space heating	$\left[\frac{kW_{heat}}{kW_{el}}\right]$
	$\dot{Q}_j^{AWHP\to RAD,max}$	Maximum deliverable heat power by AWHP to considered radiator system	$[kW_{heat}]$

Although aforementioned equations describing the AWHP behaviour seem to be simple, there is one major difficulty that has to be tackled. The maximum power and coefficient of performance (COP) are generally heavily dependent on ambient temperature, water supply temperature, and compressor frequency, making the optimisation problem highly non-linear. For arguments of computational efficiency, a linear optimisation problem is preferred (Patteeuw, 2016). Since neglecting these dependencies would lead to erratic behaviour of the heat pump, as proven by Verhelst, Logist, Van Impe, & Helsen (2012), an appropriate and well-thought approach is needed here.

To obtain a linear problem, the heat pump is considered to be modulating, but the part-load efficiency as well as the minimum modulation level are neglected. This entails a large simplification, leading to an underestimation of the heat pump performance by neglecting the part-load performance, and an overestimation by neglecting the minimum modulation level. The work of Verhelst et al. (2012) can be used as a first step in justifying this simplification –

at least regarding the COP – but extra research is needed to assess the exact influence of this simplification on the decision making process of the controller (MPC), and thus on the heat pump operation.

Neglect of part-load behaviour results in a dependency on ambient temperature and water supply temperature, that still has to be tackled. Since a deterministic simulation model is used as an emulator, based on historic weather measurement data, ambient temperature is a known input. The only remaining variable is thus the temperature of the water leaving the condenser of the heat pump. In order to ensure a linear optimisation problem, this variable should be known beforehand, so that the COP and the maximum power can be calculated prior to solving the optimisation problem. The major difficulty here is that the water supply temperature of the heat pump, which is the intermediate temperature of the water that has left the heat pump but still has to enter the gas boiler, depends on the share of both technologies in the space heating demand. This share is one of the results of the optimisation problem, and cannot be known beforehand. In order to tackle this problem, following methodology is proposed. Figure 2 gives an overview of all important variables, and how they relate to each other.

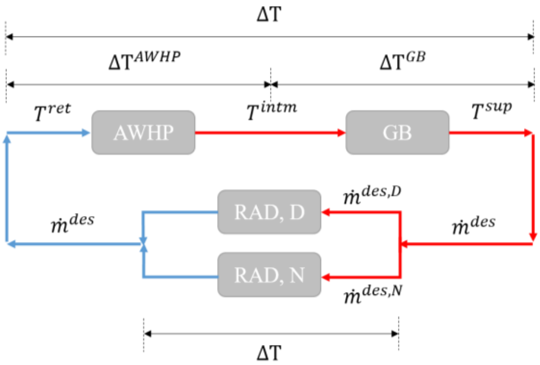

Figure 2 Schematic overview of the heating system in case the air-to-water heat pump and gas boiler are combined to supply heat to the day zone (D) and night zone (N) with radiators.

Based on the results of the optimisation of the reference scenario, being a gas boiler connected to radiators, a first estimation of the heat demand that has to be covered by the hybrid system is obtained. In order to allow the heat pump to shift its operation in time from a DR perspective, the intervals of zero heat demand in the reference case are replaced by the mean heat demand for a time period of one day. Using Equation (9), and assuming that the mass flow rate of water in the system is constant and equal to the design value, the total temperature difference, $\Delta T = \Delta T^{AWHP} + \Delta \mathrm{T}^{GB} = T^{sup} - T^{ret}$, can be calculated. Next, the radiator equation, Equation (10), computes the supply temperature to the radiators. Based on ΔT, the return temperature can then also be calculated. Finally, the intermediate temperature of the water leaving the heat pump, T^{intm}, has to be determined, which is done as follows. Starting from the hypothesis that the heat pump is always maximally utilised, three cases are possible, which are shown in Figure 3:

i) *no heat pump utilisation*: if the return temperature is higher than the maximum temperature that the heat pump can deliver ($T^{AWHP,max}$, generally taken equal to 55°C) the heat pump cannot contribute to space heating, and the intermediate temperature is equal to the return temperature;

ii) *partial heat pump utilisation*: if the return temperature is lower than the maximum temperature of the heat pump, but the supply temperature for the radiators is higher, the intermediate temperature is taken equal to the maximum temperature of the heat pump;

iii) *maximum heat pump utilisation*: if both the return temperature and the supply temperature of the radiators are smaller than the maximum temperature of the heat pump, the intermediate temperature is put equal to the supply temperature.

$$\forall j: \dot{Q}_j^{RAD,Zone,ref} = \dot{m}^{des,Zone} \cdot c_w \cdot \Delta T_j \Rightarrow \Delta T_j \quad (9)$$

$$\forall j: \dot{Q}_j^{RAD,Zone,ref} = (UA)_{RAD}^{Zone} \cdot \left(T_j^{sup} - \frac{\Delta T_j}{2} - T_j^{Zone}\right)^n \Rightarrow T_j^{sup} \quad (10)$$

With			
	$\dot{Q}_j^{RAD,Zone,ref}$	Heat power delivered by radiators in corresponding zone (D: day zone, N: night zone) according to reference scenario	$[kW_{heat}]$
	$\dot{m}^{des,Zone}$	Design mass flow rate in radiator system of corresponding zone	$\left[\frac{kg}{s}\right]$
	c_w	Specific heat of water	$\left[\frac{kJ}{kg\ K}\right]$
	ΔT_j	Temperature difference bridged by the heating system $(= T_j^{sup} - T_j^{ret})$	$[K]$
	$(UA)_{RAD}^{Zone}$	Constant overall heat transfer coefficient for radiator system in corresponding zone	$\left[\frac{kW_{heat}}{K}\right]$
	T_j^{sup}	Supply temperature to the radiators	$[K]$
	T_j^{ret}	Return temperature to the heat pump	$[K]$
	T_j^{Zone}	Indoor air temperature in corresponding zone	$[K]$
	n	Radiator exponent	$[-]$

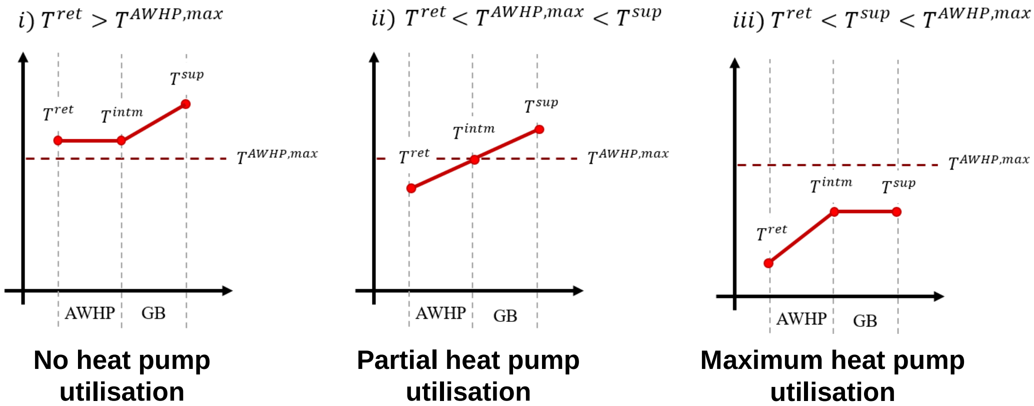

Figure 3 Possible heat pump utilisation, given the supply and return temperature of the heating system and the maximum deliverable water temperature by the heat pump.

Now that all required values are known, the COP and maximum power are calculated for each time step, using Equation (11). To avoid confusion, the nomenclature is in correspondence with Figure 2. The COP correlation is based on the work of Verhelst et al. (2012), but one additional term, containing an arc tangent, is added. This term is introduced to capture the efficiency drop of an air-coupled heat pump around 0°C due to defrosting, as explained in more detail in Section 2.1. The coefficients in the correlations are determined using capacity tables of the selected heat pumps (Daikin Europe N.V., 2018). Their numerical value can be found in Table 3.

$$x = a_0 + a_1 \cdot T_{amb} + a_2 \cdot T_{intm} + a_3 \cdot T_{amb}^2 + a_4 \cdot T_{intm}^2 + \cdots$$
$$\ldots\ a_5 \cdot T_{amb} \cdot T_{intm} + a_6 \cdot \tan^{-1}(T_{amb}) \quad (11)$$

With			
	x	The required variable, being either the COP or the maximum power of the heat pump	$[-]$ or $[kW_{el}]$
	a_i	The coefficients of the correlation	
	T_{amb}	Ambient temperature	$[K]$
	T_{intm}	Temperature of the water leaving the heat pump	$[K]$

The only remaining undetermined parameter in Equations (6) to (8) is the maximum power that the radiators can accept from the heat pump. As was the case for the gas boiler, this parameter is set by the design variables of the radiator system, and the maximum water temperature that the heat pump can deliver.

Air-to-air heat pump:

For describing the behaviour of an AAHP, Equations (6), (7) and (11) remain valid. In Equation (11), T^{intm} no longer represents a water temperature in this case, but the indoor air temperature. This temperature is again a result of the optimisation problem, but can be approximated by the temperature set-points imposed by the residents to guarantee thermal comfort, see also 2.2.2.3. The coefficients to be used in case of an AAHP can also be found in Table 3.

Table 3 Coefficients in the correlations for the COP and maximum electrical power.

	AIR-TO-WATER HEAT PUMP				AIR-TO-AIR HEAT PUMP			
	Dwelling type 1 Altherma hybrid EVLQ08-CV3		**Dwelling type 2** Altherma hybrid EVLQ05-CV3		**Dwelling type 1** Multisplit 4MXS80E		**Dwelling type 2** Split FTXM35M+RXM25M	
	COP	$\dot{P}^{max}$	**COP**	$\dot{P}^{max}$	**COP**	$\dot{P}^{max}$	**COP**	$\dot{P}^{max}$
a_0	6.428E+00	3.652E-01	7.865E+00	1.013E+00	4.334E+00	2.143E+00	4.274E+00	8.215E-01
a_1	1.783E-01	-3.863E-03	3.903E-01	-3.480E-02	3.593E-02	2.042E-02	6.135E-02	2.858E-03
a_2	-1.248E-01	8.085E-02	-1.473E-01	-9.496E-03	-5.367E-02	1.297E-02	-4.946E-02	3.723E-03
a_3	1.152E-03	-1.260E-05	1.034E-03	7.249E-04	1.738E-03	-5.498E-06	3.493E-03	-5.266E-04
a_4	8.388E-04	-5.456E-04	6.780E-04	5.747E-04	2.431E-04	-3.845E-05	1.044E-04	1.127E-05
a_5	-2.325E-03	8.482E-05	-6.323E-03	-2.888E-04	-9.797E-05	1.568E-05	7.416E-05	5.018E-05
a_6	-5.255E-03	-2.064E-02	-6.600E-02	2.536E-03	2.289E-01	0.000E+00	1.189E-02	8.614E-02

Heat emission system:

When the hybrid configuration combines the gas boiler with an AWHP, only radiators are used, which can be modelled as a thermal capacity, C_{RAD}, at a temperature T_j^{RAD}. Their behaviour is described by Equation (12), being the linearised equivalent of Equation (10). In addition, Equation (13) is needed to further link the heat sources to the heat emission system.

$$\forall j: C_{RAD}^{Zone} \cdot \frac{T_{j+1}^{RAD,Zone} - T_j^{RAD,Zone}}{\Delta t} = \dot{Q}_j^{heat\ source \rightarrow RAD,Zone} - (UA)_{RAD,lin}^{Zone} \cdot \left(T_j^{RAD,Zone} - T_j^{Zone}\right) \tag{12}$$

With

C_{RAD}^{Zone}	Heat capacity of the radiator in corresponding zone (D: day zone, N: night zone)	$[kJ/K]$
$T_{j(+1)}^{RAD,Zone}$	Radiator temperature in corresponding zone	$[K]$
$\dot{Q}_j^{heat\ source \rightarrow RAD,Zone}$	Heat power delivered by heat source to radiator in corresponding zone	$[kW_{heat}]$
$(UA)_{RAD,lin}^{Zone}$	Constant overall heat transfer coefficient for radiators in corresponding zone[3]	$\left[\frac{kW_{heat}}{K}\right]$
T_j^{Zone}	Indoor air temperature in corresponding zone	$[K]$

[3] The value of $(UA)_{RAD}^{Zone}$ used in Equation (12) is not equal to the one used in Equation (10), because of the linearisation.

$$\forall j: \dot{Q}_j^{RAD,D} + \dot{Q}_j^{RAD,N} = \dot{Q}_j^{heat\,source \rightarrow RAD,D} + \dot{Q}_j^{heat\,source \rightarrow RAD,N} \quad (13a)$$

$$\text{[ref. case or hybrid set-up B]} = \eta^{GB,sh} \cdot \dot{P}_j^{GB,sh} \quad (13b)$$

$$\text{[hybrid set-up A]} = \eta^{GB,sh} \cdot \dot{P}_j^{GB,sh} + COP_j^{AWHP,sh} \cdot \dot{P}_j^{AWHP,sh} \quad (13c)$$

With

$\dot{Q}_j^{RAD,Zone}$	Heat power delivered by the radiators in corresponding zone (D: day zone, N: night zone)	$[kW_{heat}]$
$\dot{Q}_j^{heat\,source \rightarrow RAD,Zone}$	Heat power delivered by heat source to radiator in corresponding zone	$[kW_{heat}]$
$\eta^{GB,sh}$	Efficiency of gas boiler for space heating	$\left[\frac{kW_{heat}}{kW_{gas}}\right]$
$\dot{P}_j^{GB,sh}$	Power required by gas boiler for space heating	$[kW_{gas}]$
$COP_j^{AWHP,sh}$	Coefficient of performance of AWHP for space heating	$\left[\frac{kW_{heat}}{kW_{el}}\right]$
$\dot{P}_j^{AWHP,sh}$	Power required by AWHP for space heating	$[kW_{el}]$

On the other hand, when the hybrid configuration uses an AAHP, the radiators are combined with an air-based system. In this case, Equations (14) and (15) need to be used in addition to Equations (12) and (13b) to capture the emission system's behaviour.

$$\forall j: C_{AIR}^{Zone} \cdot \frac{T_{j+1}^{Zone} - T_j^{Zone}}{\Delta t} = \dot{Q}_j^{AIR,Zone} + (\dots) \quad (14)$$

With

C_{AIR}^{Zone}	Heat capacity of the indoor air in corresponding zone (D: day zone, N: night zone)	$\left[\frac{kJ}{K}\right]$
$T_{j(+1)}^{Zone}$	Indoor air temperature	$[K]$
$\dot{Q}_j^{AIR,Zone}$	Heat power delivered via air in corresponding zone (assumed to be injected in the air node directly)	$[kW_{heat}]$

In Equation (14), focus is on the specific impact of the AAHP on the indoor air temperature. Note that this is not the only factor determining this temperature; all other influencing factors can be easily derived from Figure 4 and are lumped in the term (…). The more complete and correct expression, explicitly capturing all influences and dependencies, can be found in Equation (16) (Reynders, 2015).

$$\forall j: \dot{Q}_j^{AIR,D} + \dot{Q}_j^{AIR,N} = COP_j^{AAHP,sh} \cdot \dot{P}_j^{AAHP,sh} \quad (15)$$

With

$\dot{Q}_j^{AIR,Zone}$	Heat power delivered via air in corresponding zone (D: day zone, N: night zone)	$[kW_{heat}]$
$COP_j^{AAHP,sh}$	Coefficient of performance of AAHP for space heating	$\left[\frac{kW_{heat}}{kW_{el}}\right]$
$\dot{P}_j^{AAHP,sh}$	Power required by AAHP for space heating	$[kW_{el}]$

2.2.2.2 Building model

The heat power that has to be delivered by the combination of the heat production unit and the heat emission system, is determined by two main factors, the first being the dwelling characteristics and building dynamics presented here, and the second being the boundary conditions, such as occupant behaviour, thermal comfort requirements, weather conditions, energy prices and primary energy factor, elaborated on in Subsection 2.2.2.3.

The dynamic building behaviour is represented by a linear RC-model, shown in Figure 4, and a corresponding state-space model, succinctly presented in vector format by Equation (16). These equations are essential to calculate the instantaneous heat demand and indoor temperatures of the buildings (Reynders, 2015; Patteeuw, 2016).

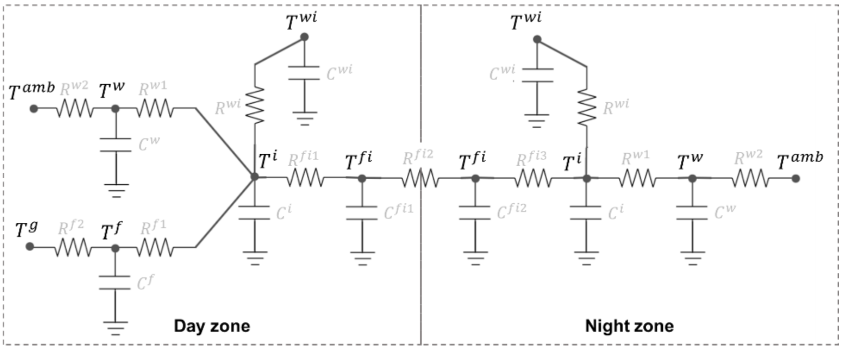

Figure 4 Structure of the 2-zone RC-model, showing all states representing the building structure as a day and night zone, together with the associated thermal capacities and resistances (same indices). Also (part of) the external disturbances are represented. Note that the gain inputs and related parameters are not shown here (adapted from Reynders, 2015).

The model shown in Figure 4 represents a dwelling as two thermal zones: a day zone, consisting of all rooms in which the occupants are active during the day, and a night zone, mainly consisting of bedrooms (Reynders, 2015).

The building structure is characterised by 9 states, being: the temperatures – in both zones – of the indoor air, T_j^i, of the external walls, T_j^w, of the interior walls, T_j^{wi} and of the floor/ceiling, $T_j^{f(i)}$. These states are grouped in the state vector $\bar{T}_j^{sh}$. The inputs for the state space model, represented by the input vector $\bar{U}_j$ in Equation (16), are: the heat power added by the radiators in both zones, and by the air. Finally, the disturbances to the model (which are in fact also inputs), are grouped in the vector $\bar{D}_j$, and can be identified as: the ambient temperature, T_j^{amb}, the ground temperature, T_j^g, the heat gains due to solar irradiation, and the internal heat gains generated by occupants and appliances.

The interaction between all aforementioned variables is expressed by Equation (16). The state space matrices $\boldsymbol{A}_j^{sh}$, $\boldsymbol{B}_j^{sh}$ and $\boldsymbol{E}_j^{sh}$ are based on the thermal resistances and capacitances representing the building structure. Their numerical value for the different dwelling types considered in this study can be found in the work of Reynders (2015).

$$\forall j: \bar{T}_{j+1}^{sh} = \boldsymbol{A}_j^{sh} \cdot \bar{T}_j^{sh} + \boldsymbol{B}_j^{sh} \cdot \bar{U}_j + \boldsymbol{E}_j^{sh} \cdot \bar{D}_j \qquad (16)$$

2.2.2.3 Boundary conditions

Occupant behaviour and thermal comfort requirements:

The occupant behaviour determines the internal heat gains and the set-points for the indoor temperature.

In this study, these heat gains and temperature set-points are considered to be fixed, predetermined profiles. The considered profile in this study is based on the StROBe model of Baetens, De Coninck, Jorissen, Picard, Helsen, & Saelens (2015) and Baetens & Saelens (2015). The internal heat gains serve as an input (disturbance) for the state space model. The temperature set-points, on the other hand, determine the minimum temperature bounds $\bar{T}_j^{sh,min}$ for the state vector $\bar{T}_j^{sh}$. Equation (17) is imposed as a hard constraint, thereby guaranteeing that thermal comfort is always met in terms of minimum allowed temperatures.

$$\forall j: T_j^{Zone,min} \leq T_j^{Zone} \tag{17}$$

With	$T_j^{Zone,min}$	Lower bound for indoor air temperature, guaranteeing thermal comfort in corresponding zone (D: day zone, N: night zone)	$[K]$
	T_j^{Zone}	Indoor air temperature in corresponding zone	$[K]$

The general trends in the selected set-point schedule that is used in this work are summarised below. It is important to stress that, since StROBe is based on real-life information, the (stochastic) occupancy profiles are no ideal repetitions of the trends mentioned below, they regularly contain deviations because of the stochastic character.

Table 4 Main trends in considered temperature set-point schedule.

	Set-point high	Set-point low	High set-point period
Day zone	21.5°C	15.5°C	07:00-21:00
Night zone	12°C	12°C	/

For the maximum allowed temperature, an arbitrary value of 50°C is imposed. Because of the minimisation of the effort related to space heating, being either the operational cost or the energy use, the system always tries to stick at the lower temperature bound. Therefore, the upper bound is of minor importance; the only requisite is that it is chosen high enough in order to prevent infeasibilities in warmer periods when indoor temperatures might become rather high (since cooling and solar shading are not considered in this study). Also, it should be different from the lower bound. Indeed, if the zone temperature would always have to be exactly equal to the imposed set-point, the flexibility offered by the heat pump cannot be addressed.

Weather conditions:

Additional factors impacting the heat power demand are the weather conditions, more specifically, the ambient temperature and the solar heat gains. These data are obtained from measurements at the Vliet test building of the KU Leuven Laboratory of Building Physics in Leuven, Belgium. The reason why measurement data are used instead of typical meteorological year (TMY) data, is twofold. Firstly, since historic energy price profiles are considered, as discussed below, it is important to use weather data of the exact same year (2017 is taken here), to ensure consistency and retention of possible correlations (e.g., electricity prices are generally low when there is a high production by solar photovoltaics (PV) or by wind turbines). Secondly, measurements also contain (more realistic) extreme temperatures, which are not present in TMY data.

Energy prices:

Since one of the objective functions aims at minimising operational cost, also electricity and gas prices are needed to be able to determine the optimal heat power profile.

In a first step, a flat profile for both electricity and gas price is imposed. The exact prices are derived from energy supplier data representative for today's price climate (VREG, 2018; Luminus, 2018; Engie, 2018). Current prices tend to favour the gas boiler over the heat pump, given the significant disproportion between taxes, grid tariffs and VAT charged on electricity and those charged on gas (Claeys & Sourbron, 2017). In order to mitigate this, four different electricity-to-gas price ratios (EGR) are used. Starting from the current price ratio, being 5.4 based on an electricity price of 0.27 EUR/kWh_{el} and a gas price of 0.05 EUR/kWh_{gas} (VREG, 2018), the gas price is relatively increased, until the EGR equals the primary energy factor of electricity. As such, only the energetic difference between electricity and gas remains, rather than an artificial (meaningless) price difference.

In a next step, also time dependency of price profiles is introduced. By progressively exposing consumers to the price variability of the day-ahead market, the heat pump demand response potential is explored. Four different price profile combinations are used:
i) *fix-fix:* a fixed electricity price profile combined with a fixed gas price profile. Here, prices are determined based on energy supplier data, as already described above.
ii) *dn-fix:* a day-night electricity price profile combined with a fixed gas price profile. Again, energy supplier data serve as a reference for the electricity price. The gas price is then determined with the help of the EGR, based on the mean of the day-night profile for electricity.
iii) *var-fix*: a variable electricity price profile combined with a fixed gas price profile. The electricity price is based on the day-ahead price increased by distribution costs. Since this study focusses on the current situation in Belgium, the day-ahead Belpex prices for 2017 are used, being the most recent full-year data available (Entsoe Transparancy Platform). The gas price profile is set up based on the mean electricity price over the previous year (2016 in this case) and the EGR.
iv) *var-var*: a variable electricity price profile combined with a variable gas price profile. In this case, the same reasoning is followed as for the var-fix profile, except that the gas price is based on the mean electricity price over the previous day. Due to the averaging over a whole day, the variations of the gas prices are in general less pronounced than those of the electricity prices.

The resulting price profiles are shown in Figure 5.

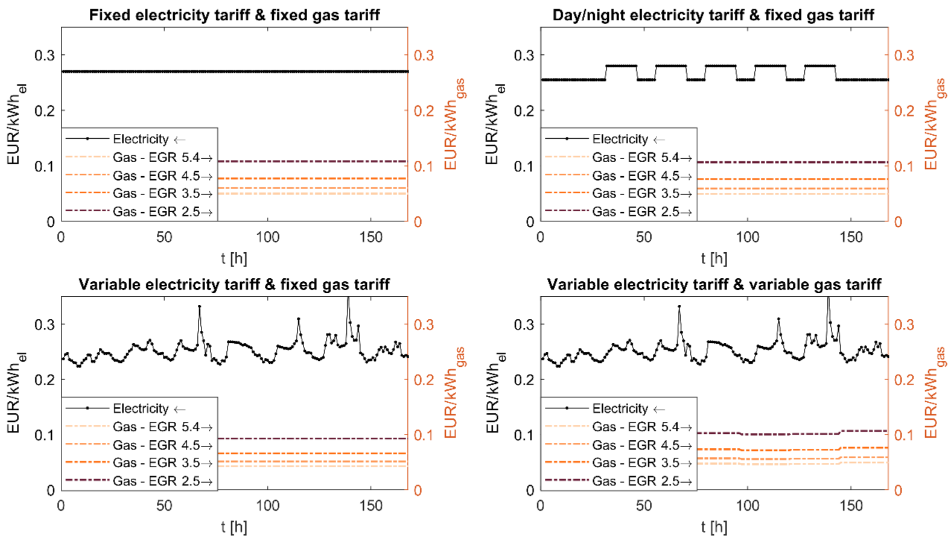

Figure 5 Different energy price profiles perceived by consumers in this study.

Primary energy factor:

The final important boundary condition is the primary energy factor (PEF). This factor represents the electricity supply side mix. In this study, the current prevailing value of 2.5 is used, although discussions are going on to lower this value down to 2.1[4] (Euroheat & Power, 2005-2006; European Parliament, 2016).

3. RESULTS AND DISCUSSION

The scenario analysis, for which the variations are summarised in Table 5, allows identifying the main factors impacting the heat pump utilisation in different hybrid set-ups, consisting either of an AWHP or an AAHP. Firstly, the impact of different objectives, different electricity-to-gas price ratios and different time-varying price profiles on the yearly performance of the hybrid systems, installed in different dwelling types, is investigated. The original heating system,

[4] At the time of paper revision the PEF of 2.1 has been approved, however simulations considered a value of 2.5.

consisting of a gas boiler coupled to radiators, serves as a reference. This reference is used to verify how the flexibility unlocked by the heat pump impacts the primary energy use and the operational cost of the heating system.

In addition, in order to get a more profound insight in the flexibility unlocked, the detailed behaviour of a hybrid heating system, and its exact response to specific external signals – such as the ambient temperature or different price signals – is analysed for one particular illustrative case.

Table 5 Parameters that are varied in the simulations.

Building	Heating system	Objective	EGR	Price profiles
Old, mildly renovated	Gas boiler	Min. cost	EGR1 (5.4)	Fix-fix
New-built, low-energy	Hybrid system with AWHP	Min. energy	↓	Dn-fix
			EGR4 (2.5)	Var-fix
	Hybrid system with AAHP			Var-var

3.1 Heat pump utilisation

This section investigates which factors succeed in increasing the heat pump utilisation. Since optimisation of the operation of the hybrid heating system focusses either on the primary energy use or on the operational cost, the variation of these two parameters with increasing heat pump utilisation is also assessed.

Figure 6 depicts the share of the heat pump in the total heat power demand according to the different scenarios described in Table 5.

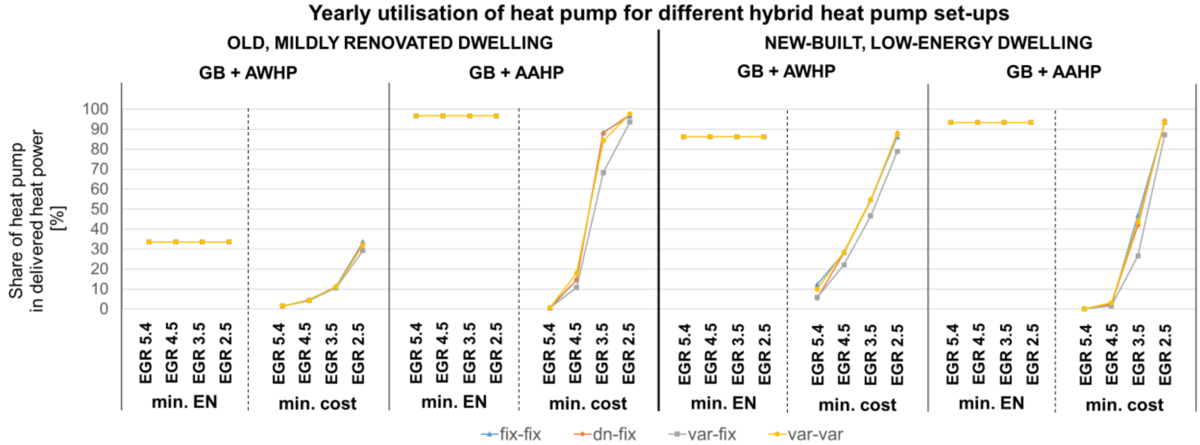

Figure 6 Yearly utilisation of AWHP or AAHP in a hybrid heating system, according to different objectives and different price scenarios, in an old, mildly renovated dwelling, or in a new-built, low-energy dwelling.

Figure 6 shows that minimisation of the primary energy use clearly facilitates the heat pump utilisation. However, a pronounced effect seems to be missing for the AWHP installed in the old dwelling. This is merely a consequence of the technical constraints of the heating system, being the high prevailing water supply temperature of the radiator system, which cannot be delivered by the heat pump. The alternative objective function, minimising operational cost, cannot induce a significant heat pump engagement under current price conditions in Belgium. This changes however when the disproportion between the gas price and electricity price is removed by gradually decreasing the EGR, and thus increasing the gas price compared to the electricity price. When decreasing the value of the EGR until it equals the PEF, the heat pump utilisation converges to the level obtained by minimising primary energy use. Finally, Figure 6 also clearly demonstrates that the specific impact of a certain energy price profile combination is rather limited; all profiles generally induce the same trend. The only profile triggering a slightly differing effect is the var-fix profile, where a variable electricity tariff is combined with a fixed gas tariff based on the mean of the day ahead price of the year before. This is the only profile where the ratio between the electricity and gas price is not always approximately constant. For the considered reference year 2017, the situation is (coincidentally) in favour of the gas boiler, due to a low mean value of the day ahead electricity price for 2016, leading to a relatively low gas price.

As can be seen from Figure 8 and Figure 9, the increasing heat pump participation leads to significant energy savings compared to the reference scenario, where only a gas boiler is in place. For the old, mildly renovated dwelling, relative energy savings of approximately 37% can be achieved in the best case. For the new-built, low-energy dwelling, relative energy savings of almost 30% are possible. These results are promising, certainly given the fact that the applied PEF is on the conservative side. These energy savings are however accompanied by a significant operational cost, which only starts to pay-off for lower EGR values.

When comparing the heating system based on an AWHP and the one using an AAHP, the AAHP clearly outperforms the AWHP in the old house. This is caused by three factors. Firstly, as already mentioned above, the high water supply temperature of the radiator system hampers the engagement of the AWHP, since the heat pump is not able to increase the water temperature above 55°C without considerable performance losses. Secondly, the water supply temperature is subject to far larger variations throughout the year than the indoor temperature. Consequently, for the same degree of heat pump utilisation, the SPF of the AAHP is on average higher than the one for the AWHP, thereby favouring the AAHP. Thirdly, the effect of prices has a huge impact in helping the AAHP compared to the AWHP when minimising the operational cost. Indeed, because of the technical constraints, the gas boiler engagement for the hybrid set-up with the AWHP remains high despite the decreasing EGR. Thereby, the impact of the increasing gas price heavily impairs the added value of this configuration, as is clearly shown in Figure 9. For the new-built house, the differences between the AWHP and AAHP are less pronounced. Although both configurations seem to be equivalent in this case, an important remark has to be made here. Where both hybrid systems are suitable for space heating, which is the focus of this paper, the hybrid system containing an AAHP – or an AWHP if it would be combined with a more appropriate emission system than radiators – also allows cooling. This is becoming an important asset, given the trend of increasing insulation and air-tightness levels, combined with global warming, leading to overheating in summer periods. This is substantiated in Figure 7, where the pronounced overheating in the new-built, well-insulated and air-tight dwelling is clearly observable in case no active cooling is applied. Since the cooling demand strongly correlates with solar radiation, an AAHP coupled to a PV system can serve as a sustainable cooling technology. This is an important factor in favour of the AAHP.

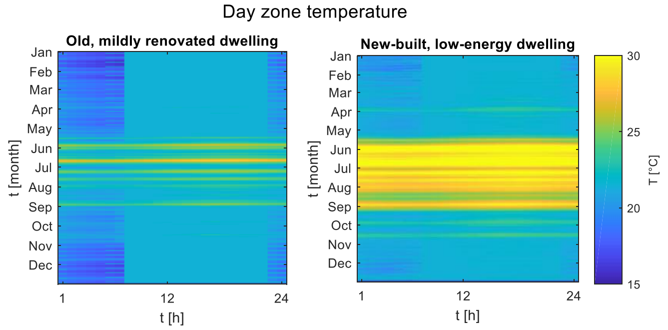

Figure 7 The evolution of the day zone temperature throughout the year for the two dwelling types considered in this study (without active cooling).

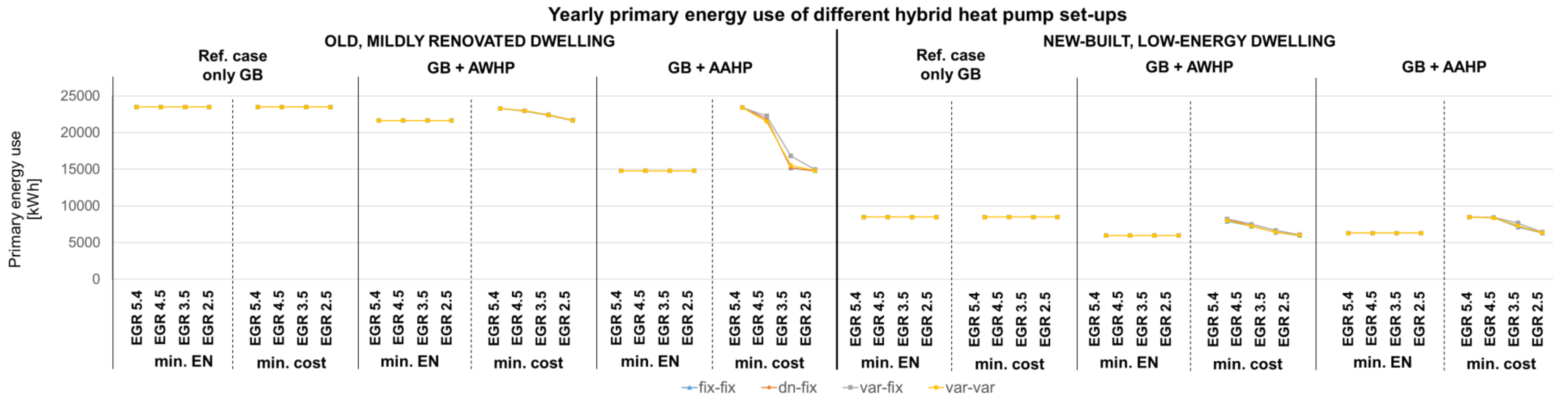

Figure 8 Yearly primary energy use of AWHP or AAHP in a hybrid heating system, according to different objectives and different price scenarios, in an old, mildly renovated dwelling, or in a new-built, low-energy dwelling. The reference heating system that only uses a gas boiler serves as a benchmark.

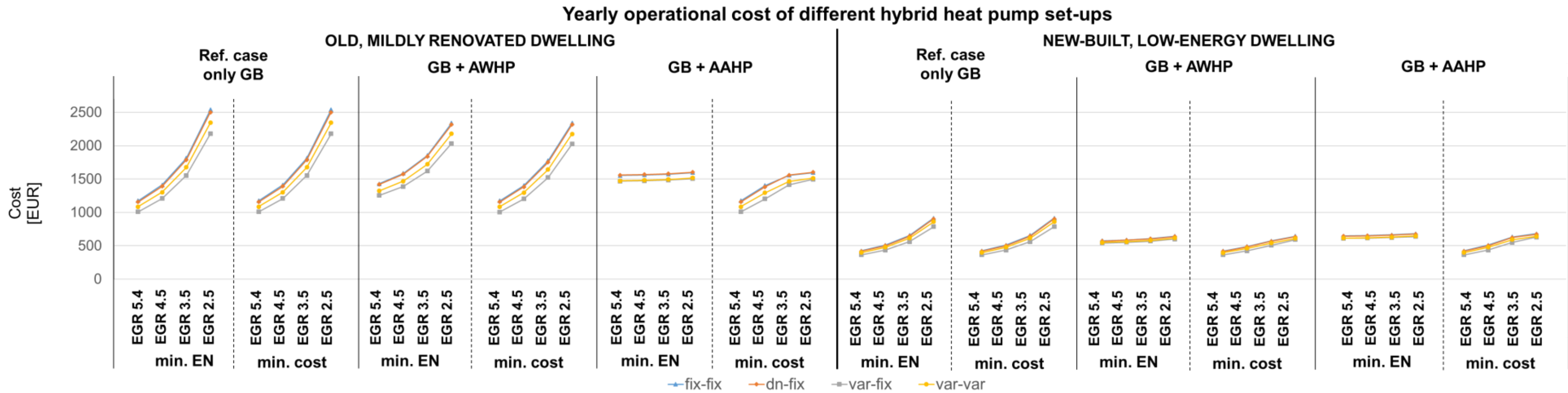

Figure 9 Yearly operational cost of AWHP or AAHP in a hybrid heating system, according to different objectives and different price scenarios, in an old, mildly renovated dwelling, or in a new-built, low-energy dwelling. The reference heating system that only uses a gas boiler serves as a benchmark.

3.2 Detailed behaviour of hybrid system

This section aims at illustrating how the yearly savings on primary energy use and operational cost, described in Section 3.1, are exactly obtained by analysing the unlocked flexibility resulting from heat pump participation. Any combination of parameters from Table 5 could be used as an illustrative case. Here, an AWHP as supplementary heat source in a new-built, low-energy building is considered, subject to a day-night electricity tariff and a fixed gas tariff. The system aims at minimising operational cost.

The operational cost is determined by the multiplication of the energy used by the heating system and the energy prices. Therefore, it is expected that the heat pump tends to shift its operation to periods of high performance and to periods of low electricity costs (being the nights and/or weekend days in case of a day-night tariff). Since the heat pump performance correlates with the ambient temperature, as shown in Equation (11), periods of high performance generally coincide with periods of high outdoor temperatures.

Figure 10 and Figure 11 illustrate that, for a decreasing EGR, the heat pump first starts to substitute the gas boiler in periods of high ambient temperature, and thus high performance. Gradually, the heat pump operation is extended to periods of low electricity prices. Finally, when an EGR of 2.5 is reached, leading to a considerable heat pump engagement, the true added value of the heat pump becomes visible. In this case, the heat pump does not merely substitute the gas boiler anymore, but also starts shifting its operation to the most optimal periods where, initially, the gas boiler was not working.

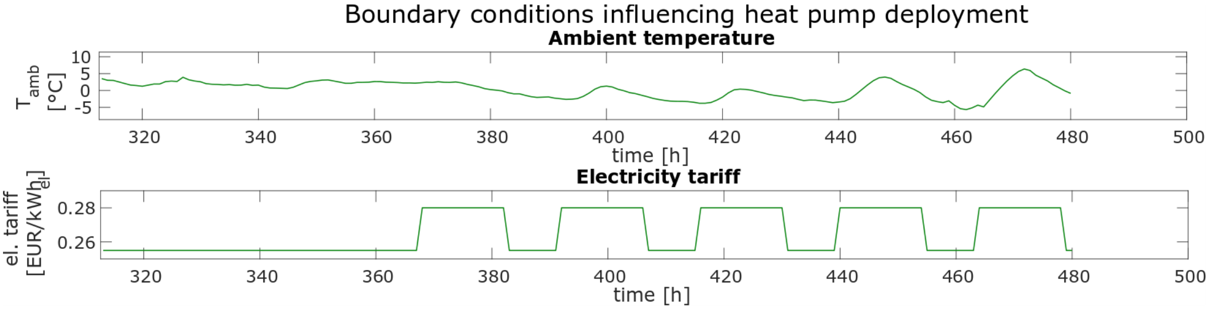

Figure 10 Two important factors influencing the heat pump operation, being i) the ambient temperature, affecting the COP, and ii) the electricity tariff, affecting the operational cost.

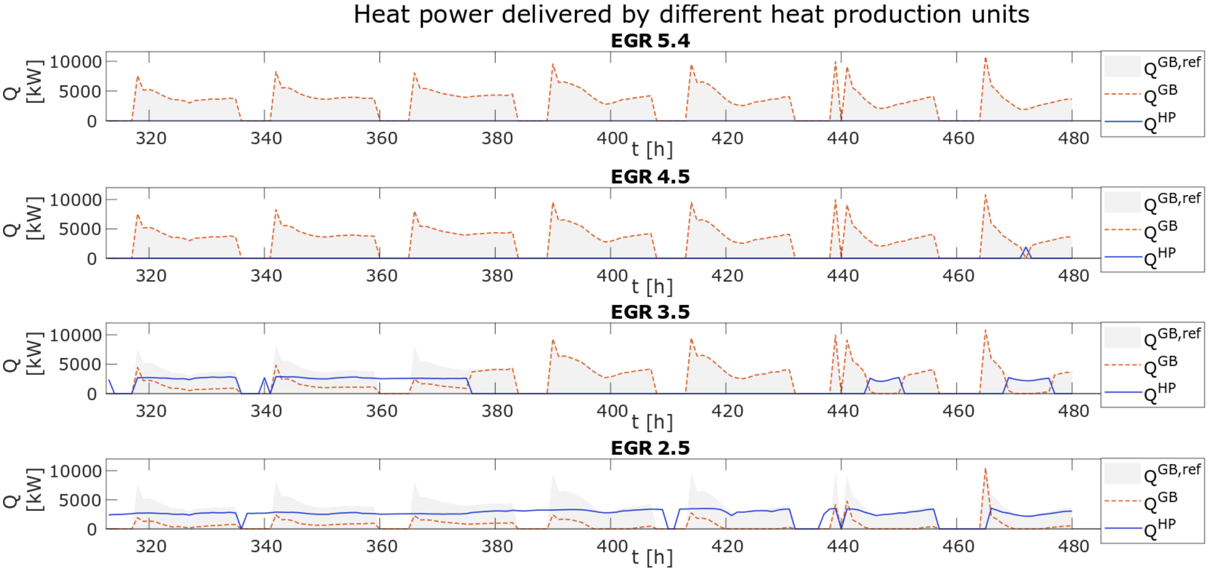

Figure 11 The evolution of the heating profiles delivered by the different heat sources for changing EGR. The grey shaded area is the heating profile when only a gas boiler supplies heat. The red dashed and blue solid curves represent the heating profile of the gas boiler and heat pump respectively.

As can be seen from Figure 12, these effects are made possible by the fact that the zone temperature does not have to strictly follow the set-point, but can deviate from it in a certain predefined temperature band that guarantees thermal comfort.

These results clearly illustrate that hybrid heat pump set-ups can shift operation as a response to external signals, which makes them a suitable technology for demand response.

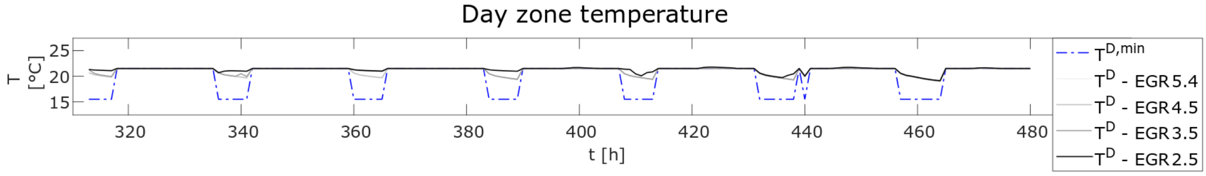

Figure 12 The day zone temperature resulting from the imposed heating profiles shown in Figure 11.

4. CONCLUSION

Two different hybrid heat pump systems, where either an air-to-water heat pump or an air-to-air heat pump serves as a supplementary heat supplier assisting a gas boiler coupled to radiators, are compared for different scenarios. The variable parameters in the scenario analysis are the dwelling characteristics (mainly age class and renovation level), the objective function of the MPC framework optimising the heating system performance, the electricity-to-gas price ratio and the energy price profiles (being a fixed or a variable, market-driven profile).

Of the different objectives, minimisation of primary energy use results in a high heat pump engagement, both for the AWHP and the AAHP. When minimising the operational cost, however, with the current price conditions, the heat pump share in the delivered thermal power is negligible. Lowering the electricity-to-gas price ratio tips the balance, converging to a high heat pump engagement when the price ratio equals the primary energy factor. Changing the specific profile of the electricity and gas price is of minor impact, as long as a rather constant electricity-to-gas price ratio is guaranteed in time. Not only the objective function and the energy prices, but also technical constraints linked to the dwelling characteristics impact the heat pump engagement. This is particularly true in the old, mildly renovated dwelling, where the high water supply temperature of the radiator system impairs the AWHP performance, clearly favouring the AAHP in this case. For the new-built, low-energy house, the differences between the hybrid system based on an AWHP and that based on an AAHP are less pronounced, in case only space heating is considered. However, the cooling potential of the AAHP, together with the overheating tendency of new-built or deeply retrofitted houses with high insulation and air-tightness levels, becomes a great added value.

A detailed analysis of the hybrid system behaviour illustrates that the introduction of a HP (irrespective of the specific type) unlocks flexibility, which can be addressed to shift operation as a response to an external control signal. Therefore, hybrid heat pump set-ups are a good candidate for demand response measures, allowing for savings in – among others – primary energy use or operational cost.

If in hybrid systems the HP would not be sized as a supplementary system, but for full load, MPC allows to further extend the share of heat pump operation, in order to increase the use of RES or decrease CO_2 emissions, e.g. according to a trajectory set by policy makers to reach their goals. This makes both hybrid heat pump systems and MPC enabling technologies for the energy transition.

All results are obtained with an MPC framework using perfect predictions and controlling a building model, not an actual building. Therefore, it has to be stressed that this study is a theoretical assessment. In order to further consolidate the conclusions given here, a study of the influence of prediction errors, or a field test, are recommended.

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