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Control strategy assessment of a small GSHP sourced DH system with end user DHW booster heat pumps

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Abstract

A small thermal grid for historic Almshouses 'the Schipjes' in Bruges was designed in 2016 and is nearing the final phase of construction while partly in operation. The houses' building envelopes were retrofitted with respect to the monumental character to decrease the heating demand and the required temperature levels. The houses are connected to a low temperature thermal grid supplied by a hybrid of a ground source heat pump (GSHP), solar thermal panels (ST) and a condensing gas boiler (not installed after predesign simulation). Domestic hot water (DHW) at higher temperature in the individual houses is provided by booster HP's, while room heating (RH) is provided by floor heating and radiators.

A limitation of thermal power creates a challenge to verify which rule based control (RBC) operates optimal for this case.

The study simulates the project using Modelica. RBC variations are simulated in which temperature levels in the system, anticipation, building integrated or central vessel storage are implemented. For each variation the resulting comfort, the share of renewable energy supply (RES) and the electrical energy use (COP) are quantified. Conclusions are a.o. that building integrated storage is needed for the load management, as well as a heating curve for the further increase of the RES system performance. The individual variations lead to a decrease of discomfort by 17%, an increase of RES by 7.4% and a decrease of electrical energy use of 25% on an annual basis.

Keywords: simulated control impact assessment, thermal grid, ground source HP, fossil free system approach, residential retrofit

1. Introduction

This paper describes a study that optimizes the operation of a residential renovation project that combines a thermal micro grid, a centralized ground source heat pump, centralized thermal solar collectors and booster heat pumps in each of the houses for domestic hot water. The concept decisions, design and sizing phases were supported by dynamic system simulations, aiming at a balanced performance increase by system approach and building retrofit. The overall aim was to realize a future oriented integrated solution towards zero fossil fuel concepts in historical city centres, which could have a large replication factor throughout Europe and beyond. The project is partly in operation, and the handover is approaching, so this study aims to define the Rule-based Control (RBC) to be programmed in order to provide thermal comfort with minimal environmental impact of the system.

2. Context

The Almshouses 'the Schipjes' is a social housing neighbourhood in Bruges, Belgium (Fig 1). It was built in the beginning of the 20th century (1907, arch René Cauwe). Today it is the property of Mintus, the social welfare organization of the city of Bruges, and houses 12 small households. In 1999 a limited retrofit was realized, providing a thin insulation layer in the roof, renewing the electrical installation and installing an individual gas fired stove (with an efficiency of less than 80%) in each house, with integrated heat exchanger to distribute heat to radiators in the kitchen, bedroom and bathroom. The domestic hot water (DHW) was delivered by a direct electrical boiler. The Schipjes has been classified as heritage in 2009, Bruges is a Unesco acknowledged historical city.

Due to non-compliance with contemporary comfort expectations a deeper renovation was planned, thereby thoroughly upgrading the energetic and ecologic aspects of the houses. The research project, funded by VLAIO (Flemish Agency for Innovation and Entrepreneurship) started in 2014, by a consortium of two universities, three companies and two social organisations (Fig 2). Several configurations of thermal supply of the thermal grid and retrofit options for the houses themselves were investigated and compared. After an experience-based long list approach, four system configurations were shortlisted and simulated, and after adding investment and operational cost evaluation the results have been leading to the finally chosen concept (Aertgeerts, Boydens & Helsen, 2016). In the study phase only 11 houses were connected to the thermal grid, during execution one house was added leading to a total of 12.

Fig. 1. Almshouses the Schipjes, birdsview

Fig. 2. Almshouses the Schipjes, the consortium partners of the renovation guidance project on site

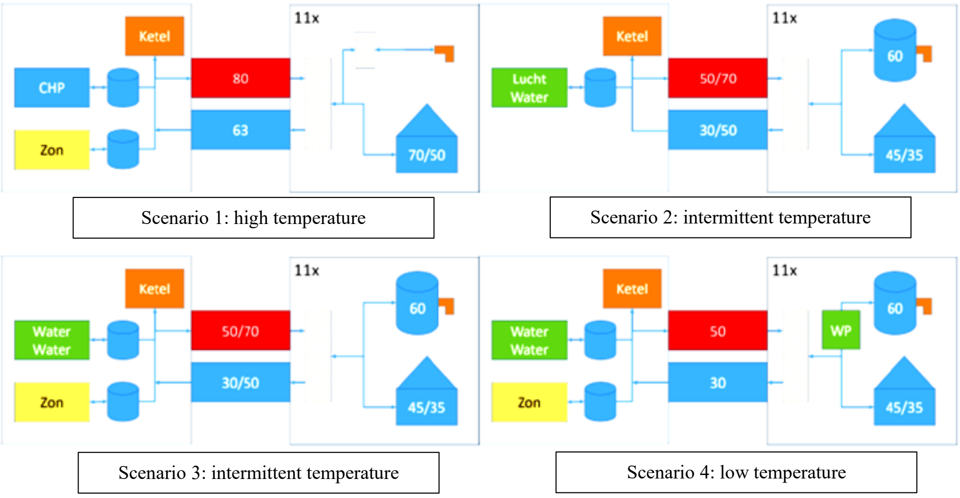

Fig. 3. Schematics of the four shortlisted system configurations

The four scenarios as illustrated in Figure 3 were selected in order:

- to assess the impact of efficiency gains and losses, among them: thermal grid operating temperatures, affecting (1) associated heat losses to the ground, (2) injection potential of the solar thermal system, (3) the COP of the heat pump;
- to compare different heat supply technologies in different configurations and operating modes with regard to their system efficiency (cogeneration (CHP), gas fired condensing boiler (GCB), air to water heat pump (AWHP), ground source heat pump (GSHP), solar thermal (ST), water to water booster heat pump (BHP)).

The gas fired CHP scenario 1 was used as a reference case, since this configuration was considered and observed the most feasible in the market for small scale collective system solutions in Belgium, around 2010-2014, by boydens engineering. Main disadvantages are the dependency on fossil fuels and the local air pollution in the city centre, as well as the maintenance cost and high system temperatures.

Scenario 2 aimed at lowering the investment cost, share of fossil fuels and system temperatures by using the AWHP as dominant supply, and applying intermittent higher system temperatures (if needed through support of a condensing gas boiler) for DHW demand, storing higher temperatures in individual storage tanks in these periods.

Scenario 3 applies the same intermittency, but using the GSHP as main thermal supply. The ST was added to temper ground source depletion, and prevent gas boiler operation for DHW in sunny periods.

Scenario 4 is implementing the same centralized supply as scenario 3 but focusses on a permanent low temperature in the thermal grid of maximum 50°C. The DHW is boosted to the required 60°C in the individual storage tanks, with decentralized BHP's in the houses.

Scenario 4 was chosen as final concept, since multiple criteria, i.e. share of renewables, solar heat supply, total primary energy demand reduction and fossil fuel reduction reached optimal levels in the system simulations, performed by The Thermal Systems Simulation research group of KU Leuven (A. Aertgeers, L. Helsen). These simulations also showed the condensing gas boiler was superfluous in this case (fig 4).

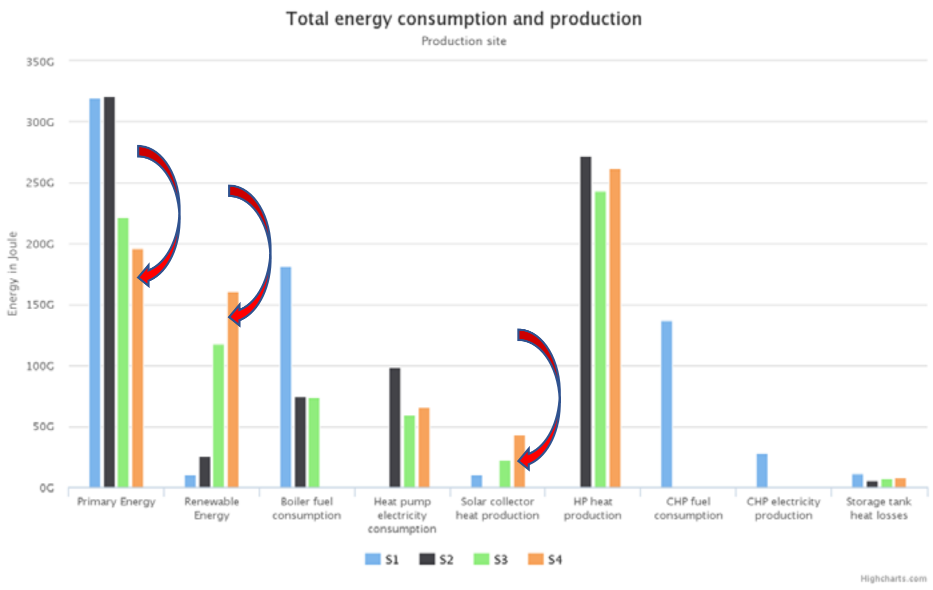

Fig. 4. Results of the first predesign simulation based comparisons, leading to the preferred scenario 4

The renovation started in 2016 and will be finalized in spring 2020. It was realized in phases, and 8 houses are already in operation since September 2019. Illustrations below show: the site plan with the thermal grid and the position of the 8 boreholes, double U, each 125 m deep (Figure 5), the supply cabin in the garden that houses the heat pump, storage tanks and pumps (Figure 6) and the booster heat pump with DHW storage mounted in the individual houses (Figure 7).

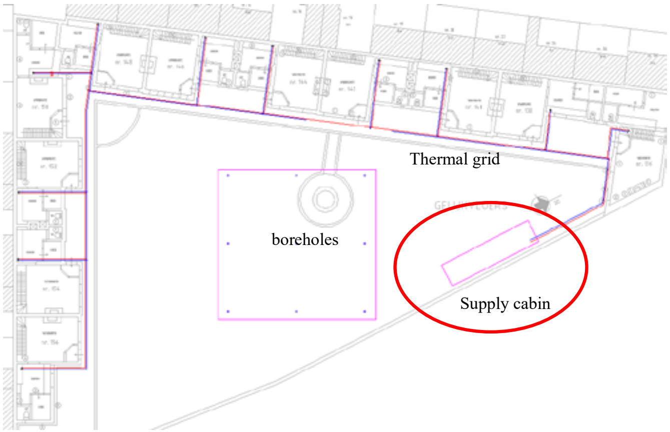

Fig. 5. The site plan with the thermal grid, and the position of the 8 boreholes, double U, each 125 m deep

Fig. 6. The supply cabin in the garden that houses the ground source heat pump, storage tanks and pumps

Fig. 7. The booster heat pump with DHW storage mounted in the individual houses

The design being consolidated and under construction, a performant RBC programming of the system is targeted and therefore this simulation based study was performed.

Furthermore, adding one house to the system in the course of the project, without changing the system sizing, raised the question whether thermal comfort would be endangered, and whether the condensing boiler would be needed anyhow. Or, in case, if a smartly implemented RBC could avoid this move back to fossil technologies.

This synthesizes the main research question: What is the impact of the control on the operation and the sizing of a heat pump based thermal grid, or alternatively stated, can we correct a given undersizing by a smarter control in a real environment?

3. Methodology

The houses and the supply, distribution and emission systems were dynamically modelled and simulated in more detail than in the predesign stage. The RBC as foreseen from designers experience was implemented in the model and the resulting thermal comfort was evaluated, together with other performance indicators, such as: share of renewable energy sources (RES) and primary energy use.

All simulations have been performed in the Modelica simulation environment using Dymola, and component models from the Modelica libraries IDEAS, Buildings and IBPSA. The explicit Euler solver was used instead of the DASSL solver (however a comparison was made in one case). For more detailed information we refer to the master thesis of Sigrid Feyaerts [1].

The hydraulic scheme of the thermal system is shown in fig 8.

Analysis of the results according to the engineered design (reference case) led to expected shortcomings, and to the creation of alternative controls. These alternative control strategies were implemented in the model and the results were compared to the reference design case.

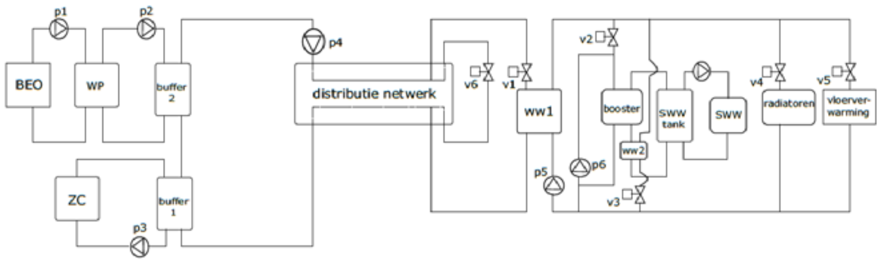

Fig. 8. Hydraulic scheme of the thermal grid, supply systems on the left side, situation in one of the twelve individual houses on the right side. BEO refers to the ground source, WP to the heat pump, ZC to the solar thermal collector, distributie netwerk to the thermal grid, ww to a heat exchanger, SWW to domestic hot water and vloerverwarming to Floor heating

The main assumptions and simplifications in the simulation model are (1) single zone modelling of the houses, (2) fixed ground source temperature of 7°C, with a COP of 3.67 (for the real installed unit) when supplying 50°C at the condenser side, (3) DHW user behaviour according to the StROBe stochastic approach [2] (however the monitored DHW use showed lower loads than the StROBe approach), (4) no internal heat gains taken into account, (5) TMY Uccle (BE) as weather data, as well as a comparison with monitored data (KU Leuven, 2017).

The reference RBC can be summarized as an on/off control of the heat pump activated by the HP buffer temperature (on if lower than 50°C-3°C for 3 min and demand in one of the houses, off if 50°C + 5°C is reached in the buffer for 5 min). ST injects if a 3°C surplus towards the solar buffer tank is noticed for 2 min, off if the ST temperature becomes lower than the buffer temperature). The secondary side of the heat exchanger of the house uses a heating curve for the radiators/floor heating (40°C, -10°C / 20°C, 20°C). Hysteresis is applied for the DHW booster HP (60/45°C) and thermostatic valves are used on the radiators.

The RBC performance for multiple scenarios (using different control strategies) is assessed using the following criteria:

1. Thermal discomfort: Kelvin-hours with temperatures below the setpoint (defined by the StROBe model).
2. Share of RES (renewable energy sources in supply):
   (solar energy supplied by ST + ground source extracted heat) / the total heat supplied
3. Total electricity demand for heating: electricity use for the GSHP and the booster HP's

4. Results and discussion

4.1 Reference RBC

Figure 9 shows how the heat supply and demand are distributed over the system components for the reference RBC. Important to stress are: (1) the centrally supplied heat to the grid (Enet) on a yearly basis , (2) the electricity supplied to the heat pumps (EhpEl, EboosEl), and (3) the dissipated heat loss in the grid (Edis). For this reference case the yearly electricity use by the heat pumps (geothermal and booster) is 154.2 GJ.

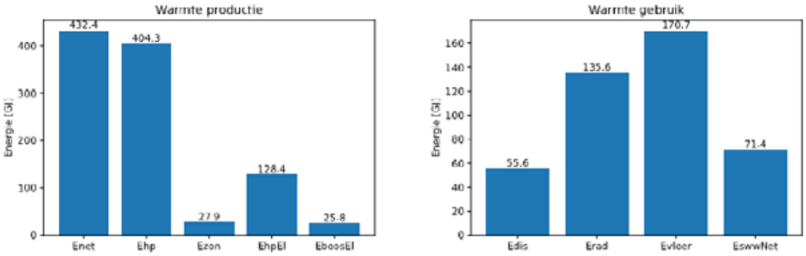

Fig. 9. Heat supply and emission per system element for the reference case

Figure 10 (left) presents the energy sources used for heat generation and (right) the distribution over the different users (grid losses, radiators, floor heating and DHW). The reference RBC results in a RES share of 66.3%, distributed as 60.2% GSHP (Egrond) and 6.1% ST (Ezon).

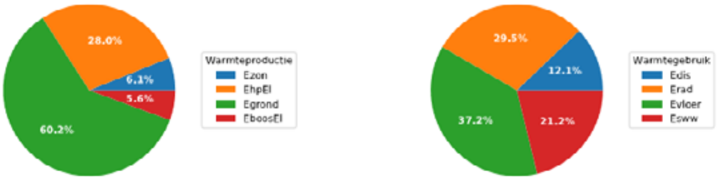

Fig 10: Heat supply and emission share for the reference case

The aggregated thermal discomfort for all houses is 17084 Kh for the full year. This result is not as such directly interpretable. However, according to ISO7730 class A buildings allow maximum 100 Kh/a outside the +/- 1°C bound thereby guaranteeing the PPD is limited to 5% [3]. Therefore, to give insight in the discomfort level, the number of Kelvin-hours that the indoor temperature set point – 1°C is not achieved is assessed, hereby not considering the first two start up hours in the morning, resulting in an average of 83 Kh/a for an individual house. Better understanding of this occurring discomfort is achieved by zooming in on a cold period in January (see Figure 11).

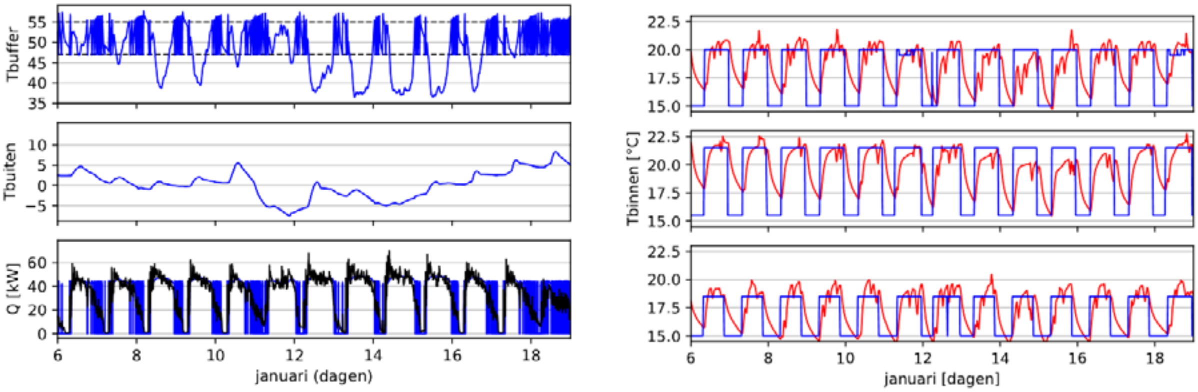

Fig. 11. Total heat (left, demand in black, supply in blue) and comfort (right, for different set points) profiles in a cold winter period for the reference RBC case

It is very clear that the night setback of the RH (room heating) creates a demand profile that varies between the peak demand (around 60 kW) and no demand over 24 hours. As the demand for DHW is prioritized in the reference RBC, and at these times the supply to the radiators and floor heating is temporarily shut off, this can affect severely the discomfort for the room heating in the morning, since the reheating of the local DHW storage takes 62 min on average. Therefore an adapted strategy for DHW reheating is an obvious goal in the advanced RBC. It is clear that simply following the peak demand would require additional thermal supply, and stepping back to adding the condensing gas boiler the most evident measure.

4.2 Alternative RBC - Adapted DHW reheating strategies:

Several variations for the DHW reheat rules have been investigated:

1. More frequent and time limited reheating of the DHW tanks can be achieved by adapting the reheat set point to 50°C instead of 45°C. Of course a higher average DHW temperature during reheat will decrease the booster HP COP. The reheating time is observed to decrease to 43 min on average. However no significant improvement is observed in the aggregated thermal discomfort.
2. Preheating DHW during night time to a higher temperature was also implemented, using a set point of 70°C. The overlap of RH and DHW demand in morning hours was as such reduced, resulting in a decrease of thermal discomfort by 10%. A decrease of the average COP of the booster HP's from 3.8 in the reference case towards 3.4 was noticed, as well as a small decrease of RES share from 66.3% to 65.9%.
3. A strategy with simultaneous RH by the radiators (only FH is off) during DHW reheating results in a lower discomfort (-17%). Especially during the day the combination of the stored heat in the FH, shut off (of FH) during DHW demand, and the available power of the radiators succeeds in maintaining indoor thermal comfort (Fig 12). In the morning hours the night setback control prevents this action.

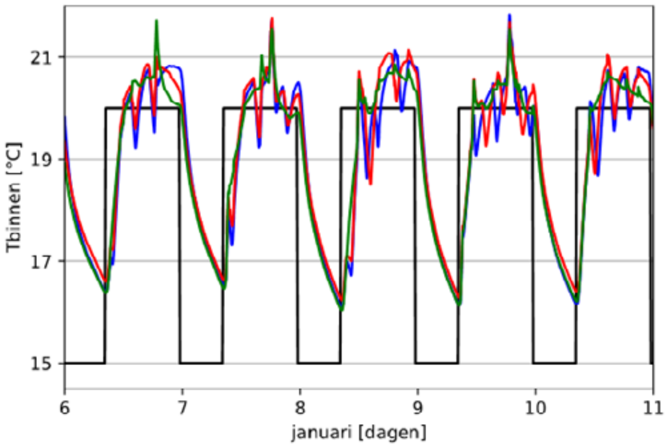

Fig. 12. Effect on indoor temperature by keeping the radiators (green line), or the floor heating (red line) activated during DHW demand (booster HP in operation), the reference RBC result is the blue profile

4.3 Alternative RBC - Anticipation:

Anticipation in cold periods of the year, where logically the limited thermal power results in more frequent discomfort hours, is a next approach. Based on the research of Basciotti and Schmidt [4] some variations have been set up. Anticipating the start-up and peaks in the morning by thermal storage in the central storage tanks at higher temperatures did not give any relevant results, due to the limited storage potential. Night storage in the houses, however, by reducing the night setback for floor heating proved to be far more effective. It decreases the required supply capacity and improves thermal comfort, with an extra electricity supply of only 1.2%. The RES share remains 66% and the total heat demand of the grid rises by only 0.3%. The higher demands during the night are largely compensated by the decrease of start-up energy use (see Figure 13), as studied by Frederiksen and Werner [5], even in this case where the insulation level of the historic houses is rather limited.

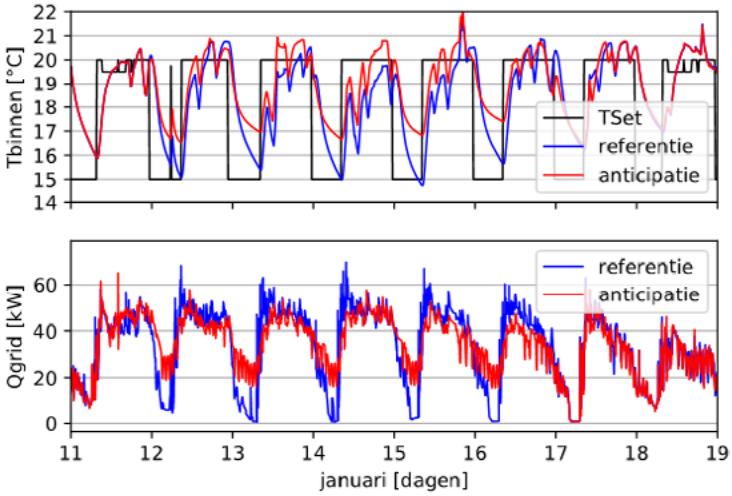

Fig. 13. The effect of reduced night setback on achieved indoor temperatures and supply peaks during cold periods

4.4. Alternative RBC - Adapted heating curves:

As a final exercise the effects of adapted heating curves are studied. Previous research of Ommen et al. [6] already resulted in optimization of supply temperatures in thermal grids with central HP supply and decentralized booster HP's. Inspired by those results, the grid is controlled by two different heating curves, selected as: (1) 50°C, -10°C / 25°C, 20°C and (2) 50°C, -10°C / 30°C, 15°C. The first led to inlet temperatures at the booster HP, which are not within the boundary constraints of the manufacturer. Both heating curves lead to a higher amount of injected solar energy and a higher COP of the GSHP. The total electricity supply decreases by 25%. The (dis)comfort however is not affected.

4.5. Summary: overview of variations investigated

An overview of the results of the described individual variations to the reference RBC is shown in Table 1. Results for the reference case applied to the measured climate data (Leuven, 2017), have been added as well. In the thermal discomfort column the improvements can be seen for the individual variations, and one should keep in mind the considerations put forward in the beginning of this section, prior to Fig 11.

Table 1 Overview of results of implemented variations to the reference RBC

RBC variation	**RES share (%)**	**Thermal discomfort (Kh)**	**COP-HP**	**COP-booster HP**	**Thermal grid heat demand (GJ/a)**
Reference	66.3	17.1 k	3.13	3.78	432.4
Preheating DHW	65.9	15.4 k	3.13	3.44	433.9
Simultaneous RH	66.6	14.1 k	3.14	3.78	433.8
Continuous FH	66.0	16.1 k	3.11	3.78	433.7
Heating curve (2)	73.7	16.9 k	4.37	3.54	414.3
Weather data 2017	66.4	11.9 k	3.09	3.78	360.9

5. Conclusion

The research case investigated handles individual variations in the RBC approach for the hybrid heat supply and emission systems in Almshouses 'the Schipjes' in Bruges, a practical case that is nearing completion. As the given installed power is limited and challenged towards the extension of the connected houses during construction the possible improvements by variations in the reference rule based control design were studied. Individual changes have shown that reasonable impact on the expected discomfort is possible, without decreasing, in some cases even increasing other performance criteria such as the share of RES and COP of the global system. Thus the degree of impact of the control on the required size of the supply systems, taking into account storage and dynamic effects, has been clarified for this specific case. This study moreover shows that a fully RES-based thermal network is feasible, even in historic city centres, provided that also the electricity used is based on RES technologies. Given the large amount of historic centres in Europe and beyond, the replication factor of this concept can be substantial.

Future work will consist in evaluating combined variations that improve the targeted criteria. The combination of continuous FH, adapted heating curve and simultaneous RH with radiators seems to be the best case to evaluate.

Acknowledgements

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