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Energy efficiency comparison of a centralized and a multi-agent market based heating system in a field test

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Abstract

For the built environment it is envisaged that in the near future the total annual heat demand could be covered by renewable sources generated within the built environment. More and more devices, such as heat pumps and solar collectors will enable a sustainable and distributed generation of heat. Centralized climate management systems are challenged by this development. Multi agent solutions which have been shown to optimize cost and energy efficiency in electricity grids have been proposed in the past to deal with this. A solution based on electronic market principles called HeatMatcher has been designed and tested in simulation mode and was next tested in an installation for floor heating of an apartment building. A centralized climate management system could also control the heating system. By varying the control for several consecutive days between both systems at identical spells of weather for different types of seasons a comparison could be made between the operation and energy efficiency of both systems. It is shown that the multi-agent system is able to control the installation in a stable way and gives priority to sustainable generation of supply to the benefit of the overall installation.

Keywords: smart energy systems; multi agent system; energy efficient; field test; heat pump; heating, autonomous agents; user comfort; thermal grids; smart cities

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1. Introduction

For the built environment it is envisaged that in the near future the total heat demand could be covered by renewable sources generated within the built environment. It is expected that the number of devices for heating and cooling will increase to achieve an energy neutral built environment. Such a build environment may include solar collectors, a heat pump, district heating, solar blinds, an air handler unit, biomass-fired plants and combined heat and power (CHP) as well as heat storage facilities. Having a substantial amount of renewable energy sources (RES) with intermittent behaviour in a distributed setting requires such systems to be connected in an intelligent and more dynamic way than today. Optimizing the operation of such an integrated heat infrastructure requires access to operational information from a large number of network nodes from both the demand side and the supply side. The way to satisfy such needs is to have a bottom-up approach rather than a top-down architecture. Intelligent agents at the level of individual devices and multi-agent systems organized in a distributed software architecture are particularly suited to this kind of application.

Agent based heat flow management has been the subject in several studies [1-5] and different authors also defined multi-agent systems for distributed electricity management. A number of these propose the use of electronic equilibrium markets as the core coordination mechanism. The PowerMatcher [6,7], a market based control concept for supply and demand matching (SDM) of electricity, stands out for its elegance and flexibility of use. In the PowerMatcher concept an agent expresses the willingness to pay or be paid for a certain amount of electricity using demand and supply bids. All bids are aggregated by a market auctioneer who determines the market clearing price that gives the best over-all match between electricity consumption and production. The agents in turn react appropriately by either starting or stopping the devices. During several field tests the PowerMatcher has shown the ability to coordinate and control the electricity grid [6].

In [8] the PowerMatcher was studied as an example for coordinating heat in a decentralized control system to preserve the energy balance of an aquifer connected to a heat pump. Based on these experiences a new P2P solution for managing heat in installations has been developed [9], called HeatMatcher. As input for the HeatMatcher the ICT requirements of [10] were used as an example. Heatmatcher is based on autonomous agents bidding on a market of which the bids are based on the amount of energy to be supplied or demanded. The energy is calculated by measuring flow and temperature. The physical design parameters, the ICT architecture and some preliminary results are described in [9]. This new study focusses on the market structure of the HeatMatcher and presents the results of a field test comparison of a centralized management system and the HeatMatcher.

Nomenclature

RES	renewable energy sources
SDM	supply and demand matching
COP	coefficient of performance
ICT	information and communication technology

1.1. Decentralized control of building climate systems

The potential of using multi agent systems and market oriented programming for controlling building environments was reported earlier in [1, 2]. Some advantages and disadvantages of agent technology over centralized control methods are explained in [1] and [11]. Currently commercial climate control systems such as Honeywell and Priva are based on centralized control systems. They manage the heating system by monitoring the complete system state and control. Due to increased control space introduced by sustainable equipment such as 1) turning on multiple condensers in a heat pump, 2) operate the heat pump while retaining the energy balance of the aquifer, 3) taking into account the intermittent supply of a solar collector, 4) setting the flow rate of a pump, 5) opening a valve, it becomes fairly difficult to a) design such a centrally oriented system and b) validate whether the system will perform as designed.

Generally there is consensus that the performance of a building climate systems is vulnerable with regard to the maintenance of the system. Initiated by user complaints and passed on by a climate system manager a service assistant, unaware of interdependencies of the system which are typical for centralized systems [11], may change certain parameters which may benefit the operation of the service the assistant is aiming for, but other parts of the building operation may hamper, thereby easily deteriorating the overall energy efficiency performance of the building. Taking into account the high cost to tune the climate system for the delivery the negative consequences of the maintenance for the operation may be huge.

Another point of interest is the vulnerability with respect to changes in the installation itself, such as replacing pipes with different parameters and pumps with other pumping speeds. Although centralized systems may be fit out with modules to cope with such changes and adapt their operation, these modules are thus costly and hence often not present in the climate system. Agents representing RES automatically adapt to their environment and take the initiative. Autonomous agents representing users in a part of a building can transmit their priority for heating and instead of supplying a certain flow of water with a temperature derived from a heating curve, tailored heating becomes possible.

The plug and play of agents should also be mentioned as an advantage. All the agents developed for this field test are designed in such a general way that they could be applied for any installation. Only the piping of an installation and the operation of a valve or a pump of which the setting may be dependent on several other devices, puts limits to the generic use of agents in an installation. This will further be elaborated in the next section.

1.2. Configuration of multiple heat markets

In coordinating the installation of a micro district heating the scope of the real time market at which it will be operating should be considered and whether just one market is sufficient or more markets are necessary. To explain and evaluate why a choice was made for a HeatMatcher system with two time markets to operate the micro district heating as field tested in this study, it is helpful to compare it with the operation of a real time market in electricity grids.

In [12] the scope of such a real time market was embedded in existing traditional markets and the devices and materials which are primarily responsible for guarding the 50 Hz frequency, which is very typical and crucial for maintaining the electricity grid in balance. The quantity of power was plotted versus the time scale of operation. On the largest time scale of days the largest quantities are traded on a day ahead market, whereas on the shortest time scale direct control by inertia on a millisecond scale and frequency controlled reserves on a scale of seconds are handling small quantities. Next to the Day ahead market an Intraday market trading on an hourly scale and a regulating power market trading on a 10-15 minutes scale are present, each trading smaller quantities at shorter time scales; the real time market comparable to the HeatMatcher is assumed to be operating at a time scale somewhere between the regulating power market and the frequency controlled reserves. Such a comparison is worthwhile when one considers that in an installation on one hand on a short time scale pressures are read, hydraulics are used and valves are controlled pneumatically, particularly for safety keeping and on the other hand on a longer time scale depending on the size of buffers and pumping speeds, heat can be stored for a longer time before it is supplied. Also for the longer time scale it is important to take into account the operational requirements of devices such as a heat pump. To achieve a good COP and to mitigate wear the turning on and off behavior of heat pumps is very important: switching on for at least 30 minutes is recommended and switching off for at least 10 minutes often is required. So controlling or trading the energy supplied by such a device should guarantee constant operation of at least about 30 minutes. Considering these requirements and constraints it was decided to operate the installation with two electronic markets as shown in fig. 1.

This configuration has been proven to be successful in operating the micro heating as described below, however one should bear in mind that in other configurations a different market structure may be needed. As an example consider the requirements of a geothermal heat source, where after turning off the geothermal pump a switch into circuit of more than several days may be required before the ground water at kilometers deep starts flowing, getting the geothermal system back into proper operation, hence another electronic market operating at a weekly a monthly scale may be needed.

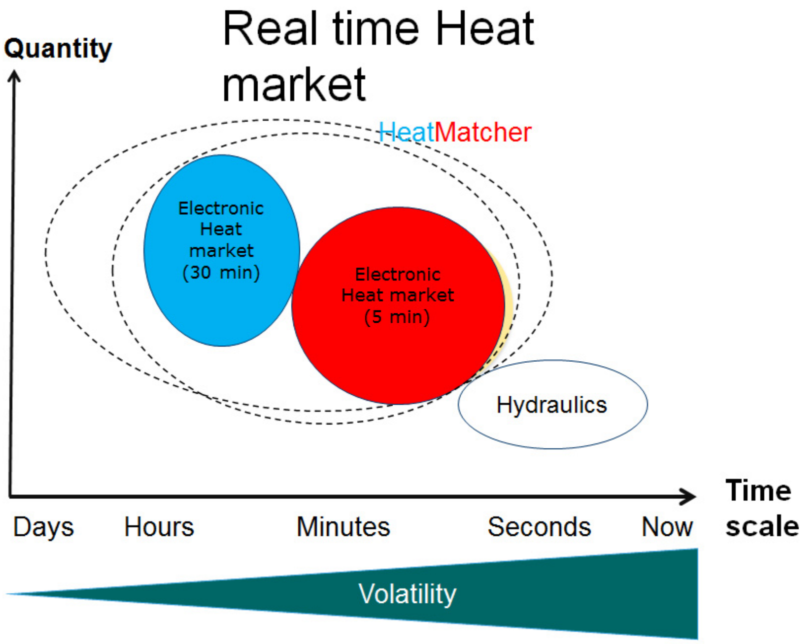

Fig. 1. The integration of a HeatMatcher market with respect to time in the existing ambient of an installation for heating purposes.

The time scales of 5 and 30 minutes are to a certain extent arbitrary. Transferring heat can be a rather slow process so a shorter time period than 5 minutes may result in undesirable behavior.

In the installation studied in this paper the piping and pumping speeds resulted in response times of temperature increases less than 2 minutes. A time scale of 30 minutes is regarded as optimal in this installation as at shorter times it is expected to deteriorate the operation of the heat pump, whereas at a longer time scale a limit is set by the time it takes for the pump to replenish the content of the buffer which is about 30 minutes.

On the 30 minute time scale in the bidding process the fossil fueled gas generators and heat pump participate as a supplier, whereas on the shorter time scale merely the gas generators are present as a supplier. On the short time scale the heat demanded by the agent representing the apartments is subtracted by the heat already exchanged in the 30 minute market.

It was already mentioned that the piping of the installation puts limits to the agents bidding on the market. Multiple energy exchange markets are present, one for each group of components that are physically connected with each other. Fig. 2 depicts the deployment of agents in the field trial showing two markets. On both, markets are run on the two different time scales of 5 and 30 minutes.

1.3. The installation of the field test

The installation of the field test site is located in a cellar. Fig. 3 shows a schematic view of the installation and fig. 4 shows a picture of some of the components which are coordinated by either the centralized system or the HeatMatcher. On the right of fig.4 a heat pump is visible with a power of 106 kW, which can be operated at two stages of equal power by two parallel condensers. The heat pump is connected to a borehole. In the middle a buffer of 1000 L is visible, on the left of it a plenum and further on the left buffers for tap water heating, which will be controlled in a second field test running in 2015. Two gas fired boilers with a power of 115 kW each for heating the rooms are located in a separate room.

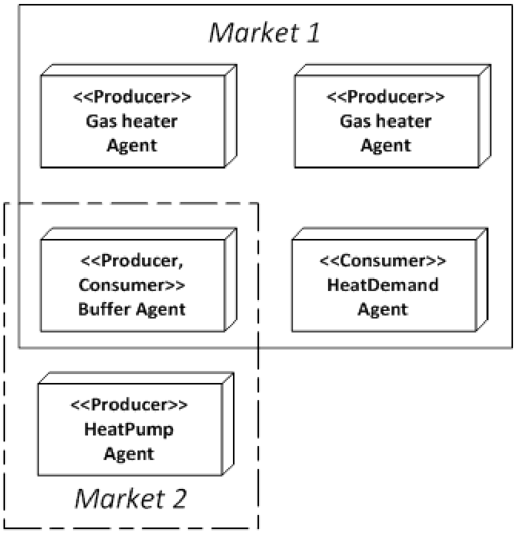

Fig. 2. Example system with two markets in which the buffer plays two roles: a consumer role in market 2 and a producer role in market 1. The heat demand agent represents the demand from the apartments, the other agents provide in concert the required heat.

A plenum is present to distribute water in case the flow to the houses for floor heating is less than the flow from the supply section to prevent undesired pressure build up. The flow of water to the apartments may be less than the flow through the buffer. The installation is designed that operation is still safe and secure on such an occasion. Then part of the water mass just circulates; water from the top of the buffer is pumped backwards through the plenum and re-enters the buffer at the bottom. It is planned to connect a circuit for domestic hot water to the circuit of room heating, to investigate optimization for further energy efficiency gain. For a schematic view of the supply of the room heating system it is referred to [9].

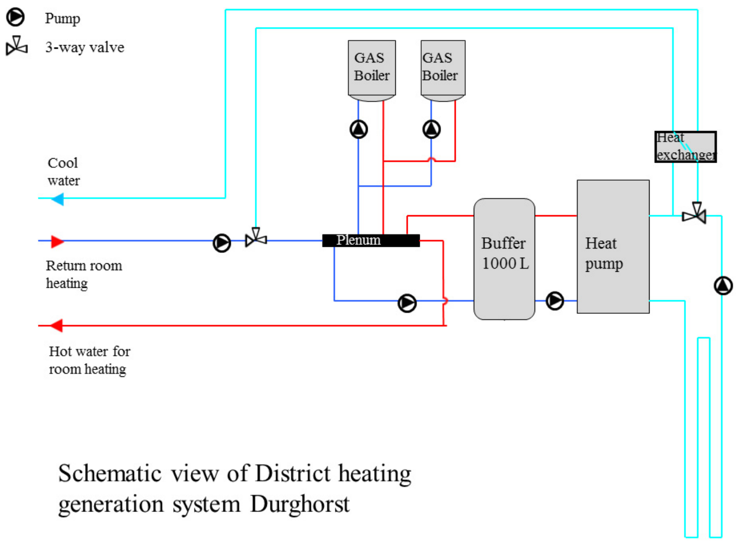

Fig. 3. Room heating supply of small district heating system Durghorst..

Fig. 4. The installation used for the field test with heat pump, buffer and plenum.

2. Results

From March 2013 until February 2014 a field test was performed covering different seasons and outdoor temperatures and hence different daily demand of energy.

Before the field test was started the operation of the system was first tested in a simulation environment with Matlab Simulink components as described in [9]. The Priva control principles were included by a separate component. The performance of the system could be tested and the energy efficiency was analyzed. In the second phase instead of the Priva Matlab component the HeatMatcher written in Java was connected to the Matlab Simulink environment. Following this procedure bugs in software could be detected before connecting it to the installation, thereby reducing the risk of undesired behavior or unacceptable wear of the individual components and installation in real operation. It was tested and confirmed that the energy demand and entrance temperature of the water used for floor heating of the houses was realized and did not exceed 45 - 50 ºC for a short period of time. Although the site in principle allows little improvement of the energy efficiency due to boundary conditions of the installation, from the simulation results an increase of the energy efficiency of 2% was shown.

During the field test the installation was either run by the centralized system or the HeatMatcher as an SDM system. The latter did run for several times, the longest test spanning a period of 20 consecutive days during a rather cold spell of weather. During operation the system was monitored and it was confirmed that the behavior of the individual components and the system was stable and the temperature entering the apartments generally was accordingly to the temperature of the heating curve. From the absence of any phone call from the inhabitants of the apartments it can be concluded that the system did serve well, supplying the right amount of heat for user comfort.

To compare the performance of both systems first the performance of the heat pump was monitored and analyzed. From the COP being in the range of 3-3,5 independent of the system in operation, it was affirmed that a comparison of performance could simply be carried out by comparing the deployment of the gas boilers. It was decided to compare the boiler deployment as a function of the heat supplied, because although average outdoor temperatures may be equal, still each single day is different. The overall result of the field test is shown in fig. 5.

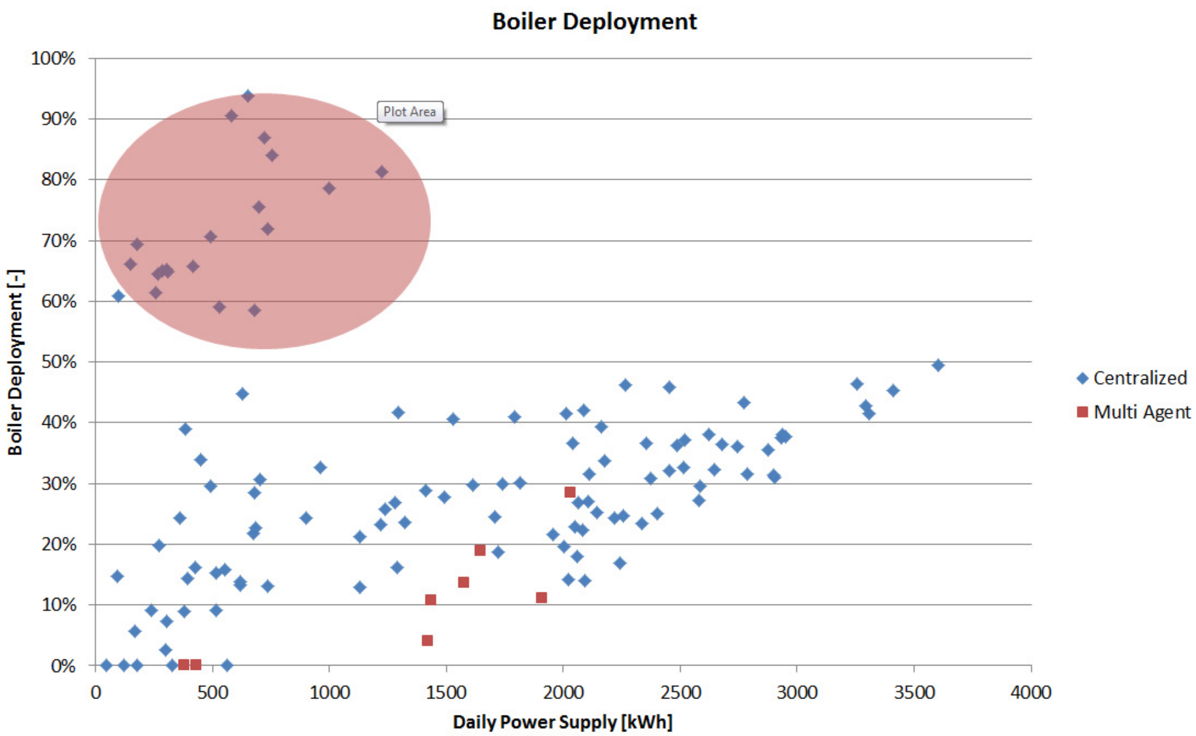

Fig. 5. The boiler deployment as a function of daily supply of energy for a centralized and a Multi Agent system at the field test site in Krommenie in the Netherlands. The centralized system as a product is the result of the combined effort of the underlying Priva hard- and software system and the company responsible for the integration and design of the installation.

Remarkably the Multi Agent system appears to have a significant better performance than the centralized system, especially at a low demand of power supply. In a red balloon results at low demand are marked with symbols representing just the control of the centralized management system. At average demand of heat the HeatMatcher also has a better performance. Results of the system tested at high demand are not available yet as the corresponding data analysis is not completed yet at the writing of this paper.

For another perception of the system's behavior, a comparison of the heat that is demanded and delivered is shown in fig. 6, as well as the outdoor temperature. As can be expected more heat is demanded during the night at low temperatures than during daytime. Generally as much heat is delivered as demanded; a more detailed analysis is described in [9], including more data analysis at a daily supply of about 2 MWh .

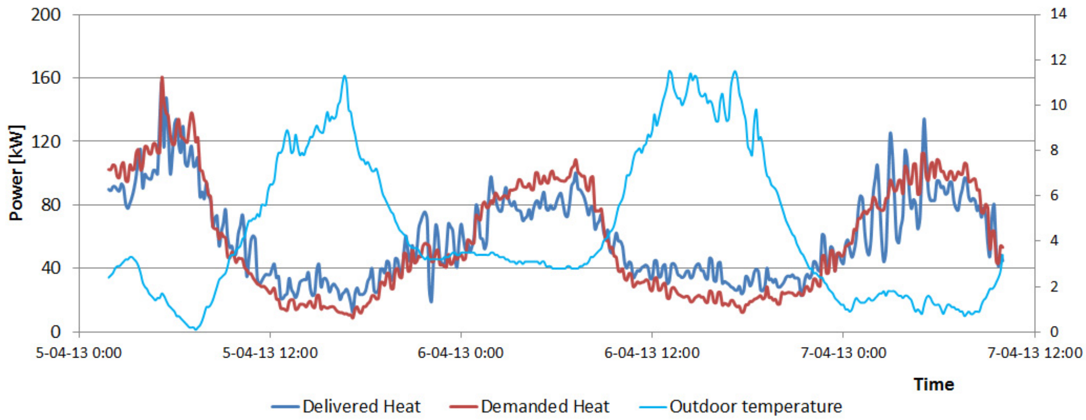

Fig. 6. The demanded and actually delivered heat to the apartments during a rather cold spell of weather in April at the field test site in Krommenie in the Netherlands.

The performance differences at low demand are striking and to have a better understanding, both fig. 7 and 8 resp. show the usage of heat pump and gas boilers for three consecutive days during the same type of season and comparable amount of daily heat delivered to the apartments ranging from 380 - 430 kWh for both systems operating. For the gas boilers a value between 0 and 1 denotes the burn ratio. The outdoor temperature varied from 7 till 10 ºC at night to 18 ºC at daytime.

When the centralized system is operating, during the night both the gas boiler and the heat pump turn on simultaneously. Such a behavior is not observed when the HeatMatcher is operating; it can also be seen that the second stage of the heat pump is turned on regularly when centrally controlled, whereas just the first stage is used by the Heatmatcher. Taking into consideration that these are not very cold days with low request of heat, it would be expected that the power supplied by the heat pump would be sufficient for heating.

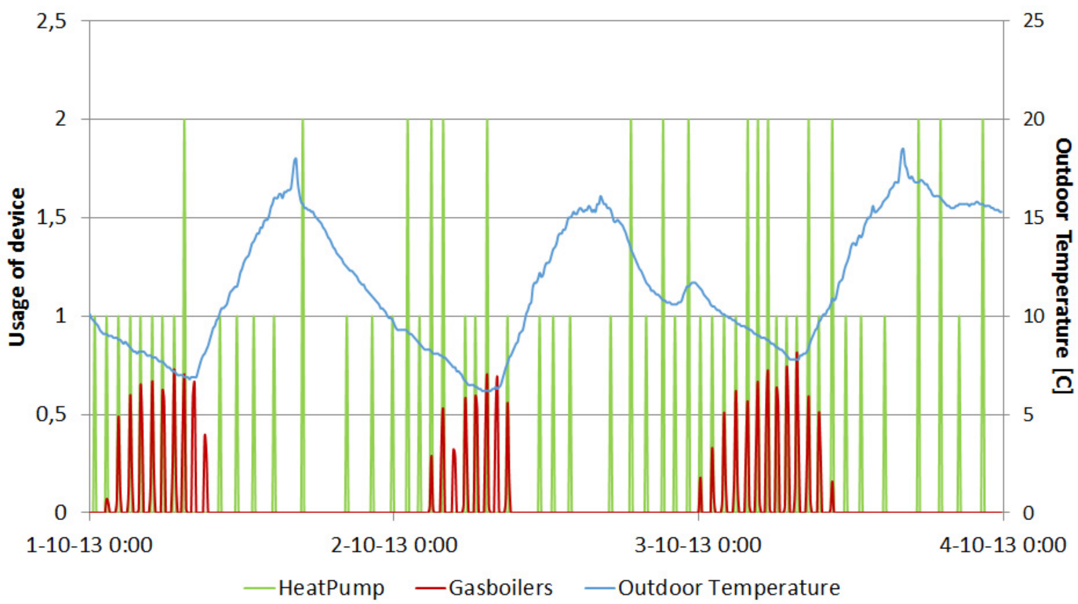

Fig. 7. The usage of the heat pump and the gas boilers with centralized operation on three consecutive days in October 2013.

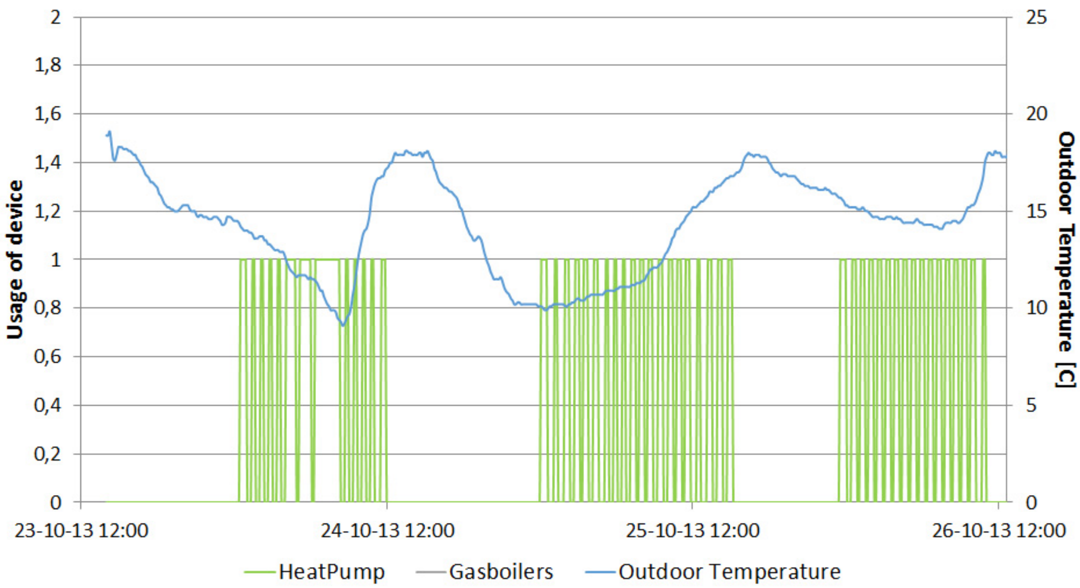

Fig. 8. The usage of the heat pump and the gas boilers on three consecutive days in October 2013 with HeatMatcher at similar outdoor temperatures and daily heat demand as when operated with the centralized energy management system

2.1. Discussion of results

Fig. 7 and 8 show the operation of the installation run by the centralized system and the HeatMatcher resp. at comparable daily heat demanded and small difference of outdoor temperature alteration. The behavior of the HeatMatcher is more energy efficient and beneficial for the lifespan of the installation as the gas boilers are kept turned off and the heat pump is operated at one stage for a longer duration of time.

This is remarkable as from rom the simulation results merely a slight improvement of performance is expected. An explanation would be that this is forthcoming the vulnerability of centralized management systems towards unexpected behavior.

As already mentioned in [9] it was observed that the flow of the buffer can be larger than the flow to the houses, resulting in a hot water flow to the bottom of the buffer, raising the buffer bottom temperature. This is clearly the case for the days studied here, the heat demand is low resulting in a small flow of water to the apartments during daytime. When the gas heaters turn on, extra flow occurs and the presence of the plenum in the installation causes even more hot water to flow into the buffer. As agreed by the system's operators this flow was stronger than expected, which is a challenge for both systems. The centralized system is rule based and apparently is not designed to cope with this unexpected behavior, whereas the HeatMatcher's agents seem more capable coping with this reverse water flow.

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