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INTELLIGENT HEATING SYSTEMS IN HOUSEHOLDS FOR SMART GRID APPLICATIONS

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ABSTRACT: To realize smart grids, there is a need for flexible supply and demand of electricity. Conventional heating systems in the Netherlands are based on gas, but new innovative systems, such as heat pumps and micro-CHPs, consume or produce electricity. If the demand for heat and the production/consumption of electricity is decoupled by using a hot water buffer, these heating systems provide the flexibility needed in smart grids. Using ECN's PowerMatcher technology, this is being demonstrated in a field-test in the Netherlands within the European project INTEGRAL.

INTRODUCTION

The incorporation of heat buffering for domestic hot water and spatial heating provides the means to have flexibility with electricity supply and demand in a smart grid. Such a heat buffer partially decouples the heat production from the heat demand. Electricity production or consumption by heating systems can then be optimized for the grid, without the comfort of the household being infringed. In such a way, a cluster of heating systems, commonly known as a virtual power plant (VPP), can reduce the power imbalance of the trader's portfolio or help the grid operator with congestion management at the local level.

In the European project INTEGRAL, normal, critical and emergency operational management of future Smart Grids is studied in order to define a common information technology and communication infrastructure to serve these grid conditions. The field test concerning normal operation circumstances is being conducted in a suburb of the city of Groningen, the Netherlands. Here, the concept of intelligent heating systems is being demonstrated using the PowerMatcher technology (http://www.powermatcher.net; www.powermatchingcity.nl).

The PowerMatcher is a multi-agent based system using an electronic exchange market to coordinate a cluster of devices with the objective of matching electricity supply and demand (Kok 2005, Hommelberg 2007). Its concept has already been demonstrated in a number of smaller field-tests and simulations (Roossien 2009, Warmer 2007). Every flexible device is equipped with a *device agent*, a piece of software that delegates the interests of the device and trades on an electronic market. Such agents attempt to operate the associated processes in an economically optimal way, whereby no central optimization algorithm is necessary and communication with the *auctioneer* (i.e. electronic market) is limited. The only information that is exchanged between the agents and the auctioneer are bids as shown in figure 1. These bids express to what degree an agent is willing to pay or be paid for a certain amount of electricity. Bids can thus be seen as the priority of a device to turn on or off. As a response to these bids, the market clearing price is returned to the agent. The device agents react appropriately by either starting to produce (or consume), or wait until the market price or priority of the device changes.

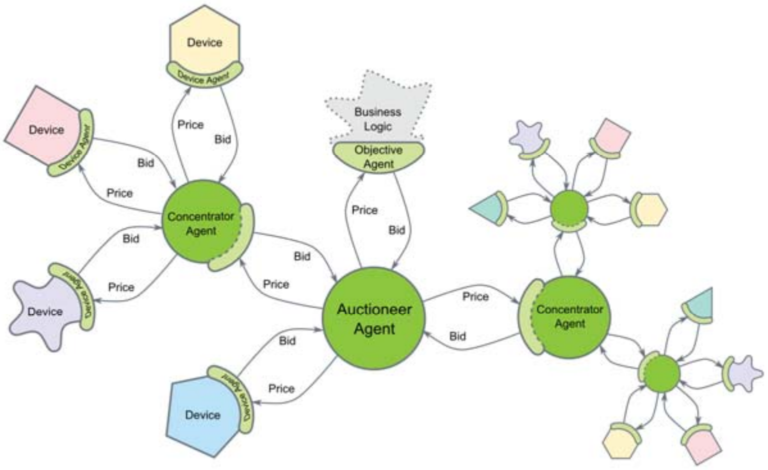

Figure 1: Schematic drawing of the PowerMatcher technology.

HEATING SYSTEMS

Twenty-five common households are participating in the field test. For these households, two types of heating systems have been designed by KEMA. Twelve houses have got a small combined heat and power unit (micro-CHP). The other thirteen houses got an electric air-water heat pump together with an external high efficient gas fired heater.

The micro-CHP unit uses gas to produce heat and electricity at the same time. It has an electric and thermal power output of respectively 1 kW and 6 kW, both of which cannot be modulated, i.e. it is on or off. Additionally, it has an internally gas fired heater that can boost up the thermal power output with another 6 kW. This auxiliary gas heater can run independently from the micro-CHP. To decouple the production of heat and electricity, the micro-CHP is connected to a 210 liter hot water buffer as shown in figure 2. The top section of the buffer holds approximately 90 liters of hot water with a temperature between 60 and 80 °C and is primarily used for hot tap water. This tap water is taken directly from the top of the buffer, without the use of a heat exchanger. The buffer is replenished from the bottom with cold water of about 10-15 °C. The bottom section of the buffer holds the other 120 liters of water and its average temperature can range between 10 and 60 °C. It is used for space heating and, as opposed to the tap water, the heat can only be extracted using the heat exchanger. The top and bottom halves of the buffer can both be heated either independently or simultaneously.

The second heating system uses the same type of hot water buffer to disconnect the consumption of electricity from the production of heat by the heat pump. This heat pump is used for space heating only, because it cannot reach high temperatures (>45 °C) without a significant drop in its coefficient of performance (COP). Therefore, the heat pump only heats up the bottom section of the buffer as shown in figure 3. Depending on the outside temperature, this section can reach temperatures between 35 and 45 °C. If the outside air temperature is below freezing point, the COP of the heat pump is too low to use it efficiently. In such situations, the external high efficient gas fired heater of 14 kW is used. Note that on average the Dutch daily mean temperature in the mid-winter season (Jan/Feb) is just above freezing point. The gas fired heater is also used to provide all of the tap water.

Monitoring and direct control of the heating system is done by a custom-designed PLC (Crouzet) connected to the heating device control system. It ensures that comfort in the houses is maintained and that the system operates safely. The PLC monitoring systems, such as the temperature in the buffer sections are available externally. Additionally, a command can be send to the PLC stating the desired temperature for the bottom section of the buffer. A PowerMatcher agent has been interfaced with the PLC to make intelligent use of the available flexibility provided by the hot water buffer. The agent can obtain the monitoring signals from the PLC, from which it can calculate the optimal desired temperature for the bottom section of the buffer. Ultimately, the decision to implement the desired temperature command lies with the PLC and therefore, installs a barrier to ensure customer comfort and system safety and security is never hindered.

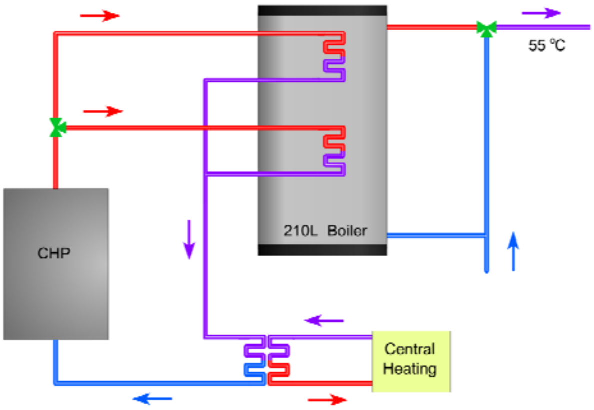

Figure 2: Hydraulic schematic of the CHP heating system with hot water buffer.

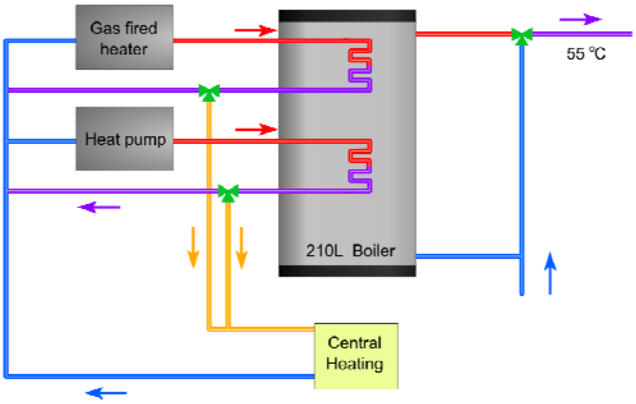

Figure 3: Hydraulic schematic of the hybrid heat pump heating system with hot water buffer.

INTELLIGENT UTILIZATION

PowerMatcher agents always bid against the marginal costs of the device they represent. However, as opposed to e.g. a diesel generator, the marginal costs of most distributed energy resources highly depend on local context and thus, change over time. Hence, the marginal costs for a CHP depends on the amount of heat demand: if the heat demand is high, the marginal costs for electricity production are low and vice versa.

The local control goal of the agent is to keep the buffer temperature within its thermal limits T_{min} and T_{max}. Hence, the buffer level is defined as:

$$L = \frac{T - T_{min}}{T_{max} - T_{min}}$$

A minimum and maximum buffer level L_{min} and L_{max} can be defined, which do not necessarily have to be 0% and 100% respectively. The need for these levels can be found in the delayed response of the devices. For example, it takes approximately 5-10 minutes after the micro-CHP has started before it can deliver heat. Similarly, the micro-CHP still produces heat after it has been stopped due to its high thermal mass. The defined buffer levels ensure that user comfort is always maintained and valuable heat is not lost. Additionally, these levels can be changed by the agent if it e.g. knows there will be a large demand for heat in the near future, although this has not been implemented in this field-test yet. The flexibility of the heating system lies within these buffer levels. The optimization strategy the device agent follows has been described by Kok. (Kok, 2009). The buffer level flexibility is mapped onto the expected price range, which is bound by the minimum and maximum price c_{min} and c_{max}. A linear mapping, as shown in figure 4, is used in this field test. However, many other mappings are possible, depending on how low or high a risk one wishes to take.

The marginal costs for the CHP can be calculated from this mapping $M : l \mapsto c$. Suppose the buffer has a fill level L which maps into a marginal cost C. The CHP will only turn on if the market price c* is higher than its marginal costs, i.e. the CHP will only offer power to the market if $C \leq c^*$.

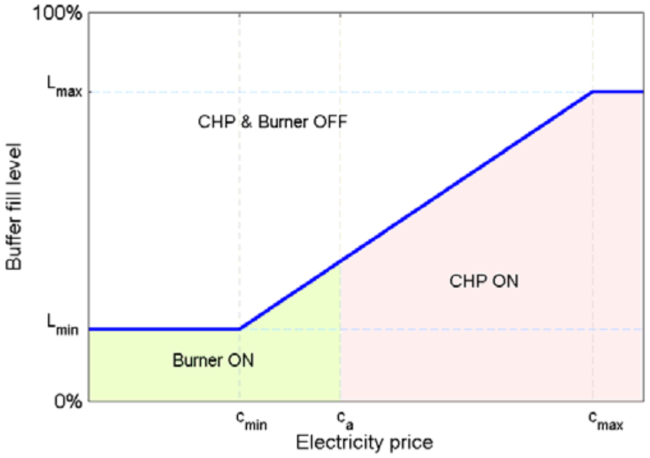

Figure 4: Desired buffer level as function of the market price for a CHP heating system

The determining factors of whether the micro-CHP or auxiliary gas burner will be utilized to heat the buffer are that of the marginal costs of each device. The break even point c_a of the micro-CHP hybrid system is given by

$$c_a = c_g \left[\frac{1}{\eta_a} - \frac{1}{\eta_{th}} - \frac{G_s}{P_{th} t_{min}} \right] \left[\frac{E_s}{P_{th} t_{min}} - \frac{\eta_{el}}{\eta_{th}} \right]^{-1}$$

where η_a is the efficiency of the gas burner, η_{th} and η_{el} are the thermal and electric efficiency of the CHP, G_S and E_s are the gas and electricity consumed by the CHP during start-up, P_{th} is the average thermal power output in normal operation and t_{min} is the minimum time the CHP must operate, excluding the start-up or cool down time. It is assumed that the price of gas c_g is constant and that the start-up costs are paid back within the minimum run time period. Using Dutch gas prices as a reference, $c_a \approx$ € 0.08. If $C < c_a$ then the gas burner is used instead of the CHP and no power is offered on the electricity market.

A similar mapping is used for the hybrid heat pump system, but because the heat pump consumes electricity instead of producing it, the curve moves from (c_{min}, L_{max}) and (c_{max}, L_{min}). The marginal costs for which utilizing the gas burner is economically more favorable is

$$c_a = \frac{\mathrm{COP}}{\eta_a} c_g$$

where COP is the coefficient of performance of the heat pump. The gas burner will be used instead of the heat pump if $C > c_a \approx$ € 0.30.

PRELIMINARY RESULTS

A first test with the CHP heating system was conducted using a sine price profile with a period of 12 hours. The CHP was located in a laboratory, but a common Dutch heat demand profile for space heating and tap water was used to remove heat from the hot water buffer. In this test, the decision making with the c_a was not yet implemented. As mentioned previously, the command from the device agent to the PLC is based on the current market price in the form of a desired fill level. As is shown in figure 5, the desired fill level sent by the agent, follows that of the market price, which corresponds with the linear mapping as described in the previous section. During periods with high market prices, the desired fill level is increased, causing the micro-CHP to fill the buffer and generate electricity. Alternately, the home demand utilized the heat within the buffer during periods of low market prices thus deferring the startup of the micro-CHP to a more economically beneficial period.

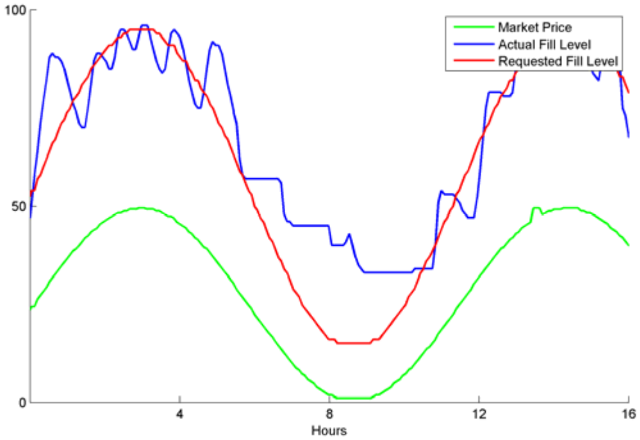

Figure 5: Test results for the micro-CHP using a sine-wave for the market price.

CONCLUSIONS

It has been discussed that innovative residential heating systems with cheap hot water buffers can decouple the demand for heat and the consumption and generation of electricity by these systems. Furthermore, the PowerMatcher technology enables the utilization of this flexibility within a smart grid without the comfort of the end user being infringed or the safety of the heating system being compromised. The first test results are promising and later this year, these 25 smart homes will demonstrate the true potential of a smart grid in for several business use cases.

ACKNOWLEDGEMENTS

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