Multi-agent control for integrated heat and electricity management in residential districts

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ABSTRACT

For the built environment it is envisaged that in the next decades the total annual energy demand, both thermal and electric, could be covered by renewable sources generated within the built environment. More and more thermoelectric elements, such as heat pumps and thermal storage, will enable conversion from heat to electricity and vice versa. Control in this environment therefore requires an integral management of both heat network and the electricity network. In this paper we present of a market-based multi-commodity algorithm for integrated coordination of electricity and heat flows at the residential district level. The algorithm is an enhancement of the PowerMatcher concept for electricity alone and inherits its advantages such as scalability and user autonomy. Some examples are given to demonstrate the usability of algorithm in residential areas to unleash a large flexibility potential of heat and electricity flows in support of the integration of renewable energy.

Categories and Subject Descriptors

I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence – *intelligent agents, multi-agent systems*.
J.2 [**Computer Applications**]: Physical Sciences and Engineering

General Terms

Algorithms, Management, Economics.

Keywords

Multi-agent systems; distributed control; renewable energy; market-based control; smart grids; domestic heating.

1. INTRODUCTION

For the built environment it is envisaged that in the next decades the total annual energy demand, both thermal and electric, could be covered by renewable sources generated within the built environment [1]. A typical future residential area may have solar and wind electric power complemented with renewable heat provided by biomass-fired plants and solar collectors, or efficient heating systems such as heat pumps (HP) or combined heat and power (CHP). Additionally, heat and electricity storage facilities may be available. Especially if energy systems are used in which heat and electricity are strongly interconnected (e.g. HP, CHP), fluctuating supply by renewable electricity sources may, partly, be balanced by the flexibility within the heat system. Optimization of residential energy flows therefore requires an integrated management of heat and electricity.

Having a substantial amount of renewable energy sources (RES) in a distributed setting requires such systems to be connected in an intelligent and more dynamic way than today. Optimizing the operation of the integrated power and heat infrastructure requires access to operational context 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.

Intelligent agents for the optimization of energy systems have been in study for quite some time. However these studies do take into account only one commodity at a time. Agent based heat flow management has been the subject in (Huberman & Clearwater [2]; Ygge & Akkermans [3]; HeatMatcher [4]; Wernstedt [5], Lacroix et all [6]). Different authors also defined multi-agent systems for distributed electricity management. A number of these studies propose the use of electronic equilibrium markets as the core coordination mechanism. The PowerMatcher [7], a market-based control concept for coordination of demand and supply of electricity, stands out for its elegance and flexibility of use. For one, it can take into account heat as a means to store electricity through use of thermal buffers (1st Trial, [8]).

In the PowerMatcher concept an agent expresses to what degree it is willing to pay or be paid for a certain amount of electricity using demand and supply bids. A bid contains the flexibility of a device to run at a certain power rate. 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. The PowerMatcher has proven itself to be a powerful demand response algorithm for electricity networks. In this paper the PowerMatcher concept is used as an outline for the development of a multi-commodity algorithm for integrated control of heat and electricity by including the heat network into the control.

Since heat is of a different nature than electricity both the locality of the heat and the potential time delays between heat production and consumption need to be addressed, as well as the routing of the heat (i.e. the control of pumps and valves). For the first issue a solution is given in this paper to deal with locally available heat supply. The latter issues are part of future research..

2. SETTING THE SCENE

As a first step in the development of the multi-commodity optimization method we consider a residential area in which heat supply is restricted to a single, centralized, heat network. In this network heat flows from centralized producers to consumers in order to meet any demand in the whole area. Heat production may be integrated with electricity usage or production as in a HP or CHP unit. The electricity network is not restricted; electricity can flow from any location to any other location within the electricity grid. The multi-commodity control algorithm aims at simultaneous optimization of the heat and electricity flows based on the availability and cost of heat and electricity supply and the flexibility of the energy demand.

In section 5 the restriction on the heat network will be abated by allowing local heat networks with local heat supply to be part of the heat network. We assume in all cases a one way heat flow: heat can be supplied from the central network to the local network but not vice versa. Consequently, a home or building having its own heat supply will not be able to deliver heat to any of its neighbors. Yet any building can take heat from the central network.

The multi-commodity algorithm will be implemented in a simulation tool that can be used as a planning tool in the development of sustainable districts with a large share of renewable energy. The final goal of the algorithm is its application as a control mechanism in real world residential areas in order to ensure optimal energy management. By using the PowerMatcher concept as an outline we will profit from its simplicity in architecture (see Figure 1) and advantages in application, such as customer autonomy, scalability and flexibility.

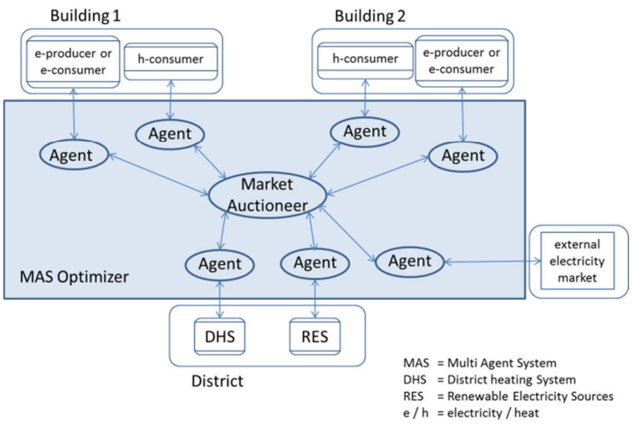

Figure 1. Single market configuration of a heat and electricity network on district level, where agents representing devices communicate with a single auctioneer. Arrows represent the flow of information.

In Figure 1 the architecture is given for the multi-commodity multi/agent system. Each building has its own heat demand (*h-consumer*) and a number of electricity consumers and producers (*e-consumer, e-producer*). These consumers and producers are represented by *agents* in the energy market. Similarly agents represent the district heat system (*DHS*), which may contain multi-commodity devices such as a heat pump or a CHP unit, potential renewable electricity sources (*RES*), such as wind power, and the *external electricity market* (to allow electricity import to and export from the district). A *market auctioneer* aggregates all bids from the agents and determines the market clearing price, which is communicated back to the agents.

3. MULTI-COMMODITY ALGORITHM

The basic multi-commodity algorithm will be discussed using the example of a simple, yet representative, heat network consisting of a heat pump (HP) and a combined heat and power unit (CHP), providing heat to a building (HD), as illustrated in Figure 2. An external electricity market (Ext.E) is connected, either as supplier of electricity (to the HP) or as consumer (to the CHP). For simplicity of demonstration electricity demand from the household itself is not considered in this example.

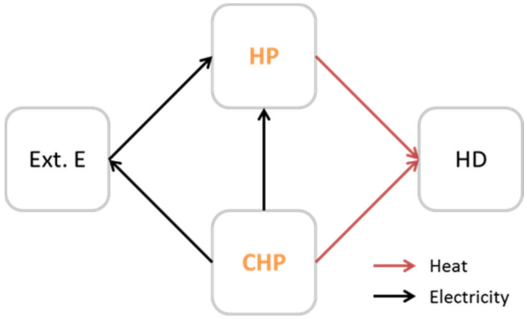

Figure 2: Example configuration. Arrows represent the flow of energy.

For an overview of the PowerMatcher concept the reader is referred to [7]. The algorithm described here differs from it in that it simultaneously matches supply and demand of electric and thermal energy. Besides single-commodity software agents also multi-commodity agents, representing the heat pump and the combined heat and power unit, act on a simultaneous electricity and heat market.

3.1 Multi-commodity Demand and Supply

The electric and thermal power bids of a multi commodity device depends on both the electricity market price p_E and the heat market price p_H. Therefore, we define two bid surfaces for every multi-commodity agent: $P_i^E(p_E, p_H)$, the electric power to be consumed (positive) or produced (negative) at electricity price p_E and heat price p_H; and $P_i^H(p_E, p_H)$, the thermal power consumption or production at these prices (i the index of the device). Prices are taken as €/kWh. Note that there is a direct relation between $P_i^E(p_E, p_H)$ and $P_i^H(p_E, p_H)$, based on the device ratio of electricity and heat.

For a heat pump it is profitable to operate if the benefits from heat production are higher than the cost of electricity. In equation form:

(1) $$p_E \leq p_H * COP$$

where COP is the coefficient of performance of the heat pump. This is illustrated in Figure 3 in which a modulating heat pump is taken with a COP that increases from 2 to 3, depending on the power output. Note that supply is represented by negative numbers.

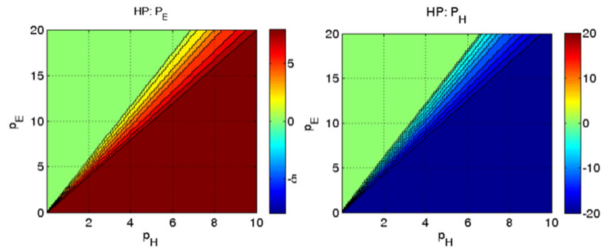

Figure 3: Electrical power bid surface (kW_{el}, left) and thermal power bid surface (kW_{th}, right) of a heat pump. The x-axis represents the heat price, the y-axis the electricity price. The colors represent the amount of power the heat pump is willing to produce as a function of heat and electricity price.

The CHP is profitable if the marginal cost (c_m) for the fuel (in €/kWh) is covered by the total selling price for heat and electricity. Having thermal and electric efficiencies ε_H and ε_E this leads to the following equation:

(2) $$\varepsilon_H * p_H + \varepsilon_E * p_E \geq c_m.$$

Taking $\varepsilon_H = 0.5$ and $\varepsilon_E = 0.1$ and assuming a marginal cost increase from 2,4 to 3,6 this leads to bid surfaces as depicted in Figure 4.

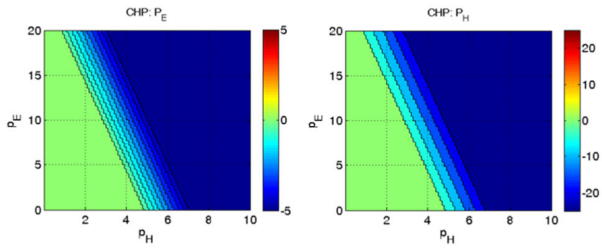

Figure 4: Electrical power bid surface (kW_{el}, left) and thermal power bid surface (kW_{th}, right) of a CHP device. The x-axis represents the heat price, the y-axis the electricity price.

Assume an external electricity market that is willing to buy electricity if $p_E \leq 5$ and to supply electricity if $p_E \geq 15$. This external market provides two boundaries on the district market's electricity clearing price, which will always be between 5 and 15.

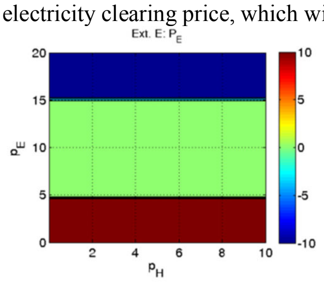

Figure 5: Bid from the external electricity market

For simplicity the building heat demand is set to a constant of 15 kW_{th}, leading to a flat bid surface. No electricity demand from the households assumed other than the heat pump.

3.2 Aggregate Bid Surfaces and Determine Equilibrium

Aggregating the different bid surfaces for electricity, $\sum_i P_i^E(p_E, p_H)$, and similarly for heat, $\sum_i P_i^H(p_E, p_H)$, leads to two aggregated bid surfaces. For the electricity bid surface an equilibrium line can be found (note that supply is defined as negative demand):

(3) $$\sum_i P_i^E(p_E, p_H) = 0.$$

Similarly an equilibrium line can be found for the heat bid surface:

(4) $$\sum_i P_i^H(p_E, p_H) = 0.$$

Note that, if the bid surfaces are continuous and strictly descending or ascending, equilibrium lines are formed that give a unique equilibrium. If the bid surfaces are non-strictly descending or ascending, then equilibrium surfaces may exist and additional criteria may be formulated to determine an optimal equilibrium price (p_E, p_H). A short discussion can be found in section 3.4.

3.3 Example Equilibrium

For our example the aggregated bid surfaces, based on Figure 3 to Figure 5, are given in Figure 6. The equilibrium lines stand out in white.

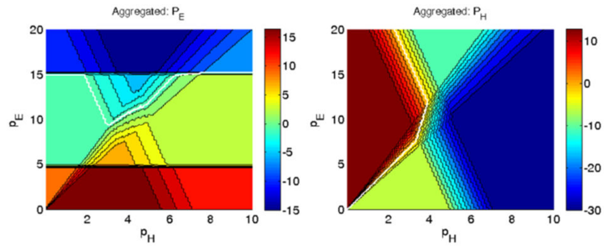

Figure 6: Aggregated electrical power bid surface (left) and aggregated thermal power bid surface (right). The solution lines are shown in white

The equilibrium, at which both electric power and thermal power supply and demand are in balance, is found at the intersection of both solution lines, which is shown in Figure 7.

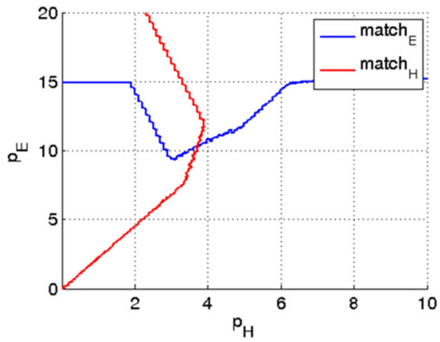

Figure 7: Equilibrium for electricity (blue) and heat (red)

The corresponding market electricity and heat clearing prices are 10.30 and 3.66, respectively. The allocated electric and thermal power of all 4 agents corresponding with these market clearing prices are indicated in Table 1. The solution is (almost) exact, as the bid surfaces are defined to be continuous.

Table 1: Allocated electrical power P_E and thermal power P_H for all 4 agents in the example configuration

Agents	Allocated P_E(in E units)	Allocated P_H (in H units)
HP	1.90	– 5.52
CHP	– 1.90	– 9.48
Ext. E	0.00	n/a
HD	n/a	15.00

Note that in the example the CHP and the HP balance each other with respect to electricity. If other electrical components are added to the configuration, such as fluctuating wind and solar power and flexible electricity consumption, it is expected that, based on a more variable electricity price one of these devices is preferred over the other.

3.4 Mathematical Notes

Although the previous section describes the base multi-commodity algorithm, the mathematical implementation differs from the approach given in equation2 (3) and (4) and Figures 6 and 7. Instead of (3) and (4) we have implemented the following equation to find an equilibrium:

$$(5)\qquad (p_E^*, p_H^*) = \arg\min_{(p_E,p_H)} \alpha_E \left(\sum_i P_i^E(p_E,p_H)\right)^2 + \alpha_H \left(\sum_i P_i^H(p_E,p_H)\right)^2,$$

where (p_E^*, p_H^*) are the equilibrium prices and parameters $\alpha_E, \alpha_H > 0$. If a minimum of *0* is reached this results in a complete balance for electricity and heat. If no equilibrium can be found, the formula guarantees that 'a best possible match' is found. The parameters α_E and α_H can be used to give preference to electrical balance ($\alpha_E > \alpha_H$) or thermal balance ($\alpha_H > \alpha_E$). Standard choice will be $\alpha_E = \alpha_H = 1$.

If all bid surfaces are convex, a unique solution for (p_E^*, p_H^*) exists. However, in some cases non-unique equilibrium lines will occur (i.e. equilibrium surfaces). In these cases it may be arbitrary which solution is favored. One choice may use a norm minimization in order to find the 'lowest price combination' for heat and electricity.

4. APPLICATION OF THE ALGORITHM

The multi-commodity algorithm is developed to be able to control the energy flows in large districts with hundreds of homes, commercial buildings and small industries. The energy network may contain renewable local production, such as wind and photovoltaic (PV), co-generation systems for heat and electricity, flexible storage systems for electricity, e.g. through electric vehicles, and for heat, e.g. tank storage, aquifers and long term thermo-chemic storage. The algorithm also can take into account flexible energy demand, both through load shifting and by making use of available buffers. The large numbers of nodes in such a network require the scalability as provided by the distributed algorithm. The algorithm also provides autonomy on the user side, as its demand functions can take into account the constraints for the user's primary processes.

In this section we demonstrate the multi-commodity algorithm in a simple setting, by extending the example from above with additional renewable power from wind and PV. The main goal of the example is to demonstrate that the control algorithm indeed gives the expected incentives to the CHP and the heat pump based on available renewable electricity.

In the example one home is modeled with a fixed electricity demand profile and heat demand profile. In the home heat is provided by a CHP unit (max 2.5 kW_{th} and 0.833 kW_{el}) and a heat pump (max 2.5 kW_{th}, with a COP between 2 and 3, linearly depending on heat production). Electricity is provided by a residential wind turbine (5.8 kW peak) and PV installation (average 3000 KWh annually). If needed, electricity can be imported from or exported to the main grid. All data used are based on real world data.

The example has been run in the simulation environment developed in work package 4 of the EU e-hub project [9]. The simulation tool dynamically calculates the energy flows in a predefined heat and electricity network based on the intelligent control of the large numbers of energy nodes as described earlier in this section.

4.1 Simulation Results

Running the simulation for one week provided us with the following insights.

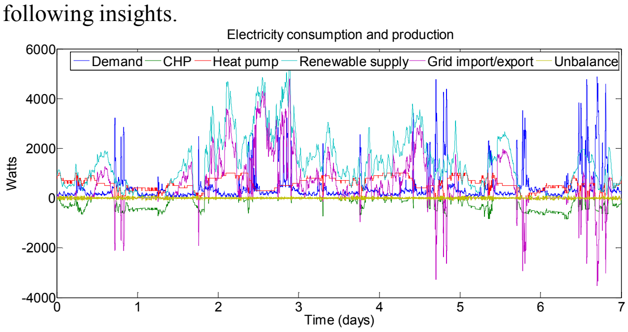

Figure 8: Electricity balance. The home's electricity demand is given by the blue line, renewable electricity supply by the light blue line; the dark green line denotes the CHP electricity supply and the red line the heat pump electricity demand; the purple line gives the imported/exported electricity from/to the main grid. Note that negative power means import.

In Figure 8 the electricity balance is given. The CHP unit produces electricity in periods of low renewable supply and in periods of high electricity demand from the home, requiring import from the main grid. This corresponds with relatively high electricity prices. As expected the algorithm gives preference to the CHP in these cases and to the heat pump at other times.

The electricity balance itself is maintained very well as denoted by the olive colored line that almost coincides with the x-axis.

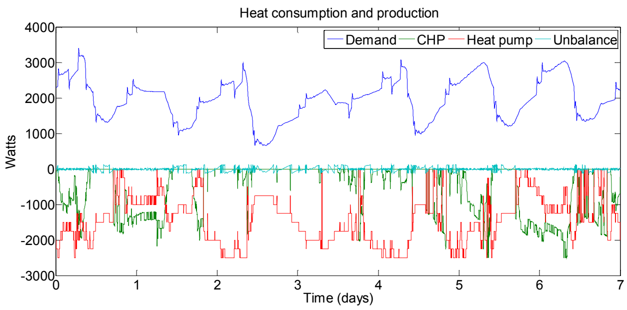

Figure 9: Heat balance. The home's heat demand is given by the blue line; the green line denotes the supply by the CHP unit, the red line the supply from the heat pump

In Figure 9 the heat balance picture confirms the conclusions from Figure 8. At most of the time the heat demand is covered by the heat pump running on renewable electricity. The CHP is used in periods when the building electricity demand exceeds the available sustainable electricity, generated by wind and sun, and in periods with low renewable electricity. The heat balance itself is maintained very well as denoted by the cyan colored line close to the x-axis.

In the example the control is driven by the fluctuations in renewable electricity production and in demand for heat and electricity. When less electricity is produced by wind and PV, or a high household demand is required, the electricity price will get higher. This will give an incentive for the CHP to switch on, leading to a lower heat price, and for the heat pump to switch off. If the CHP is not able to satisfy the total heat demand, the heat pump will be switched on again at a higher heat price. Looking closely to the price development in Figure 10 these effects can indeed be seen in the Figure 8 and Figure 9.

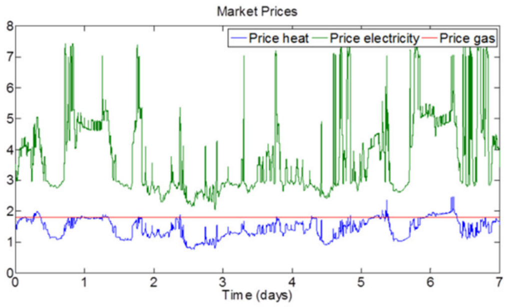

Figure 10: Market price development for heat (blue line) and electricity (green line)

Some remarks can be made for this example. First, the balances in Figure 8 and Figure 9 are not exactly zero due to discretization of the bidding surfaces. Also we did not use the flexibility of the heat demand from the home by utilizing its internal heat capacity, neither flexible power other than the CHP and heat pump. It is expected that adding these flexibilities to the model will improve the results, e.g. import from and export to the main grid may be reduced more. Furthermore, a residential installation including both a heat pump and a CHP is an unusual layout. The combination was simply selected to highlight different operating modes of the installation.

5. MULTI-LEVEL HEAT SUPPLY ALGORITHM

In the previous sections a centralized heat network was considered. In this section we go one step further and consider the situation in which heat may be generated in multiple heat networks. A typical district configuration may exist of a central heat network for all buildings and a number of local heat networks within buildings that can deliver local heat inside the building, but not to neighboring buildings. The heat supply cannot simply be aggregated at the district level, since not all heat supply flows can be matched with all heat demand. In general one building's heat supply system is not able to deliver its heat to a neighboring building. Note that there is no restriction for the electricity network: electrical energy can be transported instantaneously and without losses from any location to any other location.

For such a configuration the architecture in Figure 1 is enhanced in Figure 11 by allowing *multi-commodity devices* to provide heat inside a building, next to other *producers* or *consumers* of heat and electricity. Each building device is represented by an *agent* at a so called *energy hub*, a home gateway that prevents the heat supply bids to be transferred at the central market. Mathematically this can be done by a bid transformation at the energy hub, as shown in the next section. Based on a home match and a central market match the energy hub then can derive whether local heat supply or central heat supply is preferred.

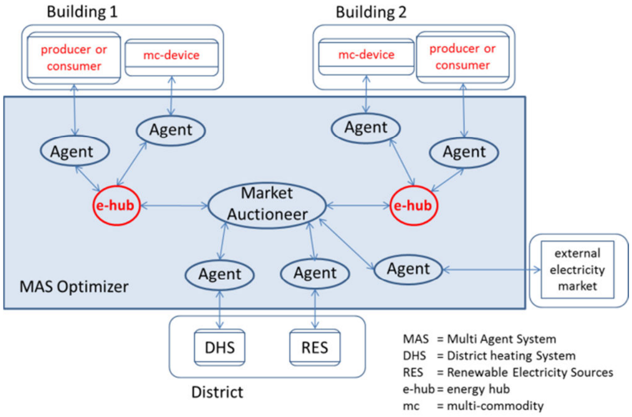

Figure 11: Multi-commodity algorithm – heat network on multiple levels, i.e. district and home level

The energy hub in Figure 11 has a similar function as a concentrator in the PowerMatcher architecture: it aggregates the home bids and implements bid transformations to keep the home supply bid local. It also implements a home market that weighs the local supply bid against the outcome of the central market.

5.1 Case for Single Heat Commodity

In this section we simplify the model by looking only at the heat commodity. In a first step, the local heat market is satisfied by matching heat on dwelling level, at the energy hub. The outcome is shown in the left part of Figure 12 for one building.

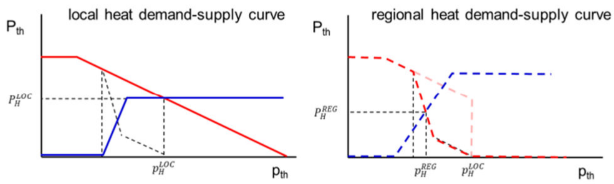

Figure 12: Handling of bid transformation from local market to regional market. The red line denotes the local heat demand (left) and the transformed local heat demand (dashed, right), while the blue line denotes the local heat supply (left), and the regional heat supply (dashed, right) resp.

The local equilibrium inside the building is reached at a heat price of p_H^{LOC}. Since any price from the regional market higher than this p_H^{LOC} will not be accepted by the building (it will prefer heat from the local market at a lower price), the demand curve to be sent to the regional market can be cut off at p_H^{LOC}. The cut-off can be done in two ways. Either the cut-off takes into account partial local supply for prices lower than p_H^{LOC}, as denoted by the dashed line in Figure 12 on the right side. The actual demand bid transformation for the local demand from the building then is defined as $P^{H_{cut}}(p)$:

(6) $$P^{H_{cut}}(p) = \sum_i P_i^{H_{dem}}(p) - \sum_i P_i^{H_{sup}}(p) \quad \text{for } p \le p_H^{LOC}$$
$$P^{H_{cut}}(p) = 0 \quad \text{for } p > p_H^{LOC}$$

where $P_i^{H_{dem}}(p)$ and $P_i^{H_{sup}}(p)$ are the heat demand and supply bids at the local market on the energy hub. The index i denotes potential different local consumers and producers. Note that from the equilibrium it follows that

(7) $\sum_i P_i^{H_{dem}}(p) = \sum_i P_i^{H_{sup}}(p)$ for $p = p_H^{LOC}$

The second way to cut off the local demand is to make a complete cut-off at p_H^{LOC}, as depicted by the transparent dashed line in Figure 12. The demand bid transformation then becomes:

(8) $P^{H_{cut}}(p) = \sum_i P_i^{H_{dem}}(p)$ for $p \leq p_H^{LOC}$

$P^{H_{cut}}(p) = 0$ for $p > p_H^{LOC}$

Which cut-off version is chosen may depend upon local preferences. Partial cut-off leads to a lower final heat price and will be preferable to the local building.

The regional market auctioneer aggregates the transformed demand functions from all buildings, each with its own p_H^{LOC}, and matches them with the aggregated supply from the regional heat network. Note that the aggregated local supply is not sent to the auctioneer. The auctioneer determines a regional equilibrium at p_H^{REG} , as shown in Figure 12 to the right (for simplicity only one building is taken into the equation). If p_H^{REG} is higher than a building's p_H^{LOC}, the regional heating system will not provide any heat to this building (the building's aggregated demand is cut off for $p > p_H^{LOC}$) and the energy hub will implement the local equilibrium price of the building, which activates the local heat supply. If p_H^{REG} is smaller than a local building's equilibrium price, then the regional heating system satisfies (part of) the local heat demand of this building. The energy hub in the building may activate additional local heat at price p_H^{REG}, if the cut-off in equation (5) still leads to positive local demand.

5.2 Case for Multi-commodity

In the previous section the heat demand is considered in a single heat commodity setting. What will happen if electricity is integrated in this market as well? As in Section 3.2 we can create a heat equilibrium line that gives for each electricity price p_E the corresponding heat price $p_H^{LOC}(p_E)$ at which the local market is in equilibrium. As in Figure 12 the heat demand is not interested in supply from the central market at any heat price higher than $p_H^{LOC}(p_E)$ and it can cut off its demand bid surface to the right of the heat equilibrium line:

(9) $P^{H_{cut}}(p_E, p_H) = \sum_i P_i^{H_{dem}}(p_E, p_H) - \sum_i P_i^{H_{sup}}(p_E, p_H)$ for $p_H \leq p_H^{LOC}(p_E)$

$P^{H_{cut}}(p_E, p_H) = 0$ for $p_H > p_H^{LOC}(p_E)$

Bringing this cut-off bid surface to the central market we must anticipate that, if the local supply is activated, it may put an additional electricity bid on the market, either as demand (as for a heat pump) or as supply (as in CHP). The central market will have to take into account this additional electricity in order to find a market equilibrium. Therefore not only the cut-off heat demand has to be supplied to the central market, but also this additional bid for electricity. Since this bid is conditional to whether local supply will be activated or not, this electricity bid is only positive for the surface on the right of the heat equilibrium line.

(10) $P^E(p_E, p_H) = \sum_i P_i^{E_{cut}}(p_E, p_H)$ for $p_H \leq p_H^{LOC}(p_E)$

$P^E(p_E, p_H) = \sum_i P_i^{E_{cut}}(p_E, p_H^{LOC}(p_E))$ for $p_H > p_H^{LOC}(p_E)$

where $P_i^{E_{cut}}(p_E, p_H)$ is the electricity supply or demand that is co-generated or co-consumed with the cut-off heat supply $P_i^{H_{sup}}(p_E, p_H)$ in equation (9).

If the central market equilibrium price (p_E^{REG}, p_H^{REG}) is located in the cut-off area of the local demand surface, then the energy hub will activate local heat supply at the price level of (p_E^{REG}, p_H^{LOC}). Otherwise the central heat supply will be activated with optionally additional local heat supply. Again, if the system does not allow simultaneous delivery from local and regional sources, then the transformed surface will be completely cut off. Equations (9) and (10) still hold, except $\sum_i P_i^{H_{sup}}(p_E, p_H)$ and $\sum_i P_i^{E_{cut}}(p_E, p_H)$ are replaced by zero components.

5.3 Example Multi-level Heat Supply

At the time of writing of the paper we have not yet implemented the multi-level algorithm into the simulation tool. Therefore it is not possible to present an example scenario here.

6. DISCUSSION & CONCLUSIONS

A future low energy or even energy neutral building environment requires smart control of flexible energy demand and supply in order to balance the variability in power supply created by e.g. wind or solar power. Energy efficient technology such as heat pumps or (biomass fired) cogeneration units demonstrates that control of heat flows may be as important as the control of flexible power. Also efficient thermal storage in underground aquifers or in thermo-chemical materials has to be included into the equation. This paper shows the feasibility of a novel algorithm for integrated management of heat and electricity based on market-based control concepts that have already shown their value for electricity alone.

Heat has a different nature than electricity. Electricity supply can be considered as a copper plate. The simultaneousness of supply and demand is the main challenge, since these must always be in balance, location and time of supply is not important. For heat this is vice versa. Location of heat generation and the time delays between generation and consumption of heat need to be addressed. This paper gives a solution for the location aspect of heat supply. Time delays will be part of future research.

In order to apply the multi-commodity algorithm in a real-time control environment also the heat flow control has to be addressed. The routing of heat by pumps or valves, after a market equilibrium has been found, to ensure that produced heat is consumed at the right places, is already under study in the next phase of the e-hub project.

Commercial exploitation of the algorithm also requires adequate handling of market dominance of – typically – a relatively small number of heat suppliers in the building environment. Regulation may enforce suppliers to base bids on marginal cost, as shown in equation (2), or to derive heat cost from electricity prices as in equation (1). Commercial application also requires the development of intelligent agents that take into account external information such as weather forecast and that anticipate on user preferences. Also intelligent agents for heat storage systems need to be developed, both for short term and long term (seasonal).

7. ACKNOWLEDGEMENTS

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information streams are coordinated, and through which different forms of energy (heat, electricity, chemical, biological) can be converted between each other or stored for later use. The project takes into account new technologies for energy efficiency at district level such as co-generation systems and long term storage systems, most prominently thermo-chemic storage, and develops the smart control in order to optimize the different energy flows in residential and commercial districts. Pieter Meulenhoff was involved in the algorithm development. The Belgian research organization Vito coordinated the developments that led to the simulation environment used in this paper for validation of the algorithm.

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