A Market Mechanism for Energy Allocation in Micro-CHP Grids

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Abstract

Achieving a sustainable level of energy production and consumption is one of the major challenges in our society. This paper contributes to the objective of increasing energy efficiency by introducing a market mechanism that facilitates the efficient matching of energy (i.e. electricity and heat) demand and supply in Micro Energy Grids. More precisely we propose a combinatorial double auction mechanism for the allocation and pricing of energy resources that especially takes the specific requirements of energy producers and consumers into account. We describe the potential role of decentralized micro energy grids and their coupling to the large scale power grid. Furthermore we introduce an emergency fail over procedure that keeps the micro energy grid stable even in cases where the auction mechanism fails. As the underlying energy allocation problem itself is NP-hard, we derive a fast heuristic for finding efficient supply and demand allocations. In addition we show the applicability of this approach through numerica.

Keywords: Combined Heat and Power; Market mechanism; Double Auction; Combinatorial allocation

1 Introduction

Over the last years fossil energy prices were rising remarkably. E.g. the price for Crude oil increased from approximately 20 USD in 1995 to more than than 65 USD as of today [25] while the prices for other fossil resources evolved similarly [13]. On the one hand rising energy prices indicate the increasing scarcity of these resources and thus implicate a need for change in our energy consumption habits, on the other hand high prices foster the development of alternative technologies for energy generation. A study from Emerging Energy Research [16] states that today wind power technology already allows electricity generation at cost below those of conventional coal fired power plants if carbon penalties of more than 30 EUR per tonne are applied.[1] Similarly Krewitt and Schlomann [17] state that energy produced from renewable resources is already competitive if external cost are included.

Taking this ongoing change process as given one needs to determine the challenges that come along with this development. In particular the effects on the future energy generation and distribution infrastructures need to be addressed [6]. Traditionally energy generation is a centralized business, mainly because the required (fossil) resources were (and still are) available "on the spot" and central generation allows to exploit some economies of scale. Throughout the last years the development of new energy generation technologies fosters the utilization of renewable energy resources. But compared to large scale power plants, energy generation through photovoltaic systems, biogas plants or even windparks is (i) a much more decentralized and (ii) a much less predictable business. Thus this development puts a lot of pressure on the current energy distribution infrastructure. Our proposition to address this issue is to develop semi-autonomous micro energy grids that bind the distributed energy generation facilities to the local demands. The local netting of energy demand and supply inside a microgrid could already reduce parts of the randomness and thus should enable the microgrid to appear

[1] In May 2006 carbon prices in the European Cap-and-Trade System already reached 30 EUR per tonne of CO_2

as a rather predictable "citizen" in the large scale grid where it buys peak demands from the outside outside world and offers free generation capacities as balancing power to others. Furthermore a combined usage of heat and power inside the microgrid will increase the overall energy efficiency.

Besides difficulties in predicting and coordinating distributed energy supply, energy consumption forecasting – especially for private households – is problematic as well. This is mainly due to two reasons: On the one hand old metering technology limits readouts in practice to annual cycles, on the other hand flat fee tariffs (e.g. 18 Ct / kWh of electricity) do not set any economic incentives for consumers to shift energy consumption from peak hours to periods of low consumption. The result is that consumers use energy more or less "at random" while energy providers are more or less blind on the energy flows inside their low voltage distribution networks. At the same time it is known from field studies that about 50% of the private households' electricity consumption is dedicated to the operation of refrigerators, freezers, (water) heaters, washing mashines or dryers [24] and thus *could* follow – at least within certain boundaries – a planned schedule.

Our solution for addressing the aformentioned challenges is to develop combined heat and power micro energy grids (CHPMEG) that are "loosely" connected to the conventional large-scale power grid minimizing energy transmission losses while maximizing generation efficiency ratios. Within a CHPMEG energy producers and energy consumers trade their energy (i.e. heat and electricity) supplies and demands on local marketplaces. Arbitrage agents ensure that the resulting energy prices within the microgrid are levelled to those on external marketplaces such as the European Energy Exchange (EEX). As markets provide an efficient matching of demand and supply *on average*, a technical balancing mechanism (spinning reserve) complements the market mechanisms to ensure stable operation of the local energy grid, even in those cases where the market-based allocation might fail without compromising the economic incentives set by the markets. The work presented in this paper is part of the project *"Self-organization and Spontaneity in Liberalized and harmonized Markets"*[2] (SESAM). The main focus of the project ist to develop an electronic energy market platform that also features mechanisms for secure and non repudiable communication between the market participants, permits the utilization of electronic trading agents and provides an electronic law mediator who supervises the electronic contract making on the platform[8]. In this paper we focus on the hybrid control mechanism for CHPMEG that is developed as part of this project. The applicability of our approach is demonstrated through numerica. The remainder of this paper is structured as follows. Section 2 describes the typical setup of a CHPMEG and describes the importance and role of energy markets within the microgrids. Based on this several requirements for the operation of CHPMEG are deduced which serve as benchmarks for the literature review in section 3. In section 4 the formal market model is introduced along with a fast heuristic for implementation purposes. Section 5 concludes with an application case study and an outlook on future work.

[2]http://www.sesam.uni-karlsruhe.de

2 Motivational Scenario

In this section we describe an application for a market based micro CHP grid which typically consists of several components connected to each other trough heat pipes and power / communication lines. Usually five key components can be identified in a micro grid as shown in figure 1 [1, 18].

1. **Consumers** are private households and small business that require electricity and / or heat.
2. **Producers** are photovoltaic systems, heaters, micro-turbines, biogas plants, etc. They generate electricity, heat or both.
3. **Spinning Reserves** provide ad-hoc energy reserves that is used to stabilize voltage and frequency of the power grid. Battery banks or spinning wheels usually provide facilities for quick electricity storage and retrieval and thus serve as spinning reserves.[3] Heat-wise grid stability is not too critical, still therms can take over the role of heat regulators as they are able to temporarily store certain amounts of heat.

[3]Balancing power from the large scale grid can complement the migrogrid's spinning reserves. Still, distinct spinning reserves are oftentimes build into the micro grid as well in order to gain a certain degree of independence from power outages in the large grid.

4. The **coupling point** is the connection between CHPMEG and the large scale grid. At this point inbound and outbound power flows are metered and regulated.

5. The **controller** is the core of the CHPMEG. It is responsible for matching the consumer's energy demandy by dispatching appropriate generators for heat and / or electricity, i.e. it has to determine an optimal production schedule given the consumption requests.

Although figure 1 depicts consumers and producers as distinct entities these roles can switch dynamically. A household might generate and sell excess electricity from its own photovoltaic system during daytime while it might consume power during night time. We require all entities within a CHPMEG, i.e. producers, consumers and spinning reserves to be connected to the controller through power lines, local area network (LAN) and – where applicable – through heat pipes as well. Furthermore we assume that heat pipe and power line capacities are sufficiently dimensioned to meet all transmission demands that might occur.

As mentioned above, the central component of this microgrid is the Controller which determines energy production and consumption of all grid participants and ensures that (i) the electricity grid is always balanced in terms of voltage and frequency and (ii) the heat grid always provides at least as much heat as required, storing or disposing overproduction in therms. Furthermore the controller should provide incentives to consumers to shift their energy consumption from peak hours to time periods with low energy demands if possible. Likewise on the producer side the controller needs to determine an operation schedule that always favors the producer with the lowest production cost for generating the required energy. If e.g. a photovoltaic system and a microgas turbine are ready to produce power for the microgrid, the photovoltaic system will likely have comparably lower production cost during sunshine periods and thus should produce the energy saving the microturbine from burning gas.

This idea could be extended even further: The controller needs to make sure that not only the cheapest producers inside the microgrid generate the required energy but that the overall cheapest producers will take over this responsibility, i.e. if the spot market price for electricity e.g. at the EEX is lower than the marginal production cost of the most expensive currently running generator in the microgrid, it should be turned off and the electricity should be purchased from the EEX instead (and vice versa). The same procedure should be applied if – during peak hours – the local generation capacity is insufficient to meet the local demands. From a technical perspective is important to note that many generators, especially combustion engines are not able to operate at below certain load levels. Thus the CHPMEG controller hast to take minimum and maximum production constraints of the respective energy producers into account as well.

Finally the netting of energy demand and supply within the CHPMEG should reduce the randomness in energy production and consumption to the outside world. At best the CHPMEG is able to announce future energy shortages (or energy reserves) as early as possible to the outside world, making its behavior as predictable as possible.

In this section we collected several different requirements that CHPMEGs and especially the CHPMEG controllers should meet. These can be summarized as follows:

R1	Online Mechanism (instantaneous matching of demand and supply)
R2	Bundled allocation of electricity and heat
R3	Price signals to indicate scarcity
R4	Min and max. allocation constraints
R5	Stable operation (balanced demand & supply)
R6	Coupling with large-scale power grid
R7	Forecasts for demand and supply

In the following section we will review related approaches for realizing this control component before we introduce our market based controller in section 4.

3 Related Work

The idea to employ market mechanisms for distributed environments is not new. Since the 60s researchers have motivated the use of markets as a means to cope with incentival problems especially for distributed computing.

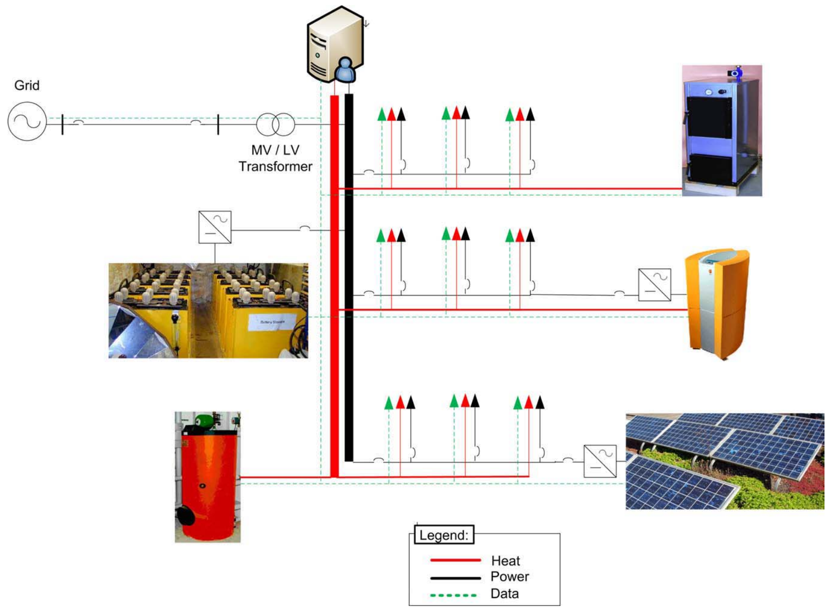

Figure 1: Schematic Layout of a Micro CHP Grid

But it was only recently that the idea of decentralization spilled over from computer grids to power grids [4, 10].

Also relatively new is the idea to use markets for the coordination of decentralized resources. Among the first, Buyya, Wolski et al. [5], and Subramoniam et al. [23] motivated the use of auctions and negotiations for Computational Grid. In their first paper, Wolski et al. [27] suggested the use of traditional auction formats such as English auctions. Eymann et al. [12] introduce a decentralized bargaining system for resource allocation. Regev et al. [21] propose the use of a Vickrey auction for allocation computational resources in distributed systems.

Although often suggested in literature, the effectiveness of traditional bargaining and auction systems in grid environments is conceivably delimited as the trading objects are traded as unbundled standardized commodities. Consequently, these auction formats fail to express demand on bundles – exposing especially owners of CHP generators to the risk of selling only e.g. electricity without selling the co-generated heat.

Reviewing the requirements upon the mechanism, it becomes obvious that the previous described mechanisms fail to satisfy these requirements. Most of the mechanisms proposed in literature do not meet the immediacy requirement in a way that they are either iterative in nature or NP hard to compute. Both properties rule out a use in highly interactive markets for different reasons. While iterative mechanisms are unsuited due to the fact that they frequent user feedback is needed, NP hard mechanisms consume too much time to be of use in large scale markets. Beside the requirement of immediacy, the negligence of capacity constraints for bids diminish the use of the proposed market mechanisms.

To account for predictability of the system time attributes, Wellman et al. model single-sided auction protocols for the allocation and scheduling of resources under consideration of different time constraints . Conen goes one step further by designing a combinatorial bidding procedure to improve the resource scheduling offering different running, starting, and ending times for different resources. Furthermore, Bapna et al propose an auction that allows to bid on bundles and on time slots. In addition, the authors also suggest a heuristic that approximates the outcome of the auction in polynomial time. However, these approaches are single-sided and hence do not create competition on both sides. Furthermore in electricity grids it might not be clear, when

Requirements	R1	R2	R3	R4	R5	R6	R7
Eymann et al. 2003	√	–	√	–	–	–	–
Buyya et al. 2001	√	–	√	–	–	–	–
Wolski et al. 2003	√	–	√	–	–	–	–
Regev et al. 1998	√	–	√	–	–	–	–
Wellman et al. 2001	–	√	√	–	–	–	–
Conen 2002	–	√	√	–	–	–	–
Parkes et al. 2001	–	√	√	–	–	–	–
Biswas et al. 2003	–	√	√	–	–	–	–
Bapna et al. 2006	–/√	√	√	–	–	–	–
Schnizler et al. 2006	–	√	√	√	–	–	√
Entchev 2003	√	√	–	–	–/√	–	–
Engler 2005	√	–	–	√	√	√	–

Legend: R1: online mechanism; R2: bundle allocation; R3: price signals; R4: capacity constraints; R5: stable operation; R6: coupling with large grid; R7: forecasts

Table 1: Literature Overview

a consumer wants to start consuming energy and how long his consumption will take. Thus integrating time schedules into the auction mechanism does not solve the problem of providing precise estimates on future consumption and production of the grid.

Demanding competition on both sides suggests the development of a combinatorial exchange. In literature, Parkes et al. introduce the first combinatorial exchange as a single-shot sealed bid auction . As payment scheme, Vickrey discounts are approximated. Biswas and Narahari propose an iterative combinatorial exchange based on a primal/dual programming formulation of the allocation problem. By doing so, the preference elicitation problem can be alleviated, as the bidders can restrict their attention to some preferred bundles in contrast to all $2n1$ possible combinations. Obviously, both approaches do not account for immediacy demands are thus not directly applicable for the problem at hand.

The MACE mechanism developed by Schnizler et al. satisfies the bundling requirement and also allows the modeling of capacity constraints but is NP hard and cannot account for application scenarios with more than 500 bids and asks within a reasonable time span . Accordingly, this mechanism can be used for batch applications, but not for those applications that require immediacy as is the case in the motivating scenario.

Enchev [11] proposes a different approach in that he uses a fuzzy logic based optimization algorithm for adjusting the energy production to a given (and possibly changing) demand pattern. This approach appears to be suitable for ensuring stable operation of the micro electricity grid, but as there are no price signals provided to indicate the scarcity of resources, consumers do not have an incentive to optimize there consumption schedules.

Engler et. al. [10] exploit the potentials of an agent based system for controlling a micro electricity grid. They show that the system operates stable under realistic conditions and even recovers automatically from exogenous shocks (brownouts). Still in this approach heat is not considered as a resource, furthermore price signals are missing so that also in this case consumers do not have an incentive to optimize their consumption.

This paper intends to tailor a mechanism for the simultaneous allocation of electricity and heat resources by coupling two separate call markets together [9] so that it accounts for the aforementioned requirements.

4 Modeling an Auction Based Energy Allocation Mechanism

The base model

Based on the aforementioned requirements we propose a double auction mechanism that is capable of co-allocating electricity and heat and additionally takes minimum and maximum allocation constraints for both goods into account (if specified by the bidders). For the description of our model we use the following notation with the superscripts e and h indicating the variable's dedication to electricity or heat respectively:

i	Index for buyers $i = 1 \dots I$
j	Index for sellers $j = 1 \dots J$
h_i	Quantity of heat requested by buyer i
h_j	Quantity of heat offered by seller j
e_i	Quantity of electricity requested by buyer i
e_j	Quantity of electricity offered by seller j
b_i^h	Maximum price per heat unit buyer i is bidding
a_j^h	Minimum price per heat unit seller j is asking for
β_i^h	Market allocation for buyer i's bid on heat
$\underline{\beta_i^h}$	Min. heat allocation constraint of buyer i
α_j^h	Market allocation for seller j's ask for heat
$\underline{\alpha_j^h}$	Minimum allocation constraint of seller j
x_i^h	Binary decision variable for buyer i's bid on heat
y_j^h	Binary decision variable for seller j's ask for heat

Using this notation we can formulate our market model as a mixed-integer maximization problem. In particular the total welfare, i.e. the difference between all allocated buyers bids b_i and all allocated sellers asks a_j is maximized (1), subject to the resulting solution being feasible. A solution is feasible only if the consumed amount of heat is leq the generated amount of heat (2) and the generated amount of electricity equals the consumed amount of electricity (3). Furthermore if a buyer's bid or a seller's ask is allocated by the market for either heat or electricity it also has to be allocated for the other product, i.e. combinatorial bids on both products cannot be split by the auctioneer but have to be allocated simultaneously. Lastly a consumer can set minimum allocation constraints for heat and / or electricity (6)-(9) that have to be taken into account as well.

$$max \quad \sum_{i \in I} \beta_i^h x_i^h b_i^h + \beta_i^e x_i^e b_i^e - \sum_{j \in J} \alpha_j^h y_j^h a_j^h + \alpha_j^e y_j^e a_j^e \quad (1)$$

$$s.t. \quad \sum_{j \in J} \alpha_j^h y_j^h h_j - \sum_{i \in I} \beta_i^h x_i^h h_i \geq 0 \quad (2)$$

$$\sum_{j \in J} \alpha_j^e y_j^e e_j - \sum_{i \in I} \beta_i^e x_i^e e_i = 0 \quad (3)$$

$$y_j^h = y_j^e \quad \forall j \in J \quad (4)$$

$$x_i^h = x_i^e \quad \forall i \in I \quad (5)$$

$$0 \leq \underline{\alpha_j^e} \leq \alpha_j^e \leq 1 \quad \forall j \in J \quad (6)$$

$$0 \leq \underline{\alpha_j^h} \leq \alpha_j^h \leq 1 \quad \forall j \in J \quad (7)$$

$$0 \leq \underline{\beta_i^e} \leq \beta_i^e \leq 1 \quad \forall i \in I \quad (8)$$

$$0 \leq \underline{\beta_i^h} \leq \beta_i^h \leq 1 \quad \forall i \in I \quad (9)$$

$$x_i^h, x_i^e \in \{0, 1\} \quad \forall i \in I \quad (10)$$

$$y_j^h, y_j^e \in \{0, 1\} \quad \forall j \in J \quad (11)$$

Assume a seller j who operates a combined heat and power (CHP) generator. He is able to produce $e_j = 10$ units of electricity which he wants to sell at a price of at least $a_j^e = 20$ ct/unit. As his generator always co-generates heat when producing electricity, j wants to sell the heat ($h_j = 30$ units) simultaneously at a price of at least $a_j^h 5$ ct/unit. Furthermore, as his generator is not able to operate at a capacity of $<$ 50% of the norm capacity, he wishes to make sure that – in case his offer is matched – the allocated amount of electricity is $\geq \underline{\alpha_j^e} = 50\%$ of the originally specified amount. For the heat on the other hand, seller j might have a thermae available capable of storing the produced heat if it cannot be sold, thus $\underline{\alpha_j^h} = 0$. In summary, the ask of seller j will consist of a tuple $A(e_j; a_j^e; \underline{\alpha_j^e}; h_j; a_j^h; \underline{\alpha_j^h}) = A(10; 20; 50; 30; 5; 0)$.

Similarly a buyer i might want to buy $e_i = 10 units$ of electricity for at most $b_i^e = 25 ct/unit$ but he is neither interested in heat nor in partial allocations. Thus buyer i's bid will be $B(e_i; b_i^e; \underline{\beta_i^e}; h_i; a_i^h; \underline{\beta_i^h}) = A(10; 25; 100; Nil; Nil; Nil)$.)

In general, combinatorial allocation problems as the one described above belong to the complexity class of NP-hard problems but this does not mean that every possible problem instance will be NP hard. Instead there usually exist problem instances that can be easily computed in polynomial time. We will further exploit this particular property for the design of our heuristic in the extended model described in the following section. For the example above we can easily solve the allocation problem by awarding the 10 units of electricity offered by seller j to consumer i ignoring the heat that j offered as well ($\alpha_j^h = \underline{\alpha_j^h} = 0$). Having solved the allocation problem like this, the pricing for the transaction still needs to be determined. In general one possible solution is to employ a Vickrey Clarke Groves (VCG) like mechanism, which is the only class of mechanisms that provides allocative efficient, individual rational and incentive compatible solutions [14]. But as solving VCG problems is NP-hard and furthermore VCG mechanisms cannot be budget balanced [19], thus we will use the maximum execution principle to determine prices. The idea is described in more detail in the next section.

The extended model

In this section we describe a heuristic that is capable of efficiently finding near-optimal solutions solving the aforementioned allocation and pricing problem in polynomial time by particularly exploiting the fact that in micro electricity grids, most of the consumers and some of the producers do not need to allocate electricity and heat at the same time. In other words, in most of the cases separate double auctions for heat and electricity would be sufficient, only e.g. for producers that rely on CHP generators, submitting bundle offers might be advantageous.

Thus our solution is to set up two slightly adapted open book call markets [9] running parallel and independently from each other. Table 2 depicts the orderbooks of an electricity and a heat call market that are meant to run in parallel. Call market trading basically means that incoming orders are collected in an open order book up to a predefined point in time. Then all orders are executed in a single multilateral trade at a price that best matches the aggregated asks and bids. On the buy side, all bids with limit prices greater or equal to the matching price are executed and vice versa for the sell side. If e.g. the ask side of the orderbook is longer, meaning more ask than buy orders exist at the clearing price, those ask orders are executed at the same fraction (pro rata) ensuring for each order that a potential minimum allocation constraint $\underline{\alpha_j^e}$ ($\underline{\alpha_j^h}$) is not violated.

Our solution for coupling the two markets together thus allowing combinatorial bids is simple. Besides the two orderbooks we use an extra table to keep track of the combinatorial constraints. In our case Table 3 is used to record these constraints[4]. The first row states that the order with order id $oid^e = 1$ and the one with order id $oid^h = 2$ have to be either executed together or not at all (AND order). Now, when the time for matching the markets is reached, each of the markets determines its optimal set of matched orders independently from the other market. In this case we extended the previous example. The electricity market is matched as before but for the heat market we now have an additional ask (*oid* 4) and an additional buy order (*oid* 5). With the only bidder in this auction offering to buy heat at most 6 ct per unit and two potential sellers offering 10 units of heat for at least 4 ct/unit and 30 units for at least 5 ct/unit respectively, the price will be set to 5 ct/unit in order to maximize the exchange volume. As a result, seller $j = 3$ sells 10 units of heat, seller $j = 1$ sells 20 units of heat, and buyer $i = 4$ buys 30 units of heat in this auction, each for 5 ct/unit.

As soon as this task is accomplished both markets indicate the results of the matching in the bundling constraint table. Orders for which the bundling constraint is violated are then deleted from both, the order books and the bundling constraint table before the market matching is executed again. This procedure is repeated until no violations occur anymore. In our case, the bundling constrained is not violated, thus the matching process is completed.

A controller that implements the mechanism as described so far would already fulfill requirements R2 (bundle allocation), R3 (price signals), and R4 (capacity constraints) but, as stated before, this is not sufficient for operating a micro CHP grid. In particular, this mechanism does not describe when the allocated resources need to be available and for how long. We overcome this limitation by discretizing time into distinct, consecutive slots of a predefined duration d, e.g. $d = 15min$. Then n bundle call auctions are set up similar futures markets at the stock exchanges one for each of the next n time slots (n being sufficiently large). We adjust the auctions' execution time intervals intervals t such that $t \leq d$. Also we ensure that a future market is closed well timed be-

[4] Non-combinatorial orders go directly into the respective markets and are thus not recorded in this table.

Orderbook Electricity

Ask					Bid				
oid	j	e_j	a_j^e	$\underline{\alpha_j^e}$	oid	i	e_i	b_i^e	$\underline{\beta_i^e}$
1	1	10	20	5	3	2	10	25	1

Orderbook Heat

Ask					Bid				
oid	j	e_j	a_j^e	$\underline{\alpha_j^e}$	oid	i	e_i	b_i^e	$\underline{\beta_i^e}$
4	3	10	4	.2	5	4	30	6	1
2	1	30	5	nil					

Table 2: Sample Orderbooks

oid^e	oid^h	$type$	$match^e$	$match^h$
1	2	AND	true	true

Table 3: Bundling Constraints

fore the underlying time slot starts. Like this all market participants can submit several orders to the respective market adjusting their combined electricity and heat demands and supplies for the next n time slots.

Setting up our mechanism like this has several advantages. Market prices on the respective markets indicate the energy scarcity in the respective time slot and thus help users decide whether to use (or not to use) energy in certain time slots. In case a user decides to change his consumption schedule he can then immediately submit orders to sell energy in case of excess capacities or to buy energy in case of increased demand. Thus micro grid particpants can continuously adjust their demand and supply profiles over time, which in turn meets our requirement R1 (online mechanism).

The two requirements R6 (coupling with large-scale power grid) and R7 (forecasts for demand and supply) are now relatively easy to satisfy by introducing a special market participant namely, a so-called arbitrage agent. Located at the coupling point (c.f. Figure 1 (4)) of the microgrid this agent can buy electricity from the large-scale grid (e.g. at the EEX) and immediately sell it inside the microgrid markets at a higher price if electricity is cheaper in the outside world and vice versa. On average this agent (i) levels market prices in both markets, (ii) ensures that generators in the microgrid are only turned on if they can be operated at competitive costs, and (iii) communicates the future aggregated energy demand (supply) of the microgrid to the large-scale grid through placing his orders on the outside market.

With the arbitrage agent in place our mechanism now fulfills all requirements but one for operating a micro energy: *Stable operation* (R5)). We claim that *one average* markets are very good of matching demand and supply. But in particular *on average* means *not always.* We already described the procedure for allocating energy resources in case of unbalanced orderbooks, which basically condenses to rationing one side of the market. In case supply is rationed, nothing much will happen besides some generators being operated at a reduced workload or even being turned off. But in case of demand rationing this means at worst that energy production and consumption become unbalanced and thus a brownout or a blackout might occur.

In order to cope with this challenge we need to introduce another (market) institution. Consider the point in time where a market will be closed because the underlying timeslot starts. At this moment energy trading becomes impossible for the market participants leaving them with the risk that they can no longer intervent (i.e. buy or sell) in case predicted and actual demand (supply) diverge due to unforeseen events (e.g. a defect generator). In such a situation the whole micro grid, especially the electricity subgrid, is likely to become unstable and will eventually collapse.

This is where the spinning reserves (c.f. Figure 1 (3)) take over control as emergency coordinators. Spinning reserves do not trade their energy capacities on the above mentioned future markets instead they provide balancing power on demand throughout the currently running time slot. In other words, the spinning reserves are responsible to level out energy (i.e. heat and electricity) demand and supply on the spot beyond the market's capabilities ensuring a stable operation of the micro grid and thus fulfilling our last requirement R5.

In order to set an incentive for regular consumers and producers not to rely on the spinning reserves, the effectively provided balancing power (heat) is charged ex post to those market participants who originated the market imbalance by deviating from their originally negotiated energy consumption (production) level. The spinning reserves are price sufficiently above the market price in order to provide market participants with a strong incentive to negotiate exactly the amount of energy that they are going to consume (produce) during a certain time slot. In other words, truth revelation becomes a dominant strategy for the market participants the shorter the remaining time until the start of a slot becomes.

5 Conclusion & Outlook

In this paper we describe a market based system for coordinating combined heat and power micro energy grids. We use bundled open book call markets to let consumers and producers of the microgrid negotiate the allocation their future energy (i.e. heat and electricity) demand and supply. Furthermore we propose the utilization of an arbitrage agent for connecting the micro (electricity) grid to the large-scale grid. We also describe a way to employ spinning reserves for stabilizing the micro grid on the spot without inferencing the principal of market based coordination.

Overall the approach for operating micro energy grids described in this paper is very interesting as it proposes several new research avenues:

- The efficiency of the mechanism introduced in this paper needs to be further evaluated, especially the average gap between optimal allocations and those allocations generated by the heuristic needs to be determined in more detail.
- Subsequently, agent based simulations could be used to further study the system's dynamics, e.g. its reactivity to exogenous shocks such as a sudden generator breakdown [15].
- Electronic agents need to be developed that automate the process of energy trading. Here a clear advantage of our model is its simplicity. The fact that e.g. consumer agents can be implemented for procuring only heat *or* electricity reduces complexity and allows the recource to related literature from algorithmic trading research.
- Trading strategies for different types of producers (i.e. wind turbines vs. micro CHP generator) and consumers need to be developed.
- Innovative preference elicitation methods are required in order to allow e.g. consumers to only specify target temperatures for certain times of the day thus leaving the task of determining the resulting optimal heat consumption profile to the agents.
- Different energy prices for different timeslots set an incentive for demand side optimization. In this area, new models need to be developed that support consumers in finding optimal or at least more efficient consumption schedules without reducing their quality of life.
- The potentials and dynamics of hierarchically organized energy grids as well as potential yo-yo effects, which might occur if a large number of microgrids are coupled together hierarchically, need further investigation.

6 Acknowledgement

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