MULTILEVEL UNIT COMMITMENT IN SMART GRIDS

Maurice G. C. Bosman, Albert Molderink, Vincent Bakker, Gerard Smit and Johann L. Hurink
Dept. of Electrical Engineering, Mathematics and Computer Science, University of Twente, Enschede, The Netherlands
m.g.c.bosman@utwente.nl

Keywords: Unit commitment, Smart grids, Column generation.

Abstract: This paper focuses on the planning of electricity resources in the developing electricity infrastructure. First we model the existing infrastructure and extend this model to a smart grid infrastructure, where we focus on the large scale introduction of small electricity generators, leading to generation possibilities at both ends of the electricity network. Then the traditional Unit Commitment Problem (UCP) is given. We extend this formulation to the Multilevel Unit Commitment Problem (MUCP), where we describe and include the possibilities that arise in the developing smart grid, in a general way. Based on the characteristics of the problem with its subdivision into different levels, a planning method for the MUCP is described. Finally we solve and analyze a scenario, where a fleet of 5000 houses is added to a small collection of power plants.

1 INTRODUCTION

The Unit Commitment Problem (UCP) (Sheble and Fahd, 1994; Padhy, 2004) is the general term for a decision problem that is related to energy generation. In this problem, deterministic or stochastic energy demand has to be supplied by a number of generators. The UCP treats the commitment of specific generators during certain time windows (i.e. generators are used to supply (part of) the demand or not) and determines the generation level of the committed generators in these time windows.

Traditionally the UCP origins from the situation where the demand is given as (deterministic or stochastic) input (Kerr et al., 1966; Groewe-Kuska and Roemisch, 2005). In the developing smart grid, new technologies emerge in generation, storage and consumption (see e.g. (United States Department of Energy, 2003; Wemhoff and Frank, 2010; Alanne and Saari, 2004; Lanzafame and Messina, 2010; Ayompe et al., 2010; Arsie et al., 2009)). This leads to interesting possibilities in demand side load management and a change in the setting of the UCP. On the one side, demand side load management gives possibilities to shift demand, such that demand becomes part of the decision making process rather than being used as input data. On the other side, different types of generation with their own characteristics are added to the set of generators. Many small-sized generators are distributed over the grid, which leads to a significant increase in the number of generators that are considered in the UCP.

These advances in the energy supply chain lead to a new formulation of the UCP, which we call the Multilevel Unit Commitment Problem (MUCP). Based on the different sizes and locations in the infrastructure, a multilevel element is added, taking into account the quantitative impact of different generators or load management. To solve this MUCP, the energy infrastructure is modeled and partitioned into various levels. The MUCP is part of a three step control methodology for smart grids ((Molderink, 2011)) in which the complete picture of the smart grid is captured: the methodology consists of prediction, planning and realtime control.

The paper is organized as follows. In the next section an overview of the energy infrastructure is given and a model is presented for this structure. Then the MUCP is formalized in Section 3. In Section 4 the outlay of a planning method is sketched. As an example, a comparison is made between a classic UCP and the MUCP in Section 5. The results for this comparison are analyzed and discussed in Section 6.

2 THE ENERGY INFRASTRUCTURE

In this section we model the energy infrastructure as a flow network. First the elements of the electricity grid are introduced using a small example. Then the grid is modeled using different elements for production, consumption, transportation and communication.

The classic energy infrastructure (or supply chain) can be clearly separated into a consumption and a production side. Consumption of energy (gas, electricity, heat, etcetera) can be predicted quite accurately, based on historic demand and currently available characteristics (of consumer behaviour, weather, etcetera) (Bakker et al., 2010). In this classic situation, the energy production of power plants is completely adjusted to match this demand. Through transmission and distribution networks this production is brought to the consumer. In Figure 1 a simplified example of the situation in a certain time period is given, in which a decision has to be made on the generation output of three generators *a*, *b* and *c*, where demand is located in f, g, h and i. The directed edges (e,f), (e,g), (e,h) and (e,i) represent the distribution network. The cables in this part of the network have a certain demand from the end points (e.g. villages, industrial areas) and a fixed network capacity for the given time period, which are given as weights $demand|capacity$. The aggregated demand of the end points f, g, h and i has to be supplied by the transmission network, which is represented by the directed edge (d,e). This demand eventually has to be produced by the three generators, which have a different production capacity. In this case, all demand can be supplied by generator b alone, whereas a combination of generators has to be committed when a or c is willing to produce, since their production capacity is insufficient to supply the actual demand alone.

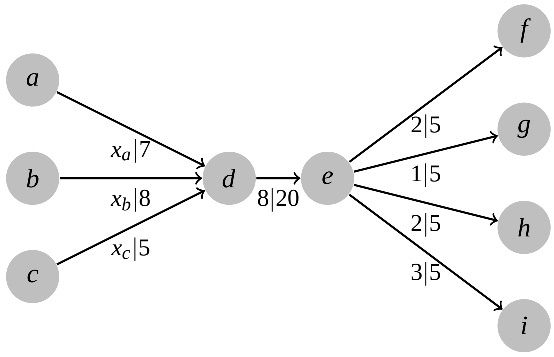


Figure 1: An example of the classic electricity infrastructure.

In the current flow network of the example, there is no bottleneck. Even if all end points would ask maximum demand (i.e. a demand equal to the distribution grid capacity), the transmission grid is able to supply this amount of electricity, and the three generators can produce this amount. When the classic infrastructure changes into the new smart grid, the classic division into a production and a consumption side becomes less clear. The original consumers also have the possibility to produce, which results in a bidirectional network. This might put more stress on the existing infrastructure. In this paper we assume that the transmission/distribution capacity of the corresponding networks is sufficient even for extreme demands.

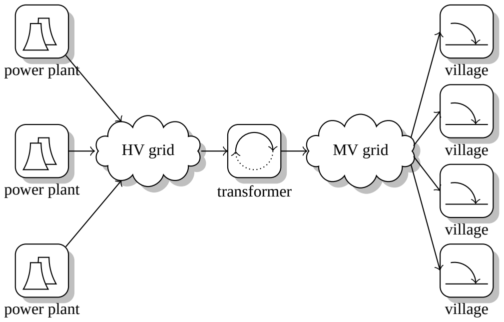


Figure 2: A model of the classic electricity infrastructure.

In Figure 2 the classic infrastructure of Figure 1 is modeled again, by using different types of nodes to stress the differences between generation, transportation and consumption. This model allows to model flows of different types, with preservation of energy, as proposed by (Molderink, 2011). As indicated in this model, we introduce additional nodes compared to Figure 1, drawn as clouds, which represent the level of the grid. The power plants are connected to the high voltage grid, which is connected to the medium voltage grid, via a transformer. The demand of the example is connected to this medium voltage grid. In the Unit Commitment Problem, the following challenge for the power plants has a central position: how to supply the given demand by the available generation possibilities, such that the total generation is done under minimum operational costs? Operational costs can be divided into energy (fuel efficiency) and cost effective costs (maintenance and startup/shutdown costs) (Sheble and Fahd, 1994; Padhy, 2004).

Figure 3 shows the extended infrastructure. As in Figure 2, directed edges show the electricity flow in the network. Some edges are bidirectional, indicating that a flow in both ways is possible. The large power plants are connected to the high voltage grid; smaller generation (e.g. windmill/solar panel parks, biogas installations, etcetera) is connected to the medium voltage grid. Note that this smaller generation is not directly coupled to the medium voltage grid, but via an additional electricity node, which is connected to an exchanging node, called ‘new generation’. This ‘exchanger’ expresses the introduction of a new, lower level in the model of the smart grid

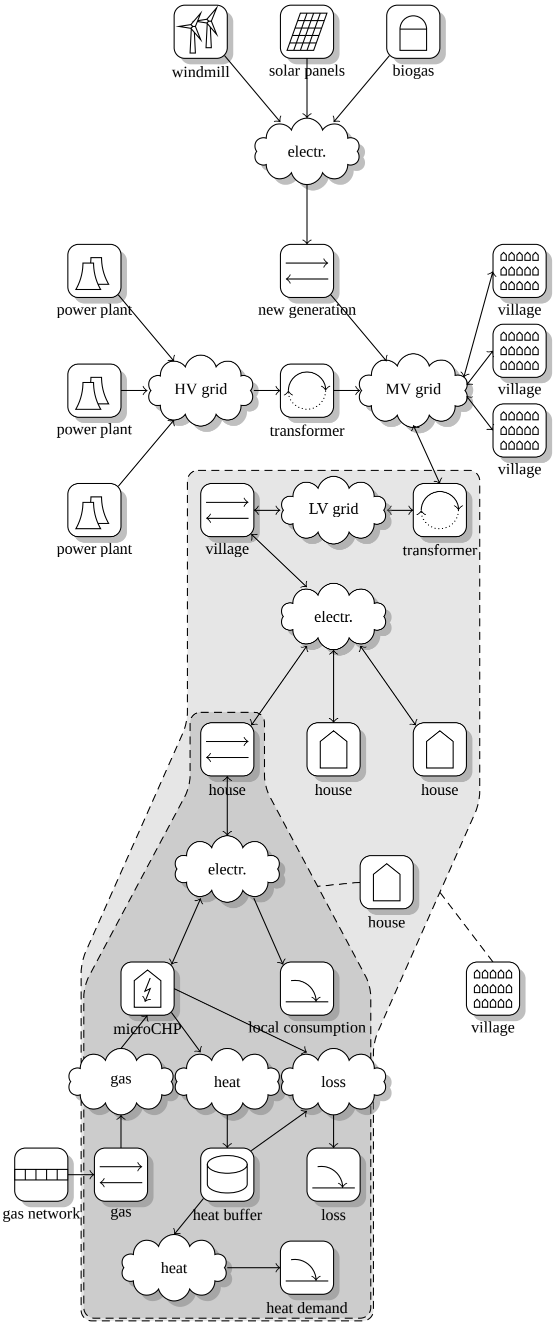


Figure 3: A model of the smart grid infrastructure.

and functions as a separator between the optimization problem on the higher level and the local commitment problem on the lower level (e.g. the smaller generation). The exchanger can be seen as a communication means between higher and lower order planning problems. This division into levels is further explained in Section 4.

Compared to the model of Figure 2, areas like villages are now modeled in more detail. In the previous model it sufficed to consider the connection of a village to the medium voltage grid, since only aggregated demand is taken into account. In the extended model a village is connected to the lower voltage grid and an exchanger is used to specify a lower level. In this lower level, a next level is introduced for the houses to model their own generation/consumption characteristics. Within the model (e.g. within the houses) different types of energy (i.e. gas and heat) are combined. This is one of the strengths of the extended model. In the model presented in Figure 3 we show the modeling of a microCHP (Combined Heat and Power generation on a household level (United States Department of Energy, 2003)), which is a device that consumes natural gas and produces both heat and electricity at a fixed ratio. It is convenient to use a heat buffer next to this microCHP to guarantee the heat supply in the house and to partially decouple heat consumption from the generation of heat (and electricity). In the model, gas import information is stored in the gas exchanger. The energy efficiency of generation can be modeled by adding energy losses. In the example, the loss flow of the microCHP has a fixed ratio to the heat and electricity generation; the loss flow of the heat buffer is determined by the state of the buffer. In a similar way, the efficiency of each type of generation can be modeled. However, for simplicity this is left out of Figure 3 and we do not consider efficiency in the remainder of this paper.

3 THE MULTILEVEL UNIT COMMITMENT PROBLEM

This section describes the Multilevel Unit Commitment Problem. Starting from the Unit Commitment Problem we derive additional constraints to formulate the MUCP.

The classic UCP aims to minimize operational costs or to maximize the profit of the system of generators. We consider the problem of minimizing costs. Operational costs are depending both on the binary commitment variables $u_{i,j}$ (specifying whether generator i is committed or not in time period j) and on the production level $x_{i,j}$ (specifying the electricity production of generator i in time period j). In general the operational costs can be described by a function $f(u,x)$, where the variables u and x run over the time horizon T for N generators. Note that startup costs are incorporated in this notation. The objective of the UCP is then to minimize $f(u,x)$. Some common constraints that are mostly used in the UCP are given in formulation (1)-(9).

$$\min f(u,x) \tag{1}$$

$$s.t. \sum_i x_{i,j} \geq d_j \qquad \forall j \tag{2}$$

$$\sum_i (u_{i,j} x_i^{\max} - x_{i,j}) \geq r_j \qquad \forall j \tag{3}$$

$$u_{i,j} x_i^{\min} \leq x_{i,j} \leq u_{i,j} x_i^{\max} \qquad \forall i,j \tag{4}$$

$$s_i^{down} \leq x_{i,j} - x_{i,j-1} \leq s_i^{up} \qquad \forall i,j \tag{5}$$

$$u_{i,j} \geq u_{i,j-k} - u_{i,j-k-1} \qquad \forall i,j,k = 1,\ldots,t_i^{mr} - 1 \tag{6}$$

$$1 - u_{i,j} \geq u_{i,j-k-1} - u_{i,j-k} \qquad \forall i,j,k = 1,\ldots,t_i^{mo} - 1 \tag{7}$$

$$u_{i,j} \in \{0,1\} \qquad \forall i,j \tag{8}$$

$$x_{i,j} \in \mathbb{R}^+ \qquad \forall i,j \tag{9}$$

Equation (2) requires that the total production satisfies the total demand; equation (3) asks for a certain amount of spinning reserve r_j, i.e. the additional available generation capacity of already committed generators. This constraint is added to guarantee a certain amount of flexibility in the case of a higher-than-predicted demand or in the case of a failure of a certain generator. The production boundaries of the generators $x_i^{\min}$ and $x_i^{\max}$ are defined in equation (4) and the ramp up and ramp down rates s_i^{up} and s_i^{down}, which determine the speed with which generation can be adjusted, are given in equation (5). Equations (6) and (7) state that the generator has to stay up and running (or stay switched off) once a corresponding decision to switch it on (or off) has been made within the last t_i^{mr} (t_i^{mo}) time periods. The decisions to commit a generator are binary decisions, where the production decisions are real numbers.

When we consider the developing energy infrastructure, we see more decentralized energy production $y_{m,j}$, where $y_{m,j}$ specifies the electricity production of local generator m in time period j. The maximum production of these types of generators is much smaller than the minimum production of a power plant: $\max_m \left(y_m^{\max}\right) \ll \min_i \left(x_i^{\min}\right)$. However, there may be very many of them. The local generators are often more limited in their production decisions than normal power plants, especially when we consider combined heat and electricity generation (e.g. micro/mini Combined Heat and Power). In this case the heat demand of the local household/glasshouse determines to a large extent the total daily generation, where some flexibility is provided by the use of a heat buffer. Also, the power output is completely determined for many of these generators, once the generator is in operational mode. This further limits the flexibility of the decision maker.

In the developing energy infrastructure, also a lot of renewable generation is introduced, which more and more takes place on a local scale. To cope with these changes we extend the given UCP formulation in the following way to a MUCP formulation.

$$\min f(u,x) - g(p,u,y) \tag{10}$$

$$s.t. \sum_i x_{i,j} + \sum_m y_{m,j} \geq h_j(d) \qquad \forall j \tag{11}$$

$$\sum_i (u_{i,j} x_i^{\max} - x_{i,j}) \geq r_j \qquad \forall j \tag{12}$$

$$z_{j,F_n}^{\min} \leq \sum_{m \in F_n} \sum_{k=1}^{j} y_{m,k} \leq z_{j,F_n}^{\max} \qquad \forall j,n \tag{13}$$

$$u_{i,j} x_i^{\min} \leq x_{i,j} \leq u_{i,j} x_i^{\max} \qquad \forall i,j \tag{14}$$

$$s_i^{down} \leq x_{i,j} - x_{i,j-1} \leq s_i^{up} \qquad \forall i,j \tag{15}$$

$$u_{i,j} \geq u_{i,j-k} - u_{i,j-k-1} \qquad \forall i,j,k = 1,\ldots,t_i^{mr} - 1 \tag{16}$$

$$1 - u_{i,j} \geq u_{i,j-k-1} - u_{i,j-k} \qquad \forall i,j,k = 1,\ldots,t_i^{mo} - 1 \tag{17}$$

$$u_{m,j} \geq u_{m,j-k} - u_{m,j-k-1} \qquad \forall m,j,k = 1,\ldots,t_m^{mr} - 1 \tag{18}$$

$$1 - u_{m,j} \geq u_{m,j-k-1} - u_{m,j-k} \qquad \forall m,j,k = 1,\ldots,t_m^{mo} - 1 \tag{19}$$

$$y_{m,j}^{\min} \leq \sum_{k=1}^{j} y_{m,k} \leq y_{m,j}^{\max} \qquad \forall m,j \tag{20}$$

$$y_{m,j} = l(u_m) \qquad \forall m,j \tag{21}$$

$$u_{i,j}, u_{m,j} \in \{0,1\} \qquad \forall i,m,j \tag{22}$$

$$x_{i,j}, y_{m,j} \in \mathbb{R}^+ \qquad \forall i,m,j \tag{23}$$

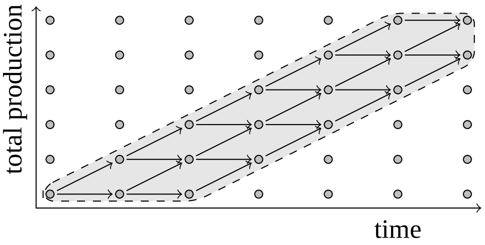
The formulation of the MUCP is given by equations (10)-(23), where the original UCP can be found in equations (11),(12) and (14)-(17). In this MUCP model we also incorporate demand side load management to alter the demand. This is formalized in equation (11) by the function $h_j(d)$. Furthermore, the local generation $y_{m,j}$ is taken into account in this equation too. The local generators have the same type of dependency constraints on runtime and offtime over time periods (equations (18) and (19)) as the large generators (equations (16) and (17)). Next to these machine dependency constraints the generators also have user dependencies, resulting e.g. from the heat demand. The use of a heat buffer, with some initial heat level, in combination with the local heat demand, determines the minimum aggregated heat production and the maximum aggregated heat production. Since heat and electricity production are directly coupled, we model this relationship using a minimally required aggregated electricity production $y_{m,j}^{\min}$ and a maximally allowed aggregated electricity production $y_{m,j}^{\max}$, as in equation (20). So, possible decisions in future intervals are not only influenced directly via runtime/offtime constraints, but they are also influenced indirectly via equation (20). As stated before, the generator output is completely determined by the commitment decisions, as in equation (21).

The planning problem for only a group of microCHPs is proven to be NP-complete in the strong sense, due to the two-dimensional aspect of the problem (i.e. a strong dependency between generation in time periods and a strong dependency between households due to the aggregated generation in the fleet)

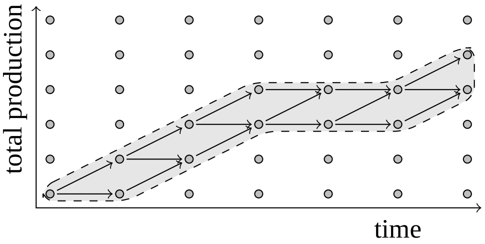
(Bosman et al., 2010). It is therefore practically intractable to solve the MUCP (of which the planning problem for a fleet of microCHPs is only a part of the problem) directly. However, heuristics have been developed to solve the planning problem for the fleet (Bosman et al., 2011). For this reason, a planning method for the MUCP is presented that uses the natural division into different production levels to separate the decisions that have to be made for the power plants and for the local generators, and still combine the two into a global Multilevel Unit Commitment decision problem.

In the MUCP, a group of local generators (called a fleet) is considered as one entity on the planning level, equivalent to a power plant. Of course, a subdivision in multiple entities F_n is allowed. Equation (13) is applied to these n fleets, which forces the aggregated production of all generators to be within upper and lower bounds $z^{\max}_{j,F_n}$ and $z^{\min}_{j,F_n}$. The most natural bounds are $z^{\max}_{j,F_n} = \sum_{m\in F_n} y^{\max}_{m,j}$ and $z^{\min}_{j,F_n} = \sum_{m\in F_n} y^{\min}_{m,j}$. These bounds may be sharpened further, since not all possible decision paths (sequences) within these natural bounds may be feasible. We explain this by giving two examples. As a first example, the capacity of the fleet may be smaller than $\sum_{m\in F_n} y^{\max}_{m,j} - \sum_{m\in F_n} y^{\min}_{m,j-1}$, which may result in a fleet decision in time period j that cannot be met by the individual generators. This would require additional bounds on the production capacity of the fleet entity.

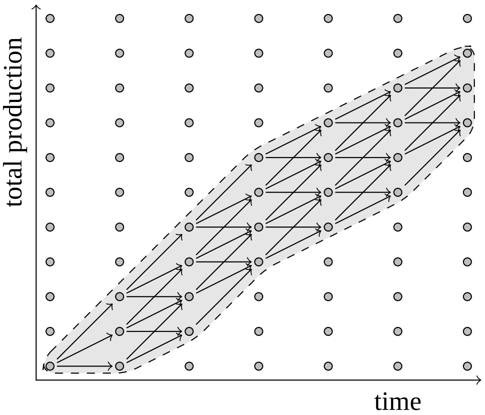
However, even if the fleet decision respects the capacity of the fleet and if the fleet decision path stays within the natural bounds $\sum_{m\in F_n} y^{\max}_{m,j}$ and $\sum_{m\in F_n} y^{\min}_{m,j}$, it can be impossible to follow this decision path by the individual generation, as shown in the second example by Figure 4. Figure 4(a) and 4(b) show the possible decision paths within the natural bounds (the gray area) for two households equipped with a microCHP; Figure 4(c) shows the combined decisions, including capacity constraints, for which the given decision path in Figure 4(d) is impossible to follow. Although the two generators may run simultaneously, independently in the fourth or in the fifth time period, it is impossible to have the two generators running simultaneously in these time periods subsequently, due to the limited possibilities for the second household in the fourth and fifth time periods. So, even when capacity constraints are added the natural bounds may not result in a fleet entity decision that is feasible for the individual generators. This is the reason why the natural bounds may be sharpened. Also, to guarantee stability, especially within the distribution network, additional constraints may be posted to the output of



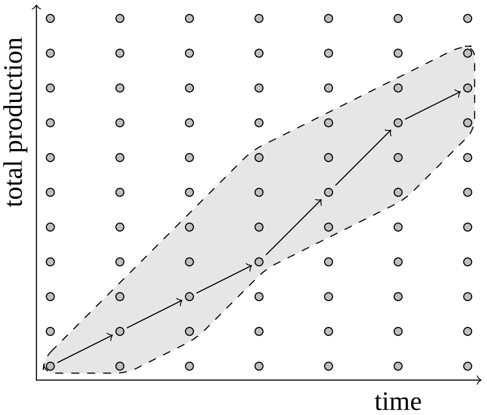
(a) Possible transitions of one microCHP.



(b) Possible transitions of another microCHP.



(c) Addition of feasible regions and possible transitions of the combination.



(d) Construction of a bid pattern which is impossible to follow.

Figure 4: A counterexample for the natural fleet bounds.

fleets of small generators.

Since the operation of the individual small generators is of minor importance in comparison with the behaviour of the fleet, we do not wish to minimize operational costs for the fleet(s). In the additional function $g(p,u,y)$ in equation (10) the profit of the fleet is maximized, when this fleet operates, using the given bounds, on an electricity market with prices p_j.

4 A PLANNING METHOD FOR THE MUCP

In Section 2 the smart grid is modeled using a division into different levels. This division is based on the amount of energy the different generators produce and forms the base for a leveled approach to solve the MUCP of Section 3. In this section, a sketch of a planning method is given, introducing patterns as building blocks for the method.

Since it is practically intractable to combine the commitment of large and small types of generation, information on the smaller generation is aggregated on a higher level by using the exchangers, as shown in the previous sections. Each fleet (e.g. village, windmill park) is then considered as one entity, with some global constraints based on the aggregated information, and treated in this simplified form in the optimization problem. Note that on this high level, local constraints on the smaller generators are discarded in the optimization problem. The objective function of this high level optimization problem reflects the original objectives; operational costs are minimized for power plants and the common fleet output is maximized for its profit on an electricity market. The decision paths that result from the optimization of the high level optimization problem for all entities (whether power plants or fleets) are called patterns. For a power plant this pattern simply reflects the commitment (and generation level) decisions that have to be made; for a fleet this pattern is the input for a new, lower level optimization problem.

On the lower level a new optimization problem is formed, which is to match the provided fleet pattern with the available individual generation possibilities as good as possible. So, the objective is to minimize the deviation from the (higher level) fleet pattern. A fleet consisting of small generators can sometimes be optimized using full knowledge about each generator (i.e. patterns can be derived directly for biogas installations, windmill parks, etcetera, based on local constraints on these types of generation). However, for a fleet consisting of houses it is harder to solve an overall optimization problem in reasonable time, where the full details of all houses are considered, especially when the number of houses is large. In this situation, a next level is introduced, using a column generation approach to provide the fleet optimization problem with so-called house patterns. The lower level optimization problem has to select individual house patterns in order to allow the fleet planner to find a combination of patterns that minimizes the deviation from the fleet pattern. Based on information from the solution of the higher level optimization problem, a column generation technique is used to extend the current pattern set for each house with new promising patterns.

Once the fleet patterns are locally optimized, the resulting patterns of the fleet planning problem that minimize the deviation from the original fleet patterns, are now communicated back to the high level optimization problem. Using this information, this problem is solved again. This can be seen as a classic UCP with altered demand (and possibly altered spinning reserve). If the result is not satisfying, additional constraints on the fleet patterns can be added to the original high level optimization problem, and the complete process can be repeated.

5 CASE STUDY

To study the influence of generation on multiple levels in the electricity grid, we set up a scenario with two levels. We choose to use two levels, to see the interaction between generators of different production capacity in a direct way. In this illustrative example we use 10 generators on the highest level, with a total production capacity of 15 MW. This capacity is divided over 5 generators with a capacity of 1 MW and a minimum production level of 0.5 MW, and 5 generators with a capacity of 2 MW and a minimum production level of 1 MW. The (absolute) ramp up and ramp down rates are equal to the minimum production for each power plant. Between the maximum and minimum production values the operator of the generator has flexibility to choose its power output, once the unit is committed. The minimum runtime and offtime are set to half an hour.

On the lowest level, we have 5000 houses containing a generator, with a total capacity of 5 MW. These generators are microCHPs (Combined Heat and Power systems on a household scale) with a production output of 1 kW. This power output is a direct result from the decision to run the microCHP on a certain moment in time. This means that there is no flexibility in the production level of committed units, although flexibility can be found in the moments in time that the units are committed. However, these moments are further constrained by the heat demand in the houses: the maximum production of the fleet over the planning horizon is 39.8 MWh and the minimum production is 35.1 MWh, which is of the same order of committing a power plant for a complete day. The minimum runtime and offtime are again set to half an hour.

In the scenario we define four use cases to study the influence of introducing a fleet of microCHPs in the UCP. For each use case we use time periods of 30 minutes length; the commitment is planned for a complete day, which comes down to 48 time periods. The total daily demand is 114.2 MWh, with a peak of 8 MW and a base load of 2.5 MW. In this scenario we do not consider demand side load management. We require a spinning reserve of 2 MW at all time periods. The objective function combines operational costs for the power plants and profit maximization for the fleet. The first use case is based on real prices from the APX day ahead market [1]. In the second use case we multiply all prices with -1, which creates artificial negative values, to compare to what extent the fleet would change its decisions. The third use case uses artificial prices that correspond to the daily electricity demand; the higher the demand, the higher the price. This use case is defined to verify if the fleet can behave in such a way that peak demand can be decreased and the demand for the power plants can be flattened. The fourth use case is the opposite of the third case, in the sense that prices are again multiplied with -1; the higher the demand, the lower the price.

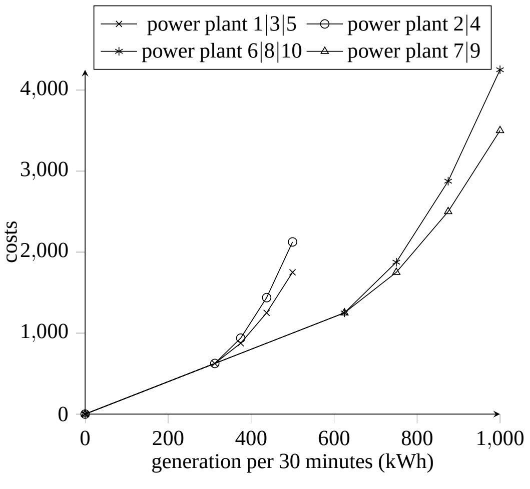


Figure 5: The operational cost functions of the power plants.

In Figure 5 the cost functions of the power plants are given. They are modeled as piecewise linear cost functions, to approximate quadratic operational cost functions. Below certain production levels (625 kWh for the large power plants and 312.5 kWh for the small power plants) the cost functions are equal, and power plants are mutually exchangeable. The start of a power plant is furthermore penalized with a cost of 1000.

The different optimization problems are modeled as Integer Linear Programming formulations in AIMMS modeling software using CPLEX 12.2 as solver. The solution method is executed on a desktop computer (2.40 GHz and 2.00 GB RAM).

6 RESULTS AND DISCUSSION

In this section we discuss the solutions of the four use cases, which are found by the planning method.

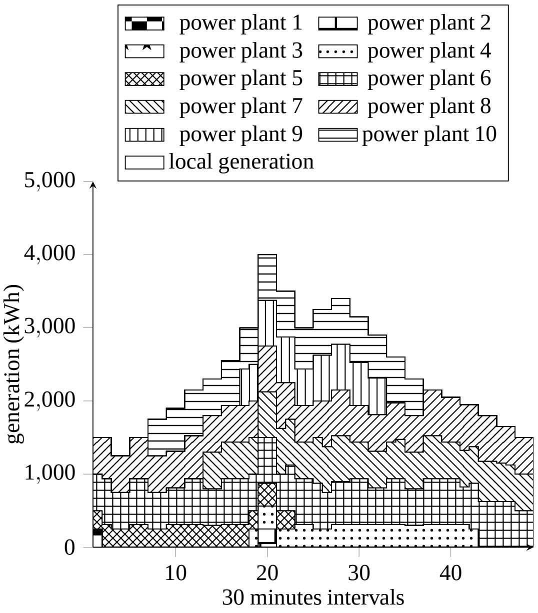


Figure 6: The solution of the UCP.

Figure 6 shows the detailed solution of the UCP, where we do not use the 5000 houses and the demand is fullfilled against minimal operational costs. The commitment and corresponding generation patterns are given for the 10 power plants. This solution is used to validate the optimization model. At any time period, the spinning reserve of 1000 kWh (=2 MW for time periods of 30 minutes length) is available within this solution. The ramp rates are taken into account; the minimum and maximum production constraints are considered too. This can best be seen when a generator shuts down. The time period before

---

[1] http://www.apxendex.com

a generator shuts down, the production is reduced to the minimum production level, which happens to be equal to the (absolute) maximum ramp up and ramp down rates. In this case the generator may shut down in the next period. We see that nine of the ten units are committed during the day; each power plant is started at most once.

Table 1 shows the results for the MUCP, where we incorporate the fleet of 5000 houses. The table shows the operational costs of the power plants, both for the initial planning with the rough fleet constraints (rough) and for the final result after applying the column generation to the fleet and replanning the power plants using the elaborated fleet pattern (result). It also shows the number of starts for the power plants, again for the rough planning and for the final result. The computational time of the result includes the computational time of the rough planning. Regarding the fleet planning, the final mismatch to the rough planning (i.e. absolute deviation from the rough planning) is given in kWh and in percentage of the total generation of the rough planning. The resulting total generation is given in the last row of Table 1. Since we mostly use artificial prices for the electricity market, we do not show the profit maximization of the fleet in more detail.

The operational costs of the result are relatively close to the rough planning operational costs in all cases. This means that the commitment of the power plants is not altered too drastically after the elaborated planning of the fleet; so, the planning method behaves as expected. Of course the final costs are higher, since the rough planning gives the optimal combination of power plant operation and fleet operation. The four use cases show that we are able to steer the fleet production by using different prices. The number of starts of the power plants increases in all cases, except for the third use case. In case 3 the power plants need only 5 starts in the final fleet planning. This is mostly due to the initial fleet planning, which is aimed to reduce the peaks in the demand. In the realization of this planning the fleet has relatively much difficulties, since the mismatch from the rough planning is the highest of the four cases. Nevertheless this realization leaves enough possibilities for the power plants to find a planning that only needs 5 commitments. The big advantage is that the fleet does not interfere too much with the base load, which simplifies the continuity of the commitment in time periods with low demand.

The computational time of the planning method stays below half an hour in all cases. This is acceptable for a practical application, especially since the column generation technique can be distributed over the smart grid in real life. The mismatch from the rough planning is below 8%. Figure 7 shows the development of the mismatch during the column generation method. The final solution is found after approximately 10 iterations. The existence of a mismatch can be partly explained by a possible impractible rough planning, but also by the fact that we used a maximum runtime of 60 seconds for the pattern matching problem, which tries to select exacly one pattern for each house to minimize the mismatch from the rough planning. This maximum runtime results in a preliminary abortion of the solution method in all four cases. From this we may conclude that the fleet might have done better, to the costs of higher computational time. Finally we see that the total fleet production approximates the upper production bound of 39.8 MWh in use cases 1, 3 and 4, whereas the total fleet production in case 2 is close to the lower production bound of 35.1 MWh. This indicates that the prices in case 2 are too negative, such that it is more cost effective to let the power plants produce more.

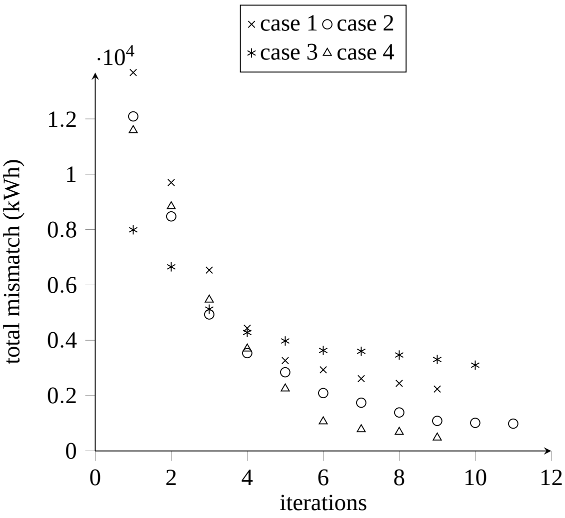
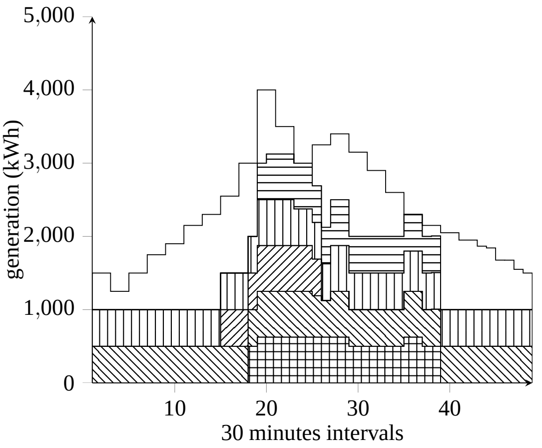


Figure 7: The mismatch during the column generation for the four use cases.

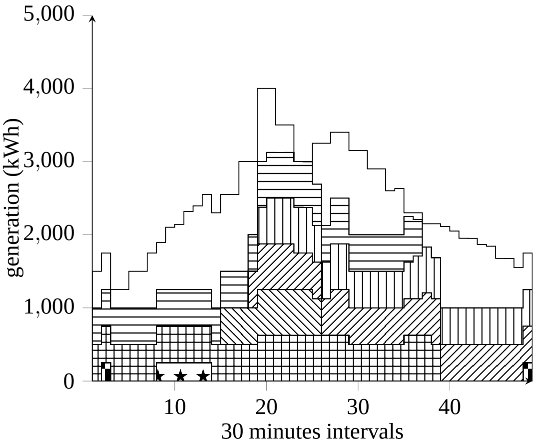
Figure 8 shows the unit commitment of the 10 power plants and the fleet production of the 5000 houses in the second use case. Figure 8(a) gives the rough fleet planning and Figure 8(b) gives the resulting, final fleet planning. We show this use case in more detail to describe two phenomena that occur. Firstly, we see three short periods of commitment of the small power plants 1 and 3 in the final planning. These commitments are not necessary to fullfill the demand; the already committed power plants could have supplied this additional demand themselves, even against lower costs. However, in that case

Table 1: MUCP results for the four cases.

	case 1		case 2		case 3		case 4	
	rough	detailed	rough	detailed	rough	detailed	rough	detailed
operational costs	158748	164846	163593	169325	154748	163230	154748	167730
# of starts	5	6	5	8	5	5	5	9
computational time (s)	32.28	1543.10	26.91	1798.19	61.72	1753.56	7.40	1451.00
mismatch (kWh)	2236.5		986		3099.5		478.5	
mismatch/rough prod. (%)	5.6		2.8		7.8		1.2	
fleet production (kWh)	38926		35589		37927		38868.5	



(a) The solution of the high level MUCP.



(b) The solution of the high level MUCP, including a detailed fleet planning.

Figure 8: The second use case in more detail.

there would not be sufficient spinning reserve left in the committed power plants. For this reason, power plants 1 and 3 have to be committed during these periods. Secondly, we see many different generators committed in the final planning, in comparison with the rough planning. However, as we have stated before, below certain production levels (625 kWh for the large power plants and 312.5 kWh for the small power plants) the cost functions are equal, and power plants are mutually exchangeable. This could explain the larger number of committed generators. Finally, we show the rough fleet planning and the final fleet planning in one overview in Figure 9. This figure shows that the rough planning is matched reasonably well.

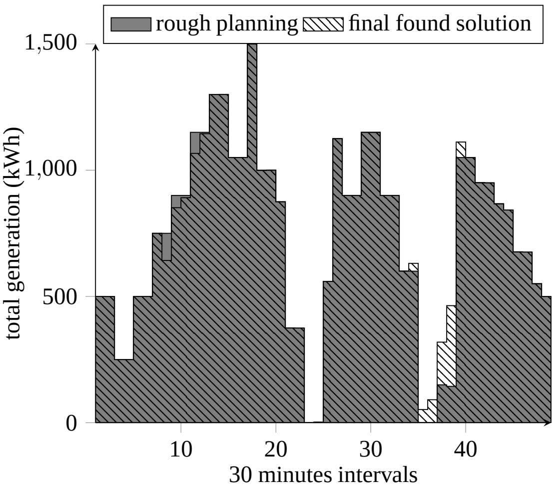


Figure 9: Comparison of rough planning and final found solution for the planning of the local generators in the second use case.

6.1 Summary

This paper presents a Multilevel Unit Commitment Problem (MUCP) for the infrastructure of a smart grid. This MUCP differs from the common Unit Commitment Problem (UCP) in its size, the difference in production levels of the different generator types, the possibility of demand side load management and storage. Objectives may also differ due to developments in the electricity markets, which leads to a partial focus shift from the optimization of the operational costs of generators to the optimization of the behaviour on the electricity market. In this paper a use case is defined where a group of 5000 houses is added to a normal UCP instance, which is planned using the proposed planning method. The results of the given scenario show that the presented approach can be applied to a fleet size of 5000 houses.

6.2 Recommendations

In future work scalability should be validated; is it possible to solve an extended scenario, where multiple fleets are optimized simultaneously? Regarding this extended scenario, the fleet sizes should be analyzed for their contribution to the high level optimization problem and the speed and quality of the underlying lower level optimization problem(s). In this extended scenario, the influence of the production capacity of low level generators on the capability to adjust the total output as a fleet also has to be studied.

Also demand side load management should be added, as well as other local generation or storage technologies, such as solar cells and heat pumps, to solve an extended real life Multilevel Unit Commitment Problem. Other types of local generation, demand side load management and local storage can be incorporated in a similar way as is done for the microCHP. However, these possibilities cannot be treated as independent fleets. An additional level needs to be introduced in the MUCP, where the interactions between these possibilities are considered as a new type of combined patterns.

REFERENCES

Alanne, K. and Saari, A. (2004). Sustainable small-scale chp technologies for buildings: the basis for multi-perspective decision-making. *Renewable and Sustainable Energy Reviews*, 8(5):401–431.

Arsie, I., Marano, V., Rizzo, G., and Moran, M. (2009). Integration of wind turbines with compressed air energy storage. In *Proceedings of the Second Global Conference on Power Control and Optimization (PCO)*, pages 11–18. Keynote lecture.

Ayompe, L. M., Duffy, A., McCormack, S. J., and Conlon, M. (2010). Validated real-time energy models for small-scale grid-connected pv-systems. *Energy*, In Press, Corrected Proof.

Bakker, V., Bosman, M. G. C., Molderink, A., Hurink, J. L., and Smit, G. J. M. (2010). Improved heat demand prediction of individual households. In *Proceedings of the first Conference on Control Methodologies and Technology for Energy Efficiency, Vilamoura, Portugal*, pages 1–6, Oxford. Elsevier Ltd.

Bosman, M. G. C., Bakker, V., Molderink, A., Hurink, J. L., and Smit, G. J. M. (2010). On the microchp scheduling problem. In *Proceedings of the Third Global Conference on Power Control and Optimization (PCO)*, pages 367–374.

Bosman, M. G. C., Bakker, V., Molderink, A., Hurink, J. L., and Smit, G. J. M. (2011). Controlling a group of microchps: planning and realization. In *Proceedings of the First International Conference on Smart Grids, Green Communications and IT Energy-aware Technologies (ENERGY 2011)*, pages 1–6.

Groewe-Kuska, N. and Roemisch, W. (2005). *Stochastic Unit Commitment in Hydrothermal Power Production Planning*. Society for Industrial and Applied Mathematics, Philadephia, PA.

Kerr, R., Scheidt, J., Fontanna, A., and Wiley, J. (1966). Unit commitment. *Power Apparatus and Systems, IEEE Transactions on*, PAS-85(5):417 –421.

Lanzafame, R. and Messina, M. (2010). Power curve control in micro wind turbine design. *Energy*, 35(2):556–561. ECOS 2008, 21st International Conference, on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems.

Molderink, A. (2011). *On the three-step control methodology for Smart Grids*. PhD thesis, University of Twente.

Padhy, N. (2004). Unit commitment-a bibliographical survey. *Power Systems, IEEE Transactions on*, 19(2):1196 – 1205.

Sheble, G. and Fahd, G. (1994). Unit commitment literature synopsis. *Power Systems, IEEE Transactions on*, 9(1):128 –135.

United States Department of Energy (2003). The micro-CHP technologies roadmap. *Results of the Micro-CHP Technologies Roadmap Workshop*.

Wemhoff, A. and Frank, M. (2010). Predictions of energy savings in hvac systems by lumped models. *Energy and Buildings*, 42(10):1807 – 1814.