

Demand side operational flexibility – a holistic stochastic optimization model for flexible consumers and prosumers

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ABSTRACT

We propose a stochastic mixed integer optimization model to support decisions for the day-ahead scheduling problem for flexible consumers and prosumers being exposed to dynamic prices at retail side of the electricity market. A general framework is designed to cover different cases and regimes, focusing on close connection to the physical energy system. The objective is maximum value creation from dispatchable technologies in the buildings' internal energy systems for heating, cooling and electricity specific purposes. Since some parameters may be uncertain, like loads and prices, we suggest a stochastic programming model where the uncertain parameters are represented through a scenario tree. The model is tested in a case study for a large college building in Norway being exposed to hourly elspot prices and a grid contract with a capacity fee. Results indicate significant cost savings even in current regime.

INTRODUCTION

More dynamics in the power systems lead to an increasing need for operational flexibility. Integration of non-dispatchable power generation, changes in consumption patterns and more dynamics in the power systems in general are examples of drivers behind the development. Traditionally such changes have been met by capacity expansions through central power generation facilities and grid enforcements. Utilizing flexibility options at the demand side is an alternative approach.

Currently there exists an unexploited potential for flexibility at the demand side, and implementation of SmartGrid technologies will increase this potential further. SmartGrid technologies at the demand side may be grouped into 3 categories:

1. Advanced metering infrastructure (AMI) (smart meters and 2-way communication between the utility and the consumer)
2. Smart appliances and infrastructure for communication, monitoring and control inside buildings
3. Technologies for production and storage of electricity, heat and cooling at demand side

The above mentioned technologies lead to a long list of potential changes, where an important one is the possibility to create cost savings based on the increased potential for flexibility at the demand side. Such flexibility has a wide

variety of benefits for the power production system, the power transmission and distribution system, the power markets as well as for the consumers and prosumers (consumers that also produce energy) ([1], [2], [3]). Hereafter the term prosumer will be used to cover flexible consumers and prosumers.

In order to generate benefits from the prosumer flexibility, incentives are needed. Such incentives may be created by dynamic pricing regimes [4] or through new market roles like energy service companies (ESCo) or aggregators, providing attractive products and services to the prosumers and the market ([5], [6], [7]). Combinations of new business models, bundling of products and services related to energy and other areas like health, security or entertainment and trading of aggregated volumes of flexibility are examples of how added value can be created for the prosumers and companies in the SmartGrid market.

The scheduling process, deciding a plan how to utilize the flexible units, will need new decision support models and IT tools. In the literature several papers are published that cover parts of this focus area, a few examples are listed below.

In [8] a model for real time demand response is described. [9] proposes a model for electricity storages and small wind turbines in households. A model for strategic (technology investment) and operational decisions for public buildings is given in [10]. Finally a model to minimize the annual energy cost and emissions of operating on-site generation and combined heat and power systems is described in [11].

In this paper we focus on the scheduling process for the day-ahead horizon assuming retail side participation with different price regimes. We aim at designing a general model that cover all types of buildings (from households to big commercial buildings) and that can handle onsite generation, storage and loads in an integrated perspective. Since the potential volumes for flexibility is the key issue, the total energy system including several energy carriers and types of loads (not only electricity specific) should be included. The target is to develop a methodology that can work in a real life situation, meaning that the model must reflect the physical underlying energy-system.

Finally, since in real life many parameters are uncertain when decisions are made, the model must be designed to handle uncertainty.

PROSUMER FLEXIBILITY MODELING

In this paper we assume participation at the retail side of the electricity market, where the prosumer is not actively trading in the market, but has a contract with a utility (or as in the Norwegian context a supply contract with a retailer and a grid tariff contract with the grid company).

The model should be able to make scheduling decisions for a day ahead. However, depending on the contract structure and the ability to move generation and load between days, the model must be designed to handle planning horizons that are longer than one day.

Even if we are focusing on benefit creation from flexibility in the electricity system (where we assume dynamic electricity prices), we know that some of the flexibility options stem from the interrelation between electricity and heating/cooling system. For this reason the model needs to be able to cover different sub-systems.

Each sub-system can have supply of primary energy carriers from outside. This may be electricity from the grid, oil or gas, district heat or sun and wind just to mention a few examples. A primary energy carrier is fed directly into an internal energy system or into a generating unit that converts from one energy carrier to another.

In addition to generating units each internal energy sub-system should have the possibility to include storage and load units. Since we are focusing on the flexibility, the loads should be characterized according to their ability to respond to pricing signals.

The flexibility options are grouped into these categories:

Load shifting covers units where the load must be met, but may be moved from one time period to another, constrained by an earliest start and latest end period. Examples of load shifting resources are industrial processes that may be moved in time, washing machines and dryers where the running period is not critical as long as the process is ready within a deadline and charging of batteries for electric vehicles (EV). In the model we will distinguish between load units where the process (with the original load profile) is moved in time (**load shifting profile**) and loads where a given volume must be met within a time frame, but where the load profile is not important (**load shifting volume**).

Load reduction means that the load may be reduced or even switched off. Such reductions imply a reduction in the total energy load, hence the reduction will not be replaced in earlier or later periods. Load reduction units may be industrial processes that are stopped, air conditioners that are switched off or run parts of the normal time and lights that are switched off or dimmed. Actions related to load reduction may have a discomfort for the user.

Generation flexibility means to regulate the generation from controllable generation units. Generation dispatching may be done by for instance heat pumps, micro CHPs,

gas/oil fired water heaters or electricity generators.

Energy carrier substitution means to cover a load with another primary energy carrier. Examples are water heating that may be done both by an electric boiler unit and with units running on gas, wood, oil or other fuels.

Storage dispatching means to control the charging and discharging process for the storage. Storage resources may be electric batteries, heat storages or hydrogen storages.

The figure below illustrates the total technology model at a generic level.

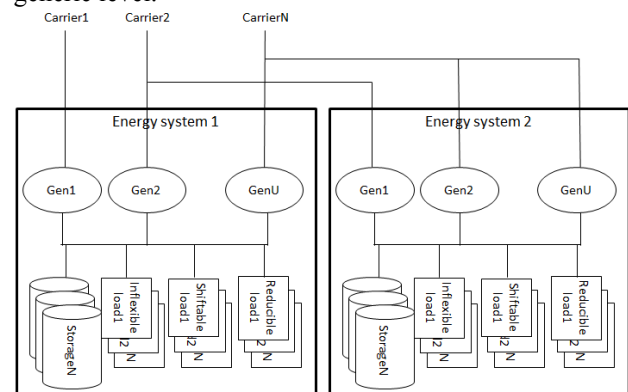


Figure 1. General technology model

The optimization objective is to minimize the total energy costs. These consist of the following elements: Cost of purchase of primary external energy carriers (split into energy related prices and capacity prices), disutility costs related to loss of comfort from reducing loads and negative costs related to sell back of surplus energy.

The objective is mathematically formulated below:

$$\min z = \sum_{s \in S} R_s \cdot \left[\sum_{a \in A} \sum_{t \in T} (P_{a,t,s}^{\text{var}} \cdot \chi_{a,t,s}^{\text{net-in}}) + \sum_{a \in A} (P_a^{\text{cap}} \cdot \chi_{a,s}^{\text{max}}) + \sum_{d \in D} \sum_{y \in Y} (X_{d,y} \cdot \sum_{t \in T} \varphi_{d,y,t,s}) - \sum_{a \in A} \sum_{t \in T} (P_{a,t}^{\text{sales}} \cdot \chi_{a,t,s}^{\text{net-out}}) \right]$$

where the indices reflect sets: S: scenarios, A: energy carriers, T: time periods, D: load units, Y: internal energy systems. The Ps represent prices for the variable part of the energy fee for an energy carrier, capacity fee and sales price, respectively. X represents the disutility cost for load reduction and the χ s represent net import of energy carrier, maximum import of energy carrier and net export of energy carrier respectively. φ represents the amount of load that is reduced. Finally R is the probability for the scenario to be realized.

In addition several constraints must be formulated to cover restrictions related to the energy carriers, generating units, storage units and load units, e.g. efficiency parameters, max/min levels and max number of load reductions. The constraints for load flexibility will require binary variables, turning the model into a mixed integer problem.

Finally we know that when the model is going to decide a

schedule, some of the parameters will possibly be uncertain. This may be the case for the consumption in the load units, for some of the electricity prices and for wind speed and solar radiation.

A deterministic approach will give the optimal decisions under the assumption that the true realized values of the uncertain data proves to be equal to the expected values. In real life this hardly happens, and the result then often turns out to be bad or even impossible to implement (infeasible).

Our model handles the uncertainty through a stochastic programming approach where the uncertain parameters are represented in a scenario tree. Each scenario consists of a possible realization of the uncertain parameter and an associated probability.

CASE STUDY

A simplified case study has been performed in order to verify the model and to illustrate the application. As a starting point a real building (housing a university college in Norway) is selected, and metered values for the total energy consumption for a 3 days' horizon in January 2010 have been collected.

The contract regime for the building is assumed to be based on elspot-prices (real prices are collected from NordPool Spot) and a grid contract with a constant energy fee, 0,23 NOK/kWh and a monthly capacity fee, 96 NOK/kW, based on actual maximum imported kWh/h for the month.

Consumption information is given as a total value for each hour, so we have done some rough assumptions in order to split consumption into each sub system. Information about possibilities to shift or reduce loads has also been missing. Even here some rough assumptions, but modest volumes, have been made to be able to test the model.

The internal energy system is divided into 2 sub-systems: one electricity specific and one heating specific. An overview of the total system is given in the figure below.

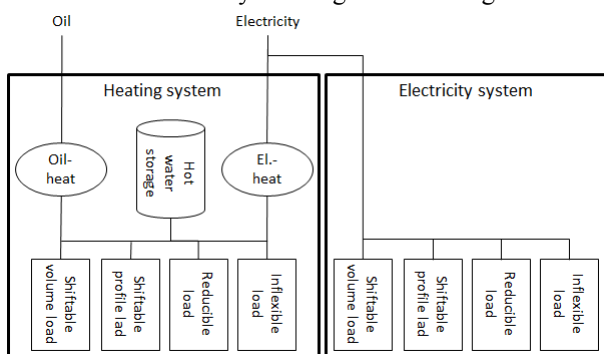


Figure 2. Technology model

The electricity system is supplied with electricity only from the external grid, but the heating system has two generators: one oil-to-hot-water unit and one electricity-to-hot-water unit. Each unit has installed capacity large enough to supply the entire heating demand. The heating system has a

storage unit and both systems have inflexible loads, shiftable profile loads (with earliest start hour 1, latest end hour 3), shiftable volume loads (with earliest start hour 12, latest end hour 16) and reducible loads (max 20% reduction between 8 and 16. Max reduction duration 4 hours, minimum time between two reductions 2 hours and max 2 reductions in the planning period).

The total energy consumption has a characteristic profile going from a steady level at approximately 1000 kWh/h from hour 1 to 7, then increasing steeply to a steady level at app. 3000 kWh/h from hour 9 to 17 and then a reduction until hour 24, see figure below.

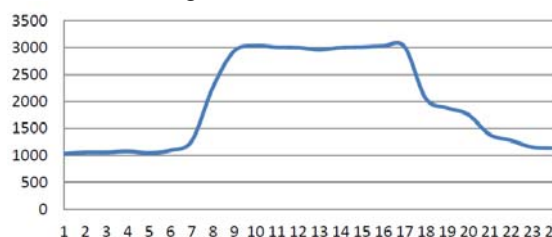


Figure 3. Metered energy consumption January 5th 2010

For the analyzed period there exists no information about what parts of the energy consumption that are related to the heating and the electricity system. As a rough assumption we have split the total consumption by allocating 70% to the heating and 30% to the electricity system.

Price information is as given in the figure below (values in NOK/kWh), where we see quite small differences in the electricity prices (based on NordPool Elspot + variable fee on the grid tariff). Price for oil is assumed 0,7 flat.

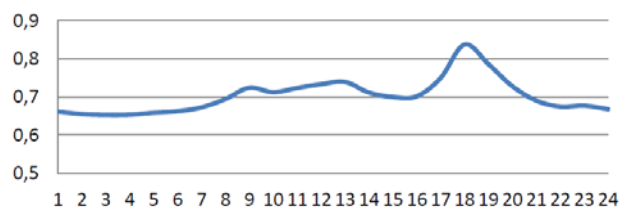


Figure 4. Price profile

In the analysis it is assumed that prices and consumption is known (certain) for the first day. For the second and third day 2 scenarios are assumed, where one scenario is based on historic prices and consumption, while the other has a 20% increase in price and 5% increase in consumption. Equal probability is assumed for the two scenarios.

The mathematical model is implemented in FICO Xpress-Mosel, and a variety of cases has been tested. In this paper we highlight 2 cases, both run for the same 3 days:

Case 1: No flexibility serving as a baseline strategy, where the energy system is run without utilization of flexibility (in line with current strategy)

Case 2: Full flexibility where utilization of the flexibility options are optimized according to input prices and flexibility constraints

Each case is analyzed for a situation where the peak hour is inside the planning period (i.e. the model minimizes the max electricity import since the max in these days will be the basis for the capacity fee) and a situation where the peak hour for the month is outside the planning period.

In reference to the objective function (see mathematical formulation in previous chapter) the first situation includes the first part (cost of energy related prices), while the second situation in addition includes the capacity fee part. Since the analyzed case has 0 disutility cost and no internal electricity generation or possibility to export heat, the 3rd and 4th part of the objective function will not be active in this case.

Table 1 shows the total costs reported from the model for the 2 cases and the 2 situations (figures in kNOK):

Total costs	No-flex case	Flex-case	Diff
Peak hour inside planning horizon	102,0	99,4	2,6
Peak hour outside planning horizon	124,5	108,5	16,0

Table 1. Overview of total costs

The difference in costs between the cases stem from switching between electricity and oil-fired water heater, load reduction, load shifting and usage of the hot water storage.

We see that the cost savings related to the energy price are 2,6 kNOK for 3 days. Assuming that this saving is representative for the whole month the aggregated cost saving would be app. 27 kNOK.

In the case where the peak hour is inside the planning period, the model reduces the max electricity load (kWh/h) from app. 3000 to app. 1000. Main contribution to this effect stems from energy carrier substitution from electricity to oil. Assuming that a 2000 kWh/h reduction is representative for the whole month, total cost savings would be app. 165 kNOK (including the energy fee savings).

CONCLUSION AND FURTHER WORK

We have proposed a general stochastic mixed integer model to support decisions for the day-ahead scheduling problem for flexible consumers and prosumers participating at retail side of the electricity market with dynamic price contracts. The model covers a variety of technologies and pricing regimes. Results from a test case indicate cost saving even with existing price regime and variability. However, a more detailed study should be performed, where the internal energy system is modeled more detailed and with realistic parameters, in particular for the flexibility.

Further research should focus on active market participation by trading actively in the market, for instance through an aggregator.

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REFERENCES

- [1] Ottesen, S.Ø., 2012, "How demand side can provide operational flexibility to the power system through a holistic aggregator concept". *International Journal on "Technical and Physical Problems of Engineering"*, 2012. 4(13): p. 144-148.
- [2] Wakefield, M., 2010, "Methodological Approach for Estimating the Benefits and Costs of Smart Grid Demonstration Projects", 2010, EPRI: Palo Alto, CA.
- [3] Aghaei, J. and M.-I. Alizadeh, 2013, "Demand response in smart electricity grids equipped with renewable energy sources: A review". *Renewable and Sustainable Energy Reviews*, 2013. 18(0): p. 64-72.
- [4] Albadi, M.H. and E.F. El-Saadany, 2008, "A summary of demand response in electricity markets". *Electric Power Systems Research*, 2008. 78(11): p. 1989-1996.
- [5] Dodrill, K., 2011, "Demand Dispatch: Intelligent Demand for a More Efficient Grid", 2011, National Energy Technology Laboratory.
- [6] Agnetis, A., et al. 2011, "Optimization models for consumer flexibility aggregation in smart grids: The ADDRESS approach", *Smart Grid Modeling and Simulation (SGMS), 2011 IEEE First International Workshop on*. 2011.
- [7] Shandurkova, I., et al., 2012, "A Prosumer Oriented Energy Market - Developments and future outlooks for SmartGrid oriented energy markets", *IMPROSUME Publication Series #32012: <http://www.ncesmart.com/Documents/SOTA%20Improsume%20Final%20version%20B.pdf>*.
- [8] Conejo, A.J., J.M. Morales, and L. Baringo, 2010, "Real-Time Demand Response Model". *Smart Grid, IEEE Transactions on*, 2010. 1(3): p. 236-242.
- [9] Del Granado, P.C., S.W. Wallace, and Z. Pang, 2012, "The value of electricity storage in domestic homes: A smart grid perspective". *Energy Systems to appear*, 2012.
- [10] EnRiMa, 2012, "Energy Efficiency and Risk Management in Public Buildings. Deliverable D4.2: Symbolic Model Specification", 2012: Universidad Rey Juan Carlos.
- [11] Siddiqui, A., 2010, "Optimal Control of Distributed Energy Resources and Demand Response under Uncertainty", *IAEE's Rio International Conference*, Brazil, June 2010.