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Economic energy distribution and consumption in a microgrid Part 2: Macrocell level controller

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Abstract: Energy management of a small scale electrical microgrid is investigated. The microgrid comprises residential houses with local renewable generation, consumption and storage units. The microgrid has the possibility of connection to the electricity grid as well to compensate energy deficit of local power producers. The final objective is to fulfil the microgrid's energy demands mainly from the local electricity producers. The other objective is to manage power consumption such that the consumption cost is minimum for individual households. In this study, a hierarchical controller composed of three levels is proposed. Each layer from bottom to top focus on individual energy consuming units, individual buildings, and the microgrid respectively. At the middle layer, a model predictive controller is formulated to schedule the building's energy consumption using potential load flexibilities. The top level energy manager is designed to distribute available power resources among the houses or sell the remainder to the electricity grid. Simulation results show the economically optimal energy consumption in the buildings and economically efficient power trading between the houses.

Keywords: Microgrid control; Demand side energy management; Model predictive controller; Indirect control; Intraday electricity market price.

1. INTRODUCTION

The global movement is toward power production mostly using renewable energy resources rather than using fossil fuels which are environmentally polluting and are being depleted very fast. These renewable energy resources, for instance solar, wind, biomass and geothermal are, by their nature, highly distributed compared to large concentrated nuclear or fossil-fuel power stations. Regaining power balance and allocation of resources in such a diverse and distributed energy market will be two big challenges. Smart grid as a newly emerging concept to be built upon the existing infrastructure of power grid is to facilitate the coordination among all the contributing production, consumption and storage units. In this scheme, a single small-scale power consumer will be no longer an inactive component, but potentially will contribute to energy management of the smart grid by providing flexibility. Capability of power generation using local generation units and making use of storage devices increase flexibility of the grid nodes.

Several world-wide studies have been conducted recently to propose new market, communication, and control layouts for the emerging large scale distributed energy systems. Encourage, NeogridEU, iPower and FlexPower are examples of many ongoing European and Danish projects that are going to develop methodologies with different approaches to overcome the smart grid imbalances.

1.1 Research Questions and Objectives

Embedded intelligent controls for buildings with renewable generation and storage (ENCOURAGE) aims to develop embedded intelligence and integration technologies that will directly optimize energy use in buildings and enable active participation in the future smart grid. The target energy saving for a network of buildings composed of distributed energy consumption, production and storage units is 20% via design of supervisory control schemes that coordinates among interplaying energy devices and buildings Skou and et. al. (2010).

As part of *Encourage*, we are going to design a supervisory controller that integrate and manage all energy units in the microgrid. The objectives are as follows:

- Energy needs of the microgrid are, as much as possible, to be provided by local generation units which are Photo Voltaic (PV) cells in our case study. The purpose is to minimize dependency to the grid power.
- The other objective is to minimize electricity consumption costs of individual households.
- The energy manger i.e. a supervisory controller is supposed to work with the existing single loop controllers in the building for instance heating thermostats.

However, the first two objectives might be conflicting, in which case priority would be with individuals' benefit. For example, there might be time intervals, during which power demand of a house exceeds its production. Assuming that power is provided by the grid at a lower price rate than the neighbouring production units in the microgrid, power would be purchased from the grid. On the other hand, policies could be enacted to promote balance between power production and consumption within the microgrid, for instance price of the locally produced power could be kept always lower than the grid electricity price.

The last objective is to be fulfilled by design of a hierarchical control structure that is shown in Fig. 1. The hierarchy is explained in Section III in more details.

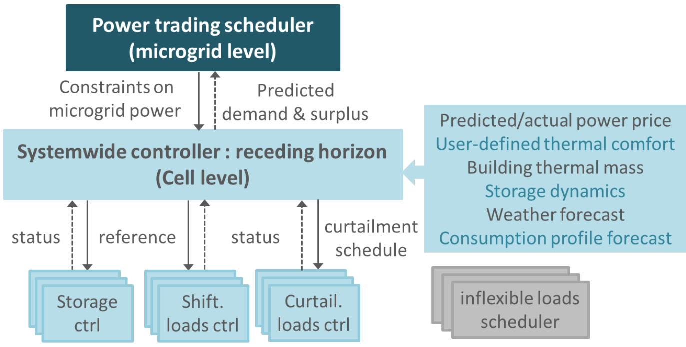

Fig. 1. Controller hierarchy for the microgrid energy management

1.2 Literature on Demand-Side Load Management

There are two mainstream approaches for energy consumption/production management toward a smarter electric grid i.e. direct and indirect control. The former relates to a set-up where an energy node in the grid informs the aggregator of its potential flexibility on consumption or production. The load flexibility is to be provided by means of some storage facilities. In return, the aggregator controls the unit based on the predicted flexibility within the limits and costs agreed upon in advance Biegel (2012). In the latter approach, price incentives are sent to distributed energy resources in order to encourage individual units for example detached houses, residential or office buildings to consume electricity when energy surpluses in the grid by shifting their power demands, and use local energy resources or the stored energy when there is power congestion or deficit in the grid Pinson (2012); Moslehi and Ranjit (2010).

The concept of indirect control within the smart grid is conceptually studied and classified in two main categories in Heussen et al. (2012b). One type of indirectness involves not direct control command but only an incentive. Operation of electrical power systems based on nodal price control was firstly addressed in the studies conducted by Fred Schweppe which is summarized in Schweppe et al. (1988). Many researches were conducted ever since studying different aspects of market-oriented approach for the electrical power system sector Jokic et al. (2009); Alvarado (1999); Alvarado et al. (2001); Alvarado (2003).

A novel generalized framework for modelling a storage node in the grid is proposed in Heussen et al. (2012a). It models any type of interactions among the energy generators/consumers and storage devices, energy leakages in transmission lines and due to energy conversions via definition of a generic power node. A control-oriented approach to modelling and optimization of microgrids is proposed in Parisio and Glielmo (2011). It exploits Model Predictive Control (MPC) in combination with Mixed Integer Linear Programming (MILP) Bemporad and Morari (1999). Load shifting based on price incentives for households in a microgrid is addressed in recent studies using optimal controller in Pedersen et al. (2011). MPC was previously addressed in Tahersima et al. (2012) for heating load management of a single residential building. Also, Tahersima et al. (2011) suggests an assistant chart that quantifies energy flexibility of households.

Main focus of the current work is on indirect control of households' energy consumption in a microgrid. A model predictive controller is formulated that systematically finds the energy consumption pattern of flexible loads provided that knowledge about other loads and productions and the building dynamics are available. In the proposed scheme electricity can also be sold to the grid and consumption can be curtailed if convenient. In contrary to the available literature, a hierarchical controller rather than a centralized one is proposed . The first advantage is that the existing stand-alone single-loop controllers at the device level are exploited. The new integrating and optimizing layer connects to the lowest layer by commanding a general reference signal to the single loop controllers. The systemwide controller is designed in a receding horizon fashion in order to incorporate building energy flexibilities based on a dynamical model, future preferences and disturbances.

The paper is structured as follows: the microgrid case study is described in the next section. Section III describes the hierarchical control strategy for energy distribution in the microgrid in more details. Focus of the paper is explained in this section. The optimal pattern for energy consumption of one building is achieved by solving an on-line optimization problem which is formulated based on the receding horizon control approach in Section IV. Section V presents the simulation results that compares cost benefits of the economic controller against the energy optimizing controller. Finally, Section VI concludes the paper.

1.3 Nomenclature

All the parameters and control variables that we used in the formulations are described in Table I.

2. A MICROGRID OF SEVERAL DETACHED HOUSES

In this section the main characteristics of the concerned microgrid are summarized . Although a specific microgrid is describe, the formulations can be generalized to any similar microgrid system.

One of the demonstration sites of the Encourage project that is the focus on in this study, is a network of eight residential buildings i.e. detached houses located in Northern Denmark. Each house is equipped with Photo Voltaic (PV) cells with capacity of producing 4kW of electricity. Thus, electricity needs of an individual house is provided partly by solar cells and the remainder could be bought from both other producers in the microgrid and the main electricity grid. That depends on the energy price provided

Table 1. Symbols and Subscripts

Nomenclature	
A	surface area (m^2)
C	thermal capacitance ($kJ/kg\,°\mathrm{C}$)
h	sampling time
K_p	proportion gain
N	prediction horizon
Q	power flow (kW)
t	time
T	building temperature (°C)
T_{int}	integration time
U	thermal transmittance ($kW/m^2\,°\mathrm{C}$)
w	electricity power (kW)
$\rho_{discomf}$	discomfort weight in the cost function ($DKK/°\mathrm{C}$)
ρ_{buy}	electricity buying price from grid (DKK/kWh)
ρ_{sell}	electricity selling price to grid (DKK/kWh)
ρ_{curt}	curtailment weight in the cost function (DKK/kWh)
ξ	integral state
β	curtailment coefficient
Subscripts	
buy	buying (power or price)
cmf	comfort (temperature)
$heat$	electrical floor heating (heat flow)
k	current time instant
out	outdoor (temperature)
pv	photo voltaic (power)
ref	reference (of building temperature)
$sell$	selling (power or price)
tol	tolerance (temperature defined by users)

by each energy source. Indoor air is heated by electrical floor heating in the houses. Measurements show that electrical space heater, electric water heater, appliances, and lighting respectively account for highest to lowest power consumption in a building. A satellite view of the houses taken from Google map is depicted in Fig. 2.

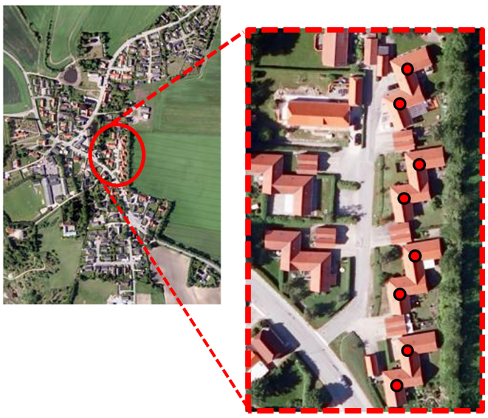

Fig. 2. The demonstration site including 8 residential houses with photovoltaic cells on top of the roofs

All the houses are similar and very well insulated. The houses are occupied by diverse types of families i.e. young couples, families with children and pensioners who are couple or single. The chosen occupancy diversity allows testing different consumption profiles for load control and energy exchange between the houses which is the normal case in a medium to large scale power island. Some houses are occupied mostly in evenings and weekends, while the others consume power often times during a week.

The microgrid is always connected to the grid. Therefore the islanded-mode is never imposed to the microgrid physically. However, the strategies should be enacted in order to make it as independent as possible from the grid. Therefore, it can purchase and sell electricity from/to the grid at any time. However, the objective is to make the trading in only one direction at a time, meaning that as long as there is power demands in the microgrid, no power will be sold to the grid.

The microgrid local power generators are renewable, non-dispatchable sources. There is no specific energy storage device to store energy for a later use. However, the building thermal mass is a dynamic energy buffer which can be charged in a controlled way, but the discharge is not controllable, although is predictable. The stored energy, naturally is in thermal form. Thus, this storage capacity makes the heating and cooling loads flexible to a certain degree determined by the building dynamics.

3. ENERGY MANAGEMENT STRATEGY

The optimal use of storage capacity and the loads can help to keep the balance in the microgrid. For this purpose we need to define flexibility of energy loads of the buildings which are building blocks of our microgrid.

We have categorized various energy loads in the building to three types i.e. shift-able loads, curtail-able loads and non-flexible loads. The last type of loads are not controllable for example appliances and multimedia devices that are directly interfered with by the user. The first two types are controllable, although differently which depends on the type of the variable being controlled and residents expectation of comfort. To give an insight, lets compare heating with lighting; A heater is controlled normally to maintain a specific thermal comfort criterion which is often specified either by a profile of reference temperature or upper and lower boundaries. In either case, time interval of heating possibly can be shifted depending on inherent heat capacity of the building and thermal tolerance degree of the building's residents. For example, the larger heat capacity of the building and the higher tolerance of the occupants, flexibility in time of heating is higher. On the other hand, light is not store-able and it is needed instantly. Therefore, it would only be possible to cut down or dim the light when it is not needed for instance when daylight is available or motion is not detected in the room. For a taxonomy on different type of loads please see Petersen et al. (2013).

The control hierarchy as shown in Fig. 1 composes three different layers. The task of each layer and the connection between the layers are described in the following.

- Device layer at the bottom of hierarchy comprises single loop controllers for controllable (shift-able and curtail-able) loads, controllable generation units (not available) and storage devices (not available). It is responsible for maintaining set-points and light adjustment.
- Cell (building) level at middle of hierarchy includes a system-wide controller that keeps the economy and comfort in balance. It minimizes the cost of electricity consumption while maintaining the comfort levels determined by the user. A priori knowledge about building dynamics, comfort preferences, weather changes,

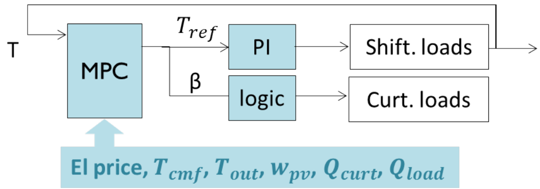

Fig. 3. Block diagram of the hierarchical supervisory controller. Inputs to the MPC are: Electricity intra-day market price, Pre-set user-defined comfort temperature (T_{cmf}), forecast of outdoor temperature (T_{out}), Prediction of electricity generation by PVs (W_{pv}), Predicted consumption profile of curtail-able (Q_{curt}) and non-flexible loads (Q_{load}). Output control signals are: a reference temperature (T_{ref}) to HVAC system controller and a coefficient of curtailment (β) to the lighting system controller.

power generation and price of electricity are needed. The forecast inputs are supplied by a prediction module which is part of *Encourage*. This layer receives status signal from device controllers i.e. heating/cooling thermostats and provide them with reference signals.

- Microgrid level at the top is responsible for distribution of locally generated energy among households with energy demands. It receives predictions of power surplus profile (for sale) and power needs profile (to be purchased) from the system-wide controllers in the middle. Based on these inputs, it predictively assigns surplus power in the microgrid among the demanding houses. The system-wide controller is designed such that power produced by PVs are consumed by the producing house at the first place. The excess is distributed by the power trading scheduler among the other houses with power deficit. It predictively determines the constraints on the amount of buying energy and selling energy for each house in the microgrid.

4. CELL-LEVEL CONTROLLER

Block diagram of the hierarchical supervisory controller at the cell level is depicted in Fig. 3. We have chosen Model Predictive Controller (MPC) as the system-wide controller Maciejowski (2002). The reason for this choice is that, all the system disturbances and future references can systematically be incorporated into the MPC. On the other hand, the middle layer has to provide a foreseen estimate of surplus and demand power to the power scheduler at the top layer. This feature would already be embedded in the system-wide controller if we choose a receding horizon controller. At the bottom layer we have designed Proportional Integral (PI) controller for heating loads. Light curtailment is done based on inputs from sensors measuring light or detecting motion.

4.1 Optimization Problem

The optimization problem is formulated in a receding horizon framework. An economic solution is achieved by penalizing power purchase from the utility grid and the microgrid in the cost function. Economic benefit of power sale to the grid and microgrid is also incorporated. Also, discomfort i.e. deviation from a comfort temperature profile is penalized. The other term in the cost function is related to curtailment penalty.

$$
\begin{aligned}
&\min_{T_{ref},\beta,w_{sell},w_{mgsell},w_{mgbuy}} \sum_{k=1}^{N}(\rho_{discmf}(k)|T(k)-T_{cmf}(k)| \\
&+\rho_{buy}(k)w_{buy}(k)+\rho_{mgbuy}(k)w_{mgbuy}(k)+ \\
&\rho_{curt}\beta_{curt}(k)Q_{curt}(k))- \\
&\rho_{sell}(k)w_{sell}(k)-\rho_{mgsell}(k)w_{mgsell}(k) \\
&s.t. \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (1)\\
&T(k+1)=a_{11}T(k)+a_{12}\xi(k)+b_1T_{ref}(k)+e_1T_{out}(k) \\
&\xi(k+1)=a_{21}T(k)+a_{22}\xi(k)+b_2T_{ref}(k) \\
&Q_{heat}(k)=c_1T(k)+c_2\xi k+dT_{ref}(k) \\
&0\le Q_{heat}(k)\le Q_{max} \\
&-T_{tol}(k)\le T(k)-T_{cmf}(k)\le T_{tol}(k) \\
&0\le\beta_{curt}\le 1 \\
&0\le w_{sell}(k) \\
&0\le w_{mgbuy}(k)\le w_{mgbuy}^{max}(k) \\
&w_{mgsell}^{min}(k)\le w_{mgsell}(k) \\
&w_{buy}(k)+w_{mgbuy}(k)=Q_{heat}(k)+(1-\beta(k))Q_{curt}(k) \\
&+Q_{load}(k)+w_{sell}(k)+w_{mgsell}-w_{pv}(k)
\end{aligned}
$$

in which k is the time instant and N is the prediction horizon. ρ_{discmf} and ρ_{curt} are coefficients of penalty for thermal discomfort and curtailment of the appertaining curtail-able loads, respectively. Control variables are curtailment coefficient β, sold power to the grid w_{sell}, sold power to the microgrid w_{mgsell} and the reference temperature of the building T_{ref}. Predicted signals and system disturbances include comfort temperature profile T_{cmf}, buying and selling price with the grid: ρ_{buy} and ρ_{sell}, buying and selling price within microgrid: ρ_{mgbuy} and ρ_{mgsell}, discomfort penalty ρ_{discmf}, curtailment penalty ρ_{curt}, curtail-able and inflexible loads Q_{curt} and Q_{load}, and electricity generation of PV cells w_{pv}, all for the next 24 hours. Amounts of energy for buying and selling appear in the same equations, but optimization will not result in buying and selling amounts to be non-zero in the same time step if as assumed $\rho_{sell}\le\rho_{mgsell}\le\rho_{mgbuy}\le\rho_{buy}$. Boundaries on building temperature T_{tol} and maximum heat flow Q_{max} are the known parameters.

The two boundaries on trading power with the microgrid are supplied by the macrocell-level controller. It determines the minimum power which can be purchased from the microgrid w_{mgsell}^{max}, or the maximum power which can be purchased by the microgrid w_{mgbuy}^{max}.

Prediction model in the MPC governs a closed loop system of the building and floor heating with PI control. Building dynamics are described using a first order model. PI controller parameters K_p and T_{int} are determined using a step response test. Considering the sampling time $h=t_{k+1}-t_k$, thermal capacitance of the building envelope and furniture C, and total thermal transmittance of the building envelope UA parameters of the closed-loop discrete time system are: $a_{11}=1+\frac{h}{C}UA$, $a_{12}=\frac{h}{C}$, $b_1=\frac{h}{C}K_p$,

$e_1 = \frac{h}{C}UA$, in the second line $a_{21} = h\frac{K_p}{T_{int}}$, $a_{22} = 1$ and $b_2 = h\frac{K_p}{T_{int}}$, and in the last line $c_1 = -\frac{h}{C}K_p$, $c_2 = \frac{h}{C}$ and $d = \frac{h}{C}K_p$. For a detailed description on deriving the closed loop model please see Tahersima et al. (2013).

The design of building-level controller in Tahersima et al. (2013) was studied via simulations and included a discussion how to determine the controller coefficients. In the next section the structure of the microgrid-level energy scheduler is described and an algorithm for running the whole hierarchical controller is proposed.

5. MACROCELL LEVEL CONTROLLER

Electricity demand of the houses in the microgrid are to be supplied by the locally installed PV cells. The positive remainder electricity will be sold to the grid and the negative remainder will be purchased from it. Each house fulfills its own power demand at the first place. The second priority is the microgrid's energy demand. The power scheduler is designed according to this consumption strategy as described in the following.

5.1 Power Trading Method

The total power surplus and demand in the microgrid will be predicted at every time step h for the time horizon of N time steps, see Fig. 4. For this purpose, we rely on the predicted power surplus and demand by the MPC.

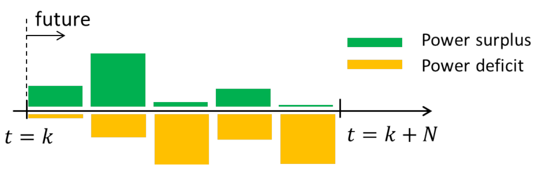

Fig. 4. Prediction of power surplus and deficit in the microgrid as a function of time

The prediction of power for sale or purchase in the next 24 hours for all the houses gives us total power demand and surplus in the microgrid:

$$w_{demand}(k) = \sum_{i=1}^{M} w^i_{buy}(k)$$
$$w_{surplus}(k) = \sum_{i=1}^{M} w^i_{sell}(k) \quad (2)$$

for $k = 1, ..., N$, the time step, N represents the prediction horizon and for $i = 1, ..., M$, with M a the total number of houses.

A share of total power surplus will be assigned to each demanding house. For a fair distribution, this share will be proportional to the house's demand as described in the following.

$$w^{max}_{mgbuy}(i,k) = \frac{w^i_{buy}(k)}{w_{demand}(k)} w_{surplus}$$
$$w^{min}_{mgsell}(i,k) = \frac{w^i_{sell}(k)}{w_{surplus}(k)} min(w_{surplus}, w_{demand}) \quad (3)$$

5.2 Power Management Algorithm

The algorithm through which the hierachical controller manages power distribution and consumption in the microgrid is given in this section. At each time step the following steps are performed.

- Step 1- At $t = k$ solve the MPC optimization problem for each house neglecting all terms related to w_{mg} both in the cost function and constraints. Thereby w_{buy}, w_{sell}, Q_{heat} and β will be derived.
- Step 2- Calculate constraints on the maximum buying power from the microgrid and minimum selling power to the microgrid using formula (2) and (3).
- Step 3- Solve the complete optimization problem for each house considering the constraints on trading power with the microgrid.
- Step 4- References generated by MPC i.e. T_{ref} and β will be sent to the single loop controllers. Actual sold and purchased power will be calculated at the next time step. The total power consumption is:

$$w^i = \begin{cases} w^i_{sell} & \text{if } w^i \geq 0 \\ -w^i_{buy} & \text{if } w^i \leq 0 \end{cases}$$

At $t = k + 1$, we can calculate the actual power sold/purchased to/from the grid or microgrid at $t = k$. If $w^i \geq 0$, then sold power to the grid and microgrid for individual houses are:

$$w^i_{mgsell} = \frac{w^i_{sell}}{\sum_i w^i_{sell}} \times min\left(\sum_i w^i_{sell}, \sum_i w^i_{buy}\right)$$
$$w^i_{gsell} = w^i_{sell} - w^i_{mgsell} \quad (4)$$

If $w^i \leq 0$, then purchased power from the grid and microgrid for individual houses are:

$$w^i_{mgbuy} = \frac{w^i_{buy}}{\sum_i w^i_{buy}} \times min\left(\sum_i w^i_{sell}, \sum_i w^i_{buy}\right)$$
$$w^i_{gbuy} = w^i_{buy} - w^i_{mgbuy} \quad (5)$$

6. SIMULATION RESULTS

Simulation results for energy management of the microgrid case study are presented and discussed in this section. Parameters of the building dynamics are chosen based on data from a low energy building i.e. very similar to the demonstration houses described in Section 2. The sampling time is one hour equal to the time interval of variations in predicted price profile. Predicted signals are assumed to be available one day ahead. This is specifically important for the price profile which is settled in an hourly basis a day ahead in the *Elspot* trading system.

The power price is determined by balance between supply and demand and fixed from 12:45 CET each day to be applied from 00:00 CET the next day Nordpool (2013). Therefore the prediction horizon for MPC is chosen 1 day. Price signals are taken from the Nordpool database for a period of one week in February 2013. Weather data is also taken from Danish Meteorological Institute (DMI). PV cells production data is achieved from Jadevej case study. Power price traded within the microgrid will be set between grid's power prices, such that it encourages the local produces to sell their power to the local customers and the local customers to buy from local producers.

The formulated MPC is implemented in Matlab using CVX optimization toolkit. In the microgrid, two different power consumption profiles are assigned to the houses. Fig. 5 and Fig. 6 depict energy management of two houses with different consumption profiles. Power shifting and shedding are performed based on electricity price, weather data, and prediction of non-flexible loads. Perfect forecast were assumed in all the simulation scenarios in this paper.

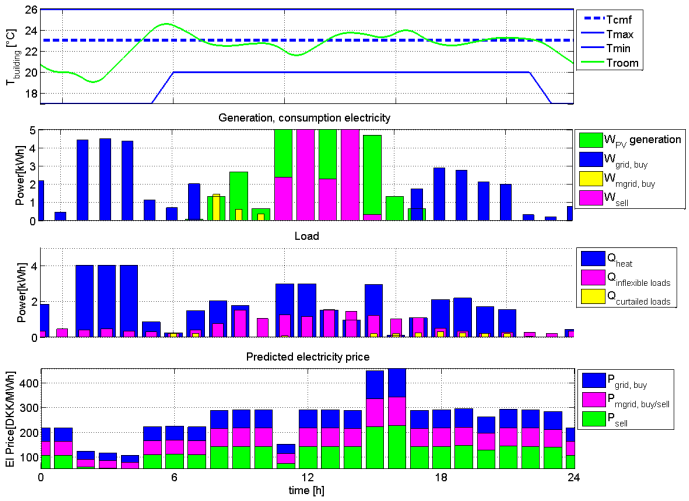

Fig. 5. a) Building type 1- Energy management of the building with more power consumption and less flexibility. comfort temperature is 23 °C and it is limited between 20 and 26 °C in the comfort zone. $Q_{curtailed}$ is the power consumption after curtailment i.e. $(1-\beta)Q_{curt}$. At the peak of price, the flexible loads are zero and only inflexible load is consuming the expensive power.

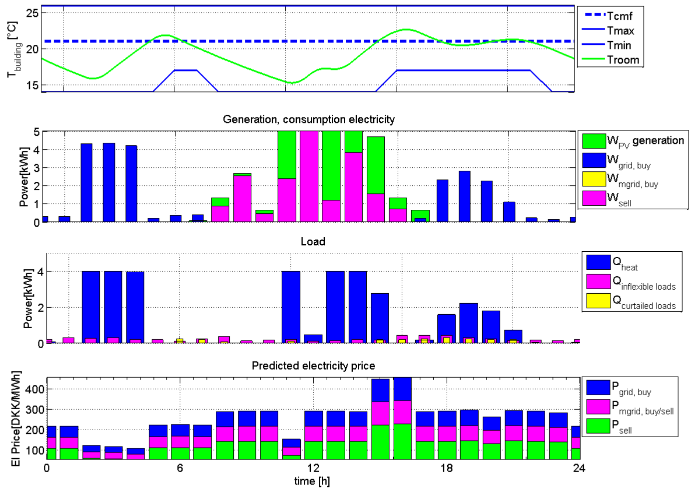

Fig. 6. b) Building type 2- Energy management of the building with less power consumption and more flexibility. comfort temperature is 20 °C and it is limited between 17 and 26 °C in the comfort zone.

Comparison of the 8 houses are depicted in the next four figures: Fig. 7, Fig. 8, Fig. 9, Fig. 10.

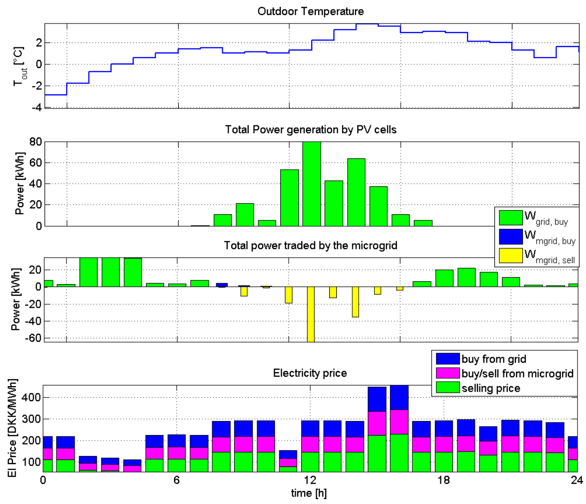

Fig. 7. . Outdoor temperature, total power generation by PV cells, power consumption and traded power

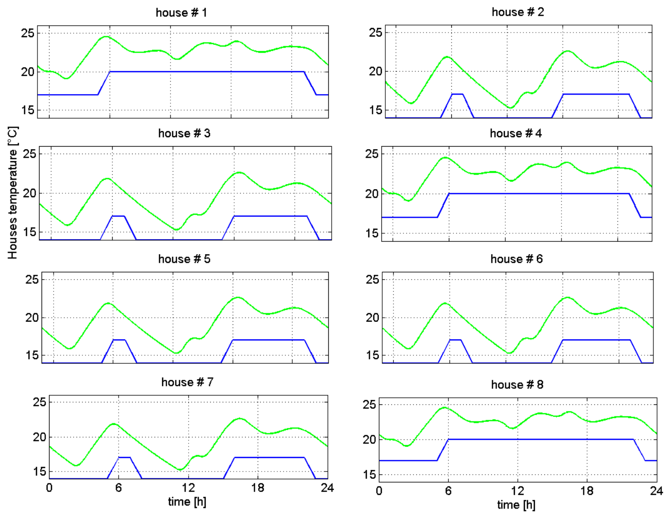

Fig. 8. Indoor temperature variations of each house is shown

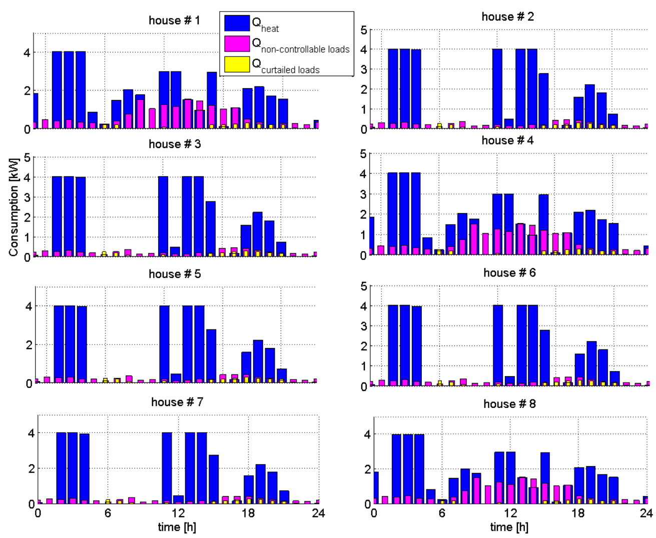

Fig. 9. Power consumption of houses loads

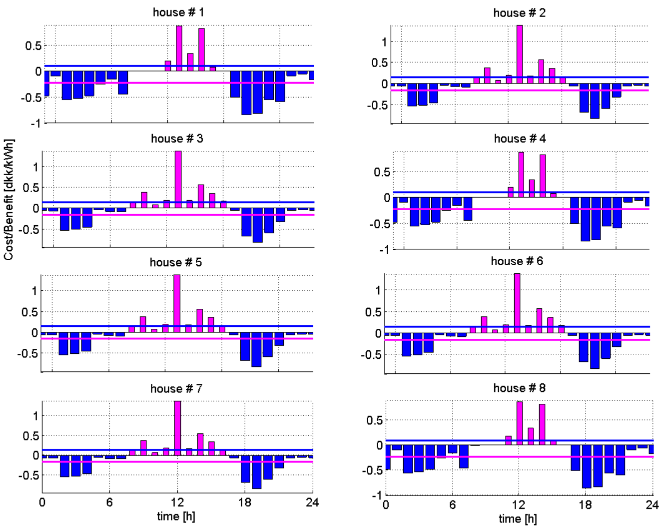

Fig. 10. Power traded with the grid and within the micro-grid. Average sold and purchased power is shown.

Cost of consumption for house type 1 has been 6.6 DKK per day while it was 4.5 DKK per day for the house type 2. Moreover, the monetary benefit of selling power is 2.26 and 3.36 for houses type 1 and 2 respectively. In total, the cost benefit of more flexibility in type 2 compared to type 1 was 73% which is considerable. It is worth mentioning that the energy price does not include tax which is in fact a large share of power price in Denmark. Considering 70% tax the monetary benefit due to consumption shift will be negligible. However, in future a high rate of tax might be diminished or redistributed in order to encourage consumers to be flexible.

7. CONCLUSION

The paper suggests a hierarchical control structure as an energy management system of a microgrid. MPC in the building-level works in combination with device layer controllers by supplying them with control references. The results show that with reliable price predictions substantial savings in energy costs are obtainable for a consumer which implement a predictive controller. The microgrid level energy manager schedules energy distribution in the microgrid based on the buildings demand and surplus in every iteration. The prediction of disturbances and grid prices assumed perfect which is not realistic. In the future studies we consider prediction error and uncertainties in the study.

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