Integrated Operation of Distributed Generation Sources and Load Responses in Microgrid

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Abstract
In this paper a comprehensive model for optimally operating a microgrid has been presented. By managing the demands at consumer side as well as Distributed Generation (DG) sources, in a 24 hours span, the microgrid is able to maximize its revenue through participating in energy and reserve market in this model. Here, the effect of real time electricity price for consumers is considered as an effective incentive for controlling energy demands and operation costs of microgrid. In proposed model, in addition to technical and economic limitations, security constrains of microgrid, the ability of energy transfer to and from neighboring microgrids and uncertainties in Renewable Energy Sources (RES) and consumers’ demand have also been considered. This model turns out to be a Mixed Integer Non-Linear Programming (MINLP) problem which has been solved by DICPT solver in GAMS software. Case studies on a 32 bus distribution test system shows that by applying the proposed method, in comparison with fixed electricity price tariff, the distribution company could increase the revenue of participants by modifying the consumption pattern and also operate the distributed energy sources in distribution network more efficiently.

Keywords: microgrid; distributed energy sources; energy management; demand response; real time electricity pricing.
Introduction

To have a smart grid, grids are transforming from centralized structure they have now days to a cellular structure with smart communication between the elements and in such structures, distributed generations and microgrids with intelligent control and energy management are basic parts of them [1]. Wide penetration of DG, advanced sensors, high speed bidirectional communications, autonomous measuring and controlling devices for managing the loads in response to energy price changes are some of characteristics of microgrids

In microgrids, energy management systems in presence of manageable DG units, random DG units, interruptible loads, Energy storage Units (ESU) and end user loads are the core elements for operating systems. By reviewing literature, we will find many papers tend to optimally operate the microgrids. In [2, 3], decentralized operating strategy has been deployed for operating microgrids. [4-9] support the idea of decentralized control for microgrids and have done the microgrid operating with this approach. In [10] a multi-period optimized model has been introduced for a microgrid with hierarchal controlling approach and this microgrid participate in wholesale energy market and the objective for this model is to maximize revenue (e.g. incomes, costs)

Some constrains such as DG generation ramp up, maximum charging rate, electrochemical discharge rate, maximum charging and discharging capacity are considered and the problem have been solved by advanced genetic algorithm

Authors of [11] have proposed an optimized operating model for microgrids with fuel cells and wind DG units in which all constrains are considered, the objectives of this model is minimize energy costs from the main grid, wind turbines and fuel cells while minimizing overall system losses and pollutants. Operation planning for short term period with two step strategy has been suggested in reference [12]. In first step, a day ahead planning has been performed in which the goal of operator is to minimize overall costs, set up controlling equipment, DG units allocation and electricity bought from wholesale market, next step is dedicated to in-day planning and with more specified data set up points are reconfigured.

In [13], a model for optimum planning of microgrids regarding to multi-period islanding mode has been proposed. The goal is to minimize all the operation costs of a microgrid which are local generation costs and energy bought from the main grid. The optimum planning is then divided to two sub-routines: grid connected mode and islanding mode. Mixed Integer Programing (MIP) has been applied to solve the problem and feasibility of islanding mode is assessed. An operation model for a microgrid with high RES penetration and demand side management while connected to main grid has been investigated in [14]. To model the uncertainties of RES, a stochastic programming approach has been applied. In [15], to ensure sufficient supplying for demands, an optimization programming for a microgrid with RES with probability concept of self-sufficient probability is introduced.

This paper introduces a comprehensive framework for optimal energy management and daily planning for microgrid with high penetration of RES and demand response ability. By applying the proposed model, microgrid could maximize its revenue by participating in energy and reserve markets and selling energy to end users of distribution network. Real time pricing (RTP) of electricity for consumers connected to microgrid, technical and financial parameters of DG units, security constrains of microgrid, the ability of transferring energy to neighboring microgrid and RES generation as well as consumer demands uncertainties are considered in this model.

The paper is organized in three sections. Daily plan modeling of an operator company for a grid with DGs and demand response capability while considering uncertainties in wind turbines generation and consumer demands are discussed in section 2. Section 3 presents a simulation of 32 bus test system with proposed model. Results are delivered and compared in this section.
Modeling the Daily planning of an operator company for a microgrid with RES and RTP

In this section, a mathematical model for daily planning of an operator for a grid with RES and consumer participating in RTP plan and their response to changes in energy prices is presented; the objective of the model is to optimally interact with reserve and energy market. In this daily planning an optimization problem should be solved while considering energy management system with respect to technical and financial issues of DG units and network equipment, market price forecasting, communication with consumers and predicting their demands and also forecasting DG unit generation regarding to:

- Interaction level with energy and reserve market
- Defining the energy price for consumers to manage their demand
- Managing the manageable DG units
- Deciding for interruptible loads
- Energy storage status
- Energy transfer with neighboring distribution networks

Energy transfer with neighboring distribution networks

In proposed model, the goal is to maximize the revenue of operator company. So, the problem is an optimization problem with following objective functions and constrains.

A. Objective function

In this section, a mathematical model for daily planning of an operator for a grid with RES and consumer participating in RTP plan and their response to changes in energy prices is

\[
\text{MAX Benefit} = \sum_{t=1}^{24} \left[ \sum_{i=1}^{n_d} d_i(t) \cdot \rho_i(t) \right] + \sum_{t=1}^{24} \left[ r_i \left( \rho_{E_t} + \rho_{R_t} \right) + (1-r_i) \rho_{R_t} \right] \times R_i

- \sum_{t=1}^{24} \sum_{i \in S_{\text{a}}}(\rho_{\text{a}i} \times P_{\text{a}t}) - \sum_{t=1}^{24} \sum_{i \in S_{\text{a}}}(\rho_{E_t} \times P_{\text{a}t}) - \sum_{t=1}^{24} \sum_{i \in S_{\text{a}}}(C_{\text{EES},t} \cdot P_{\text{EES},t})

- \sum_{t=1}^{24} \sum_{i \in S_{\text{a}}}[r_i \times C_{\text{DG},t} (P_{\text{DG},i} + R_{\text{DG},i}) + (1-r_i) \times C_{\text{DG},t} (P_{\text{DG},i})] \cdot L_t + S\text{TC}_{\text{DG},t} \cdot M_t + S\text{DC}_{\text{DG},t} \cdot N_t

\]

The first and second parts of eq. 1 represent the income from selling energy to consumers and participating in spinning reserve market, while the third and fourth parts are the costs of transferring energy with neighboring network and buy/sell energy from market. Other parts in this equation indicate operation costs of ESDs, operation costs of manageable DG units and start up and shut down costs and finally costs corresponding to interruptible loads, respectively.

B. Constrains

- Energy demand constrains

Demand response to energy price variation in day time:

In RTP plan, energy usage of consumers at each hour is recorded by electricity meters and their bills are calculated based on RTP of energy. Consumers being aware of energy price at each time, try to optimally respond to price variations. Each consumer in power system is an independent unit with unique behavior. Different responses to different electricity price scenarios are analytically modeled by Utility Function concept with their corresponding Profit Functions. The concept of demand pricing willingness is represented as an indicator for measuring the response of consumer to price variations.
Consumer response to electricity price variations in a 24 hours span based on initial energy price and initial daily energy demand has been modeled in eq. 2 [16]. This equation shows how RTP plan changes the energy consumption pattern of consumer and how the optimum efficiency of consumer demand could be reached by this program. It is important to note that the initial energy demand and initial electricity tariff are predefined and RTPs are sent to the consumers.

\[
d_e(t) = d_{ac}(t) \left[ 1 + \frac{E_c(t)[\rho_c(t) - \rho_{ac}(t)]}{\rho_{ac}(t)} + \sum_{h=1}^{24} E_c(t, h)[\rho_c(h) - \rho_{ac}(h)]/\rho_{ac}(h) \right]
\]

(2)

• Manageable DG units constrains:

DG constrains:

\[
P_{DG,i}^\text{min} \cdot L_{t,i} \leq P_{DG,i}^\text{max} \forall i \in S_{DG}
\]

(3)

\[
(P_{DG,i} + R_{DG,i}) \leq P_{DG,i}^\text{max} \cdot L_{t,i} \forall i \in S_{DG}
\]

(4)

Ramp up constrains:

\[
P_{DG,i+1} - P_{DG,i} \leq 60 \times RR_{DG,i} \forall i \in S_{DG}, t = 0, 1, \ldots, (t-1)
\]

(5)

\[
P_{DG,i} - P_{DG,i+1} \leq 60 \times RR_{DG,i} \forall i \in S_{DG}, t = 1, 2, \ldots, (t-1), P_{DG,i}^\text{lim} = 0
\]

(6)

Minimum on-time and off-time:

\[
\sum_{k=1}^{MUT} L_{t+k-1,i} \geq MUT
\]

(7)

\[
\sum_{k=1}^{MDT} (1 - L_{t+k-1,i}) \geq MDT
\]

(8)

\[
0 \leq R_{DG,i} \cdot L_{t,i} \leq \min \left( 10 \times RR_i, P_{DG,i}^\text{max} - P_{DG,i} \right)
\]

(9)

Coordination constrains:

\[
\begin{cases}
L_{t,i} - L_{t-1,i} \leq M_{t,i} \\
L_{t-1,i} - L_{t,i} \leq N_{t,i} \\
L_{t,i} - L_{t,i-1} = M_{t,i} - N_{t,i}
\end{cases}
\]

(10)

• Energy storage constrains:

\[
E_{t,i} = E_{t-1,i} + \eta_{k} \times P_{\text{Ch},i,i} - P_{\text{Dch},i,i} \forall i \in S_{DSS}, t = 0, 1, \ldots, 24
\]

(11)

\[
0 \leq P_{\text{Ch},i,i} \leq P_{\text{max}}^{\text{Ch},i,i}
\]

(12)

\[
0 \leq P_{\text{Dch},i,i} \leq P_{\text{max}}^{\text{Dch},i,i}
\]

(13)

\[
E_{t,i}^\text{min} \leq E_{t,i} \leq E_{t,i}^\text{max}
\]

(14)

\[
P_{\text{Ch},i,i} - P_{\text{Ch},i-1,i} \leq P_{\text{Ch},i,i}^\text{lim}
\]

(15)

\[
P_{\text{Dch},i,i} - P_{\text{Dch},i-1,i} \leq P_{\text{Dch},i,i}^\text{lim}
\]

(16)
打断可负荷的约束条件：

\[
\begin{align*}
\frac{p_{\text{min}}}{p_{\text{max}}} & \leq \frac{P_{\text{IL},t,i}}{F_{t,i}} \leq \frac{p_{\text{max}}}{p_{\text{min}}} & \forall i \in S_{\text{IL}}, \forall t \in S_{t,\text{IL}} \\
\frac{p_{\text{min}}}{p_{\text{max}}} & \cdot F_{t,i} \leq P_{\text{IL},j} + R_{\text{IL},j} \leq \frac{p_{\text{max}}}{p_{\text{min}}} & \forall i \in S_{\text{IL}}, \forall t \in S_{t,\text{IL}}
\end{align*}
\]

网络约束条件：

电力约束条件：

\[
\begin{align*}
\sum_{j=1}^{N} |P_{j,t}||P_{j,t}^{*}| \cos(\delta_{j,t} - \delta_{i,t} + \theta_{i}) \forall i \in S_{\text{IL}}, \forall t \in [0, \ldots, 24]
\end{align*}
\]

\[
\begin{align*}
Q_{\text{IL},j} = \tan^{-1}\left(\frac{Q_{F_{j,t}}}{P_{F_{j,t}}}\right) & \times P_{\text{IL},j}
\end{align*}
\]

电能质量约束条件：

如前所述，维持旋转储备在可接受水平是规划程序中控制不确定性在RES发电和消费者响应价格波动的基础。因此，考虑了风力发电和日常负荷需求的平均值（\(p_{\text{mean}}, \sigma_{\text{mean}}\))和标准差（\(\sigma_{\text{mean}}\))。根据风力发电作为负荷及应用正态分布求和定理，平均每天负荷需求也有平均值（\(p_{\text{mean}}, \sigma_{\text{mean}}\))和标准差（\(\sigma_{\text{mean}}\))，如下（注意，风力发电和负荷需求之间的相关性小（[17]）并因此被忽略）：

\[
\begin{align*}
\mu & = p_{\text{mean}}_{\text{D}_{\text{net}}} = p_{\text{mean}}_{\text{D}_{\text{wind}}} - p_{\text{mean}}_{\text{D}_{\text{wind}}}
\end{align*}
\]

\[
\begin{align*}
\sigma_{p_{\text{D}_{\text{net}}}} = \sqrt{\sigma_{p_{\text{D}_{\text{wind}}}}^2 + \sigma_{p_{\text{D}_{\text{wind}}}}^2}
\end{align*}
\]

在其中，\(P_{\text{DG}_{j,i}}^\text{max}\)是第j号DG单元在第i号编程中的最大DG单元功率发电，定义由 eq. 25：

\[
\begin{align*}
P_{\text{DG}_{j,i}}^\text{max} = \min \left(60 \times R_{\text{DG}_{j,i}} + P_{\text{DG}_{j-1,i}}^\text{max}, P_{\text{DG}_{j,i}}^\text{max}\right)
\end{align*}
\]

因此，等效等式为 eq. 24 是如下：

\[
\begin{align*}
\sum_{i=1}^{K_{\text{DG}_{j,i}}} & \left(\sum_{j=1}^{N} P_{\text{DG}_{j,i}}^\text{max} \cdot L_{t,i} + \sum_{i=1}^{K_{\text{DG}_{j,i}}} + \sum_{i=1}^{K_{\text{DG}_{j,i}}} \left(\eta_{i,k} \times P_{\text{DG}_{k,i}} - P_{\text{DG}_{k,i}}\right) \right) \geq P_{\text{D}_{\text{net}}} + \lambda \sigma_{p_{\text{D}_{\text{net}}}}
\end{align*}
\]

微电网运营商可以定义可接受的可靠性水平为\(\lambda\)。因此，DG单元的数量会增加，同时确保消费者在实时能够得到更高容量。
Feeder limits:
\[ S_{ij,t} (V_i, \delta_i) \leq S^\text{max}_{ij} \]  
Bus voltage limits:
\[ V_i^\text{min} \leq V_{i,j} \leq V_i^\text{max} \]  
Power station capacity:
\[ P_{\text{sub},t} \leq P^\text{max}_{\text{sub}} \]  
Limits of power transfer with neighboring microgrid:
\[ |P_{\text{int},t,j}| \leq P^\text{max}_{\text{int},j} \]  

C. Solving methodology
The proposed model for daily planning by operator is a Mixed Integer Non-Linear programming (MINLP) optimization problem solved by DICOPT in GAMS software [18]. In some special cases, the results delivered by DICOPT may not be the best results. But, this solver has a good capability of dealing with the concavity of different problems, so we could claim that the results by this method are most possibly the best rest results. The non-linear nature of load flow constrains make the whole problem MINLP. Therefore, to increase the possibility of finding optimum solution, first we solve the problem as a Mixed Integer Programming (MIP) problem assuming that all the Distributed Energy Resources (DER) are available at upstream network while neglecting the limits of microgrid; next, the results are used as initial state and inputs of MINLP.

3. Case study and analyzing the results from the proposed model
In this section, we analyze the simulation results applying the proposed model to the 32 bus test system (fig. 1) consisting of the RES listed in appendix. Candidate buses for installing DGs and corresponding capacities are driven from [19]. The data including daily price forecasting, spinning reserve and consumption pattern prediction from NYISO’s LONGL network on July 24th 2013 has been used to investigate the microgrid’s daily planning [20]. Daily load pattern is scaled based on the system load properties. Daily load forecasting, wind units’ generation, energy transferring costs to neighboring microgrids and spinning reserve and energy prices are available in appendix. The consumers are assumed to be in three categories: residential, commercial and industrial user and also all users connected to a single bus are considered to be in one category. Demand traction values for each type of consumers are listed in table 1.

![Fig1:32 radial distribution test system](image-url)
First, the results for distribution company participating in energy market is driven and analyzed. Next, we study the model for participation of the company in energy and spinning reserve markets. In both cases, it is assumed that the consumer is able to increase or decrease 15% of its initial consumption at each hour. Also, 50% of consumers are assumed to be involved in proposed pricing program.

### Table 1: Self and mutual traction values

<table>
<thead>
<tr>
<th>Customer type</th>
<th>Least load</th>
<th>Medium load</th>
<th>Peak load</th>
<th>Least load</th>
<th>Medium load</th>
<th>Peak load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household consumption (buses 2, 4, 5, 8, 9, 10, 11, 12, 14, 15, 16, 17, 18, 19, 20, 21, 22, 25, 26, 27, 32)</td>
<td>0.10</td>
<td>0.07</td>
<td>-0.24</td>
<td>-0.15</td>
<td>0.06</td>
<td>0.10</td>
</tr>
<tr>
<td>Consumer Business (buses 1, 3, 6, 7, 13, 28, 29, 30, 31)</td>
<td>0.06</td>
<td>-0.18</td>
<td>0.07</td>
<td>0.06</td>
<td>0.08</td>
<td>-0.26</td>
</tr>
<tr>
<td>Industrial consumers (buses 23, 24)</td>
<td>0.08</td>
<td>-0.22</td>
<td>0.08</td>
<td>0.08</td>
<td>0.12</td>
<td>0.14</td>
</tr>
</tbody>
</table>

### A. Distribution company participation in energy market

In this section, the microgrid operator tends to maximize its revenue in day-ahead market and also selling energy to its consumers using optimum real time energy pricing and DER optimal planning while considering technical constrains and uncertainties in wind generation and consumers’ demand.

Standard deviation of wind generation is set to be 10% of forecasted value; but due to response capability of consumers in proposed model, in this section this parameter is assumed to be 5% of forecasted value. Simulation results of solving this optimization problem for \( \lambda = 2 \) and in two cases of with and without RTP are presented in figs. 2 to 7.

Fig. 2, shows the effects of RTP on daily demand curve of the network. By sending RTP to consumers, in addition to reducing demand in high demand hours, some of these loads are shifted to low demand hours. As it can be seen, the microgrid is able to shift noticeable amount of demands to low demand hours by making low price incentives in those hours which this results to more flat daily demand curve.

![daily demand curve](image)

Fig 2: daily demand curve

Fig. 3, indicates the amount of power microgrid offers to buy from the energy market. From this figure, we can understand that this amount decreases during 7 to 18, when energy price is higher in energy market compared to DER operation costs and energy price of neighboring microgrids; the
microgrid increases its revenue by operating its own DER and offering higher energy price for the consumers. Other noticeable point is that by applying proposed RTP plan compared to non RTP case, energy buying offers from the main grid reduces during the high demand hours and rises up in low demand hours (which the price is also lower).

Fig. 3: Offer to buy the energy market

Fig. 4 presents the manageable DG generations. As indicated in this figure, all these units are at their maximum generation state during high price hours in energy market. Also, units 1 and 4 which have lower operation costs are still in use before and after these hours. In addition, with proposed RTP and consequently correction in load demand pattern, reserve capacity of microgrid reduces too and more economical operation is applied.

Fig. 4: Power generated by manageable DGs

The level of stored energy in two EES units in the grid is indicated in fig. 5. As it can be seen, these units are charged when the price is lowest (2 to 5) and during hours 13 to 15 which price in energy market is highest, they are discharged.

Fig. 5: Level of energy stored in EESs
Fig. 6, shows the amount of energy transferred in from neighboring microgrid. Considering energy price in the electricity market and energy transferring costs, our microgrid transfers energy with its neighbor during best possible hours.

Scheduled power generation to reduce power consumption in Interruptible Loads (ILs) is shown in fig. 7. As presented in this figure, in RTP mode, when the price of energy at energy market is higher than shedding ILs (85 $/MWh) the microgrid operator decides to disconnect those loads.

B. microgrid participation in energy and reserve market

In this section, it is assumed that microgrid tends to maximize its revenue in energy and spinning reserve market by RTP plan and DER optimal planning while satisfying technical constrains and uncertainties of wind generation and consumers’ demand response forecasting as well as consumers’ responding constrains. In the proposed model, probability of using reserve is considered as \( r = 0.5 \). The errors of loads demand forecasting and wind generation forecasting is same as previous section. Simulation results of applying proposed model to the test system are presented in figs. 8 to 12. Prices for each type of consumers which are same as previous section (in which the microgrid operator only participates in energy market), consequently the consumers’ demand responses are also the same (fig. 2). Fig. 8, shows the proposed amount of power offered to be bought from the energy market. As indicated in this figure, like previous case (participating in energy market only), in comparison with non RTP plan, using RTP plan results in a decrease of this amount in high demand hours and an increase during low demand hours (which energy is cheap). Power generation level and spinning reserve prepared by manageable DGs are presented in figs. 8 and 10, respectively. These figures clarify that the microgrid operator tries to maximize its revenue by offering spinning reserve from DGs during 11 to 20 in energy market. Amount of demand reduction in ILs and the spinning reserve offered by them are depicted in figs. 11 and 12.
Fig 8: power offered to be bought from energy market in day before

Fig 9: power generated by manageable DGs

Fig 10: spinning reserve offered by manageable DGs
Finally, to study deeper the consequences of applying the proposed model in daily planning of microgrid compared to flat pricing approach, costs, incomes and revenue of the microgrids for these cases are listed in table 2. As can be seen in this table, by using the RTP plan, the revenue of microgrid increases substantially in both cases, when the operator only participates in energy market or when it participates in energy and reserve market. In this case, the microgrid operator offers the optimum real time prices to end user consumers, so they can modify their demand patterns, and this way operator is able to use DERs more optimal and therefore dedicate their capacity to supply inner consumers and offer the spinning reserve for reserve market.

<table>
<thead>
<tr>
<th>Table 2: Costs, Incomes and Revenue of microgrid</th>
<th>The participation in energy market (first case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>the participating in energy and reserve market</td>
<td>with RTP</td>
</tr>
<tr>
<td>Total cost of units DER ($)</td>
<td>11818</td>
</tr>
<tr>
<td>Purchasing power from neighboring microgrid ($)</td>
<td>177</td>
</tr>
<tr>
<td>Market cost of energy ($)</td>
<td>50649</td>
</tr>
<tr>
<td>Energy sales to subscribers ($)</td>
<td>143192</td>
</tr>
<tr>
<td>the ($)reserve of Participation in market revenues</td>
<td>189</td>
</tr>
<tr>
<td>Net Income of microgrid ($)</td>
<td>80838</td>
</tr>
</tbody>
</table>

C. Conclusion
In this paper, a comprehensive model for operating a smart distribution grid has been proposed. In this model, by integrating demand side management and DER management in a twenty four hours span, by optimally operates these resources and offering RTP plan for consumers to modify their
demand patterns, operator company is able to maximize its revenue from participating in energy and reserve market as well as selling energy to its consumers. The suggested model in this paper, DER and distribution network technical constrains, demand response to variation in electricity price during the day and uncertainties from wind generation units and loads are considered. Three most important points from simulation results of applying proposed model to a 32 bus distribution test system are as follows:

1. Participating in reserve market could increase the revenue of operator company by both selling energy to consumers and participating in reserve market.
2. Applying the RTP plan and demand pattern modification, not only improve technical parameters of network such as better load profile and lower losses in network, but also delivers economic advantages such as lower energy purchased from wholesale energy market, optimal operation of DER and increase in revenue of microgrid operator.

Further improvement of proposed model could be investigated in following suggestions:

- Energy storage units in proposed model could only transfer energy to energy market. It is possible to consider them for spinning reserve applications too.
- Finding an optimum balance between the interests of operator company and consumers while adjusting the prices.
- Considering the topology of the microgrid in daily planning to increase the revenue of microgrid operator.

References


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Appendix A - Data and parameters of test system and distributed generation sources:

### Table A.1: Technical and economic specifications of programmable DGs

<table>
<thead>
<tr>
<th>R (MW/min)</th>
<th>$P_{\text{max}}$ (MW)</th>
<th>$P_{\text{min}}$ (MW)</th>
<th>SDC ($)</th>
<th>STC ($)</th>
<th>B (S/MW)</th>
<th>A ($)</th>
<th>Bus No.</th>
<th>DG No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.029</td>
<td>3.5</td>
<td>1.75</td>
<td>20</td>
<td>30</td>
<td>17</td>
<td>67</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>0.025</td>
<td>3</td>
<td>1.5</td>
<td>15</td>
<td>20</td>
<td>15</td>
<td>74</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>0.025</td>
<td>3</td>
<td>1.5</td>
<td>15</td>
<td>20</td>
<td>18</td>
<td>73</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>0.034</td>
<td>4.1</td>
<td>2</td>
<td>20</td>
<td>30</td>
<td>16</td>
<td>72</td>
<td>24</td>
<td>4</td>
</tr>
</tbody>
</table>

### Table A.2: Technical and economic specifications of LEEs

<table>
<thead>
<tr>
<th>$B$ (S/MW)</th>
<th>A ($)</th>
<th>Initial and final level of energy (MWh)</th>
<th>$\eta_{\text{ch}}$</th>
<th>$\eta_{\text{dh}}$</th>
<th>$P_{\text{max}}$, $D_{\text{ch}}$ (MW)</th>
<th>$P_{\text{max}}$, $D_{\text{dh}}$ (MW)</th>
<th>Capacity (MWh)</th>
<th>Bus No.</th>
<th>LEE No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>15</td>
<td>0.3</td>
<td>0.9</td>
<td>0.9</td>
<td>0.3</td>
<td>0.3</td>
<td>1.5</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>30</td>
<td>15</td>
<td>0.2</td>
<td>0.9</td>
<td>0.9</td>
<td>0.25</td>
<td>0.25</td>
<td>1</td>
<td>23</td>
<td>2</td>
</tr>
</tbody>
</table>
Table A.3: Power purchase agreement prices with neighbor microgrid

<table>
<thead>
<tr>
<th>($/MWh) Price</th>
<th>Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>46</td>
<td>22-24 , 1-9</td>
</tr>
<tr>
<td>78</td>
<td>18-21 ,10-11</td>
</tr>
<tr>
<td>170</td>
<td>12-17</td>
</tr>
</tbody>
</table>

Table A.4: Predicting the level of wind generation daily

<table>
<thead>
<tr>
<th>Wind generation (MW)</th>
<th>Hour</th>
<th>Wind generation (MW)</th>
<th>Hour</th>
<th>Wind generation (MW)</th>
<th>Hour</th>
<th>Wind generation (MW)</th>
<th>Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.82</td>
<td>19</td>
<td>6.89</td>
<td>13</td>
<td>8.2</td>
<td>7</td>
<td>3.61</td>
<td>1</td>
</tr>
<tr>
<td>1.64</td>
<td>20</td>
<td>6.56</td>
<td>14</td>
<td>8.2</td>
<td>8</td>
<td>5.76</td>
<td>2</td>
</tr>
<tr>
<td>3.77</td>
<td>21</td>
<td>6.40</td>
<td>15</td>
<td>6.39</td>
<td>9</td>
<td>6.23</td>
<td>3</td>
</tr>
<tr>
<td>4.59</td>
<td>22</td>
<td>2.63</td>
<td>16</td>
<td>5.25</td>
<td>10</td>
<td>6.72</td>
<td>4</td>
</tr>
<tr>
<td>6.72</td>
<td>23</td>
<td>0.33</td>
<td>17</td>
<td>8.2</td>
<td>11</td>
<td>6.89</td>
<td>5</td>
</tr>
<tr>
<td>4.26</td>
<td>24</td>
<td>0.66</td>
<td>18</td>
<td>7.54</td>
<td>12</td>
<td>6.89</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure A.1: Daily load curve of the studied system

Figure A.2: Daily market prices of energy and spinning reserve on 24 July 2013