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Valuation of markets for small-to-medium scale flexibility management solutions in various power market regimes

Master Thesis
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Contents

List of Acronyms

List of Symbols

- e_t^d: (Discharged) Energy sold at time t, MWh
- e_t^c: (Charged) Energy bought at time t, MWh
- e_t^{d-DA}: (Discharged) Energy sold in day-ahead market at time t, MWh
- e_t^{c-DA}: (Charged) Energy bought in day-ahead market at time t, MWh
- e_t^{d-RT}: (Discharged) Energy sold in real-time market at time t, MWh
- e_t^{c-RT}: (Charged) Energy bought in real-time market at time t, MWh
- r_t: Reserve sold in frequency control market at time t, MWh/h
- δ_t^{RU}: The ratio of energy to be delivered in proportion to the capacity provided for up reserve, MWh/MW
- δ_t^{RD}: The ratio of energy to be recieved in proportion to the capacity provided for down reserve, MWh/MW
- p_t^{DA}: Electricity price in day-ahead market at time t, \$/MWh
- p_t^{RT}: Electricity price in real-time market at time t, \$/MWh
- δ_t^{RU}: The probability that regulation-up control is called
- δ_t^{RD}: The possibility that regulation-down control is called
- δ_t^r: The risk premium factor for regulation reserve
- S_t: The state of system at time t, MWh
- η_s: Self-sustained efficiency (1 minus self-discharged rate)
- η_d: Charging efficiency
- η_d: Discharging efficiency
- d_t^{max}: Maximum discharging rate, MWh/h
- c_t^{max}: Maximum charging rate, MWh/h

- s_t^{max}: The maximum state of charge, MWh
- l_t^{DA}: The trading volume (load) in day-ahead market at time t, MWh/h
- l_t^{RT}: The trading volume (load) in real-time market at time t, MWh/h
- l_{max}^{DA}: The maximum trading volume (load) in day-ahead market, MWh/h
- l_{max}^{RT}: The trading volume (load) in real-time market, MWh/h
- s^+: The state of charge of a single EV while connected to the grid, MWh
- s^-: The state of charge of a single EV while disconnected from the grid, MWh
- H^c: The hours to complete charging of a EV, h
- n_t: The number of EVs on the grid at time t
- n_t^+: The number of EVs connected to the grid at time t
- n_t^-: The number of EVs disconnected from the grid at time t

Chapter 1

Introduction

1.1 Background

Background

Definition of flexibility

The challenges due to renewable penetration:

Traditional flexiblity from supply-side has limitations due to

The increasing demand can be fulfilled in various means, including conventional methods like generation (gas turbine), tramsimission (grid extend), which normally requires vast investments on infrastructure. With the develop of technologies in ICT and batteries, new options are becoming increasingly feasbile

The push and pull from market demands and technology availability is leading the policy makers to review or even revise the regulatory framework which were established based on the to allow non-discriminary participations of those new technologies.

Uncapping the potential

1.2 Technologies: options for system flexibility provision

- supply-side flexibility

  Conventional power plant response

  Curtailment of variable renewable

- Energy Storage System (ESS)

  Battery Energy Storage System (BESS)

  Pumped Hydro Energy Storage (PHES)

  Compressed Air Energy Storage (CAES)

Flywheel

- Demand Response (DR)
- Other

 Electric Vehicle to Grid (V2G)

 Electricity to Heat (E2H)

 Power to Gas (P2G) / Power to Hydrogen (P2H)

1.3 Applications, benefits and business models

1.3.1 In liberalized market

Needs of different plyaers

Player * Market * Application

Energy Markets

Ancillary Service Markets

1.3.2 In vertically integrated market

1.4 Scope and research questions

The target audience of this thesis is the management at Landis+Gyr on a high coporate level.

The ultimate goal is to provide references to support the audiences' strategic decision makings regarding flexibility management.

In order to achieve this, we conducted qualitative studies and developed quantitative models to identify: 1) the value of markets for flexiblity management

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The goal of this thesis is to:

developed a robust modeling tool with moderate complexity so that it can not only provide results in current environment but can be also reused or easily revised to provide results in case of changes in the future.

based on the tool, make quantitative as well as quanlitative analysis to provide refer

Purpose: providing references for strategic decision makings regarding flexibility management.

In order to make the analysis robust and reliable, we have built a techno-economic models which include the bottom-up dynamics of some key elements regarding the electricity markets and flexilibity technologies.

However, it shall be noticed this thesis is not intended to serve for:

project developers to design a flexiblity system or make operating (including bidding) strategies of the system

policy makers to redesign the electricity market structure, rules or other policies

grid planners to understand the needs and options of flexibility in order to acheive system relability with lowest costs

Since the concept of flexiblity management is related to a great variety of technologies, applications and Landis+Gyr is positioning globally in various markets, the scope could be very broad. Nonetheless, in order to produce viable and reliable results with a solidily established techno-economic model, we have to make comprises. According to the relevance to Landis+Gyr's business, the scopes are defined as:

The potential business model of Landis+Gyr is either to supply products to the customers to help them enable flexibility or to directly sell them flexible MWs as a service. In this case, we want to understand the value of each MW we enabled or sold. We assume Landis+Gyr will not directly partipate and trade in the power market, as it is going to place Landis+Gyr at the rival side of some customers in that market.

The value of flexibility will definitely vary according to the purpose, users' portfolio and operating strategies.

Chapter 2

Literature Review

The economics of flexibility solutions in power systems, especially electric energy storage (EES), is an active topic in research. It has drawn great attentions from the academics, investors and policy makers.

2.1 Purpose and stakeholder

2.2 Modelling methodology

2.2.1 Overview

Engineering vs system Linear vs nonlinear Deterministic vs stochastic problems Solving techniques

2.2.2 Engineering model

Price taker perfect forecast stochastic or dynamic programming Hybrid system Service mutualization

2.2.3 System model

2.3 Affecting factor

2.3.1 Techno-economic characteristics of power system

Generation

Generation mix (Renewable integration) Fuel Prices

Climate and weather

Transmission

Grid topology Transmission capacity

Consumption

2.3.2 Power market degisn and policy regulation

Player and competitive landscape

Renewable Support Scheme

Power Market Design

Market structure and rules: nodal, interval, reserve market Access

In general, the seven ISOs/RTOs require companies that service loads (i.e., the energy re- quirements of end-use customers) to provide reserves in proportion to their loads. (ref to Project Report: A Survey of Operating Reserve Markets in U.S. ISO/RTO-managed Electric Energy Regions)

Ownership and dispatch

Direct policy support

Capacity market Feed-in premium or tariff Other program

2.4 Value of results for reference

2.4.1 Demand for flexiblity in power system

2.4.2 Profitability of flexibility solutions

Chapter 3

Methodology for valuation of selected flexibility technologies in selected markets

3.1 Modular approach to build valuation models

3.2 Market-based modules

3.2.1 Revenue module

As is defined in the scope, only explicit revenues from power markets are accounted in our study. At each time step ($t \in T$), the revenue is calculate as the amount of energy (e, in MWh) offered in each energy market segment ($i \in I$), and/or amount of reserve (r, in MW) offered in each reserve market segment ($j \in J$), mutiplied by their corresponding prices (π, in \$/MWh or \$/MW). In reserve market, there are additional revenues from energy provision while the committed capacities are activated by the system operators. The amounts of energy delivered in reserve market are computed using a ratio (δ, in MWh/MW). Equation 3.1 illustrates how the overal revenue is determined.

$$Revenue = \sum_{t}^{t \in T} \left(\sum_{i}^{i \in I} \pi_t^{e,i} (e_t^{d,i} - e_t^{c,i}) + \sum_{j}^{j \in J} (\pi_t^{e,r,j} \delta_t^j + \pi_t^{r,j}) r_t^j \right) \tag{3.1}$$

where, d and c in the superscripts denote "discharge" (to release energy from flexiblity resrouces to grids) and "charge" (to intake energy from girds to flexiblity resrouces) respectively. $e_t^{d,i}$, $e_t^{c,i}$, r_t^j, are decision variables.

I and J are subsets of the selected market segments, which vary from region to region depending on their market structure.

The superset of I is the set of selected energy market segments in different geographies:

$$I \subseteq \begin{cases} \{Day\ Ahead, Real\ Time\} & PJM \\ \{Day\ Ahead, Intraday, Balancing\} & Germany \\ \{Real\ Time\} & NSW \end{cases}$$

The superset of I is the set of selected reserve market segments in different geographies:

$$J \subseteq \begin{cases} \{RegA, RegD, SR, NSR, DASR\} & PJM \\ \{PCR, SCR+, SCR-, TCR+, TCR-\} & Germany \\ \{Lower, Raise\} \times \{REG, 6SEC, 60SEC, 5MIN\} & NSW \end{cases}$$

I and J are sliced according to the business case being studied. For example, we can set $I = \{Day\ ahead\}$ and $J = \emptyset$ in order to value the offerings in day-ahead market of PJM. If there are multiple elements in $I \cup J$, it means the flexiblity resource can be reallocated to make offers to different market segments. In these cases, additional market contraits will be required in avoidance of violating actual market rules.

The ratios δ are computed from the real data, as the system average ratios using the total capacity ($\hat{e}_t^{r,j}$) and total activated energy ($\hat{e}_t^{r,j}$) at each time step.

$$\delta_t^j = \frac{\hat{e}_t^{r,j}}{\hat{r}_t^j}$$

Price signals, $\pi_t^{e,i}, i \in \{Day\ Ahead, Real\ Time\}$, can be obtained eith directly from the datasets or from the outputs of the market simulation module described in proceeding section.

$\pi_t^{e,i}, i \in \{Balancing\}$, is the the price for balancing energy (reBAP), which exist only in Germany and has been introduced in Section 4.1.2. It is also available to be retrieved from datasets directly.

Determination of prices in reserve markets, $\pi_t^{r,j}$ and $\pi_t^{e,r,j}$ varies between market geopraphies. While the general rules have be discussed in Chapter 4, hereby we will illustrate the formulations and calculations of $\pi_t^{r,j}$ and $\pi_t^{e,r,j}$, mathematically and respectively for each market.

PJM:

The real-time market price is applied for all deviations from day-ahead planned schedule, including Regulation, Primary and Supplementary Reserves.

$$\pi_t^{e,r,j} = \pi_t^{e,i} \quad i \in \{Real\ Time\}, j \in \{RegD, RegA, SR, NSR, DASR\}$$

The capacity prices of reserves are computed using a complex algorithm, taking into account a list of specifications of the resrouce, e.g. the performance & historical performance, benefits factor, milleage, etc. The detailed calculations can be found in appendix. As outputs, we will get deterministic values for $j \in \{RegA, SR, NSR, DASR\}$, and the upper and lower bounds, $\overline{\pi}_t^{r,j}$ and $\underline{\pi}_t^{r,j}$, for $i \in \{RegD\}$.

Germany:

$\pi_t^{r,j}$ and $\pi_t^{e,r,j}$ are based on principle of pay-as-bid. The weighted-average values are available in the datasets.

Australia:

The unit prices of reserve products, $\pi_t^{r,j}$ and $\pi_t^{e,r,j}$, are not available in datasets published by AEMO. Only weekly summary for total payment and recovery are provided. Due to the limits of available data, we are only able to perform calculations of total potential revenues, rather than thorough studies as in the other two geopraphies.

Since the revenue module will be used in optimizations, we re-formulate it as following:

$$Revenue = \boldsymbol{f}\, X$$

where X is the vector for all desicion variables. For certain sets of market segments I and J, X can be derived using Equation (3.2) $\sim$ (3.5) with $i \in I$ and $j \in J$.

$$X = \begin{bmatrix} E^d \\ E^c \\ R \end{bmatrix} \tag{3.2}$$

$$E^d = \begin{bmatrix} E^{d,I(1)} \\ \vdots \\ E^{d,i} \\ \vdots \\ E^{d,I(|I|)} \end{bmatrix} E^{d,i} = \begin{bmatrix} e_1^{d,i} & e_2^{d,i} & \dots & e_T^{d,i} \end{bmatrix}^T \tag{3.3}$$

$$E^c = \begin{bmatrix} E^{c,I(1)} \\ \vdots \\ E^{c,i} \\ \vdots \\ E^{c,I(|I|)} \end{bmatrix} E^{c,i} = \begin{bmatrix} e_1^{c,i} & e_2^{c,i} & \dots & e_T^{c,i} \end{bmatrix}^T \tag{3.4}$$

$$R = \begin{bmatrix} R^{J(1)} \\ \vdots \\ R^{j} \\ \vdots \\ R^{J(|J|)} \end{bmatrix} \quad R^{j} = \begin{bmatrix} r_1^j \ r_2^j \ \dots \ r_T^j \end{bmatrix}^T \tag{3.5}$$

Function $\mathbf{f}$ can be obtained analogously using Eqution (3.6) $\sim$ (3.10) with $i \in I$ and $j \in J$.

$$\boldsymbol{f} = \begin{bmatrix} \Pi^e \mid & -\Pi^e \mid & \Pi^{e,r}\Delta + \Pi^r \end{bmatrix} \tag{3.6}$$

$$\Pi^e = \begin{bmatrix} \Pi^{e,I(1)} \mid & \dots \mid & \Pi^{e,I(|I|)} \end{bmatrix} \quad \Pi^{e,i} = \begin{bmatrix} \pi_1^{e,i} \ \pi_2^{e,i} \ \dots \ \pi_T^{e,i} \end{bmatrix} \tag{3.7}$$

$$\Pi^{e,r} = \begin{bmatrix} \Pi^{e,r,J(1)} \mid & \dots \mid & \Pi^{e,r,J(|J|)} \end{bmatrix} \quad \Pi^{e,r,j} = \begin{bmatrix} \pi_1^{e,r,j} \ \pi_2^{e,r,j} \ \dots \ \pi_T^{e,r,j} \end{bmatrix} \tag{3.8}$$

$$\Pi^r = \begin{bmatrix} \Pi^{r,J(1)} \mid & \dots \mid & \Pi^{r,J(|J|)} \end{bmatrix} \quad \Pi^{r,j} = \begin{bmatrix} \pi_1^{r,j} \ \pi_2^{r,j} \ \dots \ \pi_T^{r,j} \end{bmatrix} \tag{3.9}$$

$$\Delta = diag(\delta_1^{J(1)}, \dots, \delta_T^{J(1)}, \dots, \delta_1^{J(|J|)}, \dots, \delta_T^{J(|J|)}) \tag{3.10}$$

3.2.2 Market simulation module

The revenue from arbitrage depends extensively on the movement of the price, which can be influence by factors including the activities of arbitrage themselves.

3.2.3 Market constraints

Energy constraints:

Day-ahead

$$\hat{e}_t^i - \hat{e}_t^{peak} \le e_t^{d,i} - e_t^{c,i} \le \hat{e}_t^i - \hat{e}_t^{base} \quad i \in \{Day\ Ahead\} \tag{3.11}$$

Real-time

Capacity constraints:

$$r_t^j \le \hat{r}_t^j \tag{3.12}$$

3.3 Technology-based modules

3.3.1 Cost module

3.3.2 Technology simulation module

Energy Storage

$$s_t = \eta_s s_{t-1} + \eta_c(\sum_i^{i \in I} e_t^{c,i} + \sum_j^{j \in J} \delta_t^{j,-} r_t^j) - \frac{1}{\eta_d}(\sum_i^{i \in I} e_t^{d,i} + \sum_j^{j \in J} \delta_t^{j,+} r_t^j) \quad (3.13)$$

where, the energy to reserve ratios are separated to positive and negative components:

$$\delta_t^{j,+} = \begin{cases} \delta_t^j & \delta_t^j \geq 0 \\ 0 & \delta_t^j < 0 \end{cases} \quad (3.14)$$

$$\delta_t^{j,-} = \begin{cases} 0 & \delta_t^j \geq 0 \\ -\delta_t^j & \delta_t^j < 0 \end{cases} \quad (3.15)$$

In order to formulate Equation (3.13), we first introduce a matrix denoted M:

$$M = \begin{bmatrix} \eta_s^0 & 0 & 0 & \dots & 0 \\ \eta_s^1 & \eta_s^0 & 0 & \dots & 0 \\ \eta_s^2 & \eta_s^1 & \eta_s^0 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \eta_s^{T-1} & \eta_s^{T-2} & \eta_s^{T-3} & \dots & \eta_s^0 \end{bmatrix}$$

Then M is used to construct M^I and M^J with a given pair of sets of market segments I and J.

$$M^I = \left[M^{I(1)} \mid \dots \mid M^i \mid \dots \mid M^{I(|I|)}\right] \quad M^i = M \quad \forall i \in I$$

$$M^J = \left[M^{J(1)} \mid \dots \mid M^j \mid \dots \mid M^{J(|J|)}\right] \quad M^j = M \quad \forall j \in J$$

Similar to Equation (3.10), we reconstruct the diagonal matrices with the decomposed ratios from Equation (3.14) and (3.15).

$$\Delta^+ = diag(\delta_1^{J(1),+}, \dots, \delta_T^{J(1),+}, \dots, \delta_1^{J(|J|),+}, \dots, \delta_T^{J(|J|),+})$$

$$\Delta^- = diag(\delta_1^{J(1),-}, \dots, \delta_T^{J(1),-}, \dots, \delta_1^{J(|J|),-}, \dots, \delta_T^{J(|J|),-})$$

Finally, we can derive the matrix form of Equation 3.13.

$$S = \eta_s M S_0 + \left[-\tfrac{1}{\eta_d} M^I \mid \eta_c M^I \mid M^J(-\tfrac{1}{\eta_d}\Delta^{+T} + \eta_c \Delta^{-T})\right] X \quad (3.16)$$

where, S and S_0 are vectors for the temporal and initial state, respectively.

$$S = \begin{bmatrix} s_1 & s_2 & \dots & s_T \end{bmatrix}^T$$

$$S_0 = \begin{bmatrix} s_0 & s_0 & \dots & s_0 \end{bmatrix}^T$$

Electric Vehicle

Electric vehicle to grid systems are fundamentally battery energy storage systems in term of their physical dynamics. Therefore, they can be modeled generally using the same approach as in preceding paragraphs. However, there are several attributes that uniquely characterize electric vehicle to grid systems compared to normal battery storages:

- The availability of an EV2G system, in terms of delivering both energy (in MWh) and capacity reserve (in MW), is dynamic rather than static, since the number of EVs connected in the power grid is changing all the time with the behaviors of plug-in/ plug-out.
- The energy stored in the system will be consumed not only for delivering our targeted services (arbitrage or balancing), but also for driving of EVs themselves. This part of costs will be implicitly captured by the revenue module using Equation (3.1), which will distort the real value of services provided for the grid.

Therefore, two main modifications are made to adapt the model of ESSs for better representing the EV2G systems:

1. The EV2G system is modeled as a dynamic ESS by taking into consideration the connection/ disconnection of EVs to/ from the grids.
2. The costs of energy consumed for driving are accounted, following the original plan, i.e. without controlling algorithm for grid services, and added back to the revenue in Equation

In order to implement the first measure, we introduce additional terms to represent the number of EVs entering (n_t^+), leaving (n_t^1) and remain in (n_t) the system at each time step.

$$n_t = n_{t-1} + n_t^+ - n_t^- \tag{3.17}$$

Thereby the state equation for an EV2G system is written as:

$$\begin{aligned} s_t =& \eta_s s_{t-1} + \eta_c(\sum_i^{i\in I} e_t^{c,i} + \sum_j^{j\in J} \delta_t^{j,-} r_t^j) - \frac{1}{\eta_d}(\sum_i^{i\in I} e_t^{d,i} + \sum_j^{j\in J} \delta_t^{j,+} r_t^j) \\ &+ s^+ n_t^+ - s^- n_t^- \end{aligned} \tag{3.18}$$

Chapter 4

Power Market Framework and Proposed Business Model for Flexibility Management in Selected Segments and Geographies

4.1 Power market framework

4.1.1 PJM

4.1.2 Germany

4.1.3 Balancing Energy Market

Prices for balacning energy are unified across TSOs and determined according to the balancing energy price settlement system (BK6-12-024) developed by Federal Network Agency (FNA) as of 01/12/2012.

$$reBAP = \frac{\sum netimbalanceenergycost}{\sum netimbalanceenergyvolume} \tag{4.1}$$

Chapter 5

Market Regimes

5.1 Overview

Power exchange / Power pool

Capacity or not

Locational pricing or not

5.1.1 Energy market

5.1.2 Ancillary service market

5.1.3 Capacity remuneartion mechanism

5.2 Power market design and structure

5.2.1 PJM

5.2.2 Germany

5.2.3 Australia

5.3 Regulatory and market framework for flexibility resourses

Chapter 6

Model and implementation

6.1 Overview

6.2 Market-based modules

6.2.1 Revenue modules

6.2.2 Market simulation module

6.2.3 Market constraints

6.3 Technology-based modules

6.3.1 Cost modules

6.3.2 Technology simulation module

6.3.3 Technology constraints

6.4 Optimization engine

6.5 Data

Chapter 7

Result and discussion

7.1 Market size and profitabilty in current set-up

7.2 Impact of technological developments

7.3 Impact of high penetration of flexibility

7.4 Impact of renewables integration

7.5 Impact of changes of regulatory and market frameworks

7.6 Sensitivity analysis of other parameters

Chapter 8

Conclusions and outlook

Appendix A

Model parameters

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