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

Master Thesis  
PSL1226

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Zurich, February 5, 2018



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# 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
- $\delta_t^{RU}$ : The ratio of energy to be delivered in proportion to the capacity provided for up reserve, MWh/MW
- $\delta_t^{RD}$ : 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
- $\delta_t^{RU}$ : The probability that regulation-up control is called
- $\delta_t^{RD}$ : The possibility that regulation-down control is called
- $\delta_t^r$ : The risk premium factor for regulation reserve
- $S_t$ : The state of system at time t, MWh
- $\eta_s$ : Self-sustained efficiency (1 minus self-discharged rate)
- $\eta_d$ : Charging efficiency
- $\eta_d$ : 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 flexibility from supply-side has limitations due to

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

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-discriminatory participations of those new technologies.

Uncapping the potential

### 1.2 Technologies: options for system flexibility provision

- supply-side flexibility
  - Conventional power plant response
  - Curtailement 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 players

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 corporate 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 flexibility 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 qualitative 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 flexibility technologies.

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

- project developers to design a flexibility 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 achieve system reliability with lowest costs

Since the concept of flexibility 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 solidly established techno-economic model, we have to make compromises. 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 participate 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 design 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 requirements 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 flexibility 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 ( $\pi$ , 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 ( $\delta$ , in MWh/MW). Equation 3.1 illustrates how the overall revenue is determined.

$$Revenue = \sum_t \left( \sum_i \pi_t^{e,i} (e_t^{d,i} - e_t^{c,i}) + \sum_j (\pi_t^{e,r,j} \delta_t^j + \pi_t^{r,j}) r_t^j \right) \quad (3.1)$$

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  $J$  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 flexibility resource can be reallocated to make offers to different market segments. In these cases, additional market constraints will be required in avoidance of violating actual market rules.

The ratios  $\delta$  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 either 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 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 geographies. While the general rules have been 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 energy deviated from day-ahead planned schedule is accounted based on real-time market price, shown as following.

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



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

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

$$Revenue = f X$$

### 3.2.2 Market simulation module

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

### 3.2.3 Market constraints

Energy constraints:

Day-ahead

$$\hat{e}_t^i - \hat{e}_t^{peak} \leq e_t^{d,i} - e_t^{c,i} \leq \hat{e}_t^i - \hat{e}_t^{base} \quad i \in \{Day Ahead\} \quad (3.2)$$

Real-time

Capacity constraints:

$$r_t^j \leq \hat{r}_t^j \quad (3.3)$$



## 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 balancing 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.

$$reBAP = \frac{\sum netimbalanceenergycost}{\sum netimbalanceenergyvolume} \quad (4.1)$$



## 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 remuneration 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 resources



## 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 profitability 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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