THE ENERGY INFORMATION DASHBOARD WITH INTEGRATED
COMPUTATIONAL GENERATION DISPATCH MODEL AND
WHOLESALE ELECTRICITY MARKET MODEL

by

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¹We certify that written approval has been obtained for any proprietary material contained therein.
To my dog, Bing
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Abstract

The Energy Information Dashboard with Integrated Computational Generation Dispatch Model and Wholesale Electricity Market Model

Abstract

by

JIAOJIAO CHEN

Practicing in the immersive market simulations is critical for students majored in electricity industry. However, there are no such simple tools that can help students practice generation dispatch and making transaction in the wholesale electricity market. To address this issue, this thesis proposes a novel computational framework that consists of a generation dispatch model and a wholesale electricity market model, which are integrated into the Energy Information Dashboard (EIDA). The generation dispatch model builds a generation portfolio by modeling the nuclear power plants, the wind power plants, and the coal power plants. The wholesale electricity market model allows participants to make balancing and hedge decisions in the Day-ahead Market and the Real-Time Market. Transaction through broker is also included in this framework. With these new features incorporated into EIDA, students can apply plenty of new patterns and strategies to gain experience in the immersive electricity market simulation.
1 Introduction

As financial decision becomes more and more important in generation dispatch and the wholesale electricity market, mastering financial strategies and business rules that used in both areas is critical to electricity professionals and students majored in electricity industry. For electricity professionals, several online tools are developed to help them make business decision and manage transaction. For example, InSchedule developed by PJM interconnection helps electricity professionals to submit generation schedule data, eMKT that is also developed by PJM helps electricity professionals to make business decision in the Day-Ahead market, and so on. For students majored in electricity industry, it is beneficial if they can take practice in the immersive market simulations since market and generation dispatch become more and more important in electricity industry education. However, it is impossible and impractical for students to take participant in these online tools that aimed at helping electricity professionals in business. Consequently, a simple and immersive market simulation, which helps students practice generation dispatch and making transaction in the simulated wholesale electricity market, is necessary to address these issues. This chapter first introduces the background of the generation dispatch and the wholesale electricity market. Second, it reviews several related work and then proposes a computational framework to model
the generation dispatch and the wholesale electricity market for educational purpose. Finally, it provides a brief description of how the rest of the thesis details the proposed framework.

1.1 Wholesale electricity Markets

Electricity is generated at the power station by power plants. Specifically, energy suppliers own several different kinds of power plants, such as nuclear power plants, wind power plants, coal power plants and so on. The assembly of these power plants together owned by an energy producer is called as generation portfolio. Different power plants have different characters and belong to different categories, which influence the output and operation of power plants. Energy suppliers need to cooperate with different power plants to meet various electricity demands, which are usually affected by weather condition, usage of facilities and so on. They also want to maximize their profit, so they learn and practice different strategies to dispatch generation resources in their career life. After generated at the power station, electricity is transmitted and distributed to end-user customers. Electricity can be traded in long-term and short-term like other commodity. For long-term, electricity is traded in the form of bilateral transactions that are usually signed for month. Bilateral transactions are beyond the discussion of this thesis. For short-term, electricity is purchased and sold in electricity market that consists of the wholesale electricity market and the retail electricity market. Specifically, energy suppliers usually sell electricity to the wholesale electricity market and retailers buy energy from the wholesale electricity market. Later on, the energy retailers resell energy in the retail electricity market and distribute electricity to the end-user customers. Figure 1.1
Figure 1.1. The process about how the electricity is delivered to the end-user customers.

demonstrates how electricity is delivered to the end-user customers. Note that retail electricity market is beyond the discussion of this thesis.

Financial activity plays an important role in the electricity market. Historically, the electricity market is regulated so that only single or few suppliers can participate in the market and the energy suppliers also own the transmission and distribution business. Besides, the price is controlled by the Federal Energy Regulatory Commission (FERC). As a result, the suppliers have little incentive for improving the efficiency and the cost is passed to the consumers. As the supply of electricity and the need of long-distance transmission increase, in the last decade of the 20th century, Federal Energy Regulatory Commission (FERC) realized the importance of a deregulated electricity market for improving efficiency of electricity production and transmission.
In order to deregulate the electricity market, Independent System Operator (ISO) and regional transmission organization (RTO) were established by introducing the financial activity into the electricity market. The RTO, which is in charge of the transmission and distribution as an independent role, is responsible for handling the massive electricity transmission and operating the wholesale electricity market. The establishment of ISO and RTO leads to a more fair and competitive electricity market, and therefore improves the efficiency of the transmission of electricity. Nowadays, there are ten RTOs operating in North American [1] [2], such as, PJM Interconnection LLC.

RTO proposed several rules to operate the energy market more efficiently, including the day-ahead market and real-time market. Following these rules, parties like the energy suppliers, retailers, and end-user customers enter into the electricity market to purchase and sell electricity. In particular, energy suppliers, who own several different power plants, come to the wholesale market with competitive offers to sell, and load serving entities, which are responsible for distribution and reselling the electricity to end-user customers, come to the wholesale market to buy electricity. Besides making transaction in wholesale electricity market to balance their positions, energy suppliers and retailers also can make transaction with broker, who plays as a middleman in the wholesale electricity market. Moreover, market profits and losses have a major impact on the financial viability of a power plant. Energy suppliers have more impetus for lower cost utility, which may benefit both the consumers and themselves.
1.2 Related Work

Electricity market simulation has been studied in many previous works. Generally, simulators can be categorized according to four characteristics [3]. First is the use of web-based software platforms. PowerWeb [4] is proposed as a web-based electric power market simulation tool to assess the economic and reliability impacts of given market designs as well as to train and educate students, industry professionals and policy makers. NetPMS [5] presents an Internet-Based Power Market Simulator in order to evaluate different power market rules before market execution, simulate the behaviors of power market players, train the students and market participants, as well as test the designed agents by researchers. Other structures are also discussed in [6], [7], where the browser/client/server architecture is designed and developed using different programming frameworks, such as dot-Net and C++. The second is for the purpose of education. Most simulators, such as [3], [4], [5], [6], [7], [8], can be applied for education. The third is the simulation of specific market architectures, such as the day-ahead market [9]. The fourth is the use of multi-agent system technology. A variety of multi-agent approaches [10], [11], [12] are proposed, which are the future consideration of our EIDA system. In comparison, our proposed Energy Information Dashboard (EIDA) system differs from them in the following aspects. First, EIDA is not only a pure web-based system, but also the only electricity market simulator that runs primarily on the browser's JavaScript engine. The benefit is that it can run in any environment with browser and does not depend on any other third party plugins or libraries. Second, EIDA is targeted towards the secondary market and the replay of historical scenarios, while previous work mainly focuses on the primary markets. Third, EIDA integrates different categories of power plants into one framework, while previous works only focus on one power plant. Fourth,
EIDA mainly focuses on educational purpose, which differs from some previous works, which take the education as an auxiliary functionality.

1.3 The contribution of the Thesis and Energy Information Dashboard

Energy Information Dashboard (EIDA), a dynamic web application for educational purpose, simulates a day of the wholesale electricity market [13]. To help EIDA become more immersive, this thesis proposes a novel framework which contains a generation dispatch model and a new computational wholesale electricity market model. This thesis also refactors the EIDA to integrate these two models. The proposed computational generation dispatch model incorporates different kinds of power plants to help students to master generation dispatch patterns that are influenced by the electricity load patterns. The proposed model chooses the most significant features that influence the generation dispatch to model the power plants. The power plants that are modeled characterize different power plants categories that are well adopted in electricity industry. Understanding these well adopted power plants categories is important for student to master generation dispatch. Please refer Chapter 2 for more detailed design. The proposed wholesale electricity market model models the Day-Ahead Market, the Real-Time Balancing Market, and the brokerage by carefully examining the wholesale electricity market rule. Specifically it models the market-clearing price, the transaction rules, and the calculation of profit for the wholesale electricity market. Please refer Chapter 3 for more detailed design. In order to integrate these two models, EIDA is rebuilt upon a novel market time line. This market time line plays an important role in distinguishing the Day-Ahead market, the Real-time Balancing market, and the operating day. The
market time line is also important to generation portfolio due to the generation dispatch and power plants recycling. This time line simulates the day before operating day and the operating day. By understanding the timeline of wholesale electricity market, student can practice balancing and hedging in the wholesale electricity market. Furthermore, this thesis also implements different levels of simulation in EIDA, namely the low level and the high level, for students from different backgrounds. The low level contains a simple model of generation portfolio that students do not need to handle the model of generation dispatch and the model of wholesale electricity market. The high level includes a more complicate generation portfolio that adopts the computational model of generation dispatch, and it also contains the model of wholesale electricity market. Given the level of complexity, the simulation applies historical data to model hundreds of historical scenarios to help students operate generation dispatch and make transaction in the wholesale electricity market. Finally, EIDA, including the model of generation dispatch and the model of wholesale electricity market, runs as a client-side JavaScript application in the user's browser. EIDA is divided into a front-end that is implemented with CoffeeScript [14] and Backbone framework [15], and a back-end that is implemented with Node.js [16] and CouchDB [17]. Note that the core logic of EIDA runs as a Single-Page Application (SPA) [18]. Therefore, EIDA is easily portable and off-load most server side processing [13]. Please refer the Appendix B for the screen shots of how to run the simulation in our EIDA system.

1.4 The User Stories of EIDA and the Overview of the Thesis

In EIDA, a user can select between two different simulation levels, namely the low level and the high level. If the user chooses the low-level simulation, he would have a simple
model of generation portfolio, so that the user does not need to handle the generation dispatch. Conversely, the high-level simulation has a generation portfolio that simulates generation dispatch.

Specifically, in the low-level simulation, the user has a simple generation portfolio that has a fixed generation output. The user cannot cycle the simple generation portfolio. This simple generation portfolio represents the cost of generation. While in the high-level simulation, the user has a complicate generation portfolio that is composed of different types of power plants. The generation portfolio is composed of nuclear power plants, wind power plants, and coal power plants. Different power plants have different generation output, variable costs, forced outage rate, and duration of operating. These properties of power plants can influence the predict generation, the real generation, the predict generation cost, and the real generation cost in the simulation. Chapter 2 examines the proposed generation dispatch model in detail.

The output and cost of generation portfolio and the electricity load are influenced by many factors, such as the weather condition. In order to hedge and balance the position, a user can trade in several financial markets, such as in the market operated by RTOs, and in the over-the-counter (OTC) markets. For example, a user can make virtual supply offers and virtual supply bids in the day-ahead market operated by RTOs, a user can trade with broker in the OTC markets to hedge and balance, a user can also trade in real-time wholesale market that is operated by RTOs. Furthermore, a user has several chances to trade in the markets so that he can balance the generation and load all the time. For example, in a simulation day, a user can trade in the pre-day set up segment, the balancing of the day segments, and the operating day segment. Given the predict generation and predict load in each segment, a user can choose to buy and sell in order
to hedge and balance. A user can also adjust the generation output in each segment in order to maximize the profit. A user can easily find a segment summary in the simulation. Finally, after the operating day, a user will have an overview of the performance in the whole simulation. Chapter 3 explains the financial market model more specifically.

Chapter 4 demonstrates the data flow diagram and technologies used to develop the dynamic web application; and chapter 5 concludes the thesis and discusses the future work.
2 Modeling of Generation Dispatch

2.1 Introduction

Generation dispatch of the electricity is a process of making decisions on what power plants to operate and what their output shall be by the electricity suppliers in order to meet the system load at the lowest cost. This chapter presents a novel model that simulates the generation dispatch process for educational purpose. Specifically, it first examines how the proposed EIDA system approaches the generation dispatch, and then it further explains the modeling process by providing both the design detail and the implementation detail. Finally, it closes with the future work to model power plant more accurately.

2.2 Generation Dispatch in EIDA

EIDA Generation Dispatch addresses two aspects, namely (i) the consumption pattern of electricity, and (ii) the power plants characters and the generation portfolio, by providing a computational model that allows students to practice generation dispatch. This computational model begins with applying a system load model that follows the rules of the consumption pattern of electricity. The remaining part of the section focuses on
modeling power plants by selecting the most significant features that influence the generation dispatch. It closes with setting up different power plant generation portfolios, which follow the power plants categories that are well adopted in electricity industry, for each individual.

2.2.1 The Modeling of the Electricity Consumption

The demand of electricity varies for season and time due to the use of appliances and temperature. For example, Figure 2.1 displays the forecast and actual demand in a day, which is cited from California ISO [19]. Note that those curves go up during the day, when people go to work, and go down during the night, when people are asleep.

![Figure 2.1. The forecast and actual demand in a day.](image)

The proposed model implements this widely recognized electricity demand pattern in industry, which demonstrates how demand varies between different hours in on day. The proposed model also introduces a way to simulate load and the load revenue. First,
the simulation assumes the base load of the simulation day is 7000 MWh. And the generation varies according to the temperature of the simulation day. The simulation assumes 70°F is a pleasant temperature with minimum electricity demand. When temperature is higher or lower, the electricity demand is increasing. Based on these assumptions, the simulation applies the following equation to calculate the demand of each hour.

\[ \text{Load} = 7000 + 50 \times |\text{temperature} - 70| \]  \hspace{1cm} (2.1)

Then, without the price matching between energy producer and retailer, the simulation uses the retailer price to approximate the contract electricity price. Specifically, the historical data comes from EIAs average retail price of electricity in 2010 is used for simulation. The reason why this simulation does not use multi-years data is to avoid inflation. The monthly average retail price of electricity in 2010 is presented in the Table 2.1. The mean of monthly average retail price of electricity is 9.7975, and the variance is 0.16171. Usually, the price of electricity is measured by US$ per megawatt hour. And one US cent per kilowatt hour equals to 10 US$ per megawatt hour. After conversion, the mean of the retailer price will be 97.98 US$ per megawatt hour and the standard deviation will be 0.40213.

### 2.2.2 The Modeling of the Characters of the Power Plants

Generation dispatchers try to maintain power plants at an efficient level to produce electricity all the time, which is determined by the characters of power plant. The proposed model implements the following four most important factors of power plant, namely the cost to produce electricity, the capacity, the duration of operation, as well as the forced outage rate.
The Cost of Generation Electricity. First, the proposed model models the cost of the generation electricity. Specifically, the cost of generation electricity is one of the main factors that influence the generation dispatch. Total costs of generation are decomposed into fixed costs and variable costs. Fixed costs are those costs that do not depend on the output of power plants, such as capital costs. They influence the long-term economic decisions of power plants dispatch, and are beyond the discussion of this thesis. On the contrary, variable costs, which depend on the generation of power plants, usually contribute to making the short term dispatching decisions. For example, power plants operators choose to run the power plants when the revenue can cover the variable costs in the short term, since keeping the power plants running helps cover some fixed costs that occur anyway. While power plants operators may shut down the power plants once the revenue is not enough to cover the variable costs. The proposed model takes the variable costs as an important parameter, which influences generation dispatch. Variable costs are composed of fuel cost and variable non-flue operations and maintenance.
Table 2.2. The variable cost for different power plants.

<table>
<thead>
<tr>
<th>Power Plants Type</th>
<th>Nominal Capacity (MW)</th>
<th>Variable O&amp;M Cost (MW-year)</th>
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<tbody>
<tr>
<td>Coal (Single Unit Advanced PC)</td>
<td>650</td>
<td>$4.47</td>
</tr>
<tr>
<td>Coal (Dual Unit Advanced PC)</td>
<td>1,300</td>
<td>$4.47</td>
</tr>
<tr>
<td>Solar Thermal</td>
<td>100</td>
<td>$0.00</td>
</tr>
<tr>
<td>Onshore Wind</td>
<td>100</td>
<td>$0.00</td>
</tr>
<tr>
<td>Offshore Wind</td>
<td>400</td>
<td>$0.00</td>
</tr>
<tr>
<td>Natural Gas (Conventional CC)</td>
<td>620</td>
<td>$3.60</td>
</tr>
<tr>
<td>Natural Gas (Advanced CC)</td>
<td>400</td>
<td>$3.27</td>
</tr>
<tr>
<td>Dual Unit Nuclear</td>
<td>2,234</td>
<td>$2.14</td>
</tr>
</tbody>
</table>

Note that renewable power plants, such as wind power plants and solar power plants, have zero variable O&M cost. Nuclear power plants have relatively low variable O&M costs. While fossil-based power plants have relatively high O&M variable costs. In order to model the variable cost more accurately, the proposed model endures the evolvement of modeling methodologies. Therefore, two different methodologies are adopted, one is in the present vision, and the other will be in the future work. In the present vision, the proposed model uses data from TCDB (Transparent Cost Database) to calculate the variable cost of power plants. In the future, the proposed model will use data from EIA to calculate them.

The Capacity of Power Plants. Second, the proposed model also models the capacity of the power plants. Particularly, different power plants have different generation scales.
For example, from Table 2.2, one can find out that nuclear power plants usually have high capacity, while renewable power plants usually have relatively low capacity. Furthermore, power plants from certain type with different generation scale have different capacity. For example, from Table 2.2, one can find that single unit advanced PC Coal plant has different nominal capacity from Dual Unit Advanced PC coal plant. When the generation operators try to balance the electricity production and electricity consumption, the capacity of power plants can influence the generation dispatch.

The Duration of Operation. Third, the proposed model models the duration of the operation as well. Power plant operators may need to start up and shut down power plants to cooperate the changing electricity demand for season and time. Different power plants experience different start up and shut down speeds, as well as different startup costs. Capacity of power plants also plays as a factor here. For example, nuclear and coal power plants may take hours, or even days to start up, while gas turbine power plants are more flexible to turn on and off. Experienced Power plants operators follow patterns to decide the duration of operation of power plants. The starting up and shutting down of power plants usually need to be scheduled several weeks before the operation day. The proposed model tries to model power plants with long duration of operation, and it will include the power plants model with flexible duration of operation, such as gas turbine power plants, in future work.

The Forced Outage Rate. Finally, the proposed model models the forced outage rate in order to help students understand the complexity of generation dispatch. For example, the power plant barriers forced outage, and the generation of wind turbines varies due to the wind speed. Therefore, students are asked to response to these emergencies either by operating generation dispatch or by entering electricity market to balance their
position. Forced outage rate is the breaking down probability of power plant. Power plants break down during the season and time due to equipment failures, disruption in the power plant fuel supply chain and so on [21]. Besides, different power plants have different forced outage rates. There are many statistics to describe the forced outage rate (FOR), among which the proposed model chooses EFOR since it serves as an important statistic calculated from the raw GADS (Generating Unit Statistical Brochure, 2006-2010) data. Specifically, Forced outage rate (FOR) is defined as the number of hours that the unit is on forced outage over the total number of hours in a year (which is the sum of hours that the power station is available for service and hours the power station is in forced outage) [21]. Note that FOR is an average for year. The proposed model adopts the FOR data by converting it to average forced outage rate for hour. For example, if T is the average length of the forced outage, the average forced outage for hour is \( \text{FOR}/T \). One can refer to appendix A to find out how force out rate is defined in detail.

2.3 The Design details of EIDA Generation Dispatch Model

These four factors described above characterize the power plants modeling during generation dispatch. In order to capture how these different characters of different power plants influence the generation dispatch economically, EIDA system also presents the design details of three representative power plants, namely nuclear power plants, wind power plants, as well as coal power plants, from three different categories respectively. Specifically, nuclear power plants belong to base load power plants, which have relatively low variable cost and high capacity. Wind power plant is a kind of renewable power plant, which has zero variable cost. Coal plants are categorized as the fossil-fuel power station, which burns fossil fuel to produce electricity. These three different categories
almost dominate all kinds of power plants. Therefore, this representative model can help students understand the challenges of generation dispatch and practice strategies to deal with emergence.

### 2.3.1 The Design Details of Nuclear Power Plants.

For economic and technical reasons, nuclear plants in the United States are almost invariably operated as base load units at maximum output. While having low start up and shut down speed, nuclear plants usually produce electricity efficiently with low variable cost. Nuclear power plants also have high capacity.

**The Variable Cost of Nuclear Power Plants.** The proposed model uses statistics from TCDB (Transparent Cost Database) to calculate the variable cost of power plants. Table 2.3 lists the statics gathered from TCDB.

According to the data from TCDB, the variable cost of nuclear power plants varies from 0.42 $/MWh to 6 $/MWh. To calculate the variable cost of nuclear power plant model, the proposed model first selects an interval randomly from the four intervals, namely [minimal, first quartile), [first quartile, median), [median, third quartile), as well as [third quartile, maximum]. It then selects a random value uniformly within the selected interval as the variable cost of nuclear power plant.
### The Capacity of Nuclear Power Plants

Power plants of different generation scales usually have different capacities. EIA reports the capacities of all power plants in United States every year. Table 2.4 contains the numbers of nuclear generators and total generator nameplate capacity of all nuclear power plants in United State, which is gathered from EIA Electric Power Annual Report 2010 [22].

To accommodate the capacity diversity, the proposed model calculates the average capacity of nuclear power plants with the following formulation.

\[ E_c = \frac{N_c}{n} = \frac{106,731 \text{ MW}}{104} = 1026 \text{ MW} \]  

(2.2)

where \( E_c \) is the expected capacity of a nuclear plant, \( N \) is the nuclear generator nameplate capacity, and \( n \) is number of nuclear generators.

The proposed model then uses the expected capacity of a nuclear plant to characterize the capacity of nuclear power plant model, which obeys a normal distribution with expectation of 1026, and variance of 200.

### The Duration of Operation

Nuclear plants typically operate at maximum capacity barring planned or unplanned outages during the season and time due to the relatively low variable cost, high efficiency, and long duration of starting up and shutting down. The model of nuclear plants shares the same property with nuclear power plants in industry, namely the model runs at full capacity except in the case of breaking down. In order to meet this requirement, the proposed model sets the minimum load of a nuclear power
Table 2.5. The forced outage rate used in EIDA system.

<table>
<thead>
<tr>
<th>Unit Type</th>
<th>MWTrb/Gen Nameplate</th>
<th>FOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>400-799</td>
<td>2.92</td>
</tr>
<tr>
<td>Nuclear</td>
<td>800-999</td>
<td>2.24</td>
</tr>
<tr>
<td>Nuclear</td>
<td>1000 Plus</td>
<td>2.23</td>
</tr>
</tbody>
</table>

The forced outage rates of power plants model equal to its capacity, and sets the duration of operation throughout the simulation period except forced outage.

**The Forced Outage Rate of Power Plants.** Nuclear power plants with different generation scales also have different forced outage rates. EIDA system gathers forced outage rate data from GADS (Generating Unit Statistical Brochure, 2006-2010). Table 2.5 displays the forced outage rate data which EIDA system applied in the simulation.

The proposed model uses these data to model the forced outage rates of power plants with different generation scales. For example, an operational nuclear reactor larger than 1,000MW continues generation throughout the simulation period with probability 97.77%, and fails down randomly during the simulation with probability 2.23%. A damaged generator has zero output after breaking down.

### 2.3.2 The Design Details of Wind Power Plants

Wind power plant, which converts wind energy into electricity power, is a kind of renewable plants. In order to explain the four factors, which play important roles in generation dispatch, this thesis investigates the relationship between wind speed and electricity output first.

**Wind Speed and Wind Turbines Output.** Wind farms use wind turbines to produce electrical power. The energy available for conversion with wind turbines mainly depends on the wind speed and the swept area of the turbine [23]. The proposed model
focuses on surveying the connection between wind speed and wind turbines output. The influence of swept area of the turbine is beyond the discussion of this thesis. The proposed model gives a specific introduction to a wind turbine model, which is manufactured by Siemens, to illuminate the relationship. The proposed model chooses to apply the model provided by Siemens due to the wind turbines manufacturers always provide the function between the production of wind turbine and the wind speed with their wind turbines. A more general mathematical model definitely can be applied here. However, power coefficient, which is unique to the to the wind turbine type and wind speed, is more complicating to model. The proposed model uses Siemens Wind Turbine SWT-3.6-120 as the prototype of wind power plants. The technical specifications of Siemens Wind Turbine SWT-3.6-120, which are gathered from website of Siemens [24], are listed in Table 2.6.

Note that cut-in speed is defined as the minimum wind speed at which the wind turbine will generate usable power [25]. The rated speed is defined as the minimum wind speed at which the wind turbine will generate its designated rated power [25]. Having the cut-out speed can protect the wind turbine from damage. For example, at very high wind speeds, typically between 45 and 80 mph, most wind turbines cease power generation and shut down [25]. How these three speeds related to the output of wind turbine is demonstrated in Figure 2.2.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut-in wind speed</td>
<td>3-5 m/s</td>
</tr>
<tr>
<td>Rated speed</td>
<td>12-13 m/s</td>
</tr>
<tr>
<td>Cut-out wind speed</td>
<td>25 m/s</td>
</tr>
</tbody>
</table>

Table 2.6. The technical specifications of Siemens Wind Turbine SWT-3.6-120.
Figure 2.2. The wind power curve.

<table>
<thead>
<tr>
<th>Wind speed S</th>
<th>Offered generation P</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5 m/s</td>
<td>0 MW</td>
</tr>
<tr>
<td>5-12 m/s</td>
<td>Approximately linear with the wind speed [26]</td>
</tr>
<tr>
<td>12-25 m/s</td>
<td>3.6 MW</td>
</tr>
<tr>
<td>25+ m/s</td>
<td>1.0 MW</td>
</tr>
</tbody>
</table>

Table 2.7. The relationship between wind speed and offered generation wind turbines.

According to Figure 2.2, the proposed model concludes the relationship between wind speed and offered generation wind turbines as Table 2.7:
The linear function when wind speed varies between 5 to 12 m/s is formulated as follows:

\[
P = \frac{(3.6 - 0)}{(12 - 5)} \times (S - 5) \times N \approx 0.51 \times (S - 5) \times N
\]  

(2.3)

Given the relationship between wind speed and electricity output of wind power plant, the proposed model can characterize the four factors of wind power plant. As it mentioned earlier, wind power has zero variable cost [27]. The proposed model adopts this fact to model the variable cost of wind power plants. From the technical specifications of Siemens Wind Turbine SWT-3.6-120, which are listed in Table 6, the capacity of wind power plant is 3.6 MW and the minimum load of wind power plant is 0 MW. Typically, wind power plants have very high fixed costs and zero variable costs. Sometimes, in order to ensure electricity dispatch, wind generators will bid a negative wholesale price to ensure electricity dispatch [28]. For that reason, generation operators always keep the wind power plant operate at offered generation decided by wind speed until an outage (if any). The model of wind power plants shares the same property with wind power plants in industry, namely the model is not allowed to shut down. In order to meet this requirement, the proposed model sets the duration of operation throughout the simulation period. According to the definition of forced outage, when wind plants work below cut-in speed or above cut-out speed, they experience forced outage. So, the forced outage rate of wind power plant is not a constant value. It varies with the wind speed. The proposed model follows this fact to model the forced outage of wind power plants instead of defining the EFOR of wind power plants. Note that the output of each wind turbine is relatively small, and the wind farm usually owns hundreds of wind turbines. Therefore, the proposed model models one wind power plant as a set of wind
### Coal Power Plant Statistics

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Variable cost $/MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>10.00</td>
</tr>
<tr>
<td>Third quartile</td>
<td>8.45</td>
</tr>
<tr>
<td>Median</td>
<td>6.80</td>
</tr>
<tr>
<td>First quartile</td>
<td>5.04</td>
</tr>
<tr>
<td>Minimum</td>
<td>2.99</td>
</tr>
</tbody>
</table>

| Table 2.8. The variable cost of coal power plant. |

The quantity of wind turbines in a wind power plant obeys the normal distribution with expectation of $\mu_N = 100$ and variance of $\sigma^2_N = 100$. Note that the quantity of wind turbines can only be positive.

#### 2.3.3 The Design Details of Coal power plants

Coal-fired power plant belongs to the base load plant, which typically has high fixed costs and relatively low variable cost. Coal power plant is efficient and stable.

**The Variable Cost of Coal Power Plant.** Table 2.8 lists the statistics gathered from TCDB. The thesis is based on the statistics in Table 2.8 to calculate the variable cost of coal power plant.

Another way to calculate the variable cost of coal power plant is to the sum of the fuel cost and the variable O&M cost. And the fuel cost is equal to the product of coal price and operating heat rate. The historical coal price of 2010 from EIA is 2.42 dollars per million Btu. The historical average operating heat rate of 2010 from EIA is 10415 Btu per Kilowatt-hour. The variable cost is presented in Table 2.9.

**The Capacity of Coal Power Plants.** The proposed model investigates several generation statistics of coal-fired plants. Statistics gathered from TAG Power Generation and Storage Technology Options [29] shows that different coal-fired plants share a net capacity of 800MW and minimum load of 200 MW, but with different gross electric capacity.
Table 2.9. The variable O&M cost of coal power plant.

<table>
<thead>
<tr>
<th>Plant Name</th>
<th>Gross electric capacity</th>
<th>Net electric Capacity</th>
<th>Minimum Load</th>
<th>Variable Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC Plant, WI, PRB Subbituminous</td>
<td>856 MW</td>
<td>800 MW</td>
<td>25%</td>
<td>2.1 miles/kWh</td>
</tr>
<tr>
<td>PC Plant, WI, IL#6 Bituminous</td>
<td>854 MW</td>
<td>800 MW</td>
<td>25%</td>
<td>5.1 miles/kWh</td>
</tr>
<tr>
<td>PC Plant, TX, PRB Subbituminous</td>
<td>855 MW</td>
<td>800 MW</td>
<td>25%</td>
<td>3.7 miles/kWh</td>
</tr>
<tr>
<td>PC Plant, PA, West Virginia Bituminous</td>
<td>850 MW</td>
<td>800 MW</td>
<td>25%</td>
<td>2.1 miles/kWh</td>
</tr>
<tr>
<td>PC Plant, GA, West Virginia Bituminous</td>
<td>850 MW</td>
<td>800 MW</td>
<td>25%</td>
<td>1.9 miles/kWh</td>
</tr>
</tbody>
</table>

Table 2.10. Generation statistics of coal-fired plants.

and variable costs. Please see Table 2.10 for more details. To simplify the modeling process, the proposed model assumes the model of coal plant has a net capacity of 800MW and a minimum load of 200 MW.

The Duration of Operation. Coal power plant typically runs during the season and time. Therefore, the model of coal power plants operates throughout the simulation period except forced outage. However, the proposed model finds the offered generation of coal
Table 2.11. The forced outage rate of coal power plant.

<table>
<thead>
<tr>
<th>MWTrb/Gen Nameplate</th>
<th>EFOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-99</td>
<td>11.81</td>
</tr>
<tr>
<td>100-199</td>
<td>7.14</td>
</tr>
<tr>
<td>200-299</td>
<td>7.34</td>
</tr>
<tr>
<td>300-399</td>
<td>6.76</td>
</tr>
<tr>
<td>400-599</td>
<td>8.18</td>
</tr>
<tr>
<td>600-799</td>
<td>6.69</td>
</tr>
<tr>
<td>800-999</td>
<td>4.53</td>
</tr>
<tr>
<td>1000 Plus</td>
<td>8.39</td>
</tr>
</tbody>
</table>

power plant can be adjusted between the minimum load and capacity. The proposed model models the property of coal power plant.

The Forced Outage Rate of Power Plants. Table 2.11 lists the EFOR data gathered from GADS (Generating Unit Statistical Brochure, 2006-2010), which is used to model the forced outage rate of coal power plant.

2.4 The Implementation Details of EIDA Generation Dispatch Model

The Generation Dispatch contains a Energy List Model and several methods to manage the System Status, which is presented in Figure 2.3.

Energy List Model contains different kinds of power plants, which are presented in Figure 2.4. The model() method in the EnergyList class uses factory method pattern to create different power plants.

Power plants have the same base class named Energy Prototype that includes the operations to manipulate the power plants. Figure 2.5 gives the inheritance relationship. Note that the simple model of generation portfolio is characterized by the four factors mentioned above.
2.5 Summary and Future Work

In summary, this chapter presents EIDA generation dispatch model that helps students understand the behavior of generation suppliers. This computational model approaches the generation dispatch by exploring the consumption pattern of electricity, the power plants characters and the dispatch.

EIDA now implements the base load utilities, namely nuclear power plant, coal power plant, and wind power plant that belong to the renewable power plants. These power plant models establish the foundation of modeling power plants recycling, such as recycle of gas turbine. EIDA next will focus on the intermediate load utilities and peak load utilities, both of which can recycle when load reaches a certain level. Furthermore, the project will explore more complicated methodologies to model the fuel cost of power plants, the model of forecast load from temperature, and so on.
Figure 2.4. The UML of Energy List.
Figure 2.5. The UML of Energy Prototype.
3 Modeling of The Electricity Market

3.1 Introduction

As mentioned in Chapter 1, after electricity has been generated at power station, it is transmitted through the grid and distributed to the end customers. Generally speaking, an electric generator needs to interconnect with the grid and sell electricity in wholesale electricity market. Then, retailers buy electricity from wholesale electricity market, distribute it and resale it to the end-users. Chapter 2 introduced the model of generation dispatch. This chapter focuses on explaining the model of the wholesale electricity market. Note that the electricity transmission, power distribution, and retail electricity market are beyond the discussion of this thesis. Electricity is a special commodity since it is too expensive to store, and it is challenging for RTO to balance the generation and load in the electricity market. Therefore, EIDA applies complete market rules and proposes a new model to let participants make transactions both in the one-day forward market that bases on the forecast data and in the real-time market that reflects the real-time data. The proposed model mimics the PJM wholesale electricity market, and it serves as a tool to help student practice making transaction to balance their position in the wholesale electricity market that includes the day-ahead market and the real-time
market. The model also allows students to make transaction with broker. This chapter first examines how EIDA approaches modeling the wholesale electricity market, and then it further explains the modeling process by providing both the design detail and implementation detail. It closes with a subsection on future work to model the wholesale electricity market more properly.

3.2 The EIDA Wholesale Electricity Market Model

EIDA designs rules to make the day-ahead market and the balancing market operate as a system, as follows. Offers and bids are first submitted to EIDA Day-Ahead Market. As the generation quantity and forecast load varies, participants with available demand or capacity can reoffer and rebid in the Generation Rebidding Period. Once the balancing market bidding period is over, the generation supplier cannot change their offers during the operating day. During the operating day, the balancing settlement is based on the real-time price and the hourly quantity deviations from day-ahead scheduled quantities [30]. Specifically, this section first introduces the generation and load in the EIDA wholesale electricity market. It then explains the time line of the whole simulation. After that, it emphasizes on explaining the mechanisms and the settlements of EIDA wholesale electricity market that consists of the day-ahead market, the balancing market, and the broker. It also examines the market-clearing price in EIDA. Finally it explains how EIDA gives participants a meaningful feedback and gives some examples of trading strategies. Throughout, this section examines how EIDA applies different mechanisms and data to model the one-day forward market and real-time market respectively.
### Day-Ahead Market

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>Inform the participants the load forecasts</td>
</tr>
<tr>
<td>Step 2</td>
<td>Bids and Offers for energy accepted by EIDA for Operating Day</td>
</tr>
<tr>
<td>Step 3</td>
<td>Day-ahead market is closed for EIDA evaluation</td>
</tr>
<tr>
<td>Step 4</td>
<td>EIDA clear bids with the day-ahead market-clearing price and provides a complete view of the Day ahead market profile</td>
</tr>
</tbody>
</table>

### Balancing-Market

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 5</td>
<td>Balancing market bidding is opened</td>
</tr>
<tr>
<td>Step 6</td>
<td>Balancing market bidding is closed. EIDA clear bids with the real-time market-clearing price and provides a complete view of the Balancing market bidding profile</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operating-Day</th>
<th>EIDA settle all transactions in Real-Time price</th>
</tr>
</thead>
<tbody>
<tr>
<td>After the Operating-Day</td>
<td>EIDA provides the complete view of the wholesale electricity market profile</td>
</tr>
</tbody>
</table>

Table 3.1. The time line of EIDA Day-Ahead Market and Real-time Market.

#### 3.2.1 The Generation and Load in EIDA

In the wholesale electricity market, the amount of electricity generation and the amount of electricity consumption could vary due to the weather conditions, transmission outages, or forced outages of the power plants. Therefore, the actual load and generation may differ from the forecast load and generation. EIDA keeps updating the load forecast and offers during day-ahead and the operating day. Participants can respond to these emergencies in the balancing market and during the operating day. Note that the model of load and generation is already introduced in Chapter 2.

#### 3.2.2 The Timeline of EIDA Wholesale Electricity Market

Table 3.1 shows the time line of EIDA Day-Ahead Market and Real-time Market.

Note that day ahead is operating day - 1, which is the day before operations occur. Operating day is the day during which power flows.
3.2.3 The Day-Ahead Market, Balancing Market and Broker


**The Day-Ahead Market.** In EIDA, the Day-Ahead Market is operated at the day before the delivery day. Energy suppliers need to submit offers, which demonstrate the level of production, to EIDA. Energy retailers also can submit bids, which demonstrate the level of electricity demand, to EIDA. EIDA calculates the market-clearing price, which are the ones that clear the market. Finally, the Day-ahead settlements are based on the day-ahead market-clearing price. Note that while real-time market allows only physical transaction, virtual bidding and transaction are only allowed in Day-Ahead Market, which means participants can buy and sell without physical supply in Day-Ahead Market.

**The Balancing Market.** Generation suppliers and load serving entities may alter their bids in the Generation Rebidding Period that is opened after the close of Day-Ahead Market. This bidding period of Real-Time Market also happened at the day before the operating day. If the position of energy supplier or retailer is not balanced, they can enter Generation Rebidding Period to rebid. The bidding period of the balancing market closed that the day before operating day. During the operating day, generation suppliers are not allowed to change their offer prices, and the Balancing settlement is based on the Real-time price.

**The Broker.** In order to maximize the profit, the energy buyers need to compare prices from multiple energy suppliers in the wholesale electricity market. But price comparison requires the energy buyers to invest time and other resources. As a result, the energy
brokers play as a middleman to provide the service of obtaining the best contract. Members of PJM can trade with brokers in the wholesale market.

### 3.2.4 The Day-Ahead Settlement and the Balancing Settlement

EIDA also modeled two settlements in these two markets, one is the Day-ahead settlement, and the other is the Balancing Settlement. Note that two settlements are not the same as two electricity markets. Specifically, the Day-ahead Market is a forward market, and the Day-ahead settlement is based on day-ahead market-clearing price that is calculated based on generation offers, demand bids, increment offers, and decrement bids submitted into the Day-ahead Market by energy suppliers and load serving entities. In comparison, the Real-Time Balancing Market is the real-time energy market. The Balancing settlement is based on the hourly quantity deviations from day-ahead scheduled quantities and the real-time market-clearing price that is decided by actual system operations security-constrained economic.

### 3.2.5 The Market-Clearing Price and LMP in EIDA

In EIDA, energy suppliers enter the wholesale electricity market with offers to sell and the energy retailers enter the wholesale electricity market with bids to purchase. These transactions are settled based on the market-clearing price. Market-clearing price in EIDA is a supply and demand equilibrium price, which is determined based on matching offers from electricity suppliers and bids from retailers. Specifically, if we define the clear price of the market as the price of the last offer that fulfills the demand, then the cheapest offer will clear the market first. The next cheapest one will clear the market then, and so on so forth until the demand is meet. For example, Figure 3.1 shows the offered price of five resources, and Figure 3.2 shows the 5 offered generations of these
Figure 3.1. The offered price of five resources.

Figure 3.2. The offered generation of five resources.

five resources respectively. If the demand is 215 MWh, generation supplier D offers 0.8 $/MWh for 80 MWh, so resource D clears the market first. Generation supplier E offers 1.5 $/MWh for 60 MWh, and it clears the market second. Generation B offers 2.4 $/MWh for 75 MWh, and it fulfills the demand. Consequently, the clear price of the market is 2.4 $/MWh.
EIDA developed a market-clearing model based on Locational Marginal Price (LMP) that is defined as the marginal price for energy at the location where the energy is delivered or received [31]. Note that the model of LMP is complicate and is beyond the discussion of this thesis.

### 3.2.6 The Calculation of Profit in EIDA

The calculation of profits is based on two settlements, which are correlated to each other. The Day-ahead settlement is based on the Day-ahead market-clearing price, and the Balancing Settlement is based on the real-time market-clearing price. Note that the load serving entities pay or are paid the real-time market-clearing price for demand deviation in the real-time market. Generation suppliers pay or are paid the real-time market-clearing price for generation deviation in the real-time market. For example, a load serving entity bids 10MWh in day-ahead market, and the day-ahead LMP is 20 $/MWh. During the operating day, the demand increases to 20MWh, and the real-time LMP is 15 $/MWh. The load serving entity needs to pay $350 as follows:

\[
10 \text{MW} h \times 20\$/\text{MW} h + (20 - 10)\text{MW} h \times 15\$/\text{MW} h = \$350
\]

Note that the Balancing settlement is based on the load deviation and real-time hourly LMP, and profit calculation based on LMP for simplicity.

### 3.2.7 Different response strategies and their profit in EIDA

The following tables, Table 3.2, Table 3.3 and Table 3.4, give 12 scenarios that participants respond to the market in EIDA and the calculation of each profit respectively. Accordingly, participants can adopt different transaction strategies in the wholesale electricity market. Note that the negative profit is defined as paying money. Scenarios 1
### Table 3.2. Scenario 1 to 4.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Generation Suppliers</th>
<th>Day-Ahead Market</th>
<th>Day-Ahead LMP</th>
<th>Day-Ahead Profit</th>
<th>Real-Time Market</th>
<th>Real-Time LMP</th>
<th>Real-Time Profit</th>
<th>Total Profit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>Offers 20 MWh</td>
<td>10 $/ MWh</td>
<td>200$</td>
<td>Actual Generate 30 MWh (increasing Economic Maximum generation)</td>
<td>15 $/ MWh</td>
<td>150 $</td>
<td>350 $</td>
<td></td>
</tr>
<tr>
<td>Scenario 2</td>
<td>Offers 20 MWh</td>
<td>10 $/ MWh</td>
<td>200$</td>
<td>Actual Generate 30 MWh (increasing Economic Maximum generation)</td>
<td>5 $/ MWh</td>
<td>50 $</td>
<td>250 $</td>
<td></td>
</tr>
<tr>
<td>Scenario 3</td>
<td>Offers 20 MWh</td>
<td>10 $/ MWh</td>
<td>200$</td>
<td>Actual Generate 10 MWh (Due to forced outage)</td>
<td>15 $/ MWh</td>
<td>-150 $</td>
<td>50 $</td>
<td></td>
</tr>
<tr>
<td>Scenario 4</td>
<td>Offers 20 MWh</td>
<td>10 $/ MWh</td>
<td>200$</td>
<td>Actual Generate 10 MWh (Due to forced outage)</td>
<td>5 $/ MWh</td>
<td>-50 $</td>
<td>150 $</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3.3. Scenario 5 to 8.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Generation Suppliers</th>
<th>Day-Ahead Market</th>
<th>Day-Ahead LMP</th>
<th>Day-Ahead Profit</th>
<th>Real-Time Market</th>
<th>Real-Time LMP</th>
<th>Real-Time Profit</th>
<th>Total Profit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 5</td>
<td>Loads 20 MWh</td>
<td>10 $/ MWh</td>
<td>-200$</td>
<td>Actual Demand 30 MWh (Due to weather condition)</td>
<td>15 $/ MWh</td>
<td>-450 $ -250 $</td>
<td>-450 $ -250 $</td>
<td></td>
</tr>
<tr>
<td>Scenario 6</td>
<td>Loads 20 MWh</td>
<td>10 $/ MWh</td>
<td>-200$</td>
<td>Actual Demand 30 MWh (Due to weather condition)</td>
<td>5 $/ MWh</td>
<td>-50 $</td>
<td>-50 $</td>
<td></td>
</tr>
<tr>
<td>Scenario 7</td>
<td>Loads 20 MWh</td>
<td>10 $/ MWh</td>
<td>-200$</td>
<td>Actual Demand 10 MWh (Due to weather condition)</td>
<td>15 $/ MWh</td>
<td>150 $</td>
<td>-150 $</td>
<td></td>
</tr>
<tr>
<td>Scenario 8</td>
<td>Loads 20 MWh</td>
<td>10 $/ MWh</td>
<td>-200$</td>
<td>Actual Demand 10 MWh (Due to weather condition)</td>
<td>5 $/ MWh</td>
<td>50 $</td>
<td>50 $</td>
<td></td>
</tr>
</tbody>
</table>

to Scenario 4 are the responses of the generation suppliers when the positions are not balanced.
Scenarios 5 to Scenario 8 are the responses of the load serving entities when the positions are not balanced.

Table 3.4 gives four examples of virtual bidding and calculating the profit in whole electricity markets. Note that INC is short for Increment Offers, and DEC is short for Decrement Bids. INCs lose money and DECs gain money, when the Real-Time LMP is higher than the Day-Ahead LMP, and vice versa.

### 3.3 The Design Details of the Wholesale Electricity Market

#### 3.3.1 The Model of Electricity Market Time Line

The thesis proposes a model to model the PJM wholesale electricity market, which is a simplification of the PJM market. PJM requires submission of hourly bids and offers in wholesale electricity market to calculate the LMP, while the proposed model models the historical scenarios based on historical LMPs. The proposed model aims to help students practice in immersive historical market simulation without influencing the historical LMP. Based on this idea, the proposed model requires student to respond to the historical LMPs by balancing their position or hedging transactions. The proposed model
The day before the operating day

<table>
<thead>
<tr>
<th>1st Market</th>
<th>Day-ahead Market</th>
<th>Broker Market</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd Market</td>
<td>Balancing rebidding Market (Balancing of 7:30 am, 10:30 am, 2:30 pm and 5:30 pm)</td>
<td>Broker Market</td>
</tr>
</tbody>
</table>

The operating day

The Balancing Settlement

The Billing period

Send the bill to individuals

Table 3.5. The wholesale electricity market time line.

provides one opportunity of trading in day-ahead market and five opportunities of trading during the most challenging hours in the balancing market.

Specifically, the proposed model follows the time line demonstrated in Table 3.5 to establish the system. In the day before the operating day, the proposed model allows making transactions in Day-ahead market. After finishing trading in the Day-ahead market, the proposed model allows to make transaction in the Balancing market, which contains five opportunities to trade in different peak hours respectively. Once the Balancing market is closed, the balancing settlements are based on real-time hourly LMP. Trading through broker is considered as an alternative option in the proposed system, which is allowed both in day-ahead market and real-time market. Finally, the proposed system sends a bill that calculates the revenue in the day-ahead market and the balancing market. Table 3.5 presents the model of the wholesale electricity market time line.

3.3.2 The Model of Market-Clearing Price

Based on the difference between forecast generation and forecast load, the proposed model allows generation suppliers to make transaction in wholesale electricity market.
For example, if the forecast generation is 8800 MWh and the forecast load is 9000 MWh, generation suppliers need to balance their position by buying 200 MWh in the wholesale electricity market. Note that the forecast generation and forecast load vary during the simulation. Settlements made in the wholesale electricity market are based on the day-ahead market-clearing price, balancing rebidding period market-clearing price, real-time market-clearing price, and broke price respectively. The model of the market-clearing price of each settlement is explained as follows.

3.3.3 The Clearing Price of Day-ahead Market

The proposed model uses the averaged historical Day-ahead hourly LMP over 16 peak hours to model the Day-ahead market-clearing price. Note that PJM asks participants to submit increment offers and decrement bids when they enter the Day-ahead market. After the Day-ahead market is closed, the dispatch schedule and hourly Day-ahead LMP are analyzed and published. This complex process to calculate the Day-ahead market-clearing price is under development, and is beyond the discussion of the thesis.

3.3.4 The Clearing Price of Balancing Market

The Clearing Price of Rebidding Period. Generally speaking, energy suppliers and load serving entities reevaluate their position in the rebidding period since forecast load and generation are updated instantly. The model of rebidding period includes making offers and bids in 4 peak hours of the operating day, namely 7:30 am, 10:30 am, 2:30 pm and 5:30 pm. Note that these offers and bids are not settled in real-time, so the proposed model uses forecast Real-time hourly LMP to model the market-clearing price of the rebidding period. Table 3.6 presents how to calculate the market-clearing prices respectively. The proposed model adopts this methodology since the calculated balancing
The Balancing market-clearing price for 7:30 am
(Forecast real-time LMP of 6:00 am + Forecast real-time LMP of 7:00 am)/2

The Balancing market-clearing price for 10:30 am
(Forecast real-time LMP of 8:00 am + Forecast real-time LMP of 9:00 am + Forecast real-time LMP of 10:00 am)/3

The Balancing market-clearing price for 2:30 Pm
(Forecast real-time LMP of 11:00 am + Forecast real-time LMP of 12:00 pm + Forecast real-time LMP of 1:00 pm + Forecast real-time LMP of 2:00 pm)/4

The Balancing market-clearing price for 5:30 am
(Forecast real-time LMP of 3:00 pm + Forecast real-time LMP of 4:00 pm + Forecast real-time LMP of 5:00 pm)/3

Table 3.6. Calculate the market-clearing prices.

The clearing price reflects the expectation of the real-time system dispatch, which is influenced by real-time transmission, real-time weather condition, and so on.

**The Clearing Price of Balancing Settlement.** Balancing settlement is based on the real-time LMP in PJM. The proposed model models the Balancing settlement by averaging the hourly Real-time LMP over the 16 peak hours of the operating day.

### 3.3.5 Broker Price

Trade through broker in the wholesale electricity market is an option for energy suppliers. The broker price is extrapolated from available historical data as follows. This formulation is an approximation of the wholesale electricity price expectation.

\[
BP = \frac{aLMPS + frLMPS}{2} \tag{3.2}
\]

where \(BP\) is the broker price, \(aLMPS\) is the average day-ahead LMPS, and \(frLMPS\) is the forecast real time LMPS at 6 am.
3.3.6 The Bills of Cost, Revenue, and Profit

After the operating day, the proposed model calculates the profit of each individual and sends the bills. Note that the proposed model models the markets for energy (MWH)-related commodities, while the billing account is managed using the power commodities over 16 peak hours. Table 3.7 and Table 3.8 together give an example of the calculation of profit.

3.4 The Implementation Detail of EIDA Wholesale Electricity Market

EIDA has a SimulationDay Model, which contains a GenerationDispatch Model and a SegmentList Model. SegmentList Model is responsible for modeling the wholesale electricity market. Different hour segments during the simulation day are contained in the SegmentList Model, which is presented in Figure 3.3.

In each Segment, users can add transactions to the TransactionList. The Segment also includes some system status of the current moment, which is shown in Figure 3.4.
<table>
<thead>
<tr>
<th>Generation/Forecast Load</th>
<th>8800 MWh</th>
<th>Load</th>
<th>9000 MWh</th>
<th>Deviation</th>
<th>-200 MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transaction Quantity in Day-Ahead Market</td>
<td>100 MWh</td>
<td>Transaction Quantity in Broker</td>
<td>0 MWh</td>
<td>Transaction Quantity</td>
<td>100 MWh</td>
</tr>
<tr>
<td>Averaged Day-Ahead LMP</td>
<td>20 $/MWh</td>
<td>Broker Price</td>
<td>21$/MWh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost in Day-Ahead Market</td>
<td>2000 $</td>
<td>Cost in Brokerage</td>
<td>0 $</td>
<td>Cost 1</td>
<td>2000 $</td>
</tr>
<tr>
<td>Generation/Forecast Load</td>
<td>8900 MWh</td>
<td>Load</td>
<td>8700 MWh</td>
<td>Deviation</td>
<td>200 MWh</td>
</tr>
<tr>
<td>Transaction Quantity in The Balancing Market forward trading for 7:30 am</td>
<td>300 MWh</td>
<td>Transaction Quantity in Broker</td>
<td>0 MWh</td>
<td>Transaction Quantity</td>
<td>300 MWh</td>
</tr>
<tr>
<td>The Balancing market-clearing price for 7:30 am</td>
<td>15$/MWh</td>
<td>Broker Price</td>
<td>21$/MWh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost in balancing of 7:30 am</td>
<td>4500 $</td>
<td>Revenue in Brokerage</td>
<td>0$</td>
<td>Cost 2</td>
<td>4500$</td>
</tr>
<tr>
<td>Generation/Forecast Load</td>
<td>9200 MWh</td>
<td>Load</td>
<td>8900 MWh</td>
<td>Deviation</td>
<td>300 MWh</td>
</tr>
<tr>
<td>Transaction Quantity in The Balancing Market forward trading for 10:30 am</td>
<td>0 MWh</td>
<td>Transaction Quantity in Broker</td>
<td>100 MWh</td>
<td>Transaction Quantity</td>
<td>100 MWh</td>
</tr>
<tr>
<td>The Balancing market-clearing price for 10:30 am</td>
<td>22 $/MWh</td>
<td>Broker Price</td>
<td>21$/MWh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost in balancing of 10:30 am</td>
<td>0 $</td>
<td>Cost in Brokerage</td>
<td>2100 $</td>
<td>Cost 3</td>
<td>2100 $</td>
</tr>
<tr>
<td>Generation/Forecast Load</td>
<td>9400 MWh</td>
<td>Load</td>
<td>9200 MWh</td>
<td>Deviation</td>
<td>200 MWh</td>
</tr>
<tr>
<td>Transaction Quantity in The Balancing Market forward trading for 2:30 pm</td>
<td>-200 MWh</td>
<td>Transaction Quantity in Broker</td>
<td>0 MWh</td>
<td>Transaction Quantity</td>
<td>-200 MWh</td>
</tr>
<tr>
<td>The Balancing market-clearing price for 2:30 pm</td>
<td>25 $/MWh</td>
<td>Broker Price</td>
<td>21$/MWh</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.7. An example of the calculation of profit.
Table 3.8. An example of the calculation of profit (continued).

<table>
<thead>
<tr>
<th>Transaction Quantity in The Balancing Market forward trading for 5:30 pm</th>
<th>-100 MWh</th>
<th>Transaction Quantity in Broker</th>
<th>0 MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Balancing market-clearing price for 5:30 pm</td>
<td>22 $/MWh</td>
<td>Broker Price</td>
<td>21 $/MWh</td>
</tr>
<tr>
<td>Revenue in balancing 2:30 pm</td>
<td>2200 $</td>
<td>Revenue in Brokerage</td>
<td>0 $</td>
</tr>
<tr>
<td>Generation/Forecast Load</td>
<td>9100 MWh</td>
<td>Load</td>
<td>9000 MWh</td>
</tr>
<tr>
<td>Transaction Quantity in The Balancing settlement</td>
<td>100 MWh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The Real-time Price</td>
<td>22 $/MWh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Revenue 6</td>
<td>2200 $</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost 1</td>
<td>2000 $</td>
<td>Cost 2</td>
<td>-4500$</td>
</tr>
<tr>
<td>Revenue 4</td>
<td>5000 $</td>
<td>Revenue 5</td>
<td>2200 $</td>
</tr>
<tr>
<td>Profit</td>
<td>800 $</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.4. The TransactionList Model.
Transaction can be categorized as the Day-Ahead transaction, the Real-Time transaction, the Balancing Settlement transaction, and the Brokerage transaction. These transaction prototypes share the same base class model named Transaction manage the transaction information, such as price, name, and so on. Figure 3.5 shows the inheritance relationship.

### 3.5 Summary and Future Work

This chapter first gives an overview of the EIDA Wholesale Electricity market model, and then explains the detail of the proposed model. For now, EIDA contains two level of simulation, and it will present a third level of simulation in future work. The proposed model will use offers and bids submitted by users to calculate the hourly LMPs that are then adopted in the wholesale electricity market.
4 Implementation and Technologies

4.1 Introduction

This chapter introduces the data flow diagrams of the computational framework of generation dispatch and the model of wholesale electricity market, and the software technologies, on which EIDA is built.

4.2 The Data Flow Diagram

Figure 4.1, Figure 4.2, Figure 4.3 and Figure 4.4 show all the data flow diagrams (DFD) of the proposed computational framework of generation dispatch and the model of wholesale electricity market.

4.3 The General Technologies

EIDA is a browser-based dynamic web application that runs as a client-side JavaScript application. EIDA is easily portable across different operating systems and devices. Furthermore, the present version of EIDA off-load most server-side processing expect downloading historical data and storing the profiles of users. Note that although EIDA consists of several web pages, the core logic of EIDA runs as a Single-Page Application
(SPA) [18]. Specifically, EIDA is divided into a front-end that is implemented with CoffeeScript [14] and Backbone.js framework [15], and a back-end that is implemented with Node.js [16] and CouchDB [17]. The core logic is implemented in the front-end with CoffeeScript [14], Backbone.js [15] framework, Jade templates [32] and Bootstrap framework [34]. The front-end is tested with QUnit [36] that is a JavaScript Unit Testing framework. At the back-end, historical data is stored in CouchDB [17] that is a document-based storage system built around JSON. The server-side is implemented with Node.js that is a JavaScript runtime built on Chrome V8 JavaScript engine. One can refer to previous work [13] to find the discussion of the back-end implementation that is beyond the discussion of this thesis.
Figure 4.3. Level 2 DFD that refines the simulate EIDA process.

Figure 4.4. Level 2 DFD that refines the Initialize Simulation process.
4.4 The front-end Technologies

Our front-end implementation is based on a JavaScript MVC (Model-View-Controller) framework called Backbone.js, wherein a programming language CoffeeScript is applied. In particular, as for the View layer in the MVC framework, the HTML file is generated by Jade that is compiled with Underscore [33]. The styles and components in HTML are developed around Bootstrap and JQuery [35]. As for the software test, a JavaScript Unit Testing framework called QUnit is employed. We will briefly introduce these technologies one by one. The Backbone.js is introduced first. As a JavaScript MVC library that helps us decouple the representation layer (View) from the logic (Controller) and persistence (Model) layer, Backbone.js provides structure to web applications with the functioning modules like models with key-value binding and custom events, collections with a rich API of enumerable functions, as well as views with declarative event handling [18]. The design philosophy and the functionalities that Backbone.js embodies make Backbone.js arguably one of best JavaScript MVC framework. For example, Backbone.js takes a deliberately flexible consideration regarding the length of the UI code. This flexibility makes it suitable for our browser-based web application, which contains many complex web pages that require tons of JavaScript code. With the help of Backbone.js, the maintainability, readability, and development efficiency are greatly improved. Second, CoffeeScript is applied instead of directly writing the JavaScript code due to the golden rule of CoffeeScript that the CoffeeScript code is compiled one-to-one into the equivalent JavaScript code without interpretation at runtime. In other words, we are able to enjoy the simplicity, efficiency and readability of CoffeeScript without losing any functionality and compatibility to the original JavaScript code. In our project, CoffeeScript significantly boost our development efficiency compared with the
JavaScript. Third, the design philosophy of Jade is similar to CoffeeScript, which means we can replace the intricate HTML code with a much simpler and readable code without any information loss. Fourth, as a JavaScript library that provides functional programming helpers, Underscore can be used to compile the Jade code into equivalent HTML code. As for Bootstrap, it contributes to the mobile first projects on the web by providing HTML, CSS and JavaScript integration. With the help of Bootstrap, we can build beautiful web pages with versatile and extensive features. Similarly, JQuery provides off-the-shelf functionalities for JavaScript, such as HTML document traversal and manipulation, event handling, animation, and Ajax much simpler with an easy-to-use API that works across a multitude of browsers. Finally, the QUnit framework is deliberately designed and widely recognized for the unit testing of JavaScript language.
5 Conclusion and Future work

This thesis presents a computational framework of generation dispatch, a model of wholesale electricity market to EIDA as well as a browser-based client-side JavaScript application. The computational framework of generation dispatch contains different power plants models that play different roles in generation scheduling. The model of wholesale electricity market is built around the market time line, and it contains transactions in different electricity market. Implementations and technologies applied in developing the browser-based web application EIDA are also explained. EIDA applies plenty of patterns and strategies adopted in the electricity industry, which helps the modeling process accurate. This thesis implements the base load utilities, namely nuclear power plant, coal power plant, and wind power plant that belongs to the renewable power plants. The project will focus on the intermediate load utilities and peak load utilities, both of which can recycle when load reaches a certain level. Furthermore, the project will explore new methodologies to model the fuel cost of power plants, the model of forecast load from temperature. At last, the wholesale electricity market will adopt a computational model to calculate the LMP from the bids and offers submitted by the students.
Appendix A

Forced Outage Rate (FOR)

Forced outage rate (FOR) is defined as the number of hours that the unit is on forced outage over the total number of hours in a year (which is the sum of hours that the power station is available for service and hours that the power station is in forced outage) [37]. And we can use the following equation to calculate FOR.

\[
FOR = \left( \frac{FOH}{FOH + SH} \right) \times 100\% \quad (A.1)
\]

where \(FOH\) and \(SH\) are defined in Table A.1.

Equivalent Forced Outage Rate (EFOR), which is the hours of unit failure (unplanned outage hours and equivalent unplanned derated hours) is defined as a percentage of the total hours of the availability of that unit (unplanned outage, unplanned derated, and service hours) [39]. And we can use the following equation to calculate EFOR.

\[
EFOR = \left( \frac{FOH + EF DH}{FOH + SH + EF DHRS} \right) \times 100\% \quad (A.2)
\]

where \(EF DH\) and \(EF DHRS\) are defined in Table A.2.

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forced Outage Hour (FOH)</td>
<td>Sum of all hours experienced during Forced Outages [38].</td>
</tr>
<tr>
<td>Service Hours (SH)</td>
<td>Total number of hours a unit was electrically connected to the system. [38].</td>
</tr>
</tbody>
</table>

Table A.1. FOH and SH.
<table>
<thead>
<tr>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent Forced Derated Hours (EFDH)</td>
</tr>
<tr>
<td>Definition</td>
</tr>
<tr>
<td>The product of the Forced Derated Hours (FDH) and the Size of Reduction, divided by the Net Maximum Capacity (NMC) [38].</td>
</tr>
<tr>
<td>Equivalent Forced Derated Hours During Reserve Shutdowns (EFDHRS)</td>
</tr>
<tr>
<td>Definition</td>
</tr>
<tr>
<td>The product of the Forced Derated Hours (FDH) (During Reserve Shutdowns ONLY) and the Size of Reduction, divided by the Net Maximum Capacity (NMC) [38].</td>
</tr>
</tbody>
</table>

Table A.2. EFDH and EFDHRS.
Appendix B

Screenshots of EIDA System

Example screen shots of how to run the simulation in our implemented EIDA system are shown as follows.

**Step 1. Choose low/high level.** Please see Figure B.1.

**Step 2. Choose low level. There are five tabs in the low level simulation.** Please see Figure B.2.

**Step 3. Choose generation portfolio tab.** The generation portfolio will have single item. Then everything else will be the same with the old version. Please see Figure B.3.

**Step 4. Choose high level.** There are five tabs in the high level simulation. Then choose generation portfolio tab. The generation portfolio will have several items (e.g. nuclear, wind) and items's property. Please see Figure B.4.

**Step 5. Play like usual (make some transactions and click next segment).** Some energy items may become off-line. Please see Figure B.5.

**Step 6. The off-line item will influence the generation of the whole day.** For example, the Nuclear1 is offline, and Wind2 can generate 179MW/h. So, the average generation of the whole day is: 1037(nuclear generation at 6 AM) / 16 + 179(wind generation estimated for the whole day) = 244MW. The calculation of wind generation estimated for the whole day will be explained in Step 7. Please see Figure B.6.

**Step 7. The wind power generation.** Due to the wind speed is not constant, so the wind power generation is not constant. It will change according to the wind speed. The wind power generation of the whole day is calculate by averaging 16 hours generation. Please see Figure B.7.
Figure B.1. Step 1.

Figure B.2. Step 2.
Figure B.3. Step 3.

Figure B.4. Step 4.
Figure B.5. Step 5.

Figure B.6. Step 6.
Figure B.7. Step 7.
References


[27] “Wind Turbines for Electricity”. zFacts.


