The Pennsylvania State University

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TO INVEST OR NOT TO INVEST: THE EXPLORATION OF PREFERRED INVESTMENT STRATEGIES IN CORPORATE RENEWABLE POWER PURCHASE AGREEMENTS

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Abstract

The modern society has seen a continuously growing electricity consumption and its associated environmental consequences. With recent technology advancements, renewable energy has been considered by many as a source of electricity that is both economically feasible and environmentally friendly. The investment of renewable energy projects can be intriguing, however. This research first developed a theoretical model using Multi-Objective Optimization Problem to determine the preferred investment strategies that considers both the economic and environmental benefit of a special kind of investment in renewable energy projects – Corporate Renewable Power Purchase Agreement (PPA). The proposed methods were implemented on the case study of The Pennsylvania State University in central Pennsylvania, United States. The general version of the Multi-Objective Optimization Problem required making significant assumptions that reduced the computation complexity. The study explored the uncertainty in future Wholesale Electricity Prices, which was assumed to be the source of electricity for the investors of these renewable energy projects had there been no investments made. The use of Binomial Lattice Pricing Model, Monte Carlo Simulation, and Unit Commitment produced the feasible solutions of the Multi-Objective Optimization Problem in which the corresponded Pareto Set was identified. The simplified version of the proposed Multi-Objective Optimization Problem was reduced into several Single-Objective Optimization Problems of the economic benefits of PPA investments, in which they also represent some Real Option Valuation Problems under specific conditions. While making other assumptions to maintain the tractability of these problems, the optimal solutions of the Single-Objective Optimization Problem and the Value of Options were identified. One of these Single-Objective Optimization Problem monetized the environmental benefits of PPA investments using Social Cost of Carbon published by EPA. Finally, Sensitivity Analyses were applied in some of these Optimization Problems, producing the corresponding solutions.

Keywords: Multi-Objective Optimization Problem, Single-Objective Optimization Problem, Real Option Valuation, Power Purchase Agreement, Greenhouse Gas Emission, Wholesale Electricity Price, Binomial Lattice Pricing Method, Unit Commitment, Monte Carlo Simulation.

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List of Symbols

ISO	Independent System Operator
RTO	Regional Transmission Organization
PPA	Power Purchase Agreement
PSU	The Pennsylvania State University
PJM	PJM Interconnection
MOOP	Multi-Objective Optimization Problem
SOOP	Single-Objective Optimization Problem
X	An objective in a generic Two-Objective Optimization Problem
Y	Another objective in a generic Two-Objective Optimization Problem
a	A feasible solution of a generic Multi-Objective Optimization Problem
b	Another feasible solution of a generic Multi-Objective Optimization Problem
$IHEV$	Investment Horizon Economic Value [$]
$GTEV$	Grand Total Economic Value [$]
$IHAE$	Investment Horizon Avoided Emission [Ton]
EV_t	Annual Economic Value [$]
AE_t	Annual Avoided Emission [Ton]
t	Index for investment time period [year]
f_t	Cumulative PPA Investment Size at time period t

$P_{t,k}$	Wholesale Electricity Price at Year t, intra-year period k [$/MWh]
T	Investment Horizon of Investor [year]
m	Number of intra-year, seasonal periods
k	Index for intra-year period
n	Number of days in each intra-year period
$\mathbf{E}()$	Notation for taking Expected Value
$EV_{f_t,P_{t,k}}$	Daily Economic Value [$]
r	Annual discount rate [%]
$MEF_{t,k}$	Carbon Dioxide Marginal Emission Factor [Ton/MWh]
$Q_{f_t,k}$	Daily total electricity output of renewable energy projects [MWh]
$AEP_{f_t,P_{t,k}}$	Daily Avoided Energy Payment [$]
$CPP_{f_t,k}$	Daily Total Cost of Power Purchase Agreements [$]
$RV_{f_t,P_{t,k}}$	Daily Resale Value of excess purchase in PPA [$]
$E_{f_t,k}$	Daily Avoided Energy (Wholesale Electricity) usage of investor of PPA [MWh]
$E_{f_t,j,k}$	Hourly Avoided Energy (Wholesale Electricity) usage of investor of PPA [MWh]
$D_{t,k}$	Hourly electricity demand of investor of PPA [MWh]
$Q_{f_t,j,k}$	Hourly total electricity output of renewable energy projects [MWh]
s	Index of a particular renewable energy project
S_t	Total number of renewable energy projects at time period t
$Q_{f_t,k,s}$	Daily total electricity output of renewable energy project s [MWh]
C_s	Unit cost of PPA of renewable energy project s [$/MWh]
$C_{0,s}$	Initial ($t = 0$) unit cost of PPA of renewable energy project s [$/MWh]
$q_{f_t,j,k}$	Hourly Excess Purchase of PPA
$q_{f_t,k}$	Daily Excess Purchase of PPA
p	The averaged probability of Wholesale Electricity Price to increase in between time periods

u The typical magnitude of increase in Wholesale Electricity Price if it were to increase in between each time period

d The typical magnitude of decrease in Wholesale Electricity Price if it were to decrease in between each time period

W Initial ($t = 0$) Wholesale Electricity Price

γ Projected exponential declining rate of future unit price of Power Purchase Agreement of renewable energy projects

SCC_t Annual Social Cost of Carbon interpolated from the value published by EPA

RF Regionalization Factor of unit cost ($/kWh) of renewable energy projects in PJM in comparison to the average level in the US, a value greater than 1 suggests that the cost of renewable energy projects in PJM is higher than the national average

pd Peak demand day

opd Off-peak demand day

LMP Locational Marginal Price (unit Price) of Wholesale Electricity in the regional electric power system ($/MWh or kWh)

g Index for one particular type of generation technologies in the Unit Commitment Problem

G Set for all generation technology types in the Unit Commitment Problem

CG Set for all conventionally dispatchable generation technology types in the Unit Commitment Problem

RG Set for all intermittent renewable generation technology types in the Unit Commitment Problem

K_g Parameter of projected installed capacity of generation technology type g in the Unit Commitment Problem [MW]

FP_g Parameter of projected Fuel Price of generation technology type g in the Unit Commitment Problem [$/MMBTU]

HR_g Parameter of Heat Rate of generation technology type g in the Unit Commitment Problem [BTU/KWh]

VOM_g Parameter of projected Variable Operation and Maintenance cost of generation technology type g in the Unit Commitment Problem [$/MWh]

$Pmin_{cg}$ Parameter of minimum power output of conventional dispatchable generation technology type cg in the Unit Commitment Problem [%]

R_{cg} Parameter of ramp rate of conventional dispatchable generation technology type cg in the Unit Commitment Problem [%/min]

$UTmin_{g}$ Parameter of minimum up-time of generation technology type g in the Unit Commitment Problem [hr]

$SU_{fixed,g}$ Parameter of Start-up Fixed Cost of generation technology type g in the Unit Commitment Problem [hr]

$SU_{fuel,g}$ Parameter of Start-up fuel requirement of generation technology type g in the Unit Commitment Problem [MMBTU/MW]

SRR Parameter of Spinning Reserve requirements fraction of PJM [10%]

SC Parameter of unit cost of shedding renewable energy generation in the Unit Commitment Problem [$/MWh]

$NetDem_{j}$ Parameter of net load (excluded renewable generation) of PJM in hour j of the Unit Commitment Problem [MMBTU/MW]

SR_{j} Parameter of Spinning Reserve Requirement of PJM in hour j of the Unit Commitment Problem ($SRR\times NetDem_{j}$) [MMBTU/MW]

$OpCost_{g}$ Parameter of Variable cost of generation for generation technology g of the Unit Commitment Problem ($FP_{g}\times HR_{g}/1000 + VOM_{g}$) [$/MWh]

$Avail_{rg,j}$ Parameter of availability/capacity factor of intermittent renewable generation technologies of PJM in hour j of the Unit Commitment Problem using historical data

$vTotalCost$ Variable for Total system cost of serving electricity in PJM of the Unit Commitment Problem [$]

$vStartCost$ Variable for cost of starting up electricity generation type(s) in PJM of the Unit Commitment Problem [$]

$vGenCost$ Variable for cost of generating electricity in PJM of the Unit Commitment Problem [$]

$vPenaltyCost$ Variable for cost of penalizing shedding renewable energy generation in PJM of the Unit Commitment Problem [$]

$x(g,j)$ Variable for power output of generation technology g in demand block j in PJM of the Unit Commitment Problem [MW]

$vUp(cg, j)$	Variable for whether conventional dispatchable generation technology cg turns on starting in demand block j of the Unit Commitment Problem
$vDown(cg, j)$	Variable for whether conventional dispatchable generation technology cg turns off starting in demand block j of the Unit Commitment Problem
$Aux(g, j)$	Variable for power output of generation technology g beyond its minimum load in demand block j of the Unit Commitment Problem [MW]
$vShed(j)$	Variable for shedded renewable energy generation in demand block j of the Unit Commitment Problem [MW]
$vU(cg, j)$	Binary Variable for whether generation technology cg is ON in demand block j

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Chapter 1

Introduction

In this chapter, the underlying background information are presented, the motivation and contribution of this work are outlined, relevant previous works existed in the literature are reviewed, and the overall research question in this thesis is defined.

1.1 Background Information

Global annual electricity consumption has surpassed 22,000 TWh in 2018 [1] and represented a 3.5% growth from 2017. At the mean time, the environmental effect of such large amount of electricity consumption and production is looming. Close to half of global source of carbon dioxide emission in 2014 is caused by electricity and heat production [2]. This number is not necessarily the same value in all of the countries in the world. In the United States, a bit more than a quarter of its Greenhouse gas emission is attributed to electricity consumption. Emissions of Greenhouse gases including carbon dioxide could lead to the rise of global average temperature and possibly other adverse environmental effects [3]. More significantly, almost a billion people in the world still experiences lack of access to electricity [4]. Therefore, in such a world with ever growing electricity demand, economic feasibility and environmentally friendliness have become two of the most significant concerns of electricity production and consumption.

The use of renewable energy systems such as solar Photovoltaics and wind turbines has been thought by many people as the solution to these problems. However, the investments of renewable energy projects are not without obstacles. Solar and wind energy are naturally intermittent and lack the dispatchability like most traditional power generation technologies. In addition, these renewable energy projects has only come close to become economically competitive against traditional fossil fuels in the recent years [5]. Interestingly enough, the cost structures of renewable energy projects are unlike most traditional electricity generation technologies [6] as shown in Table 1.1.

Table 1.1. Relative Ratio of Marginal to Fixed Cost for Generation Technologies

Generation Technology	Relative Ratio of Marginal to Fixed Cost
Coal	Medium
Natural Gas	Medium to high
Nuclear	Low
Oil	High
Hydroelectric	Close to zero
Solar	Close to zero
Wind	Close to zero

From examining Table 1.1, one could see that renewable generation technologies like solar and wind rather have cost structures more similar to nuclear energy than fossil fuels. This characteristic of renewable generation technologies could complicate the investment in renewable energy projects in the electric power systems. In the US, regional electric power systems can be classified into two types based upon the underlying structure – regulated utilities and competitive electricity markets. The regulated utilities are vertically integrated utility companies that own the entire generation, transmission, and distribution components of regional electric power systems. On the other hand, the competitive electricity markets present in the regions with a RTO (Regional Transmission Organization) or an ISO (Independent System Operator), where it is illegal to have a single company to have authorities in all three branches of the electric power system. Based upon the transaction method, the electric power system can be also divided into Wholesale (sale of electricity to utility and traders, then to consumers) and Retail (sale of electricity directly to consumers) components. Figures 1.1 and 1.2 from [7] show the presence of Wholesale and Retail Electricity Markets in the US.

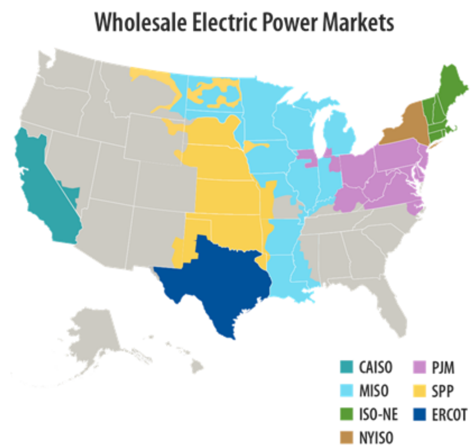

Figure 1.1. States and Regions with Wholesale Electricity Market in the US

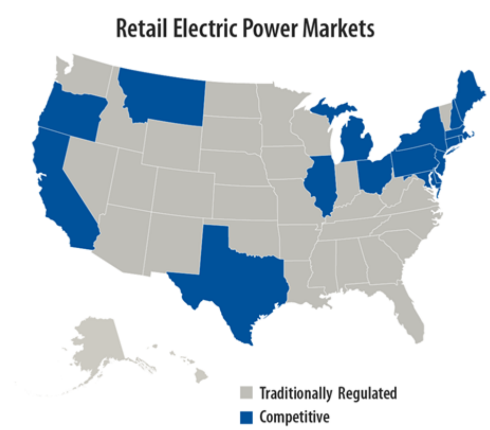

Figure 1.2. States with Retail Electricity Market in the US

This difference in systematic structure is relevant for the investments in renewable energy projects. In the regions with traditional vertically integrated utilities (grey areas in Figure 1.1), most of the renewable generation technologies are owned by the utility companies, and thus the related investments development could be challenging. In comparison, in the regions with both competitive and retail electricity markets, the development of renewable energy project can be greatly enhanced by having a greater degree of flexibility for both the renewable energy project developers and electricity end-consumer (which could be the investors in these renewable energy projects) [7].

1.2 Motivation and Contribution

Since 2014, a particular type of investment in renewable energy project has flourished – *Power Purchase Agreement* (PPA). PPA is a specific type of *Corporate Renewable Purchase* (Large investment in Utility Scale renewable energy projects). A Power Purchase Agreement (PPA) typically involves three sides, including an independent company in charge of developing the renewable energy project initially, a large renewable energy investor (which could be a large corporation, university, etc.), and the regional electric power system. The investor has the ability to sign a long term contract of typically between 10 and 25 years with the independent renewable energy developer for the electricity production from a renewable energy project.

In many cases, the power output of the renewable energy project would feed into the regional electric power transmission system. If there is an insufficient supply of electricity production from the renewable energy project, the investor of Power Purchase Agreement still needs to fulfill its remaining electricity demand from the Wholesale Electricity Market, just like without the existence of PPA. On the contrary, if the investor's purchase of electricity from the renewable energy projects exceeds its own demand in some particular time periods, the investor can resale these excess purchase back to the Wholesale Electricity Market. The expense paid by the investor of PPA to the renewable energy developer could allows these investor to use Renewable Energy Certificates (RECs) to claim its reduction of carbon footprint from the use of “renewable sources of electricity” [8–11]. For a visualization of the structure of a Power Purchase Agreement (PPA), Figure 1.3 is presented, where a solar farm is shown on the left, the regional electric power transmission system in the center, and a renewable energy investor on the right.

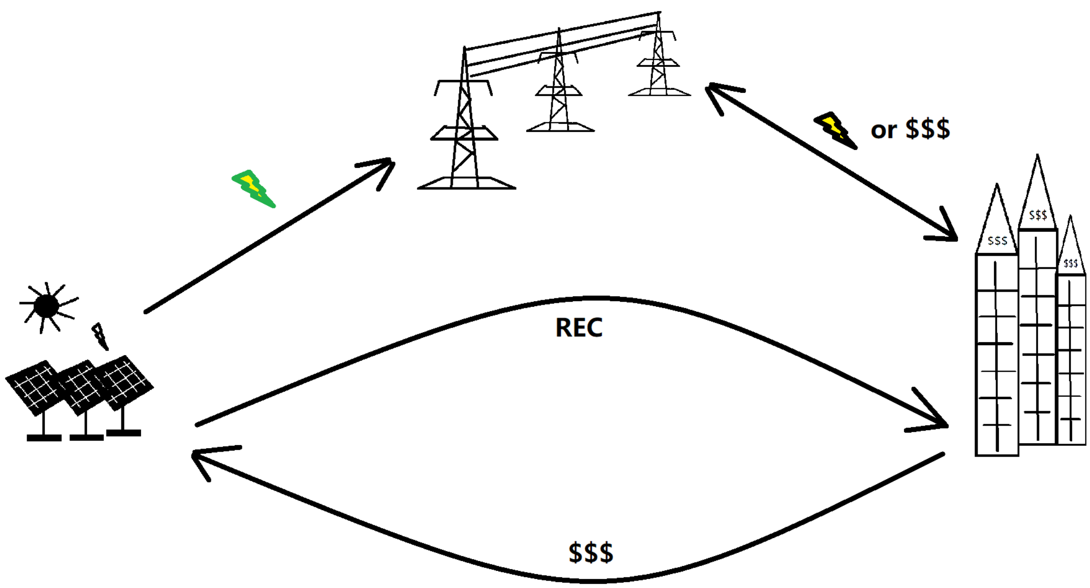

Figure 1.3. Illustration of the Structure of a Typical Power Purchase Agreement

According to [12], in 2018 alone, there are 25 unique first-time investors of Corporate Renewable Purchase, resulted in 6.43 GW of renewable energy project being invested in. This is graphically shown in Figure 1.4, where the bar chart uses the vertical axis on the left and the line plot uses the axis on the right. The numbers in Figure 1.4 includes Corporate Renewable Purchases other than Power Purchase Agreement such as outright direct ownership, but does not include any on-site development.

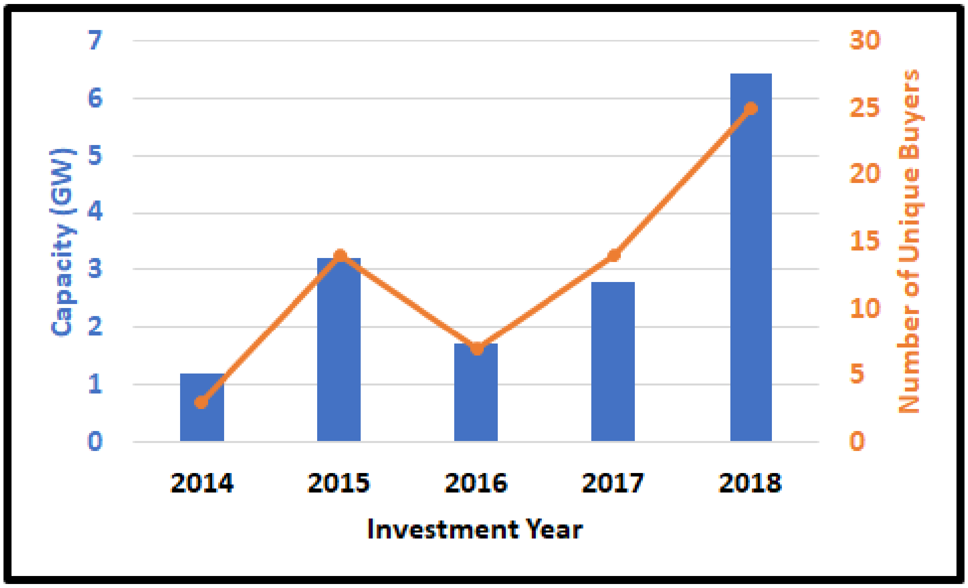

Figure 1.4. Growth of Corporate Renewable Purchases since 2014

Such high level of commercial and business interest in Corporate Renewable Purchases including Power Purchase Agreements since 2014 has demonstrated the gradual economic competitiveness of renewable energy projects and the determination of private sectors to pursue a clean energy transition before regional electric power systems could perform systematic changes. The **optimal time and size** of pursuing these investments can be key decisions for the investors of renewable energy projects that would otherwise consume large volume of Wholesale Electricity need to make, as these investments are long term and irreversible. This thesis built a theoretical framework to use Multi-Objective Optimization Problem (MOOP) to determine the **optimal time and size** of pursuing these investments, in which the two objectives are two of the most important considerations of making an investment in renewable energy projects – economic feasibility and environmental friendliness. The general formulation of the Multi-Objective Optimization Problem was reduced into Single Objective Optimization Problems (SOOP). This research is innovative that by imposing more constraints, these SOOPs are equivalent to some Real Option Valuation problems. While making significant simplifications and assumptions, these problems were solved to provide the **optimal**

investment time and size and Value of Option (net economic gain of exercising the legal right in physical assets) of Power Purchase Agreement(s) of renewable energy project(s) for a specific investor.

An investor of Power Purchase Agreement could face many future uncertainties that impact the economic and environmental outlooks of making these investments. These uncertainties also complicate the Multi and Single-Objective Optimization of the **optimal time and size** of making these investments, and in this thesis some of them will be simplified to make the decision problem easier to formulate and solve for. These uncertainties could include:

- **Wholesale Electricity Demand of Investor**, which could alter the monetary savings of using the electricity production from renewable energy project(s), holding everything else constant.
- **Future Wholesale Electricity Price**, which could influence the monetary savings of renewable energy investors from using less Wholesale Electricity.
- **Future Cost of Renewable Energy Project**, which could impact the investor's willingness to pursuit making the investment(s) in renewable energy project(s).
- **Electricity production capability of Renewable Energy Project**, which could impact the economic valuation of these intermittent renewable energy projects, as well as the environmental outlooks of making these investments. A lower electricity production translates to a lower claim of environmental benefits of the investment.
- **Future Policy Regarding Renewable Energy Project and Environmental Impact of Generation Technologies**, which could include the subsidy on renewable energy projects, implementation of taxes for environmental impact of

conventional generation technologies (such as establishment of a Carbon Emissions Tax). These could change the preference for investor of renewable energy projects over time in conjunction with the costs of these projects.

- **Future Evolution of Electric Power Systems**, which could influence the environmental outlook of making investments in PPA of renewable energy projects. If the penetration of renewable energy projects regional electric power system remains low, the environmental benefit of investments in PPA of renewable energy projects is relatively more significant, in comparison to the case where regional electric power system also undergoes significant revolution and increase in penetration of renewable energy systems.

1.3 Literature Review

Flexibility is being considered by many as a favorable term for investors in financial investments. One of the most common types of financial investment that offers investors flexibilities is an *option*. *Option* is a financial derivative that gives investors the legal right but not the obligation to pursuit certain financial transactions – namely, the right to buy or sell a certain financial asset [13]. This concept has been well established as option is now a common type of financial investment. In addition, the thought of offering investors the legal right but not the obligation to pursuit physical (real) investments and assets has been developed, where it becomes an innovative and important tool that helps to determine the feasibility of these physical (real) investments and assets. The use of the same train of thought from *options* in terms of financial investment into physical (real) investments and assets is called *Real Options*. Real Options and financial options have similarity in they both offer investors flexibilities of pursuing investments, but they are also inherently different in many aspects, and are presented in Table 1.2 [14] for a primitive understanding of the two related concepts.

Table 1.2. Comparison of Financial and Real Options

Item	Financial Option	Real Option
Value of Interest	Price of stock(s)	Value of investment(s)
Investment Time Frame	Typically months	Could be years
Effect of Time Value of Money	Interest rate	Discount rate
Marketing & Trading	Inherently traded	Not traded by nature
Negativity of Value of Assets	Rare to see	More common
Value of Option(s)	Known at exercise time	Expected value known

Beyond the similarity of Real Option and financial option that they both offer investors flexibilities of pursuing investments, the originality of Real Option and its particular application to investments of renewable energy projects is worth studying. Thus, a detailed examination of the background and use of Real Option in the investments in renewable energy projects is performed, and these information are presented in this section.

The concept of Real Option was first developed by Stewart Myers in his paper *Determinants of Corporate Borrowing* in 1977. Real Option in Myers' view is to apply the traditional financial Option Pricing theory to the valuation of investments in "real" assets, by presenting investors in "real" assets the flexibility and ability of learning over time. In Myers' words, Real Options are the "opportunities to purchase real assets on possibly favorable terms", in which "real assets" should have market values regardless of individual firms' investment strategies. Myers stated that, the value of Real Option is associated with some imperfection in the real sector, and could be firm-specific. This means that only markets that are not perfectly competitive nor in continuous, long-run equilibrium would be able to create non-zero values of Real Options, for certain firms [15]. While following this logic, the valuation structure of Real Option can be well suited for investments in renewable energy projects, where many expects an ongoing technology advancement and development in renewable energy systems in the coming years. This ongoing technology advancement and development in renewable energy systems in the world could lead to imperfect markets, and allow some firms but not all of them to gain from using Real Option(s).

The development of the theories and use of Real Options has been significant over time. First found attractive by the academia, the 1980s and 1990s saw the first cohort of articles published on Real Option's theoretical models and possible applications. Since the mid 1990s, possibly due to increase in modern computation technologies, the concepts surrounding the value of the Real Option and the surrounding techniques of Valuation has blossomed and gathered industrial interest, as an additional tool for project appraisal and investment strategy identification. Traditional energy industries (oil and gas) were amongst the first industries to consider the practical use of Real Options. Many mainstream academic finance textbooks now mention Real Option, and related conferences on the topic is attracting both industrial and academic participants [16].

Investment Under Uncertainty written by Avinash K. Dixit and Robert S. Pindyck is another cornerstone on the theory of Real Option. This book begins with a critique of a more traditional metric used in the decision making process of a firm while facing uncertainty over future market conditions – *Net Present Value*. While using the Net Present Value, a firm should pursuit an investment as long as the Net Present Value of this project is estimated to be positive. In the view of Dixit and Pindyck, the utilization of Net Present Value overlooked some significant assumptions while estimating the profitability of these investments. The most important assumptions of these are the reversibility and timing of investments. While incorporating these elements into analysis, Dixit and Pindyck argued that the profitability of investments could drastically shift. This book is enlightening as it both provides the theoretical classification and discussion of major types of Real Options as well as the practical guideline to the mathematical and technical approaches in Real Option Valuation. Some types of Real Options presented in the book can be summarized as [17]:

- The option to delay the beginning of investments to collect more information
- The option to abandon investments if market condition becomes uneconomical
- The option to break down investments into stages and make investments incrementally as the market condition progresses

The extensive literature review of Real Option Valuation in the renewable energy industry written by Mariia Kozlova in 2017 has presented a helpful summary for understanding the overall trend and interest of the academia on the subject. The first point of emphasis in Kozlova's work is that among all the articles regarding Real Option Valuation of renewable energy, its use on project investment is not the only possibility. Rather, among the articles being reviewed in Kozlova's work, around a third of them actually studied the implementation of policies regarding the adoption of renewable energy. Kozlova's review also examined the common sources of uncertainty in the Real Option Valuation Problems. Future electricity price and cost of renewable energy projects are among the most common factors that appear in about half of the articles being reviewed. The third major finding from the review is that more than 80% of the articles in the review studied the option to delay the beginning of investment of renewable energy projects. The review also determined that most of the researchers only studied one or two Real Options in a single study. Lastly, Kozlova identified that almost half of the previous papers included in the review used Monte Carlo simulation in modelling the uncertainties. Only a tad more than a quarter of the reviewed articles used Binomial Lattice Pricing Model to estimate the evolution of future electricity prices [18].

Among the previous works existed in Real Option Valuation of renewable energy project, Konstantinos Venetsanosa, Penelope Angelopouloua, and Theocharis Tsoutsos are among the pioneers in the field, represented by their work of *Renewable Energy Sources Project Appraisal Under Uncertainty: The Case of Wind Energy Exploitation Within A Changing Energy Market Environment*, published in 2002. They explored the feasibility of using a "call" like option while investing in wind technology in the newly restructured electricity market in Greece. The paper is novel in its identification of sources of uncertainty and possible flexibility in wind technology development while using Real Option Valuation. The value of the Real Options were calculated using the Black Scholes Option Pricing Model. The authors came across several conclusions that are among the common themes in Real Option Valuation. Primarily, they argued that the value of an option (net economic gain from exercising the Real Options) rises as there is a greater degree of uncertainty. Additionally, to correctly assess the numeric values in Real Option Valuation, one should begin with a rather simple approach, and then build upon the simplified framework. Finally, it is essential to identify the best time to exercise the option(s) [19].

A Real Options Model for Renewable Energy Investment with Application to Solar Photovoltaic Power Generation in China by Zhang et al in 2016 was more advancedly developed. They studied the option to delay investment on maximizing unit (per kW) investment value of solar Photovoltaic systems. Their decision structure was established by comparing the value of the investment from a single commitment decision (investing now or never) and the value with using the option. They used Geometric Brownian Motion to model several uncertain parameters in the calculation process including non-renewable energy cost, investment cost of solar Photovoltaic systems, and others. One of the driving forces of the uncertainties was the anticipated establishment of a national carbon emissions trading platform in China after the paper was completed. For the single commitment decision of investment in solar Photovoltaic systems, this paper also presented the results in terms of Net Present Value estimation. This paper has thus both numerical and analytical conclusions. The researchers believed that the existence of carbon dioxide emissions trading platform could support the investments in solar Photovoltaic system by changing a negative expected NPV to positive. With the use of Real Options Valuation, it is shown that the optimal investment time of solar Photovoltaic system requires a longer delay of two years (12 vs 10 years) had the carbon dioxide emissions trading platform were not to establish. Analytically, the authors pointed out that an increase in future government subsidy on the investment in solar Photovoltaic system could further boost its economic outlook [20].

Timing Residential Photovoltaic Investments in The Presence of Demand Uncertainties written by Gahrooei et al in 2016 [21] has provided valuable insights for this thesis. Gahrooei et al explored the independent effects of two different types of Real Options in order to maximize the expected value of investment in a residential solar Photovoltaic system. The two Real Options are the option to delay the beginning of investment (called *single-phase investment* in the article) and the option to change the size of solar panel over time (called *multi-phase investment* in the article). For the single-phase investment, Binomial Lattice Pricing Model is used by the researchers to model the uncertainty of future electricity price evolution, and Exponential decline is used to model the decrease in the cost of residential solar Photovoltaic system in the future, and the optimal investment strategies are identified. For the multi-phase investment, the optimal investment strategy also depends on the size of the residential solar Photovoltaic system at the beginning of each phase (year), and dynamic programming is used in the calculations. The methods and train of thoughts in this piece of literature ties to this thesis strongly, and will be referred back in the future as needed.

Two other pieces of literature provided instrumental guidelines in forming the decision structure and approaches of solutions for this thesis are *Investment Valuation*

Model for Renewable Energy Systems in Buildings by Kashani et al. [22] and *Evaluation of Economically Optimal Retrofit Investment Options for Energy Savings in Buildings* by Kumbaroglu and Madlener [23]. Both of these articles explored the option to delay the beginning of investment. Both [21] and [22] used a similar decision structure for the option to delay the beginning of investment where both articles compared the expected value of net benefits from deciding to invest in each period while within a fixed investment time horizon of consideration. The investor would be better to delay the investment than pursuing the investment immediately if the expected value of net benefits in a period is calculated to be smaller than the expected value of investment in future periods. In particular, [22] used an similar approach like the traditional financial option pricing model [24] to estimate the evolution of future retail electricity prices from the Binomial Lattice Pricing Model.

While examining the previously stated and other literature on Real Option Valuation of investments in renewable energy projects, one could capture several common themes. Primarily, the evolution of electric power system including the formation of an electricity market or related market (such as the carbon emissions trading platform in [20]) has a predominant impact on the most visible source of uncertainty – future electricity price. Other major sources of uncertainty could include the cost of renewable energy projects in the future as they are still experiencing technology advancement. Therefore, to account for these uncertainties, *the option to delay the beginning of investment* is a popular and worthwhile choice of study. Finally, despite the fact that many researchers have stated the environmental benefits from utilizing renewable energy projects, the focus of the researches remains on the economic outlook/monetary gains from making these investments. This could be attributed to a continuation of analysis for traditional (financial) options, as the value of a financial option depends on the monetary value of a stock. However, this could actually be only part of the truth in the investment in renewable energy projects and electric power systems. As previously discussed, economic feasibility and environmentally friendliness are two inseparable concerns of electricity production and consumption in the modern society. It can be incomprehensive to only examine the economic outlook of the investment in the renewable energy projects.

The consideration of two inseparable concerns/objectives is inherently a Multi-Objective Optimization Problem. Unlike in a Single-Objective Optimization Problem where solutions can be only either optimal or not, the classification of solutions is more complicated in Multi-Objective Optimization Problems. It is still possible to have an optimal solution that is the most appealing in all of the objective functions simultaneously, but this could be complicated or impossible to achieve in a practical problem as many objectives are inherently conflicted. Therefore, researchers more commonly define the *Non-dominated Solutions*, also known as the Pareto Set. A Non-dominated solution is a solution where no one objective function can be improved without a simultaneous detriment to at least one of the other objectives of the Multi-Objective Optimization Problems. If one were to trim down the number of objectives to two, a Multi-Objective Optimization Problems would turn into a Two-Objective Optimization Problem that is easier to define the Pareto Set. Suppose there are two objectives of consideration, X and Y, and two feasible solutions a and b in a generic Two-Objective Optimization Problem. Solution a dominates Solution b under the following conditions.

- $X_a > X_b$ and $Y_a > Y_b$; or
- $X_a \geq X_b$ and $Y_a \geq Y_b$ with strict inequality in at least one of the two conditions.

Any solution that is **not** dominated by any other solutions is part of the Pareto Set [25]. For an easy visualization of the concept of Pareto Set and Dominated Solution, Figure 1.5 is presented for its understanding.

In Figure 1.5, the two objectives of consideration are X and Y, and a bigger value is preferred over a smaller value for both X and Y. Thus, an ideal solution should be in the top-right corner of the graph. The red dots in the graph represent the Pareto Set. None of these solutions is the single Optimal solution. Meanwhile, the Pareto Set (red dots) are collectively better than the Dominated (inferior) solutions that are represented by the black dots.

As Figure 1.5 and the equations demonstrated, it can be rather easier to visualize and conceptualize a Two-Objective Optimization Problem. Practically this have been applied into the consideration of both economic feasible and environmentally friendly investments in renewable energy projects, and can be easily found in literature sources, such as [26, 27]. However, a search of previous literature shows that none of them identify a connection between Multi-Objective Optimization and Real Option Valuation Problems for investments in renewable energy projects, which provides a great opportunity for further studies.

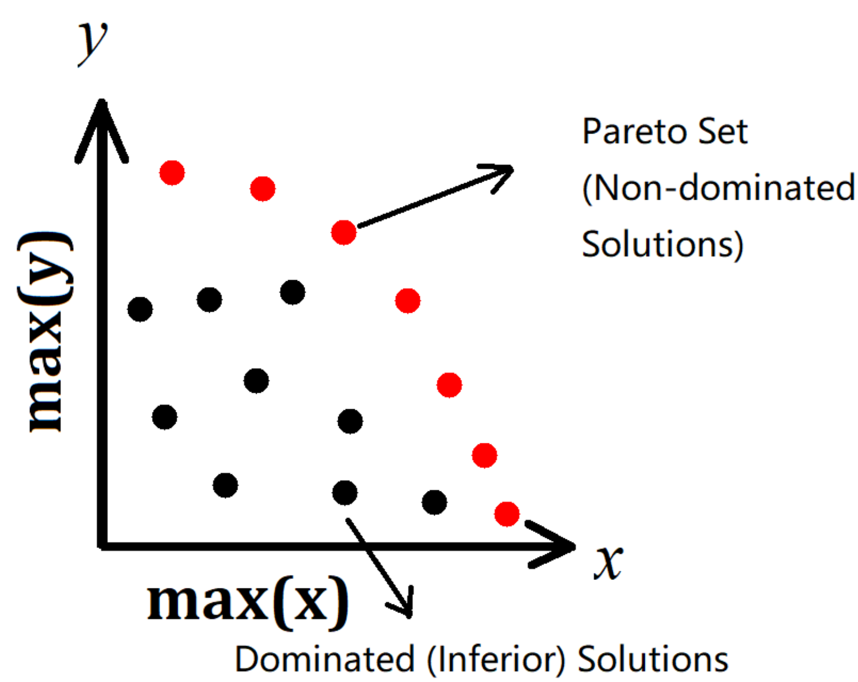

Figure 1.5. Illustration of Solutions in a Generic Multi-Objective Optimization Problem

1.4 Research Question

In this section, a research question of focus is formed. In principle, this research is interested in help answering the following question: **What incentives to large volume electricity consumer have to make substantial investments of renewable energy projects in the near term versus the long term?** Due to the relative easiness in data collection and information acquisition, and the actual demonstrated interest, the subject of study in this thesis, or the large electricity consumer and potential investor of renewable energy projects is for the case study of The Pennsylvania State University (Penn State University, PSU).

The main campus of Penn State University is geographically located in central Pennsylvania, and a significant portion of its electricity demand is fulfilled by the Allegheny Power Systems Transmission Zone of the PJM Regional Transmission Organization (a competitive wholesale electricity market), as shown in Figure 1.6. In Figure 1.6, the PJM Regional Transmission Organization is colored in dark blue, and the approximate location of the main campus of Penn State University is represented by a red star [28].

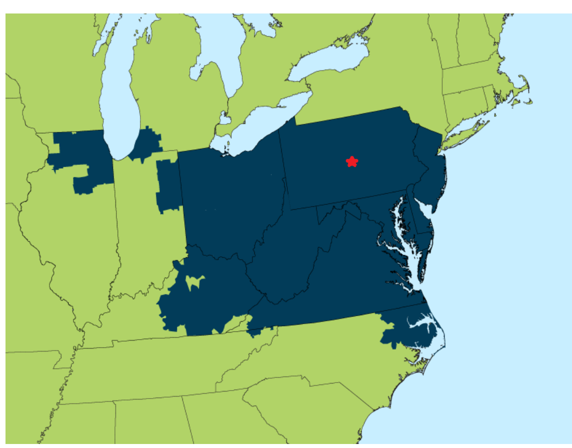

Figure 1.6. Service Territory of PJM and Approximate Location of the Main Campus of Penn State University

Penn State University has a strong commitment to reduce its carbon footprint since the early 2000s [29, 30]. It has actively engaged in Power Purchase Agreement and has considered it as potential investment strategy to further reduce its carbon footprint, as shown in Figure 1.7.

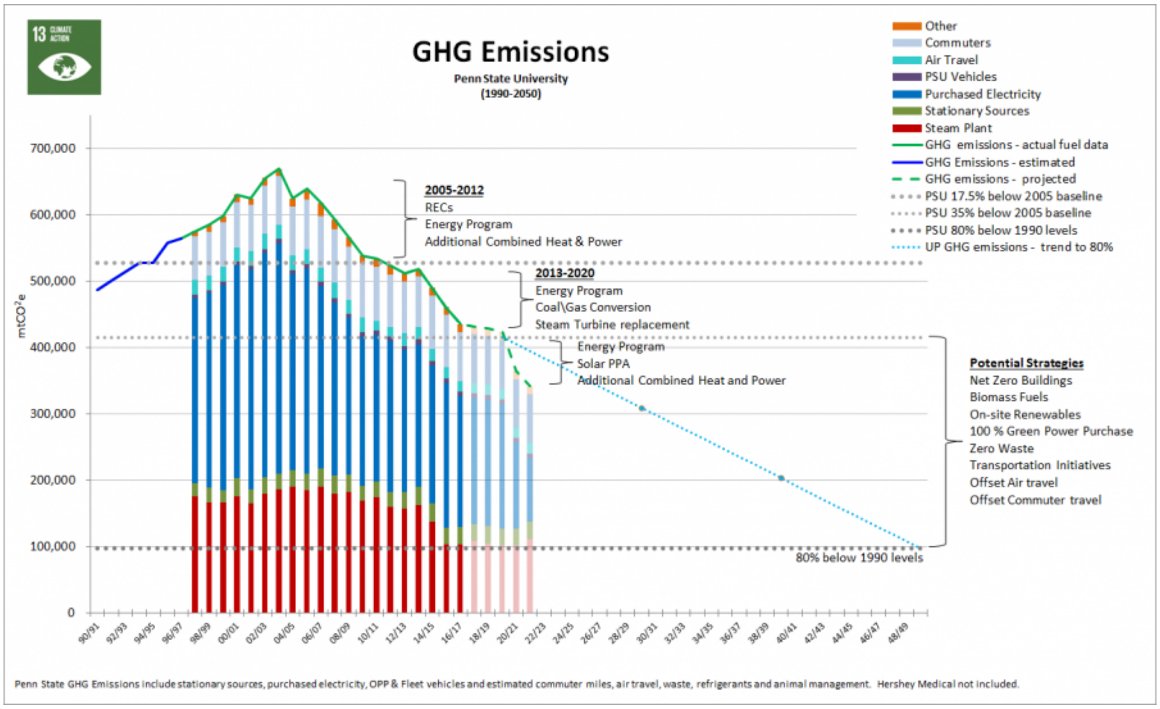

Figure 1.7. Greenhouse Gas Emission Footprint of Penn State University Since 1990

In 2019, the University signed a Power Purchase Agreement with Lightsource BP to develop a 70 MW, utility-scale solar project, on approximately 500 acres of land in Franklin County, Pennsylvania. The 70 MW solar project is estimated to provide 25% of University's statewide electricity demand over the next 25 years, and it is supporting Penn State University's goals to reduce its greenhouse gas emissions by 35% from its peak level by 2020 [31]. As a result, Penn State University could be an ideal subject of study for this research, and the focuses of this study are explained below.

In a narrower sense, the focus of the case study presented in this thesis is: **How can Penn State University use Multi-Objective Optimization Problem**

to maximize both its economic and environmental benefits (net economic outlook of using less Wholesale Electricity and carbon footprint) in the process of making investments in Power Purchase Agreements of renewable energy projects? What kinds of portfolios should it invest in, and when should it invest? The reduced versions of this Multi-Objective Optimization Problem that maximize only the economic benefits of these investments are Single-Objective Optimization Problems. They represent Penn State's investment decision problems as if it only values the economic benefits of these investments. These Single-Objective Optimization Problems are equivalent to two Real Option Valuation Problems under specific conditions, where the net economic gain of exercising these legal rights (Value of Option) were calculated. The two Real Option Valuation Problems specifically are:

- The option to delay the beginning of a particular investment, and
- The option to change the size of investments.

In addition, Sensitivity Analyses were performed on some of these Optimization/Real Option Valuation Problems. In the following chapters of this thesis, the methodology, data and relevant assumptions, results and discussion, major conclusions and future work are presented.

Finally, before getting into the specifics of this thesis, it needs to be recognized that, there are many different possible ways of understanding the feasibility of making investments in Power Purchase Agreements of renewable energy projects. The use of Real Option Valuation presented in this thesis is only one of them. In a more practical environment, the inclusion of more methods would be able to provide a more holistic understanding for the potential investor, in which they could also have more objectives beyond the economic and environmental benefits in the process of making investments.

Chapter 2

Methodology

In this chapter, the formulation of the general Multi-Objective Optimization Problem (MOOP) used by a decision maker of investment(s) in Power Purchase Agreement of renewable energy project(s) is first introduced. Followed by the formulation, the nomenclature of the symbols used in the formulation, explanations of the equations used, simplifications and assumptions that this thesis made to build a more tractable model are provided. Then, the methods used to produce the variable of uncertainty in the Optimization Problem are discussed. Afterwards, more constraints are added to this general Multi-Objective Optimization Problem to produce two Single-Objective Optimization Problems (SOOP) that focus entirely on the economic outlook of making these investments, where they also represent two Real Option Valuation (ROV) problems. Following the structure of a Real Option Valuation problem, the methods to solve for the Value of Options are discussed. The calculation of the Value of the Options connected the Optimization Problems with Real Option Valuation problems. Finally, the use of Sensitivity Analysis on these Optimization and Real Option Valuation Problems are also addressed.

2.1 Multi-Objective Optimization Problem of Decision Maker

A decision maker (investor) of investments in Power Purchase Agreement(s) of renewable energy project(s) has to evaluate the **optimal time and size** of pursuing these investments by considering both (a) the Economic and (b) the Environmental outlooks from making these investments.

2.1.1 Problem Formulation

The formulation of this Multi-Objective Optimization Problem includes the following Objective Functions, and they are calculated by the equations underneath them.

$$\max_{f_t} IHEV(f_t, P_{t,k}) = \sum_{t=0}^{T} EV_t \tag{eEconObjFun}$$

and

$$\max_{f_t} IHAE(f_t, MEF_{t,k}) = \sum_{t=0}^{T} AE_t \tag{eEnveObjFun}$$

Which are calculated by:

$$EV_t = \sum_{k=1}^{m} n \times \frac{\mathbf{E}(EV_{f_t,P_{t,k}})}{(1+r)^t} \tag{eEVAnnual}$$

$$AE_t = \sum_{k=1}^{m} n \times MEF_{t,k} \times Q_{f_{t,k}} \tag{eAEAnnual}$$

$$EV_{f_t,P_{t,k}} = AEP_{f_t,P_{t,k}} - CPP_{f_t,k} + RV_{f_t,P_{t,k}} \tag{eEV}$$

$$AEP_{f_t,P_{t,k}} = E_{f_t,k} \times P_{t,k} \tag{eAEP}$$

$$E_{f_t,k} = \sum_{j=1}^{24} E_{f_t,j,k} \tag{edailyECalc}$$

$$E_{f_t,j,k} = min(Q_{f_t,j,k}, D_{t,k}) \tag{ehourlyECalc}$$

$$Q_{f_t,j,k} = \sum_{s=1}^{S_t} Q_{f_t,j,k,s} \tag{ehourlyQCalc}$$

$$Q_{f_t,k,s} = \sum_{j=1}^{24} Q_{f_t,j,k,s} \tag{edailyQSCalc}$$

$$Q_{f_t,k} = \sum_{j=1}^{24} \sum_{s=1}^{S_t} Q_{f_t,j,k,s} \tag{edailyQCalc}$$

$$CPP_{f_t,k} = \sum_{s=1}^{S_t} Q_{f_t,k,s} \times C_s \tag{eCPP}$$

$$RV_{f_t,P_{t,k}} = q_{f_t,k} \times P_{t,k} \tag{eRV}$$

$$q_{f_t,k} = \sum_{j=1}^{24} q_{f_t,j,k} \tag{edailyqCalc}$$

$$q_{f_i,j,k} = max[(Q_{f_t,j,k} - D_{j,k}), 0] \tag{ehourlyqCalc}$$

2.1.2 Nomenclature of Symbols

This section provides the nomenclature of the symbols used in the formulation of the Multi-Objective Optimization Problem (MOOP) used by a decision maker of investment(s) in Power Purchase Agreement of renewable energy project(s).

Table 2.1: Nomenclature of Symbols used in the MOOP

Symbol	**Definition**
$IHEV$	Investment Horizon Economic Value [$]
$IHAE$	Investment Horizon Avoided Emission [Ton]
Continued on next page	

Table 2.1 – continued

Symbol	Definition
EV_t	Annual Economic Value [$]
AE_t	Annual Avoided Emission [Ton]
t	Index for investment time period [year]
f_t	Cumulative PPA Investment Size at time period t
$P_{t,k}$	Wholesale Electricity Price at Year t, intra-year period k [$/MWh]
T	Investment Horizon of Investor [year]
m	Number of intra-year, seasonal periods
k	Index for intra-year period
n	number of days in each intra-year period
$\mathbf{E}()$	Notation for taking Expected Value
$EV_{f_t,P_{t,k}}$	Daily Economic Value [$]
r	Annual discount rate [%]
$MEF_{t,k}$	CO_2 Marginal Emission Factor of Electricity Market [Ton/MWh]
$Q_{f_t,k}$	Daily total electricity output of renewable energy projects [MWh]
$AEP_{f_t,P_{t,k}}$	Daily Avoided Energy Payment [$]
$CPP_{f_t,k}$	Daily Total Cost of Power Purchase Agreements [$]
$RV_{f_t,P_{t,k}}$	Daily Resale Value of Excess Purchase in PPA [$]
$E_{f_t,k}$	Daily Avoided Energy usage of investor of PPA [MWh]
$E_{f_t,j,k}$	Hourly Avoided Energy usage of investor of PPA [MWh]
$D_{t,k}$	Hourly electricity demand of investor of PPA [MWh]
$Q_{f_t,j,k}$	Hourly total electricity output of renewable energy projects [MWh]
s	Index of a particular renewable energy project
Continued on next page	

Table 2.1 – continued

Symbol	Definition
S_t	Total number of renewable energy projects at time period t
$Q_{f_t,k,s}$	Daily total electricity output of renewable energy project s [MWh]
C_s	Unit cost of PPA of renewable energy project s [$/MWh]
$q_{f_t,j,k}$	Hourly Excess Purchase of PPA
$q_{f_t,k}$	Daily Excess Purchase of PPA

2.1.3 Explanation of Equations, Simplifications and Assumptions

- **eEconObjFun**: The decision maker (investor) of investment(s) in Power Purchase Agreement of renewable energy project(s) wants to maximize its Investment Horizon Economic Value by choosing the **optimal investment size** at each **investment time period**. The Investment Horizon Economic Value is the sum of Annual Economic Values, EV_t, from present time ($t = 0$) to the end of the Investment Horizon ($t = T$). The use of an Investment Horizon is required for the modelling structure of some of the methods used in this thesis.

- **eEVAnnual**: To account for the limitation of data and simplify for the electricity output of renewable energy projects, each year is divided into m intra-year, seasonal periods, in which each period k has n days sharing the same Daily Economic Value $EV_{f_t,P_{t,k}}$ because of the same electricity production of the renewable energy projects in each hour j of each day in the n days of the intra-year, seasonal period k. Finally, the use of an Expected Value is to account for the uncertainty in future Wholesale Electricity Price $P_{t,k}$, in which this is a single set of values in each intra-year period k of Year t.

- **eEnveObjFun**: In addition to the Investment Horizon Economic Value, the decision maker (investor) of investment(s) in Power Purchase Agreement of renewable energy project(s) also wants to maximize its Investment Horizon Avoided Emission. Likewise to the Investment Horizon Economic Value is the sum of expected annual Economic Values, $IHAE$ is the sum of Annual Avoided Emissions, AE_t.

- **eAEAnnual**: Annual Avoided Emission is dependent on the intra-year, seasonal period carbon dioxide Marginal Emission Factor of Wholesale Electricity Markets, $MEF_{t,k}$, which is assumed to be a single value for any hour j in the n days of intra-year, seasonal period k of year t. It is also dependent on daily electricity production of renewable energy projects with total size f_t in each hour j of a day in the intra-year period k in year t, $Q_{f_t,k}$. The electricity production of renewable energy projects are limited by their capacity, which is not provided in the data acquired and presented in Chapter 3. Thus, the term *Standard Size* was devised to describe the size and electricity production of these renewable energy projects. For each unit of *Standard Sized* renewable energy project, their electricity production is assumed to be constant (no degradation over time) in between each year of the Investment Horizon. To create more tractable models, it was assumed that the investor of renewable energy projects must invest in whole number multiples/blocks of the *Standard Sized* renewable energy projects with electricity productions also the multiples of the *Standard Sized*. *Unit Commitment* was used to find the carbon dioxide Marginal Emission Factors of Wholesale Electricity Markets, $MEF_{t,k}$. Unit Commitment is an optimization problem typically used to determine the operation schedule of electricity generating units in an electric power system at different time steps (typically hourly intervals) with time changing loads under different set of constraints and environments [32]. Therefore, Unit Commitment can be used to determine the marginal units of electric power systems, and thus was used to estimate the hourly Marginal Emission Factors of electric power systems in Wholesale Electricity markets. It is assumed that the investor's investment of renewable energy projects does not change the marginal units of electric power systems in any given hour of the entire Investment Horizon. The use of Unit Commitment to estimate hourly Marginal Emission Factors has to be taken with a grain of salt when it is used to study the potential Avoided Emission of carbon dioxide from Power Purchase Agreement of renewable energy projects, where the time span of these projects are often in the range of 10 to 25 years.

- **eEV**: The Daily Economic Value ($EV_{f_t,P_t,k}$) is the total economic effect of pursuing an investment in Power Purchase Agreements of renewable energy projects in a day. A positive value (i.e. a saving) is preferred over a negative one (i.e. a cost). It is the summation of Avoided Energy Payments (AEP) less the Cost of Power Purchase (CPP) plus the Resale Value of Excess Purchase (RV) in the day.

- **eAEP**: The term Avoided Energy Payment is used to define a monetary saving for the investor of the Power Purchase Agreement. This saving exists because of the structure of a Power Purchase Agreement, as the investor could consume a lower level of electricity from the wholesale electricity market that it would have to consume had there been no Power Purchase Agreement. The daily Avoided Energy Payments in the intra-year period k of year t is the product of two values, the Daily Avoided Energy usage of investor of PPA $E_{f_t,k}$, and Wholesale Electricity Price $P_{t,k}$.

- **edailyECalc**: Daily Avoided Energy usage of investor of PPA $E_{f_t,k}$ is the sum of Hourly Avoided Energy usages of investor of PPA $E_{f_t,j,k}$. Therefore, no change of electricity demand of investor of renewable energy projects across different years of the Investment Horizon is also assumed.

- **ehourlyECalc**: Hourly Avoided Energy Usage of the investor of PPA $E_{f_t,j,k}$ is the lower of two values, (a) total hourly electricity production of renewable energy projects with total size f_t in each hour j of a day in the intra-year period k in year t, $Q_{f_t,j,k}$, and (b) the electricity demand of the investor in this hour, $D_{t,k}$.

- **ehourlyQCalc**: Total hourly electricity production of all renewable energy projects with total size f_t in each hour j of a day in the intra-year period k of year t is the sum of individual hourly electricity production of all renewable energy projects $Q_{f_t,j,k,s}$ invested at the time.

- **edailyQSCalc**: Total daily electricity production of individual renewable energy project s in the intra-year period k of year t is the sum of individual hourly electricity production of this renewable energy projects $Q_{f_t,j,k,s}$.

- **edailyQCalc**: Total daily electricity production of renewable energy projects with total size f_t in the intra-year period k of year t is the double sum of hourly electricity production of all renewable energy projects over all hours of a day.

- **eCPP**: This is the daily total cost of investments in Power Purchase Agreement of renewable energy projects with total size f_t, which is the product of unit price of each piece of Power Purchase Agreement C_s that does not implicitly consider its subsidy, and the total daily electricity production of the Power Purchase Agreement of the corresponding renewable energy project, $Q_{f_t,k,s}$. The unit price of each piece of Power Purchase Agreement C_s is a deterministic value that can be calculated by assuming its initial cost/unit price ($t = 0$) of this Power Purchase Agreement ($C_{0,s}$), and C_s can be approximated by the equation $C_s = C_{0,s}e^{-\gamma t}$, where γ is defined as an *annual declining rate* of unit cost of Power Purchase Agreement that can be calculated from industrial projection of future costs of renewable energy projects, and the subscript t in this case represents the time in which this investment becomes effective. This means that once the PPA of a particular renewable energy project begins, its C_s does not change over the entire Investment Horizon. However, if the investor of PPA decides to pursuit in different pieces of investments in the entire Investment Horizon in different time periods, their unit cost would be different.

- **eRV**: The daily Resale Value of Excess Purchase in the intra-year period k of year t is the product of two values, the Daily total Excess Purchase of investor of PPA $E_{f_t,k}$, and Wholesale Electricity Price $P_{t,k}$ in the day.

- **edailyqCalc**: The daily total Excess Purchase of investor of PPA $E_{f_t,k}$ is the sum of hourly Excess Purchase of investor of PPA $E_{f_t,j,k}$.

- **ehourlyqCalc**: The hourly Excess Purchase of investor of PPA $E_{f_t,j,k}$ is the portion of the total hourly electricity production of all renewable energy projects with total size f_t in each hour j of a day in the intra-year period k in year t, $Q_{f_t,j,k}$, that exceeds the electricity demand of the investor in the hour, $D_{j,k}$. If $Q_{f_t,j,k}$ is less than $D_{j,k}$ in any hour, $E_{f_t,j,k}$ for this hour is 0.

2.2 Simulation of Uncertainty in Wholesale Electricity Price

As previously indicated, the only source of uncertainty this thesis explores is in future Wholesale Electricity Prices. In this thesis, two methods will be used to generate statistical distribution and evolution of this variable of uncertainty, based upon historical data. The two methods are the Binomial Lattice Pricing Model and Monte Carlo Simulation, in which their methodology and their use in this thesis are explained in the following sections.

2.2.1 Binomial Lattice Pricing Model

Binomial Lattice Pricing Model creates two sets of lattices that grows linearly in the size of the dimensions as the mandated length of the Investment Horizon increases. The first lattice of the two is a "price" lattice, i.e., the different possible future Wholesale Electricity Prices in each time period/phase (year) in the Investment Horizon. The other lattice is a "probability" lattice, i.e., the probability of facing these future Wholesale Electricity Prices in each time period. As previously described, these lattices grow linearly in the size of the dimensions, meaning a lattice of an investment decision problem of Investment Horizon of t years would have a dimension of $(t+1) \times (t+1)$. The use of $(t+1)$ instead of t is to account for $t = 0$, which is the convention of designating present time. The method used to calculate the values in the lattices involves the following steps to determine three parameters of historical Wholesale Electricity Prices.

1. Calculate the natural logs of the historical Wholesale Electricity Prices in each time period (year). To do this, there are necessary steps of pre-processing of the historical Wholesale Electricity Prices that will be discussed in more detail in the Data and Assumptions Chapter of this thesis.

2. Calculate the differences of the natural logs of the post-processed historical Wholesale Electricity Prices in adjacent time periods (years) (between each time period and the next).

3. Calculate the mean (ν) and standard deviation (σ) of all of the differences that were calculated in the previous step.

After the mean (ν) and standard deviation (σ) of all of the differences were calculated, one could use the following simplified equations to find three parameters of historical Wholesale Electricity Prices, represented by the symbols p, u, and d [24]. The symbol p represents an averaged probability of Wholesale Electricity Prices to increase in between time periods, and thus 1 - p is the probability of Wholesale Electricity Prices to decrease in between adjacent time periods. The symbols u and d represent the typical magnitudes of increase/decrease in wholesale electricity Price if it were to increase/decrease in between each time period.

$$p = 0.5 + 0.5(\nu/\sigma) \tag{2.1}$$

$$u = e^{\sigma} \tag{2.2}$$

$$d = e^{-\sigma} \tag{2.3}$$

The product of u and d is 1, and thus leading to the linear growth of size of the dimensions in a Binomial Lattice. Tables 2.2 and 2.3 demonstrate a paired example of the Binomial Price and Probability Lattices using the symbols p, u, and d. W is the symbol used to represent the initial ($t = 0$) Wholesale Electricity Price, and the Investment Horizon T is 2. The interpretation of the lattices is that, for a given location (cell) of the Price Lattice, the probability of the Wholesale Electricity Price to be at that value, is the value of the Probability Lattice at the same corresponding cell.

Table 2.2. Example of Price Lattice

$P(t=0)$	$P(t=1)$	$P(t=2)$
W	$u \times W$	$u^2 \times W$
	$d \times W$	W
		$d^2 \times W$

Table 2.3. Example of Probability Lattice

$Pr(t=0)$	$Pr(t=1)$	$Pr(t=2)$
1	p	p^2
	$1-p$	$2p \times (1-p)$
		$(1-p)^2$

In this thesis, the use of the two Lattices provided the capability of calculating the expected value of different possible Economic Values of deciding to invest in Power Purchase Agreements in different time periods (year) based upon different probabilities of Wholesale Electricity Prices, if the investor of Power Purchase Agreement only pursuit a single piece of investment.

2.2.2 Monte Carlo Simulation

If an investor of Power Purchase Agreement of renewable energy projects has the ability to invest incrementally, it has the knowledge of the Wholesale Electricity Prices at that time and prior, but faces uncertainty of future Wholesale Electricity Prices until the end of the Investment Horizon. To account for this incremental investment structure, it is necessary to perform simulations of Wholesale Electricity Price evolution. This can be achieved by using Monte Carlo Simulations, which obtains a large number of random samples from using a predefined probability distribution. In this case the probability distribution is a Binomial Distribution with probability p is the averaged probability of Wholesale Electricity Prices to increase in between time periods.

Figure 2.1 presented an example of three different paths of the future Wholesale Electricity Price evolution, with the Investment Horizon of 8 (8 periods in addition to $t = 0$), and parameters $W = 10$, $p = 0.5$, $u = 1.25$, and $d = 0.8$.

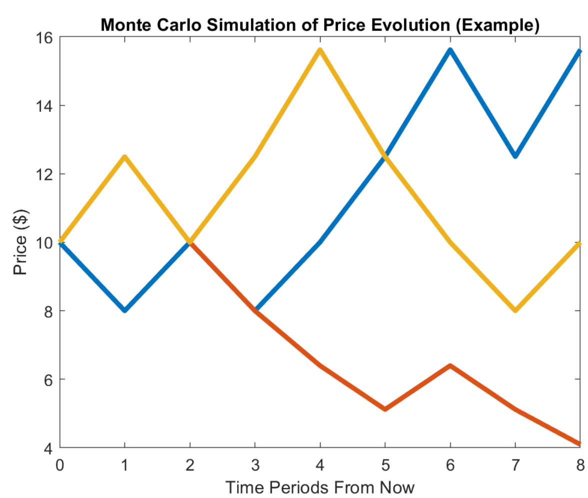

Figure 2.1. Monte Carlo Simulation of Price Evolution (Example)

In this thesis, Monte Carlo Simulations were used in conjunction with the Binomial Lattice Pricing Model to account for the Expected Annual Economic Values when an investor is assumed to possess the legal right but not the obligation to pursuit investment of Power Purchase Agreement of renewable energy projects incrementally.

2.3 Simplification of MOOP, Reduction into SOOP & Connection with Real Option Valuation

The Multi-Objective Optimization Problem of both the economic and environmental outlooks of Power Purchase Agreement of renewable energy projects by identifying the **optimal time and size** of making these investments can be beneficial, but simplified versions of this problem is easier to solve for the solutions. An assumption made that drastically reduced the complexity of these problem was that an investor of Power Purchase Agreement of renewable energy projects can only consider the change of its total size of investment, f_t, once per each year (time period).

With this simplification, each "feasible solution" of the Multi-Objective Optimization problem is a paired value of Investment Horizon Economic Value and Investment Horizon Avoided Emission of the investment in Power Purchase Agreement of renewable energy projects, at each year of the Investment Horizon. The Pareto Set of these "feasible solutions" is the set/portfolio of investment strategies in which the investor cannot improve its Investment Horizon Economic Value without decreasing its Investment Horizon Avoided Emissions of its investment in Power Purchase Agreement of renewable energy projects. This thesis presents the Pareto Set of this Multi-Objective Optimization Problem from directly using free professionally published software from plugging in the "feasible solutions" that were first computed using assumption made above and the methods and equations described in the last two sections.

In addition, if a decision maker of investments in Power Purchase Agreement of renewable energy project(s) makes its investment decision based upon the economic outlook of these investments, the MOOP is reduced into a Single-Objective Optimization Problem (SOOP) only. By using Single-Objective Optimization Problems, single optimal investment strategies of the investor and its economic benefits could be identified. The decision maker could apply its SOOP on either only $IHEV$ or use a more comprehensive SOOP to capture both the economic and the monetized environmental benefits of making these investments. The two approaches should have different optimal investment strategies and corresponding Economic Value. After imposing further constraints, these SOOPs were also considered as Real Option Valuation problems. These SOOPs and Real Option Valuation problems are further described in the next few sections.

2.3.1 SOOP of $IHEV$ While Possessing The Option to Delay the Beginning of Investment

When the general Single-Objective Optimization Problem of $IHEV$ is further constrained by limiting the total size of investment, f_t, to be constant, this Single-Objective Optimization Problem is equivalent to a Real Option Valuation problem in which the investor of Power Purchase Agreement of renewable energy project want to identify the *optimal investment time* of a particular investment, while possessing *the option to delay the beginning of investment*.

From the beginning ($t = 0$) to the end ($t = T$) of the Investment Horizon, in each time period/year t, the investor has to make an investment decision between (a) investing in the time period, or (b) delay and reevaluate the investment in the next time period. The investor would be better off to **delay and reevaluate** the investment to future periods than **pursuit the investment immediately at a period** if the $IHEV$ from investing in the time period is smaller than the $IHEV$ from investing in the next time period, but should **pursuit the investment immediately at a time period** if the $IHEV$ from investing in the time period is larger than the $IHEV$ from investing in the next time period. By doing so, the investor would sign a single piece of Power Purchase Agreement in the optimal investment time that would be effective from the beginning of that period, but only values the economic benefit of the investment to the end of the fixed Investment Horizon.

2.3.2 SOOP of $IHEV$ While Possessing The Option to to Change the Size of the Investment

In an investment decision making process where one can invest incrementally, the **optimal investment size** of Power Purchase Agreements of renewable energy projects should be a value that is unique to each time period of Investment Horizon in each simulated paths of Wholesale Electricity Price evolution, by using the Single-Objective Optimization Problem of $IHEV$. The total size of investment, f_t, is no longer constrained in this Optimization Problem. However, the limitation to change the investment size once per time period (year) is maintained. Under these conditions, this Single-Objective Optimization Problem is equivalent to a Real Option Valuation problem in which an investor of Power Purchase Agreement of renewable energy project wants to identify the optimal time(s) of making size changing investment decision while possessing *the option to change the size of the investment* (the legal capability to pursuit incremental investments of Power Purchase Agreements of renewable energy projects).

To maintain the tractability and computation easiness of the model, some additional assumptions are made. Primarily, in between adjacent time periods (years), the investor of Power Purchase Agreements of renewable energy projects can only change the investment size by a single block of the *Standard Sized* renewable energy project. Additionally, once the investor decides to invest in the Power Purchase Agreement of a particular type of renewable energy project (solar or wind) in a time period (year), it cannot switch to invest in the other type in any future time periods (years) of the Investment Horizon. As a numeric example, at a time period (year), the investor cannot have PPA investment in solar farms collectively worth 4 times the *Standard Size* before making investment decisions and deciding on investing in solar farms either more than 5 times the *Standard Size* or the same size of PPA investment in solar farms but coupled with any non-zero size of PPA investment in wind farms.

Based upon the assumptions made, from the beginning ($t = 0$) to the end ($t = T$) of the Investment Horizon, in each time period/year t, the investor has to make an investment decision between (a) **investing in one unit/block** (one multiple of *Standardize Size*) of a particular type of renewable energy project in the time period, or (b) **do nothing** until the next time period. This way, the optimal investment decision of an investor of Power Purchase Agreement of renewable energy projects is much easier to find, where it should only make an (incremental) investment of Power Purchase Agreement of renewable energy project in time period t if the change in Investment Horizon Economic Value from making this investment in this time period is positive.

2.3.3 SOOP of $GTEV$ While Possessing The Option to Delay the Beginning of Investment

A new variable called the *Grand Total Economic Value* $GTEV$ was developed for the separate Single-Objective Optimization Problem for an investor that values both the economic and environmental outlooks of investments in Power Purchase Agreement.

The five-year Social Cost of Carbon published by EPA [33] was first linearly interpolated into annual values (SCC_t), in which they can be used to represent the monetary value for the investor gives to each unit of Avoided Emission in a year. In this Single-Objective Optimization Problem, for the easiness of computation, the total size of investment, f_t, was also constrained to be constant. Mathematically, $GTEV$ was computed by using Equation **eGTEVObjFun**.

$$\max_{f_t} GTEV(f_t, P_{t,k}, MEF_{t,k}) = \sum_{t=0}^{T} EV_t + \sum_{t=0}^{T} AE_t \times SCC_t \qquad \text{(eGTEVObjFun)}$$

This way, the SOOP is equivalent to another Real Option Valuation problem, where the investor of Power Purchase Agreement of renewable energy project wants to identify the *optimal investment time* (that includes both the economic outlook and the monetized environmental outlook) of a particular investment, while possessing *the option to delay the beginning of investment*. The decision structure of an investor following this investment strategy is similar to what is being proposed in Section 2.3.1, where the investor would be better off to **delay the evaluation** of the investment to future periods than **pursuit the investment immediately at a period** if the $GTEV$ from investing in the time period is smaller than the $GTEV$ from investing in the next time period, but should **pursuit the investment immediately at a time period** if the $GTEV$ from investing in the time period is larger than the $GTEV$ from investing in the next time period. By doing so, the investor would sign a single piece of Power Purchase Agreement in the optimal investment time, which by virtue of using the Social Cost of Carbon, could be a different value from what is identified in Section 2.3.1. Finally, a investor of Power Purchase Agreement of renewable energy project could monetize the Social Cost of Carbon at a different value than [33], essentially changing the relative importance of the environmental benefits of pursuing PPA investments.

2.3.4 Calculation of Value of Option

In most of the referenced articles studying the Real Option Valuation of investments in renewable energy projects, researchers tend to explore one more economic attribute (metric) of utilizing the Real Options – the Value of the Options (the net economic gain from exercising the Real Options). In this thesis, the Value of Options are considered as the *Economic Value of the Options*. There is a different set of Economic Value of Option for each of the two types (and three types) of Real Option Valuation Problems (the option to delay the beginning of investment, and the option to change the size of the investment in Power Purchase Agreement of renewable energy projects). These two *Economic Value of the Options* are identified as the Economic Value of the Option to Delay ($EVOD$) and the Economic Value of the Option to Change Size ($EVOCS$). Furthermore, the Economic Value of the Option to Delay ($EVOD$) is different for investors that only values the economic outlook ($IHEV$) of making investment in Power Purchase Agreement of renewable energy projects, and those that also values and monetizes the environmental benefits of such investments using Social Cost of Carbon.

While holding the constraint that only a single piece of investment can be made, if a investor does not possess the *the option to delay* but still wants to make the investment, the investor could only make this investment immediately. Thus, the Economic Value of the Option to Delay ($EVOD$) is the difference of the following two terms: (1) the Investment Horizon (or Grand Total) Economic Value of the investment in the Power Purchase Agreement of a particular renewable energy project while investing at the **optimal investment time**, and (2) the Investment Horizon (or Grand Total) Economic Value of the same investment of the Power Purchase Agreement **immediately** ($t = 0$). By this approach, the Economic Value of the Option to Delay ($EVOD$) is guaranteed to be a non-negative value. The smallest possible Economic Value of the

Option to Delay (*EVOD*) of zero indicates it is optimal to invest in the Power Purchase Agreement immediately, excluding the peculiar case where both of the values used to calculate it are 0. Mathematically, these calculations for investors that values $IHEV$ or $GTEV$ are shown in Equations 2.4 and 2.5 respectively.

$$EVOD_{IHEV} = \sum_{t=t_{optimal}}^{T} EV_t - \sum_{t=0}^{T} EV_t \tag{2.4}$$

$$EVOD_{GTEV} = \sum_{t=t_{optimal}}^{T} EV_t + AE_t \times SCC_t - \sum_{t=0}^{T} EV_t + AE_t \times SCC_t \tag{2.5}$$

In this thesis, the annual Economic Values EV_t for the calculation of *the option to delay* the beginning of investments is completed by summing the Expected Value of Daily Economic Values from each set of possible Wholesale Electricity Prices and their probabilities in each year of the Investment Horizon using the **Binomial Lattices**. Therefore, in this case, the two terms used to calculate the Economic Value of the Option to Delay are unique to a given set of parameters, and thus the Economic Value of the Option to Delay is also a unique value for the same set of parameters.

On the other hand, while holding other assumptions true, when an investor of Power Purchase Agreement of renewable energy projects is not constrained by only allowing to make a single piece of investment, it will make the first piece of investment as soon as the Investment Horizon Economic Value of making this investment is positive. Then, it will invest incrementally as long as the Investment Horizon Economic Value increases from making these investments (a net positive change in Investment Horizon Economic Value). Thus, along a particular path of future Wholesale Electricity Price evolution, the Economic Value of the Option to Change Size (*EVOCS*) is the difference of the following two terms: (1) The Investment Horizon Economic Value that includes the sum of all of the positive Annual Economic Values of the investment in the Power Purchase Agreement in the entire Investment Horizon, and (2) the first occurrence of positive Annual Economic Value in this particular path of future Wholesale Electricity Price evolution. Thus the Economic Value of the Option to Change Size (*EVOCS*) is also guaranteed to be a non-negative value. Mathematically, the calculation of *EVOCS* is shown in Equation 2.6.

$$EVOCS = \sum_{t \in PositiveEV_t}^{T} EV_t - \sum_{t = firstpositiveEV_t}^{T} EV_t \tag{2.6}$$

In this thesis, the annual Economic Values EV_t for analyzing *the option to change size* of investments is calculated by summing the Expected Value of Daily Economic Values from each set of possible Wholesale Electricity Prices and their probabilities in each year of the Investment Horizon using the path of Wholesale Electricity Price evolution from **Monte Carlo simulations** in addition to **Binomial Lattice Pricing Model**. Therefore, the two terms used to calculate the Economic Value of the Option to Change Size are unique to a single path of Wholesale Electricity Price evolution for any given set of parameters. Therefore, the Economic Value of the Option to Change Size is also unique to a single path of Wholesale Electricity Price evolution for any set of parameters. This means that for a given set of parameters, by using **Monte Carlo simulations** and **Binomial Lattice Pricing Model**, the Economic Value of the Option to Change Size have a statistical distribution, instead of being a single value.

2.4 Sensitivity Analyses of SOOP

Sensitivity Analysis is a tool to understand the relative significance of different parameters in comparison to each other. To perform a Sensitivity Analysis on these Multi and Single-Objective Optimization/Real Option Valuation Problems, a set of parameters were first calculated as the base case parameters, from pre-processing the information from the data available. These base case parameters were used to calculate the values of interest using the Binomial Lattice Pricing Model and Monte Carlo Simulation when needed. The specific values of the base case parameters will be presented in the next chapter after introducing the data and their pre-processing. After an value of interest (which could be the Optimal investment time, $IHEV$, $GTEV$, $EVOD$, or $EVOCS$) from the base case parameters were determined, the same analytical procedure were carried out after adjusting one of these parameters at a time just like before, while remaining the rest of the parameters constant. To understand the relative significance of these parameters, while adjusting these parameters, they change by the same **relative** amount (percentage) rather than absolute amount that could create meaningless results.

In this thesis, there are seven parameters that the Sensitivity Analysis was performed on and plotted in a Tornado Chart, including:

- The annual discount rate of investments in Power Purchase Agreement of renewable energy projects (r)
- The averaged probability of Wholesale Electricity Prices to increase in between time periods (p)
- The typical magnitude of increase in Wholesale Electricity Price if it were to increase in between each time period (u)
- The typical magnitude of decrease in Wholesale Electricity Price if it were to decrease in between each time period (d)
- Initial Wholesale Electricity Price (W)
- Initial unit price of Power Purchase Agreement of a particular renewable energy project ($C_{0,s}$)

- Projected typical exponential declining rate of future unit price/cost of Power Purchase Agreement of renewable energy projects (γ)

2.5 Limitation of Model and Summary of Methods

The modelling structure and methods discussed in the previous sections created a limitation in the study. By virtue of using a finite Investment Horizon, the simulation of Wholesale Electricity Price and Marginal Emission Factor evolution ends at the last year of the Investment Horizon, and so are the calculations of Economic Value and Avoided Emission. This means that, if the investor of Power Purchase Agreement of renewable energy projects chooses to invest in closer toward the end of the Investment Horizon, the effective length of these PPA investments are only a few years. Therefore, this could inherently produce results that encourage investors to participate in PPA investment earlier in the Investment Horizon.

Before presenting the data used in this thesis, a flow chart is provided for the convenience of readers as shown in Figure 2.2. This flow chart includes the methods used in the thesis and some expected results from using the methods described in this chapter and data described in the next chapter.

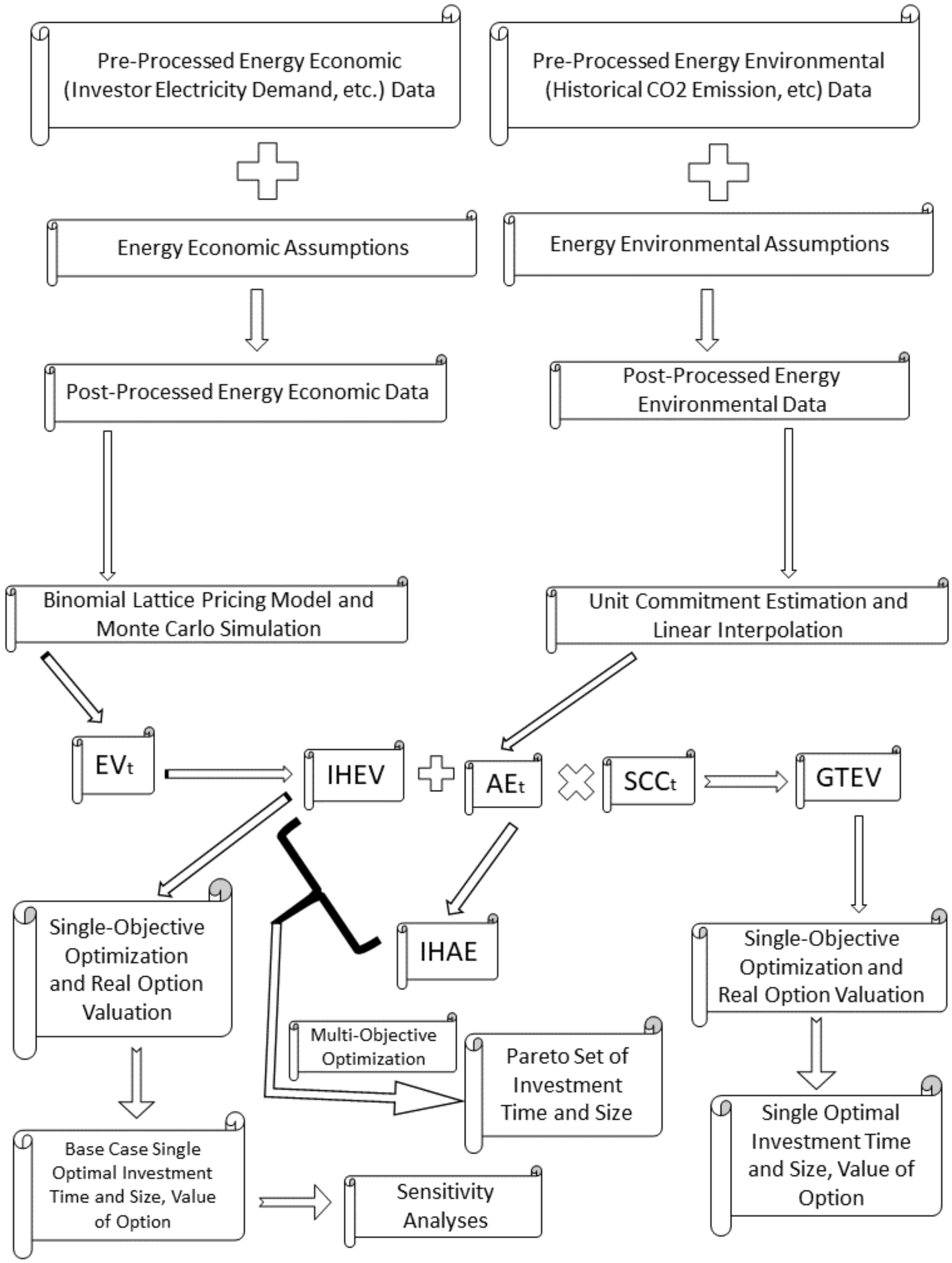

Figure 2.2. Summary of Methods Used in This Thesis

Chapter 3 | Data Selection and Assumptions

In this chapter, the most important pieces of data used in this thesis are discussed. To fully utilize these pieces of data, some assumptions are needed and also presented here. Without making these assumptions, the entire calculation process cannot proceed. Finally, for these data to be useful in accordance to the methods described in Chapter 2, the pre-processing of these data are also presented as necessary. There are in principle three categories of data overall, and will be discussed in detail in the forthcoming sections.

- Specially requested, investor (Penn State University) provided data
- Publicly accessible data used for economic analyses
- Publicly accessible data used for environmental analyses

3.1 Investor (Penn State University) Specific Data

Penn State University as the subject of the case study has provided three types of data, and this thesis proposed several assumptions to fully utilize them. The three types of these data can be summarized as below.

1. Hourly electricity demand data of a representative day for each of the two intra-year seasonal periods for the investor (Penn State University). The two intra-year seasonal periods are listed as (a) summer and (b) fall and spring, and were considered as Peak demand and an Off-peak demand periods.

2. Hourly electricity production data for two sample renewable energy projects (one solar farm and one wind farm) in the same two representative days for the intra-year seasonal periods.

3. Investor collected range and average unit cost ($/kWh) of investment in Power Purchase Agreements with solar farms in 2018.

The first two pieces of the provided data are presented in Appendix A, and the third piece of the provided data is presented in Appendix B. The third piece of the provided data reveals that the unit price/cost ($/kWh) of investment in Power Purchase Agreements with solar farms demonstrates Economies of Scale. Economies of Scale is defined as a decrease in firm's long-run average costs as its quantity of output increases [34], and in terms of renewable energy projects it can be understood as decrease in unit costs as the capacity of the renewable energy projects increases. As introduced in Chapter 2, because the data does not include the capacity of these sample renewable energy projects, the term *Standard Size* was devised to describe the size of these renewable energy projects (solar and wind farms).

Figures 3.1 and 3.2 graphically represented the power outputs of the *Standard Sized* renewable energy projects and Penn State University's electricity demand in the two intra-year seasonal periods, where Figure 3.1 is for Summer (peak demand period) and Figure 3.2 represents the same set of values in Fall and Spring (Off-peak demand period). In each day of the peak demand period, the *Standard Sized* solar and wind farm can each produce approximately 45 MWh of electricity. In the Off-peak demand period, the value of solar is approximately halved, whereas the value almost doubles for wind.

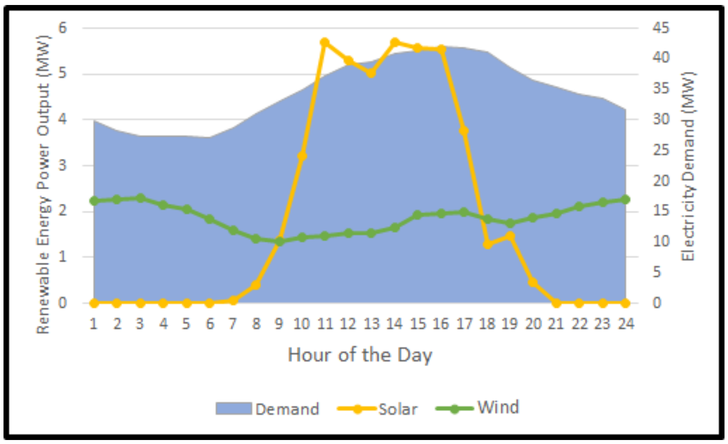

Figure 3.1. Investor Electricity Demand and Power Output of Renewable Energy Projects in Summer

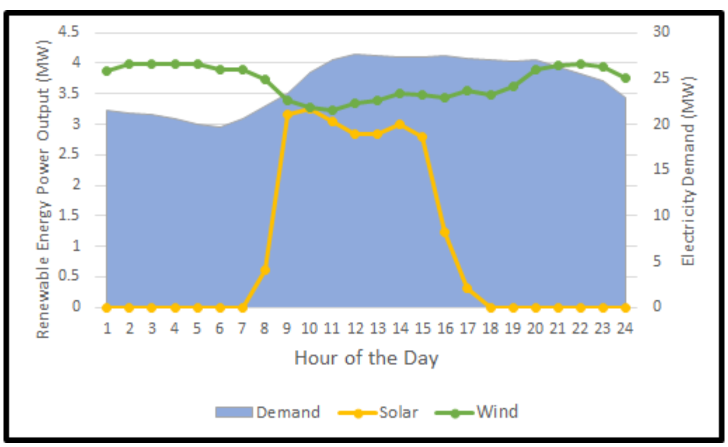

Figure 3.2. Investor Electricity Demand and Power Output of Renewable Energy Projects in Fall and Spring

Continuing the convention of *Standard Sized* renewable energy projects and using some data pre-processing methods including linear interpolation, the third piece of data is formally presented in Table 3.1.

Table 3.1. Initial Cost of Investment/Unit Price of PPA in Solar Farms

Scale of Solar Farm's Electricity Production	$/MWh
Standard Sized	44.17
2 × Standard Sized	43.89
3 × Standard Sized	43.61
4 × Standard Sized	43.34
5 × Standard Sized	43.06
6 × Standard Sized	42.78
7 × Standard Sized	42.50
8 × Standard Sized	42.23
9 × Standard Sized	41.95
10 × Standard Sized or Above	41.67

These **initial** ($t = 0$) costs of solar farms have the potential to decline in the future based upon the time the investor decides to begin the investment as described in Chapter 2. The rate of decline γ follows data that are described in the next section.

As the electricity demand and renewable energy projects power outputs data only involves two intra-year periods, they are assumed to be each 180 days long. This means that annual electricity demand and power outputs of renewable energy projects can be estimated by Equations 3.1 and 3.2, where the subscripts *pd* and *opd* represented the values of the two intra-year seasonal periods, summer (On-Peak), and fall and spring (Off-Peak). Likewise, the calculations of Annual Economic Value and Avoided Emissions in Chapter 2 were simplified into Equations 3.3 and 3.4.

$$D_t = 180 \times (D_{t,pd} + D_{t,opd}) \tag{3.1}$$

$$Q_t = 180 \times (Q_{t,pd} + Q_{t,opd}) \tag{3.2}$$

$$EV_t = 180 \times \frac{E(EV_{t,pd}) + E(EV_{t,opd})}{(1+r)^t} \tag{3.3}$$

$$AE_t = 180 \times (MEF_{t,pd} \times Q_{f_{t,pd}} + MEF_{t,opd} \times Q_{f_{t,opd}}) \quad (3.4)$$

3.2 Economic Analyses Data and Assumptions

To complete the Economic Value calculations of investments in Power Purchase Agreement of renewable energy project(s), several other types of data are needed. Some assumptions are introduced as well.

The first type of data is used to represent the Wholesale Electricity Price that is paid by the investor of Power Purchase Agreement of renewable energy projects had it not chosen to pursuit these investments. For the subject of this study, Penn State University, this is represented by the load weighted-average real-time LMP (Locational Marginal Price) of the PJM Interconnection from 2007 to 2018, retrieved from PJM Market Reports [35]. The data was initially provided as monthly values as shown in Table C.1, and it was aggregated (arithmetic average) into the values of two intra-year seasonal periods (summer, and fall and spring). This aggregated LMP data is graphically shown in Figure 3.3. These data were used to estimate the parameters needed for generating the Binomial Lattices by following the methods described in Section 2.2.

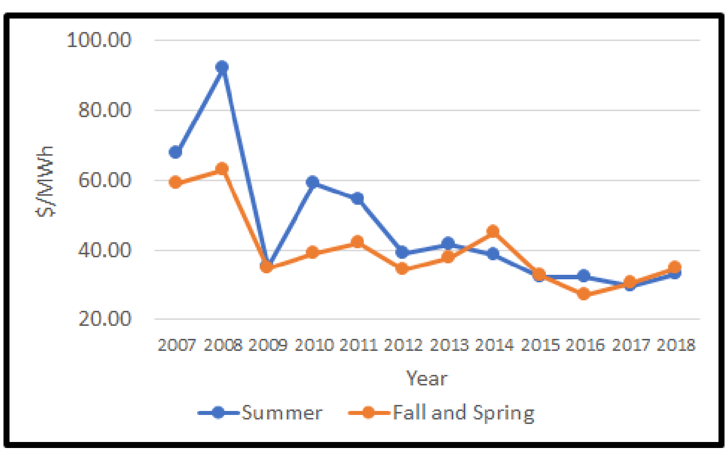

Figure 3.3. Historical Wholesale Electricity Price Evolution

The second type of data is the unit cost/price (\$/kWh or \$/MWh) of investment in Power Purchase Agreements for wind farms only in 2018. This value is retrieved from the *2018 US Wind Technologies Market Report* [36]. This data has the intrinsic similarity as what is provided by the investor, Penn State University, for the solar farms, that they are both measured in terms of dollar per unit of electricity output. Additionally, it also has the potential to decline in the future based upon the time the investor decides to begin the investment, just like the unit cost (\$/kWh) of investment in Power Purchase Agreements with solar farms.

There are also distinctive characteristic to this piece of data. These values represent a nationwide (location-independent), generation-weighted average value. Being a generation-weighted average value can be more beneficial than not as it already accounts for possibility of economies of scale in wind farms. However, caution is needed when using a nationwide value as suggested by the report. This thesis used the report to produce a Regionalization Factor (RF) to account for the relative high unit cost/price of wind energy projects in the states within the PJM Interconnection, comparing to the entire nation. In this research, this Regionalization Factor (RF) is approximated to be 1.90 and is assumed to be constant in the entire Investment Horizon. This means that Equation 3.5 can be used if one were to have the nationwide, generation-weighted average, unit cost of investment in Power Purchase Agreements of wind farms, $C_{s,national}$, where once again the subscript s is used to identify the particular investment in Power Purchase Agreement of a specific wind farm.

$$C_s = RF \times C_{s,national} \tag{3.5}$$

The last type of data used in the Economic Value calculations of investments in Power Purchase Agreement of renewable energy projects is used to model the potential to decline in the future unit cost (\$/kWh or \$/MWh) – annual declining rate of unit price of Power Purchase Agreement, γ.

There are two points of re-emphasis while using the annual declining rate of unit price of Power Purchase Agreement (γ). Primarily, γ only describes the time varying effect of unit cost/price of Power Purchase Agreement. It has no direct relationship with economies of scale or size of Power Purchase Agreement investments. Furthermore, this thesis has taken an arithmetic average of fitted exponential declining rate of publicly accessible **projected** costs of investments in solar farms in the future. Therefore, it is not how these costs (PPA Price of solar farms) has been declined over time until the time this thesis is written, where it has seen a much aggressive decline. This also implies that this particular γ does not work for projecting costs of investments in wind farms. The publicly accessible **projected** costs of investments in solar farms used in this thesis includes *Annual Technology Baseline 2019* from National Renewable Energy Laboratory (NREL) [37], *Electricity Generation Technology Cost Projections* produced by Commonwealth Scientific and Industrial Research Organization (CSIRO, Australia) [38], and *Utility-Scale Solar 2019* prepared by Lawrence Berkeley National Laboratory (Berkeley Lab) [39]. To model the potential to decline in the future unit cost of Power Purchase Agreement from wind farms, the values stated in the *2018 US Wind Technologies Market Report* [36] and the Regionalization Factor are used, as this report is also the source of the initial unit costs/price. By virtue of using these values, an assumption was made that the unit cost of Power Purchase Agreement for the studied investor, Penn State University, would decline like these stated sources as it make investment(s) at different time(s). Tables D.1 and D.2 presented the base case values of these unit costs.

To proceed with the entire calculation process, additional assumptions that are made include the Investment Horizon T of **25** years. As a rewind to Chapter 2, this means that, for example, if Penn State University begins the investment in a Power

Purchase Agreement of a renewable energy project at $t = 10$, the accounting of $IHEV$ and $IHEV$ of EV_t and AE_t stops at $t = T = 25$, and the EV_t and AE_t of this particular project in $t \leq 10$ is 0. Additionally, the base case discount rate is assumed to be **10** percent. Tables 3.2, 3.3 and 3.4 are used to display the Base Case parameters used in the Base Case Economic Value calculations of investment(s) in Power Purchase Agreement of renewable energy project(s).

Table 3.2. Seasonal Independent Base Case Parameters

r (%)	T (Years)	$C_{0,solar}$ (\$/MWh)	$C_{0,wind}$ (\$/MWh)	γ_{solar} (%)
10	25	44.17	48.82	3.2

Table 3.3. Summer Only Base Case Parameters

p (%)	u	d	W (\$/MWh)
41.34	1.46	0.69	32.85

Table 3.4. Fall and Spring Only Base Case Parameters

p (%)	u	d	W (\$/MWh)
40.31	1.28	0.78	34.86

3.3 Environmental Analyses Data and Assumptions

The use of publicly accessible data for the calculation of Avoided Emission of carbon dioxide of investments in Power Purchase Agreement of renewable energy projects completed the environmental analyses. This involved the use of some other types of data. This thesis followed the steps below to provide estimations of the Avoided Emissions.

- Examined the trend in historical values of Marginal Emission Factors for interested electric power systems
- Identified and justified possible rationales for change in Marginal Emission Factors over time

- Used Unit Commitment to estimate the marginal generation technology of interested electric power systems in projected future
- Developed the evolution of Marginal Emission Factors of electric power systems in Wholesale Electricity Markets over the Investment Horizon of consideration
- Produced the Avoided Emission (AE_t and $IHAE$) of carbon dioxide from Power Purchase Agreement of renewable energy projects

In the following subsections, the specific approaches of each of the first four steps are explained followed by related results, by using assumptions and publicly accessible data, and the last step will be presented as part of Results and Discussions in the next Chapter.

3.3.1 Historical Carbon Dioxide MEF Data and Trend

Because the investor of Power Purchase Agreement of renewable energy projects identified in this thesis is Penn State University, the electric power system of interest would be the PJM Interconnection, as the majority of Penn State University's electricity consumption would come from Wholesale Electricity from PJM, had there been no investments of PPAs.

In this case, two reports produced by the PJM Interconnection, *2012-2015 CO_2, SO_2 and NO_X Emission Rates* [40] and *2014-2018 CO_2, SO_2 and NO_X Emission Rates* [41] were used to extract historical data. The data was presented as two monthly values for On-Peak and Off-Peak hours as presented in Table E.1. To pair with the Economic Analysis where two intra-year seasonal periods (Summer, Fall and Spring) are used, a two-step process was devised. First, a Marginal Emission Factor for each month was first calculated using the specific definition of On-Peak and Off-Peak hours in PJM

Interconnection as presented in Table E.2 by taking a weighted average of the values from On-Peak and Off-Peak hours [42]. Then, an arithmetic average in between the relevant months was used to calculate a value for the two representative seasonal periods (Summer, Fall and Spring) in each year. This historical carbon dioxide MEF evolution is plotted in Figure 3.4. A decrease over time regardless of seasonality is observed.

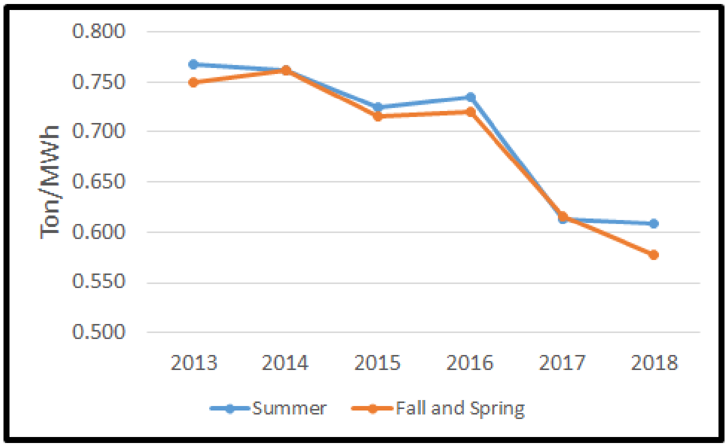

Figure 3.4. PJM Historical Carbon Dioxide MEF Evolution

3.3.2 Rationale for the Change in MEF

In the same set of reports where the Historical carbon dioxide MEF data were extracted, the rationale behind this decline is also presented – the growth of natural gas based generation technologies serving as marginal units in the PJM Interconnection in the same time span, as illustrated by Figure 3.5. Over the time span of 7 years, the relative frequency of coal based electricity generation technologies being marginal units plummeted but that of natural gas soared.

The trend presented in Figure 3.4 is supported by Figure 3.5, and the values are also validated by other sources. A research report submitted to Pennsylvania Department of Environmental Protection suggested that the carbon dioxide Marginal Emission Factor for natural gas based electricity in Pennsylvania (A significant member state of PJM) is approximately 0.508 Ton/MWh [43]. This value is within understandable range of what is calculated for the value in recent years as shown in Figure 3.4, which is reasonable as other generation technologies still contributed visibly to PJM's marginal units. This validation of historical data is valuable, but the next task – projection into the future is more important for the overall analysis.

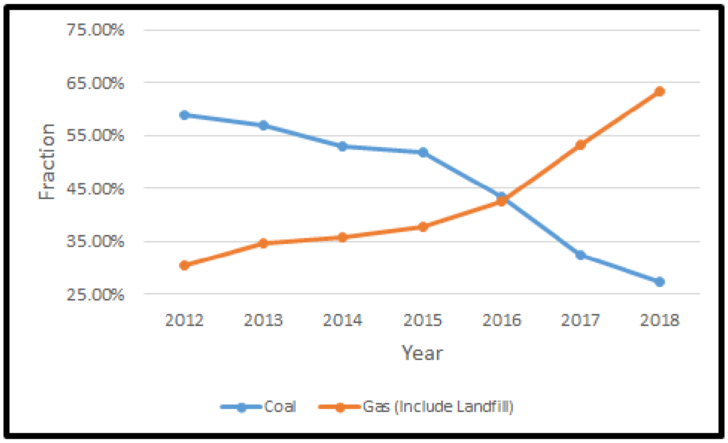

Figure 3.5. PJM Historical Marginal Unit Frequency Evolution

3.3.3 Unit Commitment and MEF Estimation

As described in Chapter 2, Unit Commitment is an optimization problem that can be used to determine the marginal units of electric power systems, and thus was used to estimate hourly Marginal Emission Factors (*MEF*) of electric power systems in Wholesale Electricity markets. It could be essentially impossible to perform a precise determination of hourly Marginal Emission Factor values for a distant (more than 10 years) future, as it would be both a computational intensive process as well as hard to predict what electricity generation units exists in the PJM Interconnection at the time. Therefore, this thesis developed a Unit Commitment problem on a generation technology level, for the PJM Interconnection in 2034. The reason that this problem solved for the year 2034 (rather than later) is due to the structure of the Unit Commitment problems, where hourly electricity demands of electric power systems of interest are needed. PJM Interconnection has its own projection of annual demand growth rate (0.4%) [44], for a 15-year period that ends at year 2034. Additional pieces of data used to solve the Unit Commitment problem (and the methods to extract them when necessary) include the following:

- *Projected typical demand levels in a representative day each, of the two intra-year seasonal periods (Summer, Fall and Spring), in 2034:* The typical demand levels are first calculated by averaging the value in each hour of a day (for example, 9 AM) in all days of the two intra-year seasonal periods (Summer, Fall and Spring), from electricity demand levels in PJM in 2018 [45]. Then the corresponded values in 2034 are projected using the PJM Interconnection's own projection of 15-year annual demand growth rate (0.4%) [44].

- *Typical hourly availability of intermittent renewable generation technologies:* This was completed using typical electricity production level from intermittent renewable generation technologies (solar, wind and hydro) first by averaging the value in each hour of a day (for example, 9 AM) in all days of the two intra-year seasonal periods (Summer, Fall and Spring) from PJM in 2018 [46]. These values are then divided by the installed generation capacity of PJM as described in [47].

- *Projected installed capacity of electricity generation technologies types in 2034:* This was completed with the aid of the Regional Energy Deployment System (ReEDS) [48] and additional information from Monitoring Analytics (A spun-off company from the Market Monitoring Unit of PJM Interconnection found in 2008) and EIA. ReEDS is a model developed by NREL to simulate the evolution of the bulk power system—generation and transmission through 2050, including installed capacity of electricity generation technologies types in each state. This could be inaccurate for the Unit Commitment modelling as PJM's Service Territory includes some partial states as seen in Figure 1.6. Therefore, for these states that are not entirely within the PJM, their power generation technology in the future are calculated by multiplying (1) the fraction of generation capacity in the state that is in PJM in 2018 with (2) the projected state level generation technology capacity in future years in ReEDS. To find (1), (3) the PJM generation capacity in each state in 2018 from Monitoring Analytics' PJM State of the Market Report [47] is divided by (4) total generation capacity in each state in 2018 from EIA [49].

- *Projected fuel price of electricity generation in 2034:* The *Annual Energy Outlook* (AEO 2019) [50] produced by EIA was the major data source, coupled with other fuel price information, including for biomass specifically [51] and accounting for relatively low price of natural gas in the PJM Interconnection compare to the rest of the United States [52, 53].

- *Variable Operation and Maintenance Costs and Heat Rates of electricity generation technologies:* These information are also from AEO 2019 [50].

- *Parameters related to the operational flexibility of electricity generation technologies:* These values are adapted from [54, 55] and described in Appendix F.

Using these data, the Unit Commitment Problem used this thesis is formulated as a Mixed-Integer Linear Program and is fully described in Appendix F. The model was run in GAMS, with the results shown in Figures 3.6 and 3.7.

The results from the Unit Commitment Problem discussed in Appendix F suggest that the marginal (used to produce electricity that satisfy the last unit of demand) generation technology in the PJM Interconnection in the projected future (2034 in this case) would be natural gas, which means that the Marginal Emission Factors of carbon dioxide of PJM at that year should generally reflect the emission intensity of natural gas based electricity generation technologies.

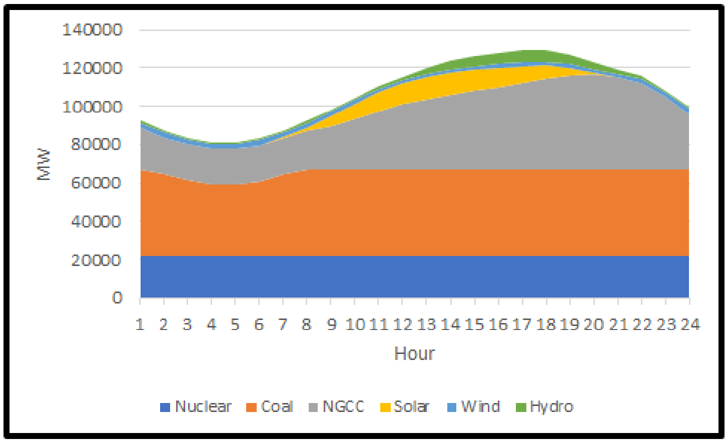

Figure 3.6. Result of Unit Commitment for Summer 2034

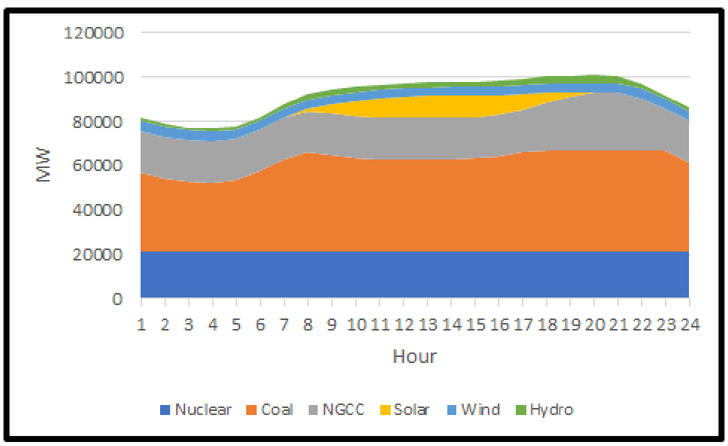

Figure 3.7. Result of Unit Commitment for Fall and Spring 2034

3.3.4 Evolution of Future Marginal Emission Factors

This thesis used a linear interpolation of Marginal Emission Factor of carbon dioxide, from the Marginal Emission Factor values in 2018 to the end of the assumed investor (Penn State University)'s Investment Horizon of 25 years. The value of Marginal Emission Factors at the end of this Investment Horizon of 25 years in both intra-year seasonal periods (Summer, Fall and Spring) are assumed to be the Marginal Emission Factor of carbon dioxide for natural gas based electricity generation technologies only, approximated to 0.508 ton/MWh as described in [43]. The values of the years in between would be uniformly decreased from the values in 2018 that were shown in Figure 3.4. The specific values of these Marginal Emission Factors over the Investment Horizon are displayed in Appendix G. With these Marginal Emission Factors interpolated, the Annual and Investment Horizon Avoided Emissions of investments in Power Purchase Agreements of renewable energy projects were estimated. As suggested in Chapter 2, this allows the investors to evaluate the environmental outlook of these projects and perform the Multi-Objective evaluation of the potential investment strategies. Finally, these Avoided Emissions were monetized using the Social Costs of Carbon from EPA [33], and allow the investor to decide on a single optimal investment strategy by using the Single-Objective Optimization Problem that captures the monetary value of these Avoided Emissions as described in Section 2.3.3.

Chapter 4

Results and Discussion

In this chapter, the results and discussions regarding the Multi and Single-Objective Optimization/Real Option Valuation Problems are presented, using the methods described in Chapter 2 and the data discussed in Chapter 3. The results in this chapter generally follows the order of the methods described in Chapter 2, which could be generalized into six cases, including the following:

- Case 1: The simplified Multi-Objective ($IHEV$ and $IHAE$) Optimization Problem of Penn State University where it could only invest once and invest in the *Standard Sized* solar farm
- Case 2: Single-Objective ($IHEV$) Optimization/Real Option Valuation Problem of Penn State University where it could invest only once and invest in the *Standard Sized* solar farm
- Case 3: Single-Objective ($IHEV$) Optimization/Real Option Valuation Problem of Penn State University where it could invest incrementally in single multiple of *Standard Sized* solar farm in between two time periods (years)

- Case 4: Single-Objective ($GTEV$) Optimization/Real Option Valuation Problem of Penn State University where it could invest only once and invest in the *Standard Sized* solar farm

- Case 5: Single-Objective ($IHEV$) Optimization/Real Option Valuation Problems of Penn State University where it could only invest once but in combinations of variously sized solar and wind farm

- Case 6: Sensitivity Analyses on the Single-Objective ($IHEV$) Optimization/Real Option Valuation Problem of Penn State University where it could only invest in the *Standard Sized* solar farm

4.1 Results and Discussion for Case 1

This section presents the results and discussion for the simplified Multi-Objective Optimization Problem of Penn State University where it could only invest once and invest in the *Standard Sized* solar farm. Each point in Figure 4.1 represents a feasible solution for this MOOP.

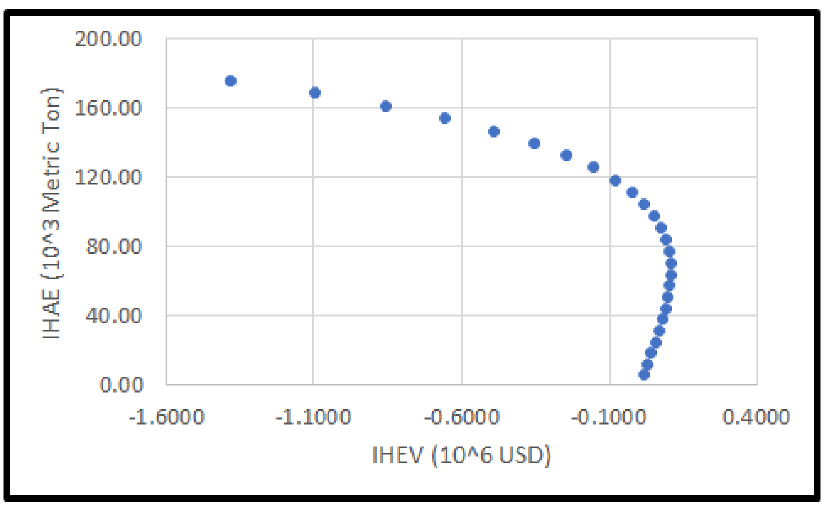

Figure 4.1. Feasible Solutions of the Simplified MOOP for the *Standard Sized* Solar Farm

From the constraints being made, each point in Figure 4.1 represents a paired values of $IHEV$ and $IHAE$ by deferring the investment time by one more year from $t = 0$. Using an Investment Horizon T of 25 years, including $t = 0$, there are 26 feasible solutions to this constrained Multi-Objective Optimization Problem. The solution in the top-left corner of figure represents investing at $t = 0$, and the solution in the bottom-right corner of figure is the paired values for investing at $t = T$ (25). These feasible solutions generally appear in arc shape with the "turning point" represents the paired values of $IHEV$ and $IHAE$ by deferring the investment time to $t = 16$. These paired values are also further apart in between each other when t is small, and getting closer and closer to each other as the investment time reaches the end of the Investment Horizon.

These feasible solutions are then inputted into Trade Space Visualizer (ATSV) developed by the Applied Research Laboratory at Penn State University. ATSV is a Java-based data visualization tool that allows users to explore the relationship between multi-dimensional data sets, and is capable of finding Pareto Set of these discrete multi-dimensional data [56].

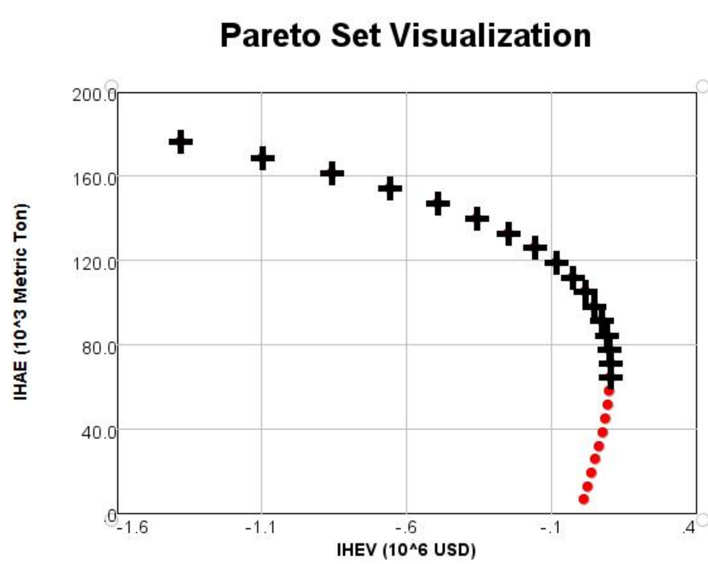

Figure 4.2. Dominated Solutions and Pareto Set of the Simplified MOOP for the *Standard Sized* Solar Farm

Figure 4.2 presented both the Pareto Set as well as the Dominated Solutions of the constrained Multi-Objective ($IHEV$ and $IHAE$) Optimization Problem of Penn State University where it could only invest once and invest in the *Standard Sized* solar farm. The "turning point" of the arc shape that was first discussed in Figure 4.1 was of significance. Every investment strategy above it and itself (investment time of $t \leq 16$) are in the Pareto Set, illustrated by a + sign on top of the point. The red points represents the Dominated Solutions. This means that for the best interest of the investor, Penn State University, it shall not defer its investment time beyond 16 years from $t = 0$. Thus, there will be in total 17 solutions in the Pareto Set (a portfolio) that the decision maker can choose from. In this portfolio of investment strategies from investing at $t = 0$ to the next 16 years, by deferring the investment for one extra year in each investment strategy, Penn State University as an investor is essentially facing a trade off between claiming a worse environmental outlook (smaller $IHAE$) and receiving a better economic benefit (larger $IHEV$).

4.2 Results and Discussion for Case 2

Following the discussion of Chapter 2, an investor like Penn State University could only value the economic outlook ($IHEV$) of making the single investment of Power Purchase Agreement in a particular renewable energy project by having a Single-Objective ($IHEV$) Optimization Problem that can be also considered as a Real Option Valuation Problem. This section presents the result in Figure 4.3 for this decision problem of Penn State University, where it could invest once and only once in the *Standard Sized* solar farm. Values of interests for Penn State University as an investor includes the Optimal Investment Time, Optimal Investment Horizon Economic Value, and Value of Option (Economic Value of the Option to Delay).

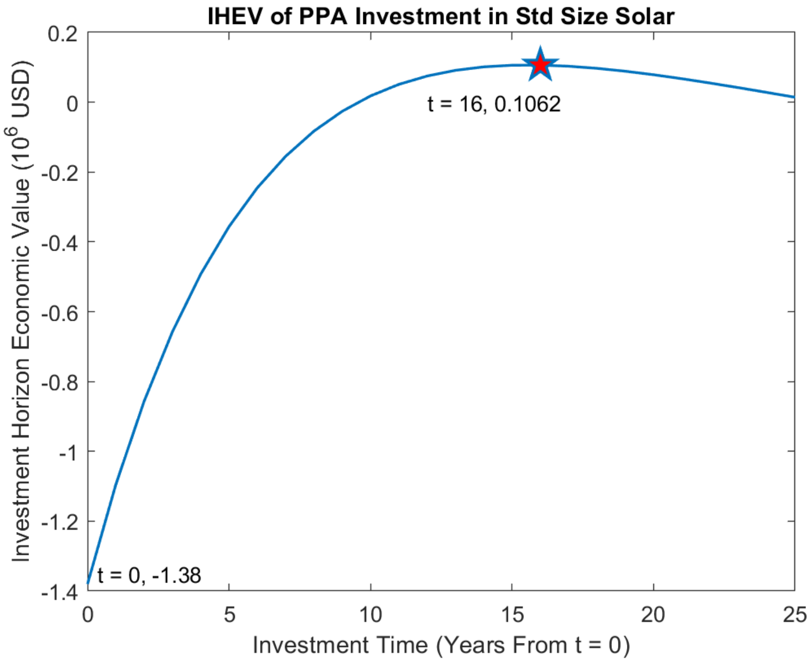

Figure 4.3. IHEV of the *Standard Sized* Solar Farm

From examining Figure 4.3, one can see that $IHEV$ increases rapidly from $t = 0$ until $t = 10$, where it turns from being a negative value (net cost) to positive value (net saving) for Penn State University. Then $IHEV$ continues to increase but at a much slower rate until it peaks out at $t = 16$, and decrease gradually until the end of Investment Horizon ($t = 25$). This provides a few key takeaways. Primarily, on average, Penn State University is not suggested to invest before $t = 10$. Additionally, on average Optimal Investment Time for Penn State University is $t = 16$, in which Penn State University shall sign a 10-year long PPA from that year. The $IHEV$ from investing in this year, the Optimal Investment Horizon Economic Value, is approximately 0.1062 Million US Dollar (a net saving of a bit more than a hundred thousand dollars). If one were to consider this problem as a Real Option Valuation Problem, the Value of Option ($EVOD$) is the difference between this Optimal Investment Horizon Economic Value and the Investment Horizon Economic Value of the immediate ($t = 0$) investment, which is approximately 1.48 Million US Dollars. This means Penn State University on average saves 1.48 Million US Dollars from deferring the investment to 16 years from $t = 0$.

The trend in $IHEV$ could explain the arc shape of the feasible solutions in Figures 4.1 and 4.2. The reason that the $IHEV$ have this trend is related to the modelling structure used in this thesis. By using the **Binomial Lattice Pricing Model**, there is a fixed Investment Horizon that is defined first, where the values of Investment Horizon Economic Value only accounts for the Annual Economic Values of the investor from the time that the investor decides to invest to the end of the Investment Horizon. Additionally, the *Standard Sized* solar farm is small enough that it is impossible to produce enough electricity to create excess purchase for Penn State University as an investor. Therefore, the annual Economic Values are essentially the differences between the Avoided Energy Payments and Cost of Power Purchase, which depend on the Wholesale Electricity Price and Unit Cost of Power Purchase, respectively. Until the $IHEV$ breaks even at $t =$ 10, the Wholesale Electricity Price is expected to be lower than Unit Cost of Power Purchase, until the Optimal Investment Time of $t = 16$. The results of $IHEV$ flattens after deferring the investments beyond $t = 16$, and these results can be less than ideal. These solutions represent investments in PPA of effective length of less than 10 years long that are rather practically rare to see.

4.3 Results and Discussion for Case 3

Following the modelling structure of this thesis, investors like Penn State University could invest incrementally (but only in single multiple of *Standard Sized* and in a particular type) while only values the economic outlook. By also using **Monte Carlo Simulations**, the $IHEV$ at the end of the Investment Horizon would be different for each path of future Wholesale Electricity Price evolution. This would create statistical distributions for both $IHEV$ and the $EVOCS$ (Economic Value of the Option to Change

Size of Investment). This thesis have ran 10,000 samples of **Monte Carlo Simulations** of Wholesale Electricity Prices evolution, and calculated the corresponded $IHEV$ and $EVOCS$. Figures 4.4 and 4.5 presented the results for this incremental investment structure for solar farms.

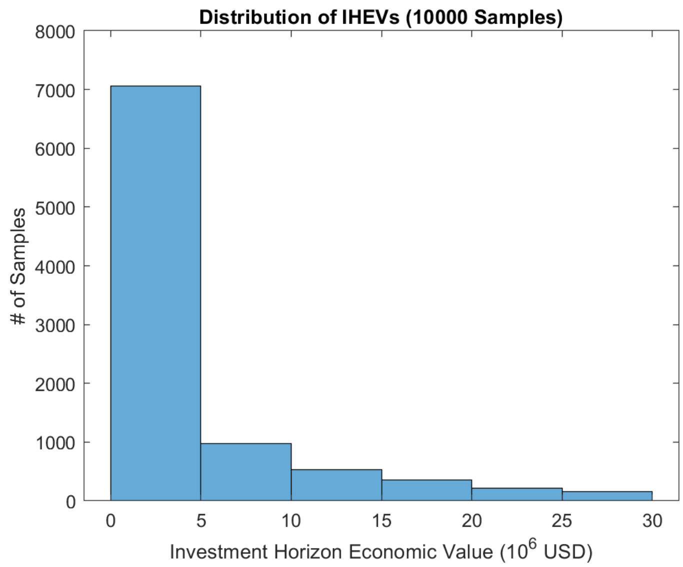

Figure 4.4. Distribution of IHEVs for Incremental Investment

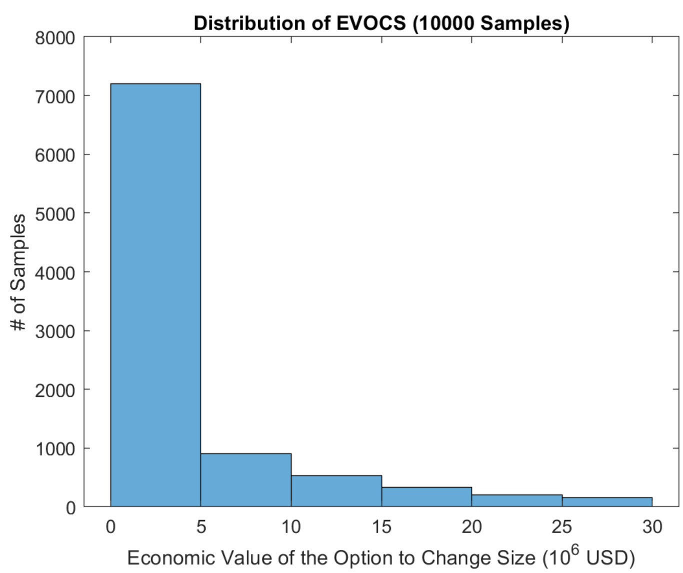

Figure 4.5. Distribution of EVOCS for Incremental Investment

The statistical distributions for $IHEV$ and the $EVOCS$ are almost visually indistinguishable in the rang of 0 and 30 Million US Dollar in bins of 5 Million US Dollars. It can be seen that the monetary saving (and net saving) of from possessing the ability to invest incrementally for Penn State University is typically less than 5 Million US Dollars, with the chances of saving much more accounting for the remaining less than 20% of the time. Also, these histogram does not shown the outliers, where Figure 4.6 shows that there is a less than 1% chance to have a net saving ($EVOCS$) of more than 100 Million US Dollars. Figures 4.4, 4.5 and 4.6 have thus encouraged investors to engage in incremental investments of renewable energy projects via PPA.

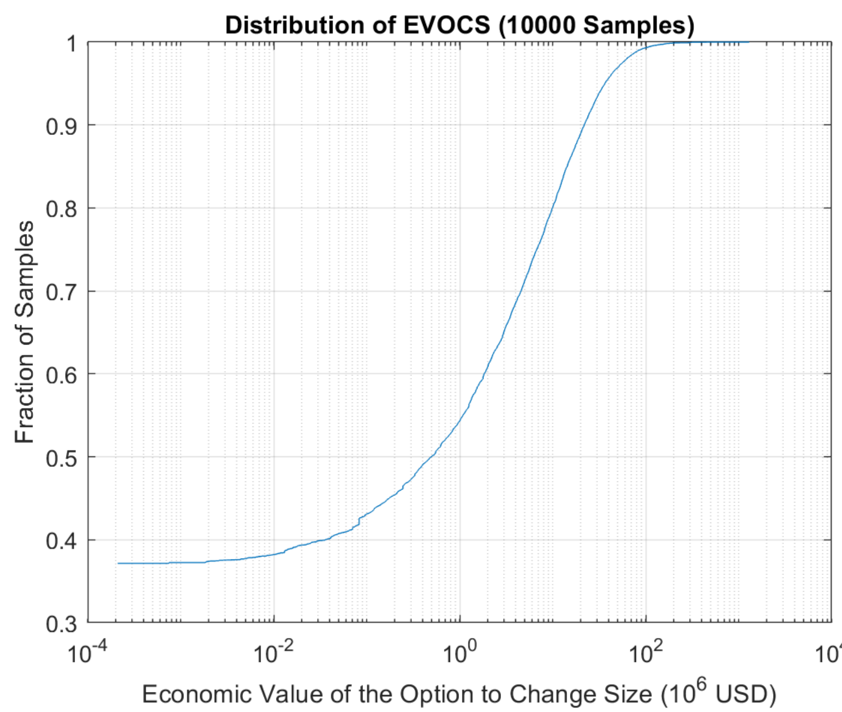

Figure 4.6. CDF of EVOCS for Incremental Investment

Figures 4.7 and 4.8 would provide offer investors like Penn State University a different perspective compare to Figures 4.4, 4.5 and 4.6. Figures 4.7 identified that in more than 40% of the samples it is economical to invest within 5 years from $t = 0$, and the mode of Initial Investment Time ($t = 1$) is a much shorter deferment time suggested by the Optimal Investment Time from Figure 4.3. Additionally, Figure 4.8 suggested that a bit more than 50% of the samples chose to invest in less than 5 times the *Standard Size* (incrementally invest less than 5 times in total, which would not create any excess purchase using the modeling structure and data described in Chapters 2 and 3).

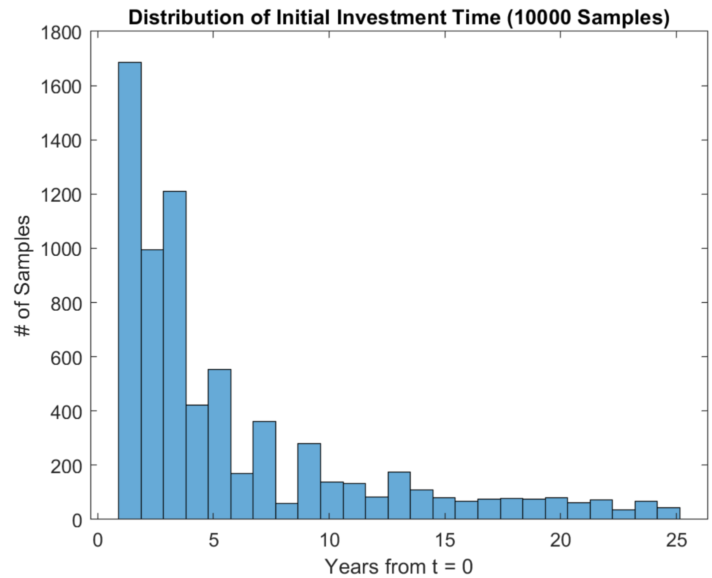

Figure 4.7. Distribution of Initial Investment Time

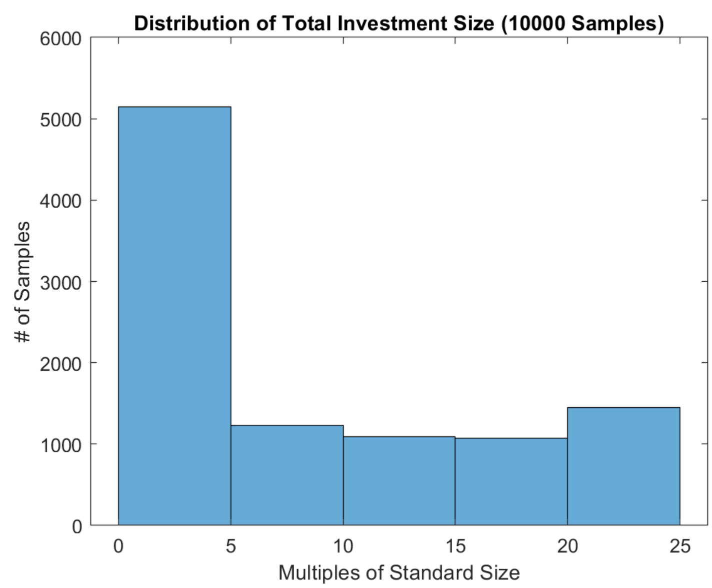

Figure 4.8. Distribution of Investment Size

4.4 Results and Discussion for Case 4

In Chapter 1 of this thesis, it was clearly stated that Penn State University as an investor of Power Purchase Agreement has a commitment to reduce its carbon footprint. This means that by virtue of deciding to pursuing an investment in PPA, it is not entirely monetary-value driven. It is therefore not entirely accurate to only use the Single-Objective Optimization and Real Option Valuation Problem on the economic outlook ($IHEV$) of making the single investment of Power Purchase Agreement in a particular renewable energy project to evaluate the optimal investment strategy. Instead, the use of $GTEV$, the economic outlook that includes the monetized value of the environmental outlooks would be better. Like the SOOP of $IHEV$, there are metrics such as the Optimal Investment Time, Optimal Investment Horizon Economic Value, Value of Option (Economic Value of the Option to Delay) that were identified as well. The use of $GTEV$ has one caveat, however. It is inappropriate to add Economic Values that are calculated from different discount rates (r). In Figure 4.9, both the $GTEV$ and $IHEV$ shown are computed using the base case discount rate from computation of Social Cost of Carbon from [33], which was a value of 3%. The distance between each pair of $GTEV$ and $IHEV$ in the figure represents the monetary effect of Investment Horizon Avoided Emissions, from deferring the investment time of one extra year.

Several observations can be made from examining these two curves. Primarily, the distance between each pair of $GTEV$ and $IHEV$ have shrink over time. This should be attributed to the fact that by postponing the beginning time of the investment, the effective length of PPA investment was reduced, and diminishes the Investment Horizon Avoided Emissions. Additionally, these two curves suggested vastly different optimal investment strategy. The use of $IHEV$ suggests the optimal investment time is 17 years from $t = 0$, with an Economic Value of the Option to Delay the beginning of the investment (net monetary saving from having the ability to postpone the beginning time of the investment time) of a bit less than 3 Million US Dollars. However, The use of $GTEV$ shifts the optimal investment time to only 2 years from $t = 0$. $GTEV$ is also positive in all time periods in the Investment Horizon, suggesting Penn State it is having a net saving regardless of the investment time. The Optimal Grand Total Economic Value approximately is 8.42 Million US Dollars. The $EVOD$ of postponing this investment only improves the $GTEV$ of immediate ($t = 0$) investment by less than 1%.

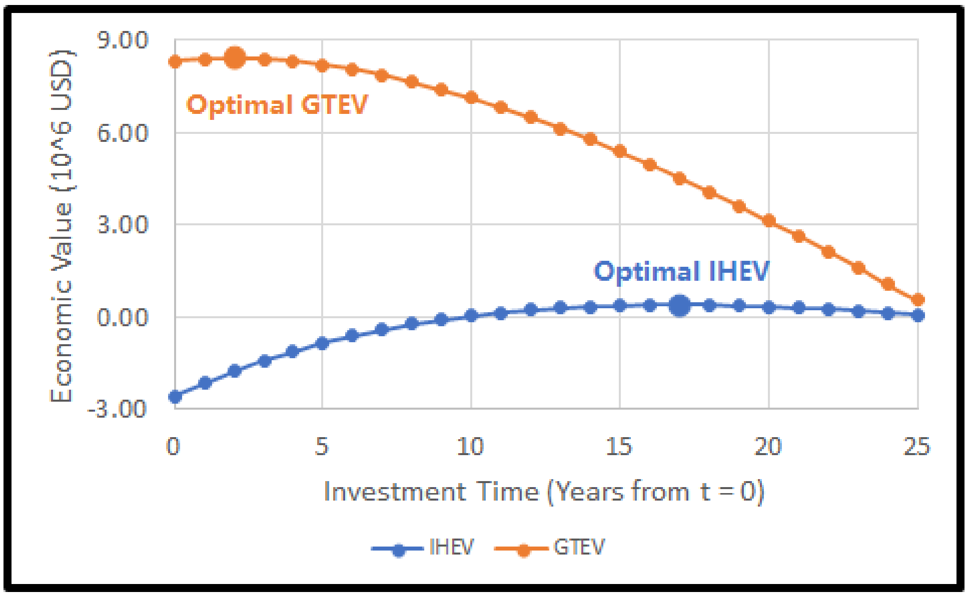

Figure 4.9. GTEV and IHEV of *Standard Sized* Solar Farm at 3% Discount Rate

Finally, as described in Chapter 2, Penn State University as an investor of Power Purchase Agreement of renewable energy projects could value the Social Cost of Carbon at a different level as the EPA does in [33]. This way, for each level of Social Cost of Carbon, Penn State University is anticipated to receive a different cumulative Economic Value at the end of the Investment Horizon, even if it may engage in the same investment. As expected, Figure 4.10 suggests that an increase in Penn State University's value of Social Cost of Carbon would encourage it to engage in a PPA investment towards earlier in the Investment Horizon, while holding everything else equal.

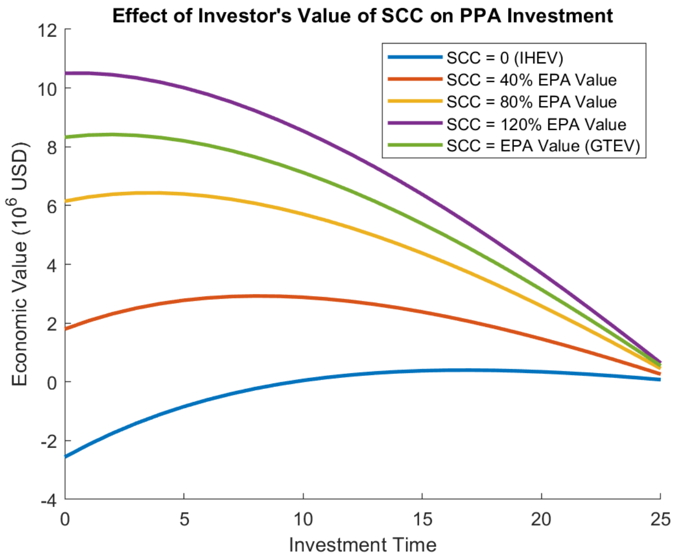

Figure 4.10. Effect of Investor's Value of SCC on PPA Investment of *Standard Sized* Solar Farm

4.5 Results and Discussion for Case 5

Figure 4.3 offered investors like Penn State University the economic outlook ($IHEV$) of making the single investment of Power Purchase Agreement in a particular renewable energy project. While it identified important metrics including the Optimal Investment Time, Optimal Investment Horizon Economic Value and Value of Option for such investment, an investor could be interested in investment of vastly different sizes, for example, it could choose to invest in a solar farm much larger than the *Standard Sized* one. Or it could invest in a portfolio of renewable energy projects including one wind farm and one solar farm, with different sizes. The results in this section are different from Figures 4.4 through 4.8 where in this section only a single investment decision can be made, but its size and type is no longer limited like in Figure 4.3. The size limit imposed in this section is that an investor like Penn State University can only invest in combinations of less than or equal to 10 times the *Standard Size*, for both solar and wind farms. Thus, the values of $IHEV$ are represented by a 3-dimensional matrix of size $11 \times 11 \times 26$, with the first two dimensions represent all the possible investment size combinations, and the last represents the investment time.

In Figure 4.11, a heat-map like plot is presented, where the axes represented the sizes of wind and solar farm, and the value of interest is the $IHEV$ of immediate investment (beginning investment of Power Purchase Agreement of variously sized renewable energy projects at $t = 0$). Figure 4.11 presents several key messages for an investor like Penn State University. Primarily, all of the $IHEV$ shown in the figure are negative, meaning that on average, pursuing any sized investment (within the size limit of Figure 4.11) is a net cost for Penn State University. Additionally, as all of the $IHEV$ shown are negative, the optimal investment size is the *Standard Sized* solar farm, with an $IHEV$ same as the value in the bottom left corner of Figure 4.3, which is -1.38 Million US Dollars. Finally, to achieve the same $IHEV$, there is an approximate 1:4 ratio between the size of wind and solar farms. This means that the $IHEV$ of investing in the *Standard Sized* wind and solar farms collectively worth 9 times the *Standard Sized* is approximately the same as that of 2 times the *Standard Sized* Wind and 5 times the *Standard Sized* Solar, as well as that of 3 times the *Standard Sized* Wind and 1 times the *Standard Sized* Solar.

Figure 4.12 used the same heat-map like plot for the Optimal $IHEV$ for all of the possible investment sizes, using the same axes to represent the sizes of wind and solar farm. From examining Figure 4.12, the key takeaway message is that, the largest Optimal $IHEV$ does not come from the largest investment size (10 times the *Standard Sized* Wind and 10 times the *Standard Sized* Solar). Rather, it come from only investing in 10 times the *Standard Sized* Solar). These could be attributed to the relative high level of Unit cost of PPA in wind farms for the investor (Penn State University) comparing to the future evolution of Wholesale Electricity Prices.

Like the analysis performed in Figure 4.3, this Single-Objective $IHEV$ Optimization Problem was considered as a Real Option Valuation Problem. The difference between each pair of points in Figures 4.11 and 4.12 produces the the Economic Value of the Option to Delay ($EVOD$) for all of the possible investment sizes, showing that on average the net saving from delaying these investment is the largest when Penn State University chooses to pursuit the investment in both the largest solar and wind farm.

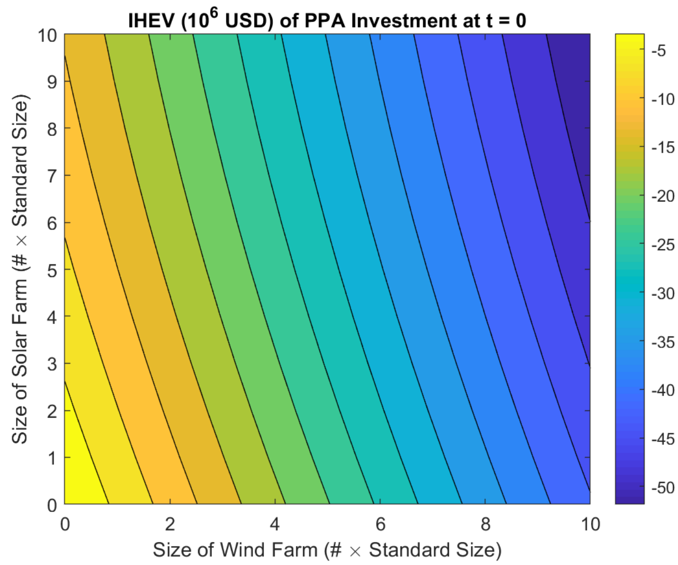

Figure 4.11. IHEV of *Non-Standard Sized* PPA Investments at $t = 0$

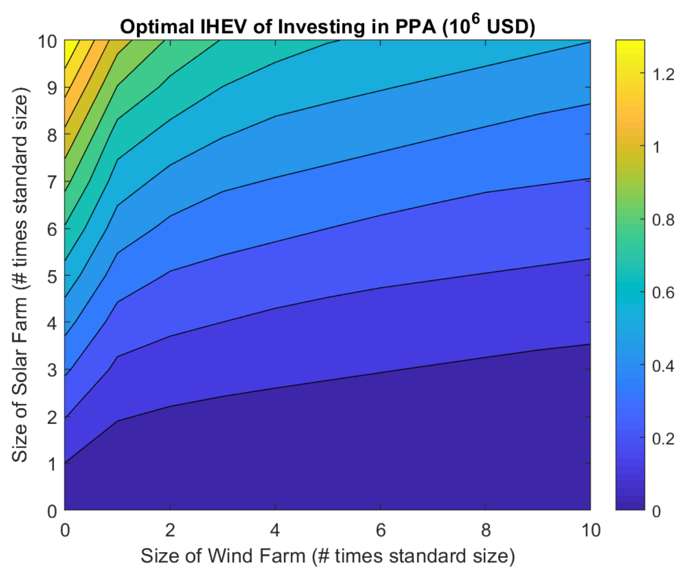

Figure 4.12. Optimal IHEV of *Non-Standard Sized* PPA Investments

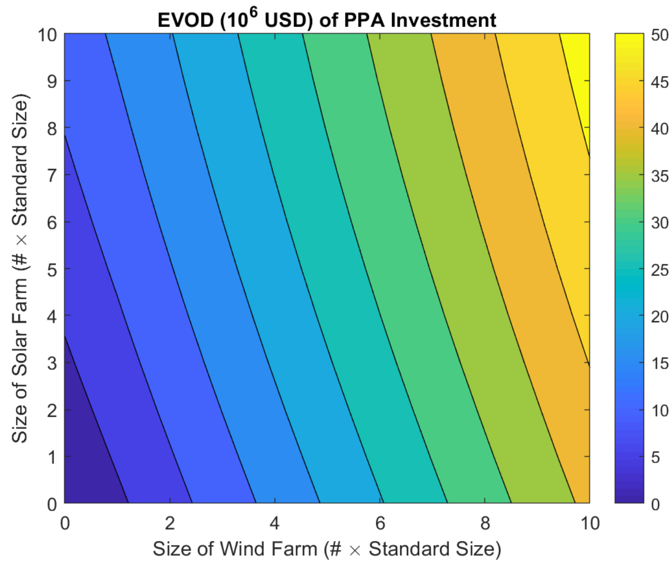

Figure 4.13. EVOD of *Non-Standard Sized* PPA Investments

4.6 Results and Discussion for Case 6

If one were to coincide the two curves of $IHEV$ from Figures 4.3 and 4.9, one can see that the reduction of discount rate by more than half (from 10% to 3%) only postponed the Optimal Investment Time by one extra year (from $t = 16$ to $t = 17$), but almost doubles the $IHEV$ of pursuing an immediate investment (from -1.38 to -2.56 Million US Dollars). This would trigger the question of which of the the seven parameters discussed in Chapter 2 was the most impactful on the economic benefits of the same investor, while adjusting them by the same **relative** amount. As discussed in Chapter 2, the use of Sensitivity Analysis would help answering this question, and this section presented the results of these analyses for making a single investment (while possessing the ability to delay the beginning of the investment/*the option to delay*) for the *Standard Sized* solar farm. Unless stated otherwise, the base case values represents the results discussed in Section 4.2 and using the parameters from Tables 3.2, 3.3 and 3.4.

Table 4.1 presented the Sensitivity Analyses on the Optimal $IHEV$ of Penn

State University while pursuing only the investment in the *Standard Sized* Solar farm. The results in the table is also illustrated in Figure 4.14.

Table 4.1. Sensitivity Analyses on the Optimal $IHEV$ of *Standard Sized* Solar Farm (10^6 USD)

Adjusted Magnitude/Parameter	r	p	u	d	W	$C_{0,s}$	γ
Increase by 10%	0.09	0.78	2.09	1.30	0.18	0.07	0.13
Base Case	0.106						
Decrease by 10%	0.13	0.78	-0.01	-0.01	-0.06	0.17	0.08

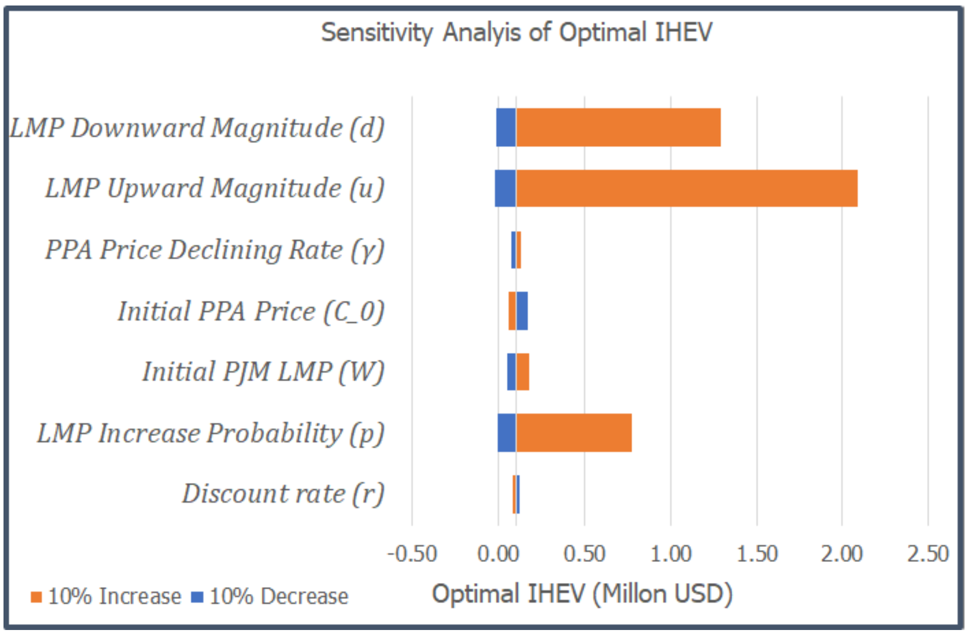

Figure 4.14. Sensitivity Analyses on the Optimal IHEV of *Standard Sized* Solar Farm

From using Table 4.1 and Figure 4.14, it can be seen that by changing the same **relative** amount of 10%, the parameters related to the volatility of Wholesale Electricity Price evolution (p, u, and d) are the most impactful on the Optimal $IHEV$ of investing in the *Standard Sized* Solar farm. This is especially true for the parameter u, which represents the typical magnitude of increase in Wholesale Electricity Price if it were to increase in between each time period in the future. The projected exponential declining rate of future Unit Price of Power Purchase Agreement of solar farms, γ, is the least impactful of all of these parameters other than the discount rate r, suggesting that the uncertainty in technical development of solar farms and reduction in unit cost of Power Purchase Agreements should not deter the commitment in making the investment.

The Sensitivity Analyses on the Optimal Investment Time of pursuing the same investment demonstrated a similar level of impact for the parameters and in the same direction as seen in Figure 4.15. For example, a decrease in the Initial Unit Price of Power Purchase Agreement, C_0, leads to an increase in the Optimal $IHEV$ and a decrease in Optimal Investment Time. Also, the decrease of Discount Rate (r) and declining rate of future Unit Price of PPA (γ) by 10% has no impact on the Optimal Investment Time.

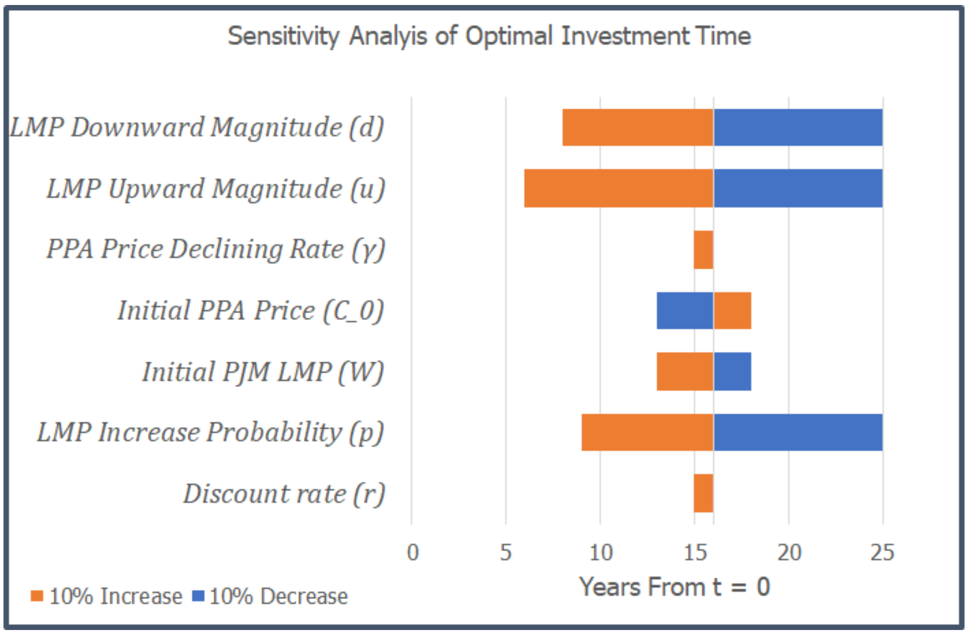

Figure 4.15. Sensitivity Analyses on the Optimal Investment Time of *Standard Sized* Solar Farm

Finally, Figure 4.16 represented the Sensitivity Analyses on the $EVOD$ of pursuing the same investment, which represents the average net saving for Penn State University as an investor while possessing the capability to postpone the beginning of the investment to the Optimal Investment Time. The parameters related to the volatility of Wholesale Electricity Price evolution (p, u, and d) once again dominated the impact on these net savings. The declining rate of future Unit Price of PPA (γ) is also among the least significant parameters of the ones that are explored. Compare to Figure 4.14, the effect of varying Discount Rate (r) and Initial Wholesale Electricity Price (W) has visibly grew, but are still overshadowed by the parameters that are directly related to the volatility of Wholesale Electricity price.

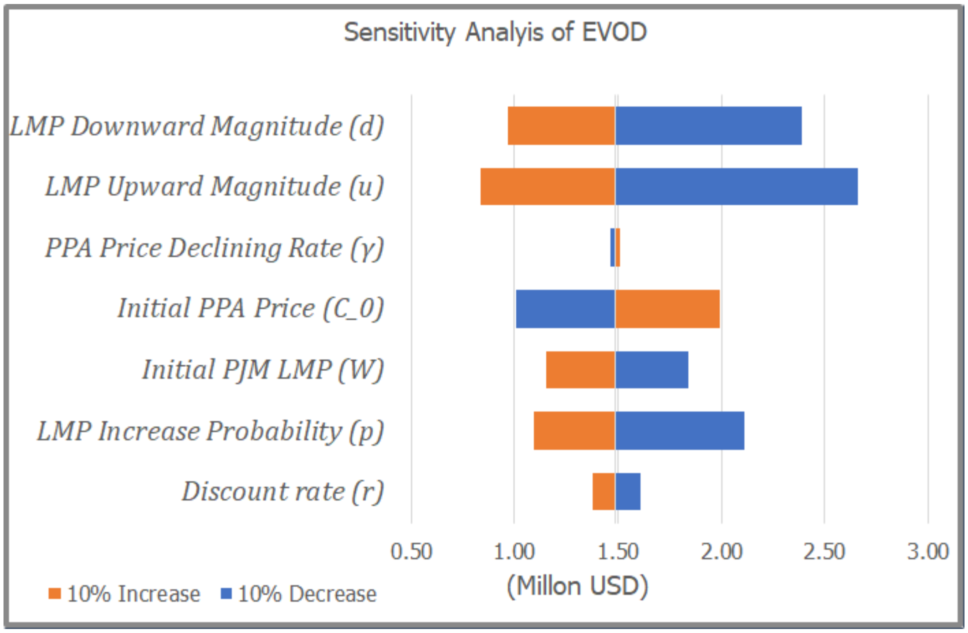

Figure 4.16. Sensitivity Analyses on the EVOD of the *Standard Sized* Solar Farm

Chapter 5

Conclusion and Future Work

This thesis has explored the motivation of the investors of large scale renewable energy projects in between the immediate and distant future via Corporate Renewable Power Purchase Agreement(s). By modelling the investment decision structure using Multi and Single Objective Optimization Problems, after making substantial assumptions that reduces the computation difficulty and modelling intractability, the preferred investment strategies and their economic and environmental outlooks were analyzed using tools including the **Binomial Lattice Pricing Model**, **Monte Carlo Simulation** and **Unit Commitment**. This research is also innovative in its establishment of connection between Optimization Problems and Real Option Valuation Problems. This chapter presents a major analytical conclusion corresponding to each set of the results discussed in Chapter 4, and reflects on the possible improvements and extensions that future researchers could have build upon.

1. The use of Multi-Objective Optimization Problem does not offer Penn State University a single optimal investment time that maximizes both the economic and environmental benefits of pursuing a particular investment in Power Purchase

Agreement. Instead, it faces a fundamental trade-off between the two objectives by postponing the investment time further to the Investment Horizon, until it reaches the time period (year) in which it receives the largest economic benefits of pursuing the PPA investment. It is not suggested to defer investment further beyond that time period.

2. If the investment decision making process of Penn State University is purely monetary value driven while using a Single-Objective Optimization Problem, and it is limited to make a single investment, then on average an immediate investment would not yield the most economical outlook.

3. If Penn State University can choose to invest in Power Purchase Agreements incrementally, then on average, it should begin the investment in the immediate future. The strategy of incremental investments also offers Penn State University higher net monetary savings comparing to limiting to only invest once. Additionally, from a monetary standpoint, even if Penn State University have the capability to sell back its excess Power Purchase as a stream of revenue, it is not suggested to do so. However, if Penn State University still possesses the naming right and claim of reduction of carbon footprint by using the Renewable Energy Certificates on its excess purchases, its preferred investment strategies would be much more complicated to evaluate.

4. By monetizing the environmental benefit of pursuing investments of Power Purchase Agreement of renewable energy projects, Penn State University is encouraged to invest much earlier than if it were to only value the economic benefits of these investments only. In the base case scenario, the shift is expected to be 15 years.

5. If Penn State University were to choose invest in the immediate future, a larger investment size on average corresponds to higher net cost, while holding everything

else constant. Also, in between the investment of a large, Utility-Scale solar farm and a large wind farm, on average, the optimal economic outlook of investing in a solar farm in the distant future is better for Penn State University. However, the investment in a portfolio of a large solar farm and a large wind farm offers Penn State University the largest net monetary saving, if it were to invest at the optimal investment time.

6. The volatility of future Wholesale Electricity Prices can significantly swing the economic outlook of pursuing the investment of a long-term, irreversible Power Purchase Agreement. On the other hand, Penn State's optimal investment decision is highly insensitive to the unit cost declination of Power Purchase Agreement that could be associated with the technical development (or lack of development) of renewable energy systems.

The modelling structure of using Multi and Single Objective Optimization Problems to determine the preferable investment strategies of Corporate Renewable Power Purchase Agreement(s) as well as the connection between these Optimization Problems with Real Option Valuation Problems established in this thesis should be able to fill some gaps in the literature. It can contribute to the academia in both the field of Multi-Objective Optimization as well as Real Option Valuation, with particular applications on the investments of renewable energy projects. Potential investors can also use the modelling structure developed in this thesis and apply on its own consideration of investment in Corporate Renewable Power Purchases. This however does not mean this research is perfect and cannot be improved upon.

Primarily, this thesis used a finite Investment Horizon that is the typical maximum length of a Power Purchase Agreement – 25 years. This produces less than ideal consideration of economic and environmental benefit for the cases where the investor decides to invest closer towards end of the Investment Horizon, and thus encouraged the investor to engage in earlier investments of Power Purchase Agreement of renewable energy projects. To make the comparison more valid, a longer period of simulation of both Wholesale Electricity Price and Marginal Emission Factor could be helpful, enabling the exploration of PPA investment strategies that are of the same length.

Additionally, by deciding to use tools including the **Binomial Lattice Pricing Model**, **Monte Carlo Simulations** and **Unit Commitment**, there have been significant simplifications that reduces the computation complexity and intractability of the model. The Motivation and Contribution of this thesis identified 6 sources of uncertainty that could complicate the modelling structure of this problem, and this thesis chose to only model the uncertainty in future Wholesale Electricity Price while essentially making the following assumptions:

- No change of Wholesale Electricity demand pattern of the investor over the period of Investment Horizon
- Deterministic decline of future cost(s) of renewable energy project(s)
- Constant Intra-year Periodical electricity production capability of renewable energy projects and no degradation over time
- No change in regional future policy regarding renewable energy project and environmental impact of generation technologies
- A linear transformation of the Marginal Emission Factors of carbon dioxide for the PJM Interconnection that is exogenous to the investor's PPA investment(s)

To reduce the number of feasible solutions, it was also assumed that Penn State University as an investor could only change its investment decision in renewable energy projects once a year and in whole number multiples of the *Standard Size*. Additionally, for the tractability of the model, the decision structure used for the incremental investments also limit the investment type and the size of increments in between time periods. Coupling these assumptions together, it implies that, in between two year, Penn State University as an investor of Power Purchase Agreement of renewable energy projects, only has the choice of making a defined incremental size of Power Purchase (while receiving a pair of deterministic economic and environmental benefits) or do nothing until the following year.

While some of the assumptions that this thesis made are more realistic than others, making these assumptions have indeed significantly reduced the complexity of the computation and modelling of these investment decision problems. However, the accuracy of these assumptions also severely impact the accuracy of the model. Therefore, a more holistic approach that encompasses more if not all of these uncertainties can help establishing a better model. This would create great opportunities for future research to build on, and producing more robust results.

Appendix A

Investor Electricity Demand and Sample Renewable Energy Power Outputs Data

This Appendix presents the electricity demand for the studied investor and power outputs for two sample renewable energy projects data as described in Chapter 3.

Table A.1: Investor Electricity Demand and *Standard Sized* Renewable Power Output Data (Summer)

Hour	Solar (MW)	Wind (MW)	Demand (MW)
1	0.00	2.23	29.94
2	0.00	2.26	28.32
3	0.00	2.30	27.47
4	0.00	2.16	27.27
Continued on next page			

Table A.1 – continued

Hour	Solar (MW)	Wind (MW)	Demand (MW)
5	0.00	2.06	27.41
6	0.00	1.85	27.20
7	0.07	1.61	28.72
8	0.41	1.40	31.01
9	1.37	1.35	33.18
10	3.22	1.43	34.82
11	5.70	1.47	37.15
12	5.32	1.54	39.13
13	5.02	1.54	39.55
14	5.68	1.67	40.91
15	5.58	1.94	41.44
16	5.55	1.97	42.10
17	3.77	1.98	41.88
18	1.28	1.85	41.16
19	1.46	1.75	38.57
20	0.48	1.87	36.48
21	0.00	1.98	35.33
22	0.00	2.13	34.31
23	0.00	2.21	33.67
24	0.00	2.27	31.69

Table A.2: Investor Electricity Demand and *Standard Sized* Renewable Power Output Data (Fall and Spring)

Hour	Solar (MW)	Wind (MW)	Demand (MW)
1	0.00	3.88	21.56
2	0.00	3.99	21.24
3	0.00	3.99	21.01
4	0.00	3.98	20.60
5	0.00	3.99	20.06
6	0.00	3.91	19.69
7	0.00	3.89	20.68
8	0.61	3.73	21.93
9	3.16	3.39	23.36
10	3.25	3.27	25.59
11	3.04	3.22	27.04
12	2.85	3.35	27.72
13	2.84	3.40	27.43
14	2.99	3.50	27.29
15	2.80	3.48	27.30
16	1.23	3.43	27.44
17	0.32	3.55	27.22
18	0.00	3.49	27.03
19	0.00	3.61	26.93
20	0.00	3.89	27.07
21	0.00	3.97	26.21

Continued on next page

Table A.2 – continued

Hour	Solar (MW)	Wind (MW)	Demand (MW)
22	0.00	3.99	25.54
23	0.00	3.94	24.75
24	0.00	3.76	22.96

Appendix B

Range and Average Unit Cost of Power Purchase Agreements of Solar Farms in 2018

This Appendix provides the range and average unit cost ($/kWh) of investment in Power Purchase Agreements with solar farms in 2018 data collected by Penn State University as described in Chapter 3.

Table B.1. Range and Average Unit Cost of Power Purchase Agreements of Solar Farms in 2018 Collected by Penn State University

Annual Power Output (10^6 kWh)	Rate Range ($/kWh)	Average Rate ($/kWh)
<20	0.03500 - 0.05050	0.04417
20 - 60	0.02945 - 0.07400	0.04197
>60	0.02975 - 0.05200	0.04167

Appendix C

Historical Wholesale Electricity Price Data

This Appendix provides the load weighted-average real-time LMP of the PJM Interconnection from 2007 to 2018 as described in Chapter 3.

Table C.1: Historical Wholesale Electricity Price

Month-Year	LMP ($/MWh)
January-2007	44.93
February-2007	72.58
March-2007	56.72
April-2007	59.07
May-2007	55.26
June-2007	61.21
July-2007	62.27
August-2007	78.87
Continued on next page	

Table C.1 – continued

Month-Year	LMP ($/MWh)
September-2007	62.23
October-2007	64.15
November-2007	56.83
December-2007	62.18
January-2008	68.79
February-2008	69.12
March-2008	70.19
April-2008	70.31
May-2008	63.87
June-2008	103.17
July-2008	97.42
August-2008	75.84
September-2008	69.74
October-2008	51.02
November-2008	52.97
December-2008	51.51
January-2009	59.69
February-2009	45.93
March-2009	41.10
April-2009	34.65
May-2009	34.04
June-2009	34.54

Continued on next page

Table C.1 – continued

Month-Year	LMP ($/MWh)
July-2009	33.26
August-2009	37.42
September-2009	30.81
October-2009	34.85
November-2009	32.64
December-2009	43.45
January-2010	54.22
February-2010	45.25
March-2010	36.74
April-2010	37.64
May-2010	43.99
June-2010	52.96
July-2010	68.41
August-2010	55.75
September-2010	44.87
October-2010	34.97
November-2010	36.58
December-2010	55.18
January-2011	52.94
February-2011	44.44
March-2011	40.53
April-2011	44.88

Continued on next page

Table C.1 – continued

Month-Year	LMP ($/MWh)
May-2011	53.08
June-2011	53.07
July-2011	62.99
August-2011	46.60
September-2011	41.01
October-2011	36.34
November-2011	34.89
December-2011	33.40
January-2012	33.44
February-2012	30.05
March-2012	29.85
April-2012	28.39
May-2012	34.58
June-2012	30.45
July-2012	50.04
August-2012	37.07
September-2012	36.20
October-2012	36.54
November-2012	40.93
December-2012	30.60
January-2013	37.22
February-2013	35.17

Continued on next page

Table C.1 – continued

Month-Year	LMP ($/MWh)
March-2013	39.82
April-2013	38.51
May-2013	39.50
June-2013	37.75
July-2013	51.62
August-2013	35.22
September-2013	41.25
October-2013	34.58
November-2013	33.61
December-2013	37.55
January-2014	126.76
February-2014	70.82
March-2014	75.90
April-2014	39.73
May-2014	44.49
June-2014	44.02
July-2014	37.87
August-2014	34.42
September-2014	36.37
October-2014	36.58
November-2014	37.90
December-2014	33.22

Continued on next page

Table C.1 – continued

Month-Year	LMP ($/MWh)
January-2015	38.42
February-2015	72.16
March-2015	42.02
April-2015	30.44
May-2015	34.09
June-2015	32.16
July-2015	34.52
August-2015	30.08
September-2015	33.31
October-2015	28.22
November-2015	26.61
December-2015	25.10
January-2016	30.43
February-2016	25.95
March-2016	22.97
April-2016	29.14
May-2016	23.96
June-2016	28.52
July-2016	32.53
August-2016	35.59
September-2016	31.26
October-2016	28.13

Continued on next page

Table C.1 – continued

Month-Year	LMP ($/MWh)
November-2016	25.79
December-2016	32.57
January-2017	32.60
February-2017	25.60
March-2017	32.30
April-2017	28.52
May-2017	31.51
June-2017	28.32
July-2017	32.90
August-2017	27.73
September-2017	33.57
October-2017	28.27
November-2017	28.75
December-2017	40.77
January-2018	83.63
February-2018	26.47
March-2018	33.13
April-2018	35.23
May-2018	38.33
June-2018	31.32
July-2018	32.95
August-2018	34.26

Continued on next page

Table C.1 – continued

Month-Year	LMP ($/MWh)
September-2018	35.14
October-2018	33.90
November-2018	33.40
December-2018	31.00

Appendix D

Projected Unit Cost of PPA of Renewable Energy Projects

This Appendix provides the base case projected unit costs ($/MWh) of Power Purchase Agreements of renewable energy projects as described in Chapter 3. Table D.1 is for solar farms, where going across each column represents a change in size (from the *Standard Size* to ten times the *Standard Size*), and going down each row represents a year of delay in the beginning of investment from present time (t = 0, Year 2018, to t = 25). Table D.2 is used for wind farms and only has one column of data as stated in Chapter 3 this a generation-weighted average value.

Table D.1. Base Case Projected Unit Cost ($/MWh) of Power Purchase Agreements of Solar Farms

t/Size	1	2	3	4	5	6	7	8	9	10
0	44.17	43.89	43.61	43.34	43.06	42.78	42.50	42.23	41.95	41.67
1	42.78	42.51	42.24	41.97	41.70	41.43	41.16	40.90	40.63	40.36
2	41.43	41.17	40.91	40.65	40.39	40.13	39.87	39.61	39.35	39.09
3	40.13	39.87	39.62	39.37	39.12	38.87	38.61	38.36	38.11	37.86
4	38.86	38.62	38.37	38.13	37.89	37.64	37.40	37.15	36.91	36.66
5	37.64	37.40	37.17	36.93	36.69	36.46	36.22	35.98	35.75	35.51
6	36.45	36.22	36.00	35.77	35.54	35.31	35.08	34.85	34.62	34.39
7	35.31	35.08	34.86	34.64	34.42	34.20	33.97	33.75	33.53	33.31
8	34.19	33.98	33.76	33.55	33.33	33.12	32.90	32.69	32.47	32.26
9	33.12	32.91	32.70	32.49	32.28	32.08	31.87	31.66	31.45	31.24
10	32.07	31.87	31.67	31.47	31.27	31.07	30.86	30.66	30.46	30.26
11	31.06	30.87	30.67	30.48	30.28	30.09	29.89	29.70	29.50	29.31
12	30.09	29.90	29.71	29.52	29.33	29.14	28.95	28.76	28.57	28.38
13	29.14	28.95	28.77	28.59	28.41	28.22	28.04	27.86	27.67	27.49
14	28.22	28.04	27.87	27.69	27.51	27.33	27.16	26.98	26.80	26.62
15	27.33	27.16	26.99	26.82	26.64	26.47	26.30	26.13	25.96	25.78
16	26.47	26.30	26.14	25.97	25.81	25.64	25.47	25.31	25.14	24.97
17	25.64	25.48	25.31	25.15	24.99	24.83	24.67	24.51	24.35	24.19
18	24.83	24.67	24.52	24.36	24.21	24.05	23.89	23.74	23.58	23.42
19	24.05	23.90	23.75	23.59	23.44	23.29	23.14	22.99	22.84	22.69
20	23.29	23.14	23.00	22.85	22.70	22.56	22.41	22.27	22.12	21.97
21	22.56	22.42	22.27	22.13	21.99	21.85	22.71	21.56	21.42	21.28
22	21.85	21.71	21.57	21.43	21.30	21.16	21.02	20.88	20.75	20.61
23	21.16	21.03	20.89	20.76	20.63	20.49	20.36	20.23	20.09	19.96
24	20.49	20.36	20.23	20.11	19.98	19.85	19.72	19.59	19.46	19.33
25	19.85	19.72	19.60	19.47	19.35	19.22	19.10	18.97	18.85	18.72

Table D.2. Base Case Projected Unit Cost ($/MWh) of Power Purchase Agreements of Wind Farms

Investment Time (Years from $t = 0$, 2018)	Unit Cost ($/MWh)
0	48.82
1	46.85
2	46.61
3	45.74
4	44.86
5	44.04
6	43.27
7	42.53
8	41.80
9	41.10
10	40.42
11	39.78
12	39.16
13	38.82
14	38.31
15	37.78
16	37.49
17	36.90
18	36.68
19	32.62
20	31.00
21	29.45
22	28.63
23	28.26
24	28.04
25	26.67

Appendix E

Historical Carbon Dioxide MEF Data

This Appendix provides the data related to historical carbon dioxide Marginal Emission Factor Data from PJM Interconnection's reports, as described in Chapter 3. Table E.1 is the actual MEF data, Table E.2 is the number of hours in On-Peak and Off-Peak periods of each months.

Table E.1. PJM Historical MEF Data

CO2 (lbs/MWh)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2012 On-Peak	1338	1341	1460	1286	1531	1479	1581	1449	1520	1698	1745	1769
2012 Off-Peak	1281	1303	1315	1208	1453	1262	1353	1217	1391	1614	1695	1678
2013 On-Peak	1619	1648	1696	1455	1520	1666	1708	1817	1686	1716	1539	1798
2013 Off-Peak	1752	1722	1704	1606	1658	1655	1652	1670	1766	1723	1703	1777
2014 On-Peak	1548	1439	1453	1522	1636	1729	1740	1690	1750	1692	1721	1810
2014 Off-Peak	1664	1602	1627	1650	1671	1691	1608	1630	1682	1861	1848	1944
2015 On-Peak	1728	1564	1578	1673	1775	1729	1654	1745	1643	1575	1547	1549
2015 Off-Peak	1826	1606	1587	1540	1670	1463	1505	1522	1524	1414	1441	1366
2016 On-Peak	1617	1632	1696	1692	1669	1604	1711	1799	1814	1373	1660	1616
2016 Off-Peak	1520	1505	1600	1537	1563	1381	1572	1679	1618	1495	1364	1643
2017 On-Peak	1292	1396	1187	1426	1318	1308	1480	1467	1514	1412	1308	1381
2017 Off-Peak	1588	1428	1255	1363	1340	1192	1340	1347	1277	1480	1439	1444
2018 On-Peak	1319	1362	1334	1394	1251	1350	1454	1407	1360	1397	1215	1199
2018 Off-Peak	1328	1285	1344	1302	1160	1232	1302	1335	1216	1219	1124	1202

Table E.2. Number of Hours in On-Peak and Off-Peak Periods of Each Months

Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2012 On-Peak	336	336	352	336	352	336	336	368	304	368	336	320
2012 Off-Peak	408	360	391	384	392	384	408	376	416	376	385	424
2013 On-Peak	352	320	336	352	352	320	352	352	320	368	320	336
2013 Off-Peak	392	352	407	368	392	400	392	392	400	376	401	408
2014 On-Peak	352	320	336	352	336	336	352	336	336	368	304	352
2014 Off-Peak	392	352	407	368	408	384	392	408	384	376	417	392
2015 On-Peak	336	320	352	352	320	352	368	336	336	352	320	352
2015 Off-Peak	408	352	391	368	424	368	376	408	384	392	401	392
2016 On-Peak	320	336	368	336	336	352	320	368	336	336	336	336
2016 Off-Peak	424	360	375	384	408	368	424	376	384	408	385	408
2017 On-Peak	336	320	368	320	352	352	320	368	320	352	336	320
2017 Off-Peak	408	352	375	400	392	368	424	376	400	392	385	424
2018 On-Peak	352	320	352	336	352	336	336	368	304	368	336	320
2018 Off-Peak	392	352	391	384	392	384	408	376	416	376	385	424

Appendix F

Unit Commitment Problem Formulation

This Appendix presents the Mixed-Integer Linear Programming (MIP) formulation of the Unit Commitment problem that is described in Chapters 2 and 3 of the thesis. Unless stated otherwise, in the nomenclature, the use of subscript j indicates the value is time dependent, and the use of subscript g indicates the value is generation technology dependent. When g is used in combined with c or r limits the generation technologies only to a particular subset of all of the generation technologies as described below.

F.1 Nomenclature

F.1.1 Indices and Sets/Subsets

$j \in J$	Demand Blocks, 1, 2, 3 …23, 24 [hr]
$g \in G$	All generation technology types

$g \in CG$	Conventionally dispatchable generation technology types
$g \in RG$	Intermittent renewable generation technology types

F.1.2 Parameters

K_g	Projected installed capacity [MW]
FP_g	Projected Fuel Prices [$/MMBTU]
HR_g	Heat Rate [BTU/kWh]
VOM_g	Projected Variable Operation and Maintenance cost [$/MWh]
$Pmin_{cg}$	Minimum power output [%]
R_{cg}	Ramp rate [%/min]
$UTmin_g$	Minimum up-time [hr]
$SU_{fixed,g}$	Fixed start-up cost [$/MW]
$SU_{fuel,g}$	Start-up fuel requirements [MMBTU/MW]
SRR	Spinning Reserve requirements fraction of PJM [10%]
SC	Unit cost of shedding renewable energy generation [$/MWh]
$NetDem_j$	Net load (excluded renewable generation) [MW]
SR_j	Hourly Spinning Reserve Requirement ($SRR \times NetDem_j$) [MW]
$OpCost_g$	Variable cost of generation ($FP_g \times HR_g/1000 + VOM_g$) [$/MWh]
$Avail_{rg,j}$	hourly capacity factor of renewable gen. tech. of PJM in hour j

F.1.3 Variables

$vTotalCost$	Total system cost of serving electricity in PJM [$]
$vStartCost$	Cost of starting up electricity generation type(s) in PJM [$]

$vGenCost$	Cost of generating electricity in PJM [$]
$vPenaltyCost$	Cost(Penalty) of shedding renewable energy generation in PJM [$]
$x(g,j)$	Power output of generation technology g in demand block j [MW]
$vUp(cg,j)$	Whether gen. tech. cg turns on starting in demand block j
$vDown(cg,j)$	Whether gen. tech. cg turns off starting in demand block j
$Aux(g,j)$	Power output of gen. tech. g in hour j beyond its min. load [MW]
$vShed(j)$	Hourly shedded renewable energy generation [MW]
$vU(cg,j)$	Whether gen. tech. cg is ON in demand block j (binary) [0,1]

F.2 Equations and Explanations

F.2.1 Equations

$$\min_{x,vUp,vDown,Aux,vShed,vU} vTotalCost = vStartCost + vGenCost + vPenaltyCost \tag{eObjFun}$$

s.t.

$$vStartCost = \sum_{j=1}^{24}\sum_{g=1}^{6} vUp(cg,t) \times K_{cg} \times (SU_{fixed,cg} + SU_{fuel,cg} \times FP_{cg}) \tag{eStartCost}$$

$$vGenCost = \sum_{j=1}^{24}\sum_{g=1}^{6} x(cg,t) \times OpCost_{cg} \tag{eGenCost}$$

$$vPenaltyCost = \sum_{j=1}^{24} vShed(j) \times ShedCost \qquad \text{(ePenaltyCost)}$$

$$x(cg, j) \leq K_{cg} \times vU(cg, j) \qquad \text{(ePmax)}$$

$$x(cg, j) \geq K_{cg} \times vU(cg, j) \times Pmin_{cg} \qquad \text{(ePmin)}$$

$$\sum_{g=1}^{6} x(cg, j) = NetDem_j \qquad \text{(eDemand)}$$

$$vU(cg, j) \leq vU(cg, j-1) + vUp(cg, j) - vDown(cg, j) \qquad \text{(eState)}$$

$$Aux(cg, j) - Aux(cg, j-1) \leq 60 \times R_{cg} \times K_{cg} \qquad \text{(eRampUp)}$$

$$Aux(cg, j-1) - Aux(cg, j) \leq 60 \times R_{cg} \times K_{cg} \qquad \text{(eRampDown)}$$

$$x(cg, j) = Aux(cg, t) + vU(cg, j) \times Pmin_{cg} \times K_{cg} \qquad \text{(eAux)}$$

$$SR_j \geq \sum_{g=1}^{9} vU(g,j) \times K_g - x(g,j) \tag{eSpinReserve}$$

$$vU(cg,j) \geq \sum_{i=t-UTmin_{cg}}^{j} vUp(cg,j) \tag{eMinUp}$$

$$1 - vU(cg,j) \geq \sum_{i=t-UTmin_{cg}}^{j} vDown(cg,j) \tag{eMinDown}$$

$$x(rg,j) = K(rg,j) \times Avail_{rg,j} \tag{eRenewable}$$

F.2.2 Explanations of Equations

- **eObjFun**: This is the overall Objective Function. The objective is to minimize the total system cost of serving electricity in PJM, which is the sum of start-up costs, electricity generation costs, and penalty costs.
- **eStartCost**: The start-up costs consist of both the fixed cost to start using a particular generation technology, and the corresponding fuel costs to start them up.
- **eGenCost**: The electricity generation cost sums across all conventionally dispatchable generation technologies (six types, including Biomass, Coal, NGCC, NGCT, Nuclear, and Steam) in all demand blocks.
- **ePenaltyCost**: The penalty cost serves to penalize when the electricity production of intermittent renewable generation technologies has to be shed.
- **ePmax**: Conventionally dispatchable generation technologies cannot produce more

electricity than its installed capacity.

- **ePmin**: Conventionally dispatchable generation technologies has to produce electricity at a level above than its minimum load.

- **eDemand**: The total electricity production of conventionally dispatchable generation technologies in each demand block has to fulfil the net load of PJM, i.e. the electricity demand after accounting for electricity production from intermittent renewable generation technologies.

- **eState**: In each demand block, the generation technologies has to be either producing electricity (committed and on) or not (off). If it is on, it cannot be turned on in the hour. If it is off, it cannot be turned off in the hour. It has the freedom to adjust in between on and off, if other requirements are being met, such as ramping constraints described below.

- **eRampUp**: If the generation technology(ies) is(are) increasing output level(s) in between hours, it must be within a reasonable range dictated by one of its fuel characteristic — ramp rate. The ramp rate of nuclear units is very low and much higher for natural gas based units, including natural gas combined cycle and combustion turbines (NGCC and NGCT).

- **eRampDown**: This equation is the opposite case to the last equation where this equation accounts for generation technology(ies) decreasing output level(s) in between hours.

- **eAux**: This auxiliary equation is to ensure consitency in the electricity production level in conventionally dispatchable generation technologies.

- **eSpinReserve**: This equation is used to ensure there is enough Spinning Reserve within the PJM Interconnection, i.e., there would not be a sudden shortage of electricity if the demand were to spike up between demand blocks.

- **eMinUp**: Certain conventionally dispatchable generation technologies such as Nuclear and Coal are only feasible to operate (up) for a minimum number of hours before deciding to turn off (and then operate again later).

- **eMinDown**: This equation is the counter to the last equation where conventionally dispatchable generation technologies such as Nuclear and Coal are only feasible to turn off (down) for a minimum number of hours before deciding to operate again later.

- **eRenewable**: This equation is a simplified approach to account for renewable energy generation in PJM, by using the product of (a) installed capacity (projected) of intermittent renewable generation technologies and (2) historical hourly availability of renewable energy generation technologies, in representative sample days and hours (demand blocks).

Appendix G

Projected MEF Evolution

This Appendix provides the projected carbon dioxide MEF evolution until the end of Investment Horizon as described in Chapter 3.

Table G.1. Projected Carbon Dioxide MEF Evolution

Year in Investment Horizon	Year	Summer (Ton/MWh)	Fall and Spring (Ton/MWh)
0	2018	0.609	0.577
1	2019	0.605	0.575
2	2020	0.601	0.572
3	2021	0.597	0.569
4	2022	0.593	0.567
5	2023	0.589	0.564
6	2024	0.585	0.561
7	2025	0.581	0.559
8	2026	0.577	0.556
9	2027	0.573	0.553
10	2028	0.568	0.551
11	2029	0.564	0.548
12	2030	0.560	0.545
13	2031	0.556	0.542
14	2032	0.552	0.540
15	2033	0.548	0.537
16	2034	0.544	0.534
17	2035	0.540	0.532
18	2036	0.536	0.529
19	2037	0.532	0.526
20	2038	0.528	0.524
21	2039	0.524	0.521
22	2040	0.520	0.518
23	2041	0.516	0.516
24	2042	0.512	0.513
25	2043	0.508	0.508

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