GRIDSIM: A FLEXIBLE SIMULATOR FOR GRID INTEGRATION STUDY

by

Suresh Rathnaraj Chelladurai

B.Tech, Anna University, India, 2012

THESIS SUBMITTED IN PARTIAL FULFILMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

COMPUTER SCIENCE

UNIVERSITY OF NORTHERN BRITISH COLUMBIA

November 2016

Abstract

Global warming and the increasing cost of fossil fuels have driven researchers to focus on renewable and cleaner sources of energy like wind, water, and solar. These energy sources show promise for sustainability and reduced greenhouse gas emissions, the only disadvantage of them is that they are intermittent and currently expensive. Measuring the impact of integrating new energy sources into an existing grid system is not feasible. Therefore, Modeling and Simulation becomes an indispensable approach. Several tools exist for modeling and simulation of the power grid. They primarily focus on analyzing smart grids and are complex to use for integration studies. Designing and implementing software that allows the users to model and simulate power grid system for integration study is the primary motivation of this thesis. We propose, GridSim, an easy, intuitive software to perform grid integration analysis and its use is illustrated through case studies.

Dedicated to my Mom, Dad and Lucille

Acknowledgements

Start by doing what's necessary; then do what's possible; and suddenly you are doing the impossible

Francis of Assisi.

Throughout my time as a graduate student in Prince George, many people have supported me in one way or another. I would like to thank them all.

First and utmost, I would like to express my special appreciation to my supervisor, Dr. Alex Aravind. Thank you for providing me with so much support - personally, academically and financially. In particular, I would like to thank you for encouraging my research throughout the different directions it has taken. I would like to thank my committee members Dr. Matthew Reid and Dr. Iliya Bluskov for their valuable time and for serving as my committee members. I would like to thank the external examiner and the chair of my defense for reading my thesis. Special thanks to Dr.Maheshwari Aravind, Dr. Ajit Dayanandan, Shamitha Aravind and Harsha Aravind for making me feel at home during my initial stay in Canada. Special thanks to Dr. Anita Chelliah for proof reading by thesis.

I would like to thank my friends and family members. My cousin Murugalakshmi for providing me emotional support and encouragement during difficult times. Special thanks to my friends Shanthini Rajendran, Dorob Wali Ahmad, Raja Gunaskeran, Aarthi Babu and Praveen Kumar for providing me with delicious food, great advices and helping me in every aspect of personal and grad life.

I owe my deepest thanks to Lucille Williams for making me feel at home and treating me like her son. My dad and mom for financial support.Also, my brother for encouraging me to apply to UNBC.

Contents

List of Figures

List of Tables

Acronyms

AC Alternating Current.

ACGT Advanced Combined Cycle Gas Turbine.

AMQP Advanced Message Queuing Protocol.

API Application Programming Interface.

BC British Columbia.

BES Bulk Energy Storage.

CAES Compressed Air Energy Storage.

CCGT Conventional Combined Cycle Gas Turbine.

CO_2 Carbon Dioxide.

DC Direct Current.

EIA Energy Information Administration.

FOM Fixed Operation and Maintenance Cost.

GHG Greenhouse Gas.

GWP Global Warming Potential.

HVDC High Voltage Direct Current transmission lines.

JMS Java Messaging Service.

JSON Javascript Object Notation.

kW Kilowatt (10^3 watts).

kWh Kilowatt-hour.

LCOE Levelized Cost of Electricity.

MW Megawatt (10^6 watts).

MWh Megawatt-hour.

NoSQL Not Only Structured Query Language.

PHES Pumped Hydro Energy Storage.

RE Renewable Energy.

SQL Structured Query Language.

$\mathbf{T}_e$ Total Energy.

TN Tamil Nadu.

V2G Vehicle to Grid.

VOM Variable Operation and Maintenance Cost.

WWS Wind, Water and Solar.

Publications from this thesis

[1] S. Rajendran, S. R. Chelladurai, and A. Aravind, "An adaptive road traffic regulation with simulation and internet of things," in *Proceedings of the 2016 Annual ACM Conference on SIGSIM Principles of Advanced Discrete Simulation*, ser. SIGSIM-PADS '16. New York, NY, USA: ACM, 2016, pp. 3–11. [Online]. Available: http://doi.acm.org/10.1145/2901378.2901406

[2] S. R. Chelladurai and A. Aravind, "A simple forecast analytics of future greenhouse gas emissions for British Columbia and Tamil Nadu," in Proceedings of the Fourth International Conference on Business Analytics and Intelligence, 2016.

Chapter 1

Introduction

The contribution of this thesis is related to the simulation of power grid systems [1]. In this chapter, we first provide the background for the work presented in this thesis by discussing the future energy trends, existing power grid system and research trends. We also describe the statement and motivation behind our work. Next, we outline the key contribution of our research. Finally, a roadmap of the thesis is presented.

1.1 Future Energy Trends

In the last several decades, worldwide energy consumption has grown tremendously. Looking at the history, electricity went from a novelty to a necessity due to modernization and electrification. The Energy Information Administration (EIA) predicted that the world energy consumption would increase by 1.4 % per year between 2012 and 2040. Although the power consumption increase per year appears small, if compounded, it will cause the energy consumption increase of 48 % from 2012

[1] This work has a brief history. The original idea of building a flexible smart grid simulation system for various prediction studies and data analytics was conceived by Dr. Alex Aravind in the early 2008 and he started building the system with the help of an undergraduate student Nic Waller in 2009 [16]. Then, it was continued to the next stage later in 2011 by a Master's student Viswanathan Manickam. My thesis work started from this stage.

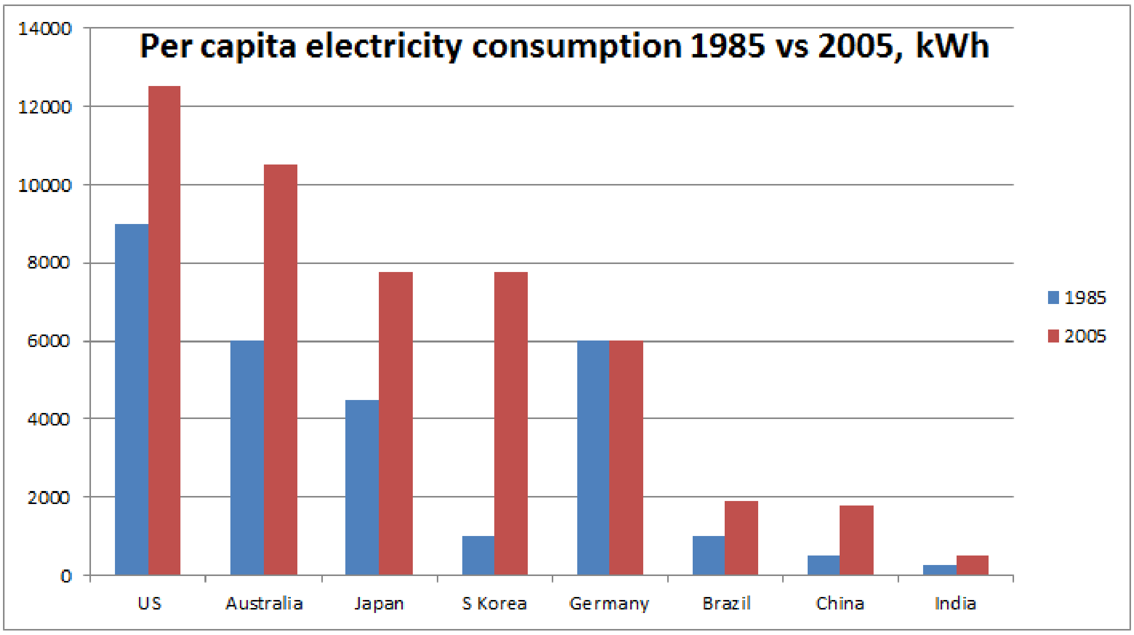

Figure 1.1: Per capita electricity consumption in kWh. Galvin Electricity Initiative 2007. [1]

to 2040 [17]. In our view, based on the worldwide energy consumption of the recent past, this is a conservative estimate, and it could be much higher. The reason for the increase in energy consumption can be attributed mainly to population growth and per capita electricity consumption. The per capita electricity consumption is shown in Figure 1.1.

In developed countries like the US, Australia, and Japan the per capita electricity consumption is relatively high when compared to developing countries like China and India. This can be attributed to a sophisticated lifestyle, including the use of television, personal computers, and electric vehicles. Developing countries like China and India have greater growth in per capita energy consumption mainly due to industrialization. Also per capita, by its definition, includes the population of the country. A small increase in per capita energy consumption has a great impact on the total energy consumed for densely populated countries. It is very likely that the developing countries like China and India will be the largest consumer of electricity in a few years from now. The estimated future growth trend is shown in Table 1.1.

Category	1950	2000	2050(est.)
World Population	2.6 B	6.2 B	8.3 B
Electricity as % total energy	10.4%	25.3%	33.7 %
Cell Phone Connections (USA)	0	0.8B	5B
Electric hybrid vehicles	0	55,800	3M

Table 1.1: Example of future growth trends [1]

The estimated population growth is 8.3 billion in the year 2050 and the increasing per capita energy demand will drastically increase the total energy consumed. The number of electric vehicles is estimated to grow to 3 million. However, this estimate is likely to be low as electric vehicles are already popular in the consumer market. The number of cell phone connections is calculated only for the USA, but for developing countries like India, it is likely to be higher. The number of personal computers is projected to increase to 8 billion, but there is a high probability that smartphones and tablets will replace personal computers.

1.2 Existing Power Grid System

The power grid is a complex engineering system created by humans. The power grid system is responsible for generation, transmission, distribution, and management of electrical energy. Figure 1.2 provides a simplified overview of an electrical grid with critical subsystems.

A generating station generates electrical energy from fuel (for example, a coal-fired power plant uses coal as its fuel) or other energy sources. The electrical energy generated is transmitted as electrical current at a specific voltage. The voltage needs to be stepped up to a higher voltage using “Step Up” transformers to reduce power loss before being transmitted over a long distance. At the consumer end, the voltage is stepped down using a “Step Down” transformer. This is a simple overview of the electrical power grid system. A detailed discussion can be found in [18] .

The current grid system works on a pull model where the demand controls the production of electrical energy. The electrical grid adapts to the user demand by producing more or less electrical energy. For example, a power plant might produce 100 units of electrical energy while the user demand is only 95 units. The Alternating Current (AC) frequency will become higher than the nominal frequency of 60 Hz. This change in frequency of the electrical grid will be sensed by the control systems in the power plant and cause the power plant to reduce its generation of electrical energy. Failure to match the user demand will cause the frequency of the grid system to change causing a power outage. The process of matching the consumer's power demand is a complex optimization problem, which has been studied in detail in [19], [20], [21].

1.3 Existing Energy Sources

Current power generation is still dominated by fossil fuels (oil and coal), as shown in Figure 1.3.

The early dominance of fossil fuel was mainly due to economic reasons as fossil fuels were cheaper to extract. It is estimated that the coal reserve can last up to 150 years with the current consumption rate [22]. Researchers did not study the serious impact of burning fossil fuel until early 1900's. Only when Svante Arrhenius and Thomas Chamberlin discovered that the burning of fossil fuel would cause an increase in greenhouse gases concentration in the Earth's atmosphere did people realize the need for Renewable Energy (RE). From then on, people have slowly started looking for renewable sources of energy. Although there was a steady increase in the use of RE sources from 1988 to 2014, its percentage contribution to total energy requirements is relatively constant due to increasing energy consumption.

1.4 Need for more Renewable Energy

With increasing energy needs, relying on fossil fuels as a primary energy source becomes a serious issue. Fossil fuels are becoming more expensive to extract and

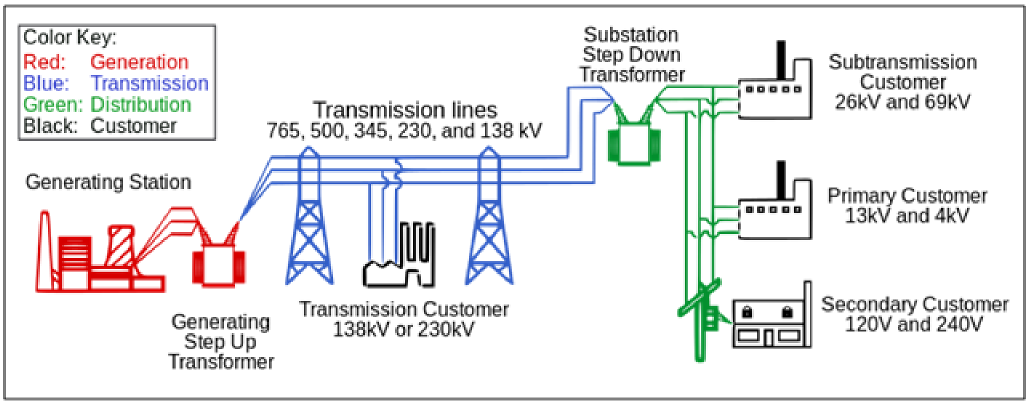

Figure 1.2: Current power grid system [2]

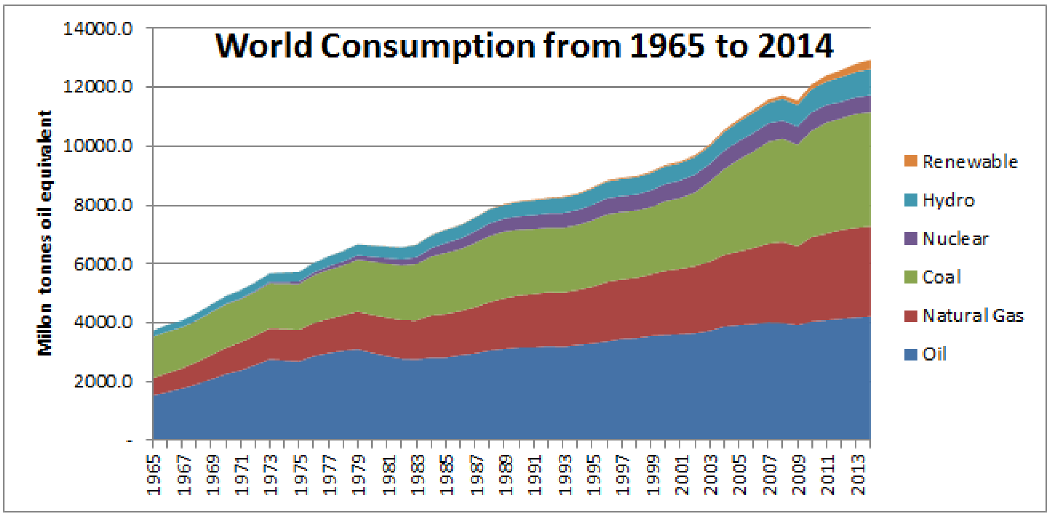

Figure 1.3: Energy source contributions to total energy (Million tonnes oil equivalent) [3]

are fast depleting. The burning of fossil fuels for producing electrical energy has caused an increase in emission of Greenhouse Gas (GHG). Since the beginning of the industrial revolution, the world Carbon Dioxide (CO_2) grew 800-fold, causing the world temperature to rise by 0.8 °C on average [23]. The increase in global temperature has caused polar ice caps to melt and the water level of oceans to rise. The need for reducing carbon emission by using RE for power generation is discussed in [24]. Studies performed by researchers on carbon abatement estimate that 170 megatons of CO_2 can be avoided by using wind and solar power in the United States [25]. Jacobson and Master estimate that 60% of the energy generated from coal can be replaced with wind power to meet the Kyoto Protocol greenhouse target [26].

Since the wind and solar energy farms can be distributed, it can also help to prevent blackouts. Suppose there are 1000 wind farms each of 1 MW capacity. A single power plant failure in this case will only cause a loss of 1MW. Compare that to the case of a nuclear power station producing 1 GW. Small scale integration of RE can be done with existing infrastructure by treating them as load modifiers [27]. As the penetration capacity of RE increases, additional infrastructure for load balancing like energy bulk storage is necessary, incurring extra costs. Also, RE, due to their variability (change in power production due to climatic conditions), does not provide frequency support to maintain the grid stability and is still an open area for research [28]. Several barriers have prevented RE from becoming a mainstream energy source. These barriers include technological limitation, economic infeasibility, and other social and environmental issues. A survey and detailed analysis of barriers to RE are presented in [29].

1.5 Energy Research Trend

The increase of energy needs and our necessity to meet the demands have caused many researchers to look into new methods to meet future energy challenges [30]. Active research is being done related to various aspects (production, transmission, and consumption) of the aging power grid. Researchers from several fields like electrical engineering, power engineering, information technology, electronics, mathematics and other fields are working in synergy to improve the existing electricity grid system.

1.5.1 Large Scale Power Production Trend

In response to the concerns discussed, researchers are looking for sustainable renewable technologies like photovoltaic solar cells, windmills, wave and tidal power. The variable speed wind turbines improved photovoltaic cells, and other advancements show great potential for making these technologies the primary energy producers. A survey of these technological improvements is provided in [30]. Due to the technical advancement of transmission lines like High Voltage Direct Current transmission lines (HVDC) [31], the large scale power plants are moving towards offshore locations like oceans. HVDC offers lower power loss, less frequency control and other great benefits as described in [32]. Although HVDC has great potential, it has a lot of complexities when compared to AC transmission lines [32]. Alternative energy sources provide a great potential, but they are not reliable energy sources since the energy produced is directly related to the climatic condition.

1.5.2 Storage Technology

Incorporating intermittent energy sources like Wind, Water and Solar (WWS) requires technological advancement in energy storage technology. Currently, Pumped Hydro Energy Storage (PHES) is the only economically feasible energy storage that is used to store excess electrical energy. USA and Japan have the highest capacity of installed PHES system. USA has a capacity of 21,886 MW, but it only attributes to 2.1 % of the total generating capacity. PHES is resource intensive and to be installed, specifically requires a difference in elevation as its georphical conditions [33]. Bulk Energy Storage (BES) systems, which can store huge amount of electrical energy are also researched to increase the penetration of WWS energy source [34] [35] [36] [37]. There has been a significant increase in the research and development of batteries such as lead acid, lithium, nickel, redox-flow, sodium-sulfur, etc., that support large-scale grid integration. Each battery type has their advantages and limitations. Detailed study of various battery technology for storing large about of energy is performed in [38].

With the increase in the number of electrical vehicles, Vehicle to Grid (V2G) technologies is also researched for providing storage of excess energy that is generated during non-peak load [39]. A detailed study of V2G integration is described in [40]. Although V2G looks promising, it becomes feasible only after the current storage technology of batteries are improved to allow repeated charge and discharge of electrical energy with higher efficiency [41].

1.5.3 Consumer Technology and Distributed Generation

Amalgamation of informatics with other fields led to a growing trend towards intelligent energy consumption and distributed small-scale power generation called smart grids [42]. A smart grid can be defined as a power grid system in which there is a two-way information flow between the power producer and the consumer that can be used to make intelligent decisions and provide reliability, resilience, efficiency, and sustainability [43].

1.6 Atmosphere and Greenhouse Gases

In this section, we briefly describe the gases that cause global warming and the mechanism of global warming. We also discuss on the trend of CO_2 over the past few years.

1.6.1 Atmosphere and Gases

Our planet is surrounded by a layer made up of gases called the atmosphere. The atmosphere is made up of various gases like O_3,CO_2,O_2, CH_4 and N_2O. The sunlight (energy/heat) which consists of infrared radiation of higher frequency can penetrate the atmosphere. The earth, after getting heated up by the infrared radiation, starts emitting infrared radiation of lower frequency. The gases like CO_2, CH_4, and N_2O

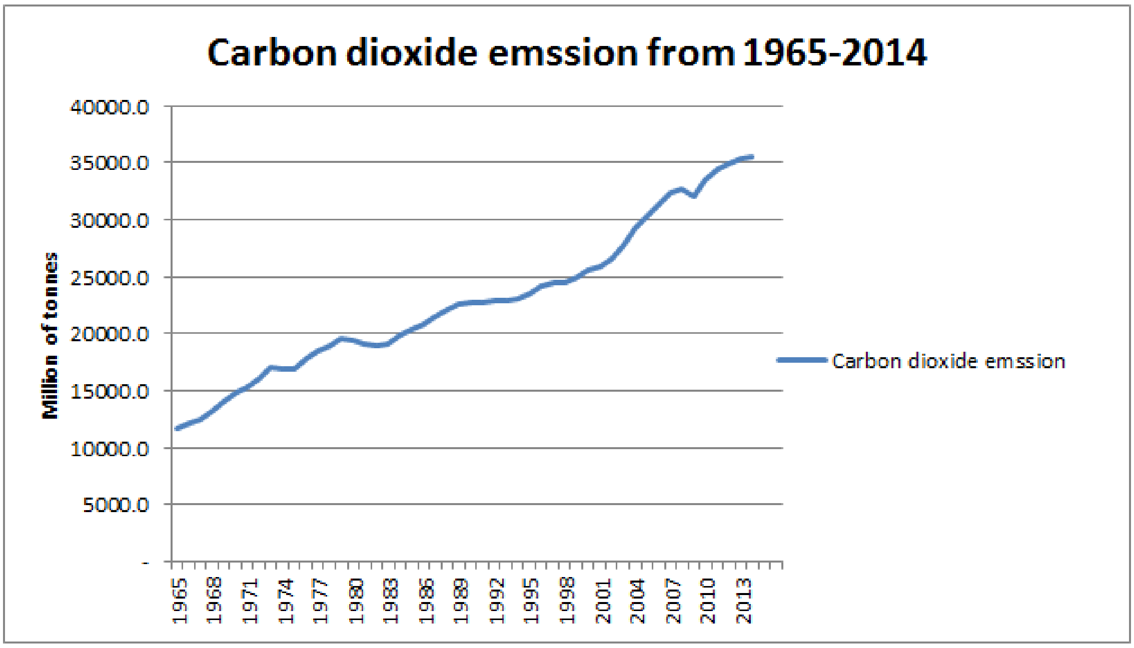

Figure 1.4: CO_2 Emissions trend 1965-2014 [3]

in the atmosphere trap this radiation which cause further heating. The activity of humans has resulted in the increase of CO_2 present in the atmosphere.

1.6.2 Greenhouse gas emission trends

Although there is an urgent need to decrease GHG emission, the average rate of increase of GHG was 0.4 percent per year from 1965 to 2014. Between 2012 and 2013, these emissions increased by 2.6 percent, which is the equivalent of 131.7 Million Metric Tonnes (MMT) of CO_2. [44]. The carbon emission trend from 1965 to 2014 is shown in Figure 1.4. The rate of increase in CO_2 has decreased from 2010 to 2014 due to technological advancement in the electrical power grid system. Increased awareness of consumers about global warming is also a key contributing factor. However, the increase in population and per capita energy consumption will not allow the trend to continue.

1.7 Motivation

Evidence of increased natural calamities due to global warming stresses the urgent need to reduce carbon emissions by integrating RE sources. However, integrating RE sources in the existing power grid is complex. Also, RE sources may not eliminate the carbon emissions completely as there are carbon emissions involved in designing, constructing, and maintaining RE sources. For example, the economic and carbon cost of building a windmill may outweigh their benefits. Some of the "big questions" that we need to answer before tackling the problem of integrating RE sources are:

- What policies should the government support for meeting future energy demand in a sustainable manner?
- Should companies focus research on particular RE technology to reduce carbon emission?
- What will be the amount of GHG emissions if the additional energy requirement is met with current energy power sources?
- How much battery storage is needed to integrate RE?
- What will be the reduction in GHG emissions if 80 % of the world energy is met with RE. Is zero carbon emission possible?
- Will the global grid [45], a vision of creating interconnection of all the electricity grid networks meet the future energy demands?
- Can RE meet 100 % of energy demand?

Constructing a real system to answer these questions is not feasible. We need a simulator that can help users to design various scenarios and measure their characteristics. The answers to the above questions can be inferred by the measured characteristics. For example, let us try to answer the specific question of policy making for reducing carbon emission. Suppose a government wants to decide to provide a subsidy for its citizens either for installing a solar panel or buying smart electronics which can schedule their energy consumption, what would be the best decision for the government? Factors such as availability of technology, the cost of technology come into play in making such a decision. Performing such analysis requires a modeling and simulation framework/tool that can simulate all the factors. The output from the computer modeling and simulation can be used to infer the answer to this question.

Computer modeling is a processes of representing a real-world entity (e.g. car, chemical, human being, etc.) into a digital prototype. During modeling entities of the system can be combined into a single entity for easier implementation. For example, a thermal power plant consists of several components like a turbine, coolant plant and boilers but it can be modeled/abstracted as a single entity. This is a valid approach as long as the abstraction provided by the model is sufficient enough for studying the system under examination [46], [47], [48].

Simulation is the imitation of real-world processes over time through a suitable model [49]. For example in vehicular simulation, the models/entities are the cars, roads, traffic lights, etc., and the simulation helps us to study the interaction of various models. Simulation modeling is used to:

- Learn about the behavior of a system without actually testing it in real life.
- Compress a longer time frame into a smaller time frame [50].
- Form predictions on future systems which are still under development.
- Perform "what-if" analysis on existing system.
- As a pedagogical tool for understanding the interaction of models.

The primary objective of this thesis is to develop a simulation software that can be used to answer questions similar to the ones listed above. Although there are various power grid simulation tools available (discussed in Chapter 2), in our view, they are not sufficiently suitable to answer these questions.

The thesis has two main contributions.

- **Simulation Software:** Develop a simulation software specialized for performing grid integration studies and its impact. We refer to this software framework as **GridSim**, and it will provide necessary support to integrate with time series data which can be provided by the sensors. It will also support advanced data analysis.
- **Simulation Library:** Various grid components are modeled and implemented as separate modules. These modules are provided in the form of a library and can be easily extended by adding new features.

1.8 Thesis Organization

The rest of thesis is structured as follows: Chapter 2 provides some background information about related work on grid simulation tools and grid integration studies. After discussing goals and design aspects of GridSim in Chapter 3, details about modeling of the grid system is given in Chapter 4. Design and implementation of GridSim is given in Chapter 5. In Chapter 6, we assess different scenarios of grid integration and decarbonization strategies. Finally, in Chapter 7, we conclude the thesis and provide future directions to extend the work carried out in this thesis.

Chapter 2

Related Work

In this chapter, we will discuss grid integration studies in detail. We then provide a classification of the available grid simulation tools based on their purpose and usage. We compare GridSim to the other available simulation tools and provide the necessary background for this research.

2.1 Grid Integration Study

Grid integration study is a methodology for evaluating the integration of renewable energy sources like wind and solar into the power grid. For example, if the government decides to replace the existing conventional power plant with renewable energy like wind turbines, what will be the impact on GHG emissions and cost? The integration is not simple since the study has to consider various aspects such as the wind variability, availability, cost, etc. Grid integration study provides a framework for performing such analysis.

Hart, Stoutenbyrg, and Jacobson have classified analytical methods for grid integration into three categories viz. [4],

1. Zeroth-order analysis - which provides information about the mean resource quality

2. First-order analysis - which helps to study resource variability

3. Second-order analysis- which considers uncertainty associated with variability

Figure 2.1 gives an overview of various integration classes available and the type of analysis that can be performed.

Class	Resource Characteristic (s)	Relevant Data	Types of Analyses
0^{th} Order	Resource quality	Annual or seasonal means	Resource atlases Regional power density analysis Small plant siting
1^{st} Order	Resource quality Resource variability	Time series data	Large plant siting Hybrid system planning
2^{nd} Order	Resource quality Resource variability Forecast uncertainty	Time series data Forecasts and uncertainties	Reliability studies Capacity credit determination Intermittency cost analysis Carbon abatement analysis

Figure 2.1: Framework for classifying grid integration [4]

2.1.1 Zeroth-order Analysis

In Zeroth-order analysis, the relevant data required for performing the analysis is the long-term average measures of resource quality. These are simple analyses over a large area and only require limited data. This type of analysis is very useful in estimating the energy density of the area. Zero order wind assessment for wind integration includes mean annual wind speed characterized into classes as shown in Figure 2.2. The power density $\overline{P}$ can be calculated using the formula shown in Equation 2.1 [51], where ρ is the air density and υ is the annual average wind speed.

$$\overline{P} = \frac{3}{\pi}\rho\bar{\upsilon}^3 \tag{2.1}$$

Wind Class	Annual Mean Wind Speeds (10m)	Annual Mean Wind Speeds (80m)
1	$v < 4.4$m/s	$v < 5.9$m/s
2	4.4m/s $\leq v <$ 5.1m/s	5.9m/s $\leq v <$ 6.9m/s
3	5.1m/s $\leq v <$ 5.6m/s	6.9m/s $\leq v <$ 7.5m/s
4	5.6m/s $\leq v <$ 6.0m/s	7.5m/s $\leq v <$ 8.1m/s
5	6.0m/s $\leq v <$ 6.4m/s	8.1m/s $\leq v <$ 8.6m/s
6	6.4m/s $\leq v <$ 7.0m/s	8.6m/s $\leq v <$ 9.4m/s
7	$v \geq 7.0$m/s	$v \geq 9.4$m/s

Figure 2.2: Wind class classification [4]

Zeroth order solar assessment considers the annual average solar isolation, a measure of the irradiance(I) integrated over a specific period, mostly a period of 24 hrs. It is measured in kWh/m^2. We can measure the amount of energy that can be produced by a solar power plant with equation 2.2 [51], where A is the area of solar panel in m^2 and $\bar{\eta}$ is the efficiency of the solar panel which can vary depending on the material used to build the solar panel. The Total Energy (T_e) can be calculated as follows:

$$T_e = IA.\bar{\eta} \tag{2.2}$$

Zeroth order RE integration does not consider the variability and uncertainty aspects of the source but provides a rough estimate of the energy capacity.

2.1.2 First-order Analysis

First order analysis considers resource variability and requires site-specific time series data. This type of analysis can be used to perform time-synchronized load balancing between producer and consumer. This analysis also takes into account ramp-up time, i.e., the time required to start an RE source and make its power available to consumers. Gas turbine units have the lowest ramp up time and can be used to match up with peak demands. This analysis does not include the uncertainty associated with variability.

2.1.3 Second-order Analysis

Second order analysis can provide additional insight by taking into account the uncertainty associated with RE sources. The additional insight can be achieved by forecasting tool which can provide day ahead information and hour-by-hour prediction. Giebel et al. estimate that the forecasting tool is necessary when the energy penetration of wind power is above 5 % [52]. This analysis provides deep insight about the technological requirement for storing excess energy which can be used to meet the power demand during an uncertain power outage. Watson et al. used the Numerical Weather Prediction (NWP) model to forecast the energy reserve required to increase penetration of wind energy.

These are the various types of analysis that can be performed on renewable energy integration. In the next section, we discuss the various simulation tools that are used for studying power grid systems.

2.2 Simulation Tools for Power Grid Systems

The power grid is a very complex system. The complexity comes from the fact that there are various interacting components. Each element of the power grid is evolving due to innovations discussed in Chapter 1. The most widely used approach to study grid integration in power grid systems is by using analytical methods. Another approach used to study the rapidly changing technology and effects on the power grid and environment is to use a computer simulation. Broadly, grid simulators can be classified into two categories: compositional (co-simulation) and standalone simulators. Compositional simulators usually provide a framework or Application Programming Interface (API), that allows integration with another system to effectively simulate power systems. On the other hand, standalone simulators are complete systems designed to, or capable of simulating grid systems. Standalone simulators, further, are classified into general purpose and special purpose simulators. General purpose simulators are designed with a broader scope in mind, and they can be used to simulate various types of power grid systems. Network simulators (NS-2) [53], OMNet++ [54] and many others fall into this class. Modeling and simulation of a power system using general purpose simulators require a lot of effort due to lack of support for implementing grid systems. Special purpose simulators are specifically designed to simulate power systems with a specific set of features. Figure 2.3 shows the basic classification of power grid simulators.

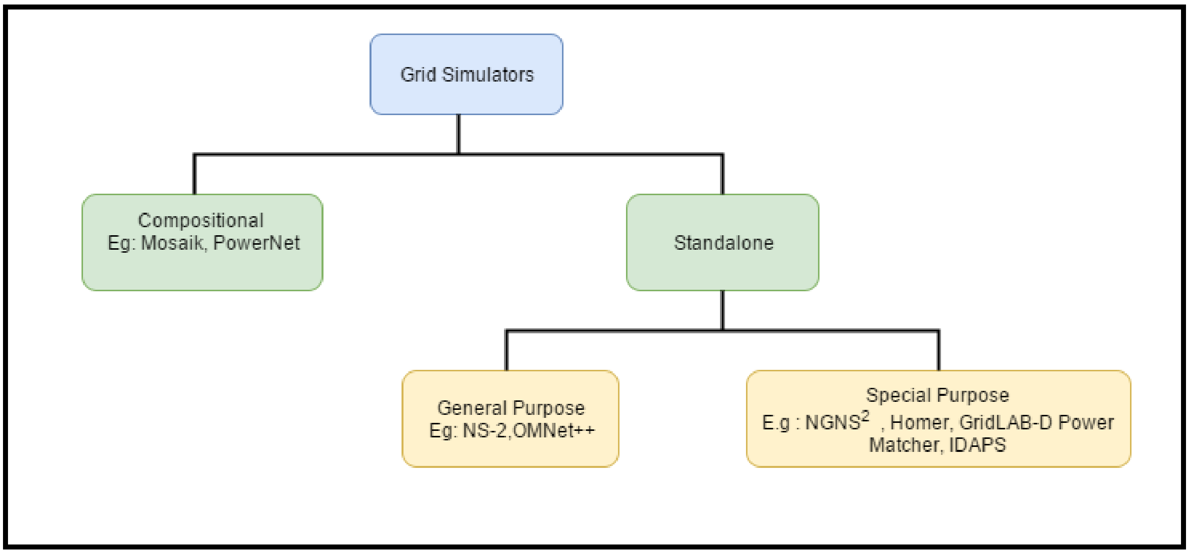

Figure 2.3: Classification of power grid simulators

2.3 Compositional Simulators

The compositional simulation (co-simulation) framework provides necessary high-level API to integrate different existing simulation frameworks. They primarily use sockets or message queues for exchanging data between different simulation models. We examine two widely used co-simulation frameworks/tools.

Mosaik [55] is a compositional simulation framework that provides a platform for integrating existing heterogeneous simulation models written in different programming languages. It is based on SimPy, a discrete event simulation library written in Python.

PowerNet [56] is a co-simulation framework developed by Liberatire and Al-Hammouri. PowerNet can simulate real-time power grid to investigate security, reliability, and performance of various control strategies. It combines NS-2 [53], a network simulator and Modellica [57], a language for modeling complex systems. NS-2 and Modelica run as separate processes, and inter-process communication is achieved using UNIX pipes. NS-2 acts as the controller and provides the necessary support for synchronization of data exchange between Modelica and NS-2.

Co-simulation framework like Mosaik and PowerNet provides API for integration with other grid simulation framework. They cannot operate as standalone simulation framework. Their functionality is heavily dependent the on simulation tool that is being integrated into the co-simulation framework.

In the next section, we discuss, in detail, the various standalone simulators used by the research community to model and simulate and thereby study power grid systems. As mentioned above, there are two types of standalone simulators. We will, therefore, discuss the general purpose simulators first and then describe various special purpose simulators to see how much support they provide for grid integration analysis.

2.4 General Purpose Simulators

Although the general purpose simulators were originally designed with flexibility to be able to model any system, they were primarily used for the purpose of modeling computer networks.

NS-2 [53] and OMNeT++ [54] are commonly used discrete events simulators that can be used to simulate power grid . They are widely used to simulate the functionality and effects of computer network protocols such as Transmission Control Protocol (TCP), User Datagram Protocol (UDP), IPv4 (Internet Protocol version 4), IPv6 (Internet Protocol version 6) and various other network protocols. Many third party libraries are available as an add-on to the simulator. Researchers have demonstrated the use of OMNet++ and NS-2 for simulating smart grids in [58], [59] , [60]. OMNet++ and NS-2 provide good support for modeling topology and network protocol which can be used in combination with other power simulation tools to simulate smart grids.

OMNet++ and NS-2 cannot be considered as a grid simulation tool because it lacks many features to simulate an electrical grid. They do not provide a user interface to design scenarios. The user should have good programming knowledge and should understand power grid systems to use these software.

2.5 Special Purpose Simulators

Although existing general purpose simulators can be used to simulate power grid systems, they still have major limitations. One simulation tool may not be able to simulate all the aspects of the power grid. There is an increasing need to study several specific aspects of the power grid system. Various special purpose simulators were designed to facilitate this. We examine some of the special purpose simulators.

2.5.1 NGNS^2

NGNS^2 (Next Generation Network and System Simulator) [9] is an object-oriented grid simulation framework written in C++. The main purpose of NGNS^2 is to simulate smart grid scenarios. It can also simulate various smart grid scheduling policies for user load management. It supports modeling of household devices including electric vehicles. It can distribute simulation of models among multiple cores using MPI (Message Passing Interfaces) [61] and OpenMP [62] threads. The parallelization in execution is completely transparent to the user which allows for reusing the same code to be run on a single machine or a cluster. This simulator requires code written in a

C++ like syntax for simulating smart grid. It cannot perform integration studies.

2.5.2 HOMER

HOMER (Hybrid Optimization Of Multiple Energy Resources) [63] is a commercially available simulation software developed specially for modeling micro-grids by the National Renewable Energy Lab; A division of the U.S. Department of Energy. The user can add different Distributed Energy Resources(DER) to a simulated grid and adjust parameters to simulate different scenarios. The models cannot be extended and primarily focus on an economic model which includes operation and maintenance of micro-grid. Although HOMER helps the user to perform various integration studies, its primary focus is on micro-grid. Since this is proprietary software, the software is not extensible and cannot be customized by the user. It can only model and simulate operation for a year with an hourly resolution. It does not allow the user to create a custom control strategy. The data analytics feature of Homer is limited and tightly coupled with the tool. It does not support integration with sensor data, which can be an important feature for integration studies.

2.5.3 GridLAB-D

GridLAB-D [64] is a power distribution system simulation and analysis tool developed by the US Department of Energy at Pacific Northwest National Laboratory (PNNL). GridLAB-D incorporates various modeling techniques including agent-based models. It is still under active development, and the last stable release is version 3.2.

The important capabilities of GridLAB-D are:

- Home appliance and equipment modeling using the latest agent-based simulation methods. Consumer behavior can be simulated on a daily, weekly or seasonal basis.
- Distributed energy generation modeling including the storage technology. Load shedding and scheduling of load can also be performed.

- Retail market modeling and simulation including contract selection, business, and operations can be conducted.
- Provides integration with MatLab, MySQL, and other database and analytical tools.
- Can efficiently use the processing power in multi-core and multi-processor environment.

GridLAB-D can examine the detailed interplay between all aspects of a power grid like power generation, transmission to end users and consumption. GridLab-D can be used to perform the following simulation:

- **Distribution Automation and Design/Evaluation:** Provide capability to perform design and analysis of distribution automation technologies such as volt-var optimization, coordination of devices and grid reliability.
- **Peak Load Management:** Helps to model and simulate various load management strategies combining advanced mechanisms such as transactive controls, centralized management, and monitoring.
- **Distributed Generation and Storage:** Can model different scenarios of distributed generation such as combined heating and power(CHP) technologies and storage systems. It can evaluate cost/benefits trade-off between infrastructure expansion.
- **Rate Structure Analysis:** Differentiated rate structure for meeting peak power demand can be studied and analyzed in detail.

In GridLAB-D, the user uses GLM (Grid Lab Model), a custom modeling language, to describe the simulation setup. The GLM allows modeling a particular hierarchy of objects e.g. A house model consisting of various appliances can be modeled.

Although GridLAB-D provides an excellent capability to model and simulate the power grid, the user should write code in C-like syntax and should understand the fine grain details of various components. Moreover, it does not allow users to model using a GUI (Graphical User Interface) and does not support simple integration studies. The simulation framework is complex to use and understand. It does not support integration with sensor data. It cannot answer the *"research questions"* discussed in Chapter 1.

2.5.4 Power Matcher

Power Matcher [65] implements supply and demand matching (SDM) using a computer based multi-agent system approach. The power matcher uses various type of agents in a hierarchical structure as shown in Figure 2.4. The main purpose of this simulator is to model smart grids using multi-agents. Each component in the power matcher is modeled as an agent that can perform autonomous actions. The power matcher has four main agents.

1. The ***auctioneer*** agent is on the top of the hierarchy and controls the entire bidding process. The auctioneer makes the decision of supply/demand based on the bid placed by the agents.

2. The ***concentrator*** can act as an aggregator of bids of child agents or cluster and helps to reduce the amount of information transmitted to auctioneer agents.

3. The role of the ***objective*** agent is to optimize a given objective based on the business logic the cluster implements.

4. The ***device*** agent is a representation of a device item e.g. washing machine, windmill, battery, etc. The device agent sends bids and receives a price based on the current state.

Power matcher considers the consumer side of the power grid system. It cannot be used to perform integration studies.

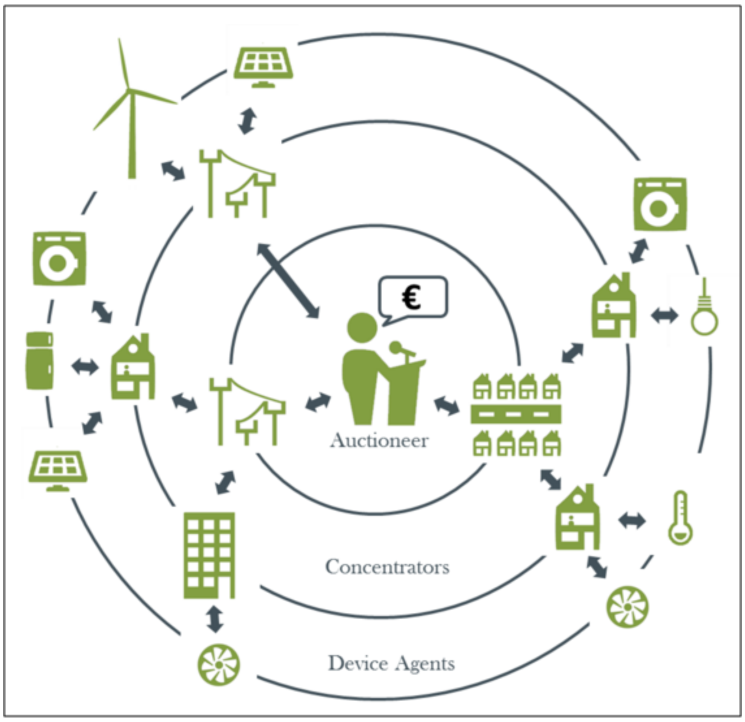

Figure 2.4: Hierarchical structure of agents [5]

2.5.5 IDAPS

The IDAPS (Intelligent Distributed Power System) is a multi-agent based microgrid simulation framework [6]. There are four different types of agents implemented using ZEUS agent toolkit [66] and they communicate between each other using TCP/IP protocol. A control agent is responsible for controlling the micro-grid by monitoring the power quality and detect any outages. Distributed Energy Resource(DER) agents are agents that manage the energy sources. User agent acts on behalf of the user to prioritize the energy consumption. Finally, the database agent stores information about the simulation run. Figure 2.5 shows the simulation setup of IDAPS.

In IDAPS, the simulation of the power grid resides in one computer modeled using MATLAB and the multi-agent system resides on the other computer as shown in Figure 2.5. The communication between the agents and the model in computer-1 uses TCP/IP protocol. Real-time measurements from computer-1 are sensed by

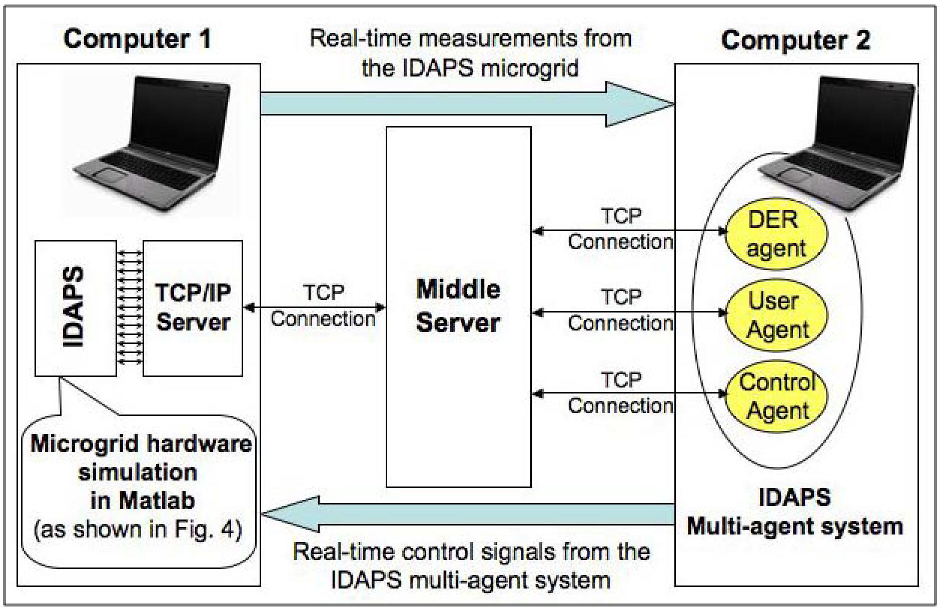

Figure 2.5: Simulation setup of IDAPS [6]

the multi-agents and are used to control the power grid by sending real-time control signals.

IDAPS simulation frameworks were primarily designed for simulating smart grid's consumer end scenarios and to help devise policies for user load management. They cannot help to answer the question regarding future energy trends and grid integration studies.

The above simulators focus on different aspects of the power grid system; there is no simulator available that specifically focuses on grid integration studies. Most of the available simulators that provide extended functionality and support for power grid systems such as HOMER, are not available as open source software. Narrowing down further, it is very obvious that very limited simulators even provide support for integration studies and support for time series data. Only very few of the simulators discussed so far have a graphical user interface for easy user access let alone an intuitive one. Most of the available simulators are not extensible; they do not provide support for additional sensor data and interchangeable data exchange format. Since GridSim was built using Java, it is not platform or OS dependent, unlike most other simulators. A comparison of various simulators is shown in Table 2.1.

Features	**HOMER**	**NGNS**[2]	**GridLab-D**	**Mosaik**
Purpose	GIS	CLS	CLS	CLS
GUI	Yes	No	No	No
Scenario Design	Click & Add	Coding	Coding	Coding
Time Series Input Data	No	No	No	No
Extensibility [1]	No	No	Yes	Yes
Data Analytics	No	No	Yes	Yes
OS Support	Windows	Windows	Not Known	Windows
License	Commercial	Not known	BSD License	Open Source

GIS - Grid Integration Study; CLS - Consumer Load Scheduling;

Table 2.1: Comparison of various simulation software

This comparison was done with grid integration study as the central theme and the insight thus obtained was used to build GridSim.

2.6 Summary

In this chapter, we reviewed the related works and that we believe sets the context for our contribution in this thesis. Next, in Chapter 3, we will look at the motivation and design consideration of our proposed simulator GridSim.

[1]Extensibility is a software design principle where the implementation of software can accommodate future requirements [67].

Chapter 3

GridSim: Purpose and Design Goals

The main contribution of this thesis is the simulation software GridSim. In this chapter, we first describe the various design goals and consideration that were used to design GriSim.

3.1 Design Goals

Among the existing simulation frameworks, although some provide high customization, the user is required to write code to implement many aspects of the model that they intend to simulate. On the other hand, a fully designed software tool provides ease of use, but it limits its use to only the models and features supported in the tool. For GridSim, we decided to choose a middle ground between a framework and a fully closed software tool. Some of the design goals with which GridSim has been developed are the following.

- **Easy extensibility**: GridSim aims to provide support for easy extensibility of components. Extensibility refers to the design principle that allows easy extension of software. GridSim implementations are driven by interface-based programming [68] and hence support easy extensibility. The list of available interfaces for extending GridSim can be found in the source code of GridSim.

- **Separation of concern**: GridSim aims to provide modules that can be added or removed as needed. The modular approach helps in extensibility. Some of the modules can be exported as a library to be used with other tools/frameworks.

- **Support for integration**: GridSim aims to support integration with real-world sensor data for time series analysis.

- **Open source**: GridSim is open source and only uses existing open source framework/tools. Every module of GridSim can be extended.

3.2 Feature Consideration

To perform various grid integration studies with ease, we believe that the following features are necessary for GridSim.

- **Intuitive user interface:** Intuitive GUI that can help the user to design various scenarios with ease.

- **Data analytics:** Advanced data analytics is required to perform analysis of simulation results for deep insights. The data analytics service is decoupled from the simulator which allows simulations independent from data analysis.

- **Integration of sensors:** A good integration study software should provide methods to integrate with real-time sensor data.

- **Easy customization:** GridSim accommodates various customization of models and control strategies.

3.3 Summary

In this chapter, we presented the motivation and design objectives of GridSim. In the next two chapters, we present the modeling of grid systems and the design and implementation of GridSim.

Chapter 4

GridSim: Modeling

In this chapter, we describe in detail the various models associated with the power grid system. First, we discuss the modeling consideration and then present an overview of main components of the power grid. We then describe each component, attributes and parameters, followed by a detailed discussion on models of energy generation units.

4.1 Modeling Consideration

The accuracy of the models depends on the purpose of the simulation. Model is an abstract representation. In this thesis, model representations are mathematical expressions with their attributes (parameters). Our design choice for the model was mainly motivated by following observations.

- "Simplicity is the key to understanding...Simplified simulations provide the best grounds for extracting major properties quickly." [69].
- "A good model is a judicious trade-off between realism and simplicity." [49].
- "So, in practice, models that attempt to be highly accurate, end up running tiny toy workloads." [70].

- “Even though the assumptions of a model may not literally be exact and complete representation of reality, if they are realistic enough for the purpose of our analysis, we may be able to draw conclusions which can be shown to apply to the world.” [46]

Next, we will discuss on the models available in GridSim.

4.2 Power Grid System

The power system that we propose to simulate consists of the following main components (models): (i)Energy generation units (ii)Energy consumption units, (iii)Energy transmission units, (iv)Energy storage units, (v)Energy control units.

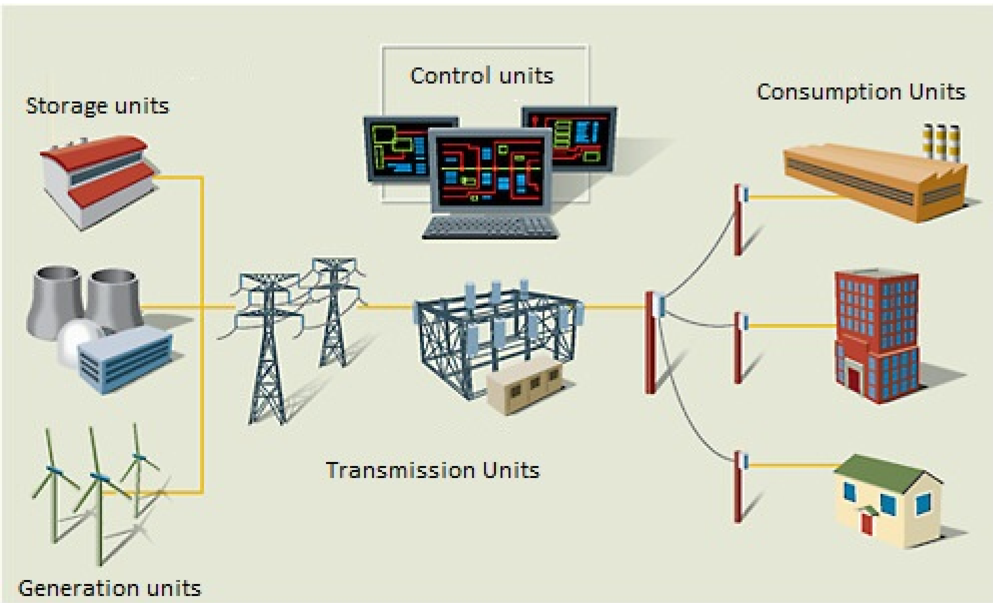

Figure 4.1: Power grid system components [7]

Energy production units produce energy that will be either stored or transmitted through energy transmission units to energy consumption units. Energy storage units store excess energy that can be used to meet future energy demand. The energy control unit manages and facilitates the energy transfer from the energy production units to the energy consumption units. Figure 4.1 shows the various units in a power grid.

Since energy generation units are the most important component of the simulation tool, they are described elaborately in section 4.3.

4.2.1 Energy Storage Units

In the proposed simulation tool, the energy storage units are used to model Bulk Energy Storage(BES) technology. The BES technology stores the extra energy generated by the energy production units. The energy stored can be consumed by the consumption unit when the energy demand is greater than the energy generated by the production units. For example, the excess energy generated from wind farms during the period of high-intensity wind can be stored in a battery for a later period when energy demands are high. Solar power plants require BES technology to store energy generated during day time. There are several types of storage technology with various use cases. BES technology, such as PHES stores the electrical energy in the form of gravitational potential energy of water. PHES can only be used for large scale storage and cannot provide frequency support to the grid. PHES Technologies, like the lead-acid battery can act as a peaking power plant but have poor depth of discharge and short lifespan. Compressed Air Energy Storage (CAES) stores electrical energy by compressing air to a very high pressure and then storing them in caverns and depleted wells. The use cases of BES are widely distributed, and the details of such can be found in [71].

All the storage units technology should extend the *Storage* interface. Currently, the simulation tool supports only a single storage class whose parameters can be modified to accommodate different storage technologies. In the simulation tool, BES technology has the following parameters.

- **Maximum capacity:** specifies the power rating of the storage unit in MW. If this value is set to -1, the power plant can have infinite capacity.
- **Levelized cost:** specifies the levelized cost of electricity in $/MWh.
- **Lifecycle carbon emission:** specifies the amount of CO_2e emitted in kg/MWh.

- **Depth of discharge:** specifies the depth of discharge of the battery. The value should be specified in percentage.

- **Efficiency:** specifies the efficiency of the battery. The default value is 0.75.

4.2.2 Energy Consumption Unit

The energy consumption unit is used to model the user demand of electrical energy. It can be used to model consumption behavior of a house, factory, city, province or a country. In the simulation tool, the energy consumption can be provided as a time series data averaged over a minute, hour, month or a year from a JSON/CSV file. It also supports input as a Gaussian distribution with a mean and variance as the parameters. The simulation tool requires at least one load to be connected to the energy control unit. In the simulation tool, the energy consumption unit has the following parameters.

- **Input file:** specifies the input file for energy consumption data as a time series data.

- **Mean Consumption:** specifies the mean parameter of a Gaussian distribution for the mean consumption of the load. Used only when input file parameter is empty.

- **Variance Consumption:** specifies the variance associated with the consumption.

4.2.3 Energy Transmission Unit

The energy transmission unit is used to model the transmission lines in the power grid. Given the energy storage, production, consumption and control units as nodes, the transmission lines are modeled as an edge connecting those nodes. In the simulation tool, the transmission line has the following parameters.

- **Maximum capacity:** specifies the maximum capacity of the transmission line in MW. Setting this to -1, makes the capacity infinite.

- **Levelized cost:** specifies the levelized cost of building the transmission line in $/km. The default value is 0.

- **Efficiency:** specifies the efficiency of the transmission line. The default value is set to 1 in GridSim model.

- **Length:** specifies the length of transmission lines in km.

To keep the model simple, the voltage variation and phase change associated with AC transmission lines are not considered.

4.2.4 Energy Control Unit

The energy control unit can be used to model new control strategy that controls and facilitates the transfer of energy from the production unit to the consumer unit. The energy control unit can model the control system used in the power grid system. The control strategy can run any of the optimization algorithms to meet the energy demand of the consumption unit. The user can write their custom strategy/optimization algorithm for the scenario they would like to simulate. Any new energy control strategy implemented should override the *Strategy* interface and implement the necessary methods. The control will be injected to the simulation engine through dependency injection during the run time.

4.3 Energy Generation Unit

The energy generation unit is used to model the various energy production technology. Energy generation units have few terminologies associated with them that are described in this section.

4.3.1 Costs

There are various costs associated with power plants. These costs are grouped into the Capital cost (CapEx /X_p), Operation and Maintenance (O&M) cost. The O&M cost can be future classified into Fixed Operation and Maintenance Cost (FOM) and Variable Operation and Maintenance Cost (VOM).

- **Capital Cost:** It is the cost associated with construction of a power plant. It includes civil/structural material cost, mechanical equipment cost, design and planning cost. It is measured in $ per kW and heavily influenced by the total capacity of the power plant.

- **Fixed Operation and Maintenance Cost(FOM):** It includes the cost associated with non-fuel expenses such as staffing, regular maintenance cost and also the fuel related expenses. X_E represents the FOM.

- **Variable Operation and Maintenance Cost(VOM):** It includes the cost associated with major unexpected maintenance and operation and varies with electrical energy generation. This cost includes waste water disposal, lubricants, chemicals, and gases.

The cost associated with the various power plants is shown in Table 4.1. These are future projected costs of power generation technologies. These estimates were generated by the U.S. Energy Information Administration (EIA) and do not represent the actual cost as some of the technologies are under research. Advanced Combustion turbine uses methane as the fuel and is one of most cost effective technology. Its has lower GHG signature than coal stations and may replace coal-fired power plants in the future. Certain technology like hydroelectric cost lesser overall when compared to a coal plant, but it is not always technically feasible to construct hydroelectric plants. The hydroelectric plant requires a suitable geological location say for instance a difference in elevation.

Technology	**Fuel**	**Nominal Capacity(kW)**	**Capital Cost ($/kW)**	**Fixed O&M ($/kW-yr)**	**Variable O&M ($/MWh)**
Advanced Pulverized Coal	Coal	650,000	3,246	37.80	4.47
Advanced Pulverized Coal	Coal	130,000	2,934	31.18	4.47
Advanced Pulverized Coal	Coal	650,000	3,246	37.80	4.47
Advanced Pulverized Coal with CCS	Coal	650,000	5,277	80.53	9.51
Conventional CT	Gas	85,000	973	7.34	15.45
Advanced CT	Gas	210,000	676	7.04	10.37
Hydroelectric	Hydro	500,000	2,936	14.13	0
Pumped Storage	Hydro	250,000	5,288	18.00	0
Onshore Wind	Wind	100,000	2,213	39.55	0
Offshore Wind	Wind	400,000	6,230	74.00	0
Photovoltaic	Solar	20,000	4,183	27.75	0
Photovoltaic - Tracking with 20% storage	Solar	150,000	4,236		

Table 4.1: U.S. technology cost specification [10]

Similarly, onshore wind plants provide an attractive capital cost, but technical feasibility limits their widespread adaptability. Wind farms require minimum wind velocity (speed and direction) to operate and occupy a lot of space. Offshore wind plant capital cost is more than onshore wind farms due to the installation of supporting structure under water. It has higher O&M costs due to the remote location and accessibility issues. The photovoltaic cells capital cost is higher due to its storage requirement. Large batteries need to be employed to store electrical energy that is generated from the solar panel. The FOM and VOM associated with Photovoltaic cell with 20% storage are not reported in [10]. However, we can assume it to be roughly equal to the photovoltaic cell. Also, it is good to notice that the higher nominal capacity tends to reduce the capital cost associated with that technology. There are other cost estimates that were performed by organizations and independent researchers that can be seen in [72], [73], [74], [75].

The capital cost of various BES technology is shown in Table 4.2. Some storage technology like PHES, CAES are highly suitable for large scale storage and have better X_E and X_p. Technology like Lead-Acid and Zinc bromine are better suited for integration with photovoltaic technologies.

BES technology	**Capital X_P ($ per kW)**	**X_E($ per kWh)**	**Efficiency**
Pumped Hydroelectric Storage	1500-2000	10-100	75-80
Underground diabatic compressed air energy storage (D-CAES)	850-1200	5-25	4.2
Underground adiabatic compressed air energy storage (A-CAES)	1100-1700	10-50	55-70
Lead acid battery(Pb-A)	450-650	300-450	75-90
Sodium sulfur battery(NaS)	350-800	250-400	75-85
Zinc bromine battery (ZnBr)	500-1500	200-400	60-75
Vanadium redox battery(VRB)	1000-15000	200-600	65-80

Table 4.2: Cost specification of selected battery technology [11]

Although Capital cost, FOM, and VOM provide the total cost of the power plant over a lifetime, it cannot accurately represent the net present value of the unit cost of electricity. Also having three cost measures makes the analysis complex and restricts users from analyzing over a smaller period (for a month). A simpler representation of the cost of the power plant is Levelized Cost of Electricity (LCOE). It is the net present value of the unit cost of electricity over the lifetime of a generating asset. It is often cited as a good measure of the overall cost of different generating technologies. Levelized cost can capture various incentives provided by the government. The levelized cost for different technology is shown in Table 4.3. The method to calculate LCOE is provided in [76]. The levelized cost for the power plant was obtained from EIA [12]. It is good to notice that the levelized cost tracks the total cost of technology provided in Table 4.1. The LCOE values are calculated based on a 30-year cost recovery period. In reality, the recovery period varies by technology, capacity of the power plant and project type. The levelized cost provided in Table 4.3 does not consider the regional variation associated with the technology. Wind farms with high average wind speed will have lesser LCOE than an average wind farm. It does not include the cost of transmission and can vary significantly based on location. For example An off-shore wind farm transmission cost will be more than an on-shore wind farm.

Dispatchable Technologies	Levelized capital cost	Fixed O&M	Variable O&M	Total system LCOE
Conventional Coal	60.4	4.2	29.4	94
Advanced Coal	76.9	6.9	30.7	114.5
Advanced Coal with CCS	97.3	9.8	36.1	143.2
Conventional Combined Cycle	14.4	1.7	57.8	74
Advanced Combined Cycle	15.9	2.0	53.6	71.4
Advanced Nuclear	70.1	11.8	12.2	94
Wind	57.7	12.8	0.0	70.5
Wind - Offshore	168.6	22.5	0.0	191.1
Solar PV	109.8	11.4	0.0	121.2
Hydroelectric	70.7	3.9	7.0	81.5

Table 4.3: U.S. average levelized costs ($/MWh) for 2020 [12].

The levelized cost of BES is shown in Table 4.4. The LCOE was obtained from Lazard's levelized cost of storage analysis [13]. The PHES has the lowest LCOE when compared to other battery technologies. However, PHES has specific use cases and is not suitable as a general purpose storage technology. PHES requires a difference in elevation to be installed. However, PHES accounts for 99% of the storage capacity installed globally. Battery technologies like Pb-A, NaS, ZnBr and VRB use chemical energy to store energy. They have higher LCOE because of limited life expectancy of chemical storage when compared to mechanical storage like PHES.

BES technology	Levelized Cost ($/ MWh)
Pumped Hydroelectric Storage	188-274
Lead acid battery(Pb-A)	402-1692
Sodium sulfur battery(NaS)	365-1079
Zinc bromine battery (ZnBr)	245-1500
Vanadium redox battery(VRB)	248-950

Table 4.4: Levelized cost of BES technology [13]

Dispatchable Technologies	Levelized total system LCOE 2020	Levelized total system LCOE 2040
Conventional Coal	95.1	91.7
Advanced Coal	115.7	105.5
Advanced Coal with CCS	144.4	127.6
Conventional Combined Cycle	75.2	82.6
Advanced Combined Cycle	72.6	79.3
Advanced Nuclear	95.2	88.9
Wind	73.6	75.1
Wind - Offshore	196.9	175.6
Solar PV	125.3	107.1
Hydroelectric	83.5	197.1

Table 4.5: levelized costs of electricity 2020 and 2040 [10]

The comparison between projected LCOE of various technologies for the year 2020 and 2040 is provided in Table 4.5. The levelized cost includes a transmission cost in the range of 1.2 to 6.00 $ per MWh. Overall we can see a decrease in levelized cost of electricity in 2040. However, conventional technologies have very little decrease in LCOE. In some cases like wind farms and conventional combined cycle generators, the LCOE has increased. This increase in LCOE can be attributed to research in other advanced technology which cannot be adapted to conventional technologies. The other reason could be an increase in the cost of fuel and labor which exceeds the improvement made in conventional technologies. The significant decrease in offshore wind technology can be attributed to research in better transmission lines like HVDC [31].

4.3.2 Maximum Capacity and Capacity factor

The maximum capacity of a power plant is the maximum power output. It is measured in kW, MW, etc. It is the maximum energy that can be supplied by the power plant in a second. The energy output of a power plant is the operational power over a period of time. It is usually measured in kWh, MWh, etc. For example, if a power plant's maximum capacity is 1250 kW and if operated at 85 % of operational power output, it's output capacity is 1000 kW. If the 1000 kW power plant is operated for one hour, it will produce 1000 kWh of electrical energy.

The capacity factor of a power plant is the ratio of its actual output to its potential output [77]. For example, if a power plant is rated at 1000 MW, and produces energy output of 576000 MWh of energy in 30 days, then its capacity factor is 80 %.

The capacity factor of a power plant is affected by several factors [78] and [12]:

- Routine failure and equipment maintenance of power plants cause plants to shut down temporarily reducing the capacity factor.
- Voluntary shutdown of the power plant due to lesser energy demand. A peaking power plant is often switched off when the base load power plant can meet the demand.
- Unavailability of fuel sources for generating power. For example, fuel supplies for the coal-fired power plant would have reduced impacting its energy output. For hydropower plant, the seasonal change can affect the amount of running water available which can cause a variation in energy output.

4.3.3 Peaking Power Plant vs. Base Load Power Plant

The power producers can be classified into two categories based on their operational characteristics.

Peaking power plant: It is also called a dispatchable power plant. They are power producers that can be quickly turned on/off to meet the energy demand of the consumers for example compressed gas turbine (CGT). Some of the advantages of peaking power plants are:

- They help to meet the power demand during peak loads.
- The capital cost to setup is less expensive.
- They help to maintain the stability of the grid by regulating the frequency.

- They can act as a backup system that can be used to meet demand when part of the base load energy plant fails.

Some limitations of dispatchable power plants are:

- They are more expensive to operate than a primary unit of energy.
- They cannot produce a high volume of electrical energy.
- They have a higher carbon emission than the base load power plant.

Base load power plant: These power plants are the primary generator units and always produce a constant amount of energy irrespective of the consumer power demands for example coal-fired power plant. They take hours to start and stop. Some advantages of base load power plants are:

- They are cheaper to operate and maintain.
- They can produce a greater volume of electrical energy when compared to peaking power plants.

Some limitations of base load power plants are:

- They cannot be switched on/off immediately. Turning on can take hours before the unit becomes operational.
- They cannot be used to maintain the grid frequency.
- The excess electrical energy produced during lower demand period is often wasted.

4.3.4 Types of Power Producers

The following components for production technology are modeled.

- Coal power plant
- Peaking power plant (Dispatchable Power Plant)
- Nuclear power plant
- Solar power plant
- Wind farms
- Hydropower plants

4.3.4.1 Coal Power Plant

The coal-fired power plant produces electrical energy by converting the heat energy of coal into electrical energy. It contributes to 70% of the total electrical energy produced globally. Coal is burned to generate heat energy which is used to convert water into steam. The steam is used to turn the turbine under a magnetic field to produce electricity. The coal-fired power plant is a chief contributor of GHG emission. Nearly 40% of the cost of building new coal plants is spent on pollution control.

In the simulation framework, coal power plant has the following parameters.

- **Maximum capacity:** specifies the power rating of the station in MW. If this value is set to -1, the power plant can have infinite capacity.
- **Mean capacity factor:** specifies the mean of capacity factor. The default value is set to 0.85.
- **SD capacity factor:** specifies the standard deviation of capacity factor. The default value is set to 0.1.

- **Levelized cost:** specifies the levelized cost of electricity in $/MWh.
- **Lifecycle carbon emission:** specifies the amount of CO_2 emitted in kg/MWh.
- **Dispatchable:** boolean value that can be set to true to make the power plant dispatchable.
- **Life span:** specifies the lifespan of the wind turbine in years.

4.3.4.2 Wind Power Plant

The wind farms consist of one or more wind turbines. A wind turbine converts the kinetic energy of the wind into mechanical energy. The mechanical energy from the rotation of the turbine is converted into electrical energy. A wind turbine produces energy that is directly proportional to the cube of wind speed and the diameter of the rotor blade.

In the simulation framework, the wind farm has the following parameters.

- **Maximum capacity:** specifies the power rating of the station in MW. If this value is set to -1, the power plant can have infinite capacity.
- **Levelized cost:** specifies the levelized cost of electricity in $/MWh.
- **Capital cost:** specifies the capital cost in $ per MW. Will be ignored if levelized cost is specified.
- **Maintenance cost:** specifies the maintenance cost in $ per MWh. Will be ignored if levelized cost is specified.
- **Life span:** specifies the lifespan of the wind turbine in years.
- **Lifecycle carbon emission:** specifies the amount of CO_2 emitted in kg/MWh.
- **Minimum wind speed:** specifies the minimum cut-off speed for a wind turbine.

- **Rotor diameter:** specifies the diameter of the rotor (D). Rotor diameter is used to calculate the area (A) of the wind turbine using equation 4.1.

$$A = \frac{\pi}{4} D^2 \tag{4.1}$$

- **Number of units:** specifies the number of wind turbine units (n) in the wind farm.

- **Efficiency:** specifies the efficiency (η) of the wind turbine. The default value is set to 30%.

- **Air density:** specifies the air density (ρ) at the location. The default value is set to 1.225 kg/m^3.

- **Wind speed:** specifies the average wind speed ($\bar{v}$) at the location of the wind farm. The wind speed should be a time series data from a JSON or CSV file. The wind speed can be averaged over a minute, hour or year depending on the simulation scenario.

- **Minimum wind speed:** specifies the minimum cut-off speed for a wind turbine.

  Equation 4.2 calculates the power produced by the wind turbine [51]. The power generated, P_{gen}, is not directly converted into output power. It is restricted by the power curve of a wind turbine which follows equation 4.3 where v_{min} is the cut-off speed of the wind below which the power generated is not useful and assumed to be zero. Sometimes the wind speed is too high and likely to cause damage to the wind turbine. To avoid damage, the wind turbine is made parallel to the wind direction and power output is zero. P_{output} calculated is multiplied by the scenario time unit (t) and η to produce the total energy output of the wind turbine as shown in equation 4.4.

$$P_{gen} = \frac{3}{\pi} \eta A \rho \bar{v}^3 \tag{4.2}$$

$$P_{output} = \begin{cases} 0\ if\ \ v_{min} > \bar{v} \\ P_{gen}\ \ if\ \ P_{gen} < max\ capacity \\ 0\ \ if\ \ P_{gen} > max\ capacity \end{cases} \tag{4.3}$$

$$T_e = P_{output} n t \tag{4.4}$$

4.3.4.3 Nuclear Power Plant

A nuclear reactor uses nuclear reaction (fission) to produce electrical energy. The heat generated from nuclear fission of nuclear fuel like uranium is used to drive the steam turbine to generate energy. Nuclear reactors are primarily used as a base load power plant. A nuclear reactor has a high capital cost and low operating cost. They emit less GHG but produce radioactive waste which is highly hazardous.

In the simulation framework, a nuclear power plant has the following parameters.

- **Maximum capacity:** specifies the power rating of the plant in MW. If this value is set to -1, the power plant can have infinite capacity.
- **Mean capacity factor:** specifies the mean of capacity factor. The default value is set to 0.85.
- **SD capacity factor:** specifies the standard deviation of capacity factor. The default value is set to 0.1.
- **Levelized cost:** specifies the levelized cost of electricity in $/MWh.
- **Lifecycle carbon emission:** specifies the amount of CO_2 emitted in kg/MWh.
- **Dispatchable:** specifies the boolean value that can be set to make the power plant dispatchable. The default value is set to false.

4.3.4.4 Solar Power Plant

A solar power plant uses a set of solar panels to convert sunlight into electricity using photovoltaics effect. Since the solar power plant can only produce energy during the time of good solar isolation, it often requires a BES technology. The solar panel generates Direct Current (DC), which needs to be converted into Alternating Current (AC) for integration into the grid system. The storage, conversion from DC to AC negatively affects the efficiency. The type of material which is used to construct the solar panel also affects the efficiency. Some solar power plants track the movement of the sun throughout the day to get maximum solar isolation.

In the simulation framework, a solar power plant has the following parameters.

- **Maximum capacity:** specifies the power rating of the solar plant in MW. If this value is set to -1, the power plant can have infinite capacity.
- **Levelized cost:** specifies the levelized cost of electricity in \$/MWh.
- **Capital cost:** specifies the capital cost in \$ per MW. Will be ignored if levelized cost is specified.
- **Maintenance cost:** specifies the maintenance cost in \$ per MWh. Will be ignored if levelized cost is specified.
- **Life span:** specifies the lifespan of the solar power plant in years.
- **Lifecycle carbon emission:** specifies the amount of CO_2 emitted in kg/MWh.
- **Area:** specifies the area of the solar panel in square meters.
- **Efficiency:** specifies the efficiency (η) of the solar panel and electrical component like DC to AC conversion system. The default value is set to 12%.
- **Solar isolation:** specifies the average solar isolation(θ) in kW/m^2 . The solar isolation should be time series data from a JSON or CSV file. The solar isolation

can be averaged over a minute, hour, year, etc. depending on the simulation scenario.

The total energy output(T_e) of the solar plant can be calculated using equation 4.5, where t is the time unit of the scenario.

$$T_e = \theta \eta t A \tag{4.5}$$

4.3.4.5 Hydro power plant

A hydropower plant converts the kinetic energy of the flowing water into electrical energy. A hydropower plant contributes to 70% of the renewable energy produced and 14% of the total energy produced globally [79].

In the simulation framework, a hydropower plant has the following parameters.

- **Maximum capacity:** specifies the power rating of the plant in MW. If this value is set to -1, the power plant can have infinite capacity.
- **Mean capacity factor:** specifies the mean of capacity factor. The default value is set to 0.4.
- **SD capacity factor:** specifies the standard deviation of capacity factor. The default value is set to 0.2.
- **Levelized cost:** specifies the levelized cost of electricity in $/MWh.
- **Lifecycle carbon emission:** specifies the amount of CO_2 emitted in kg/MWh.
- **Dispatchable:** specifies the boolean value that can be set to make the power plant dispatchable. The default value is set to false.

4.3.4.6 Peaking Power Plant

A peaking power plant is used to provide electrical energy when the base load power plant cannot meet the energy demand of the load. They have the ability

Producer Technology	Maximum capacity(MW)	Mean capacity factor	Standard deviation capacity factor	Levelized cost $ / MWh	Lifecycle Carbon Emission kg / MWh	Dispatchable
Coal power plant	10000	0.85	0.2	60	850	No
Peaking power plant	1000	NA	NA	75	500	Yes
Nuclear power plant	10000	0.85	0.1	95	20	No
Solar power plant	1000	NA	NA	125	97	No
Wind farms	2	NA	NA	75	25	No
Hydropower plant	5000	0.6	0.2	74	25	No

Table 4.6: Default value of parameters for various power producer technology

to control the power output based on the energy need. Conventional Combined Cycle Gas Turbine (CCGT) and Advanced Combined Cycle Gas Turbine (ACGT) are commonly used as the peaking power plant. They use either oil or natural gas as fuel. In the simulation framework, the peaking power plant has the following parameters.

- **Maximum capacity:** specifies the power rating of the plant in MW. If this value is set to -1, the power plant can have infinite capacity.
- **Levelized cost:** specifies the levelized cost of electricity in $/MWh.
- **Lifecycle carbon emission:** specifies the amount of CO_2 emitted in kg/MWh.
- **Dispatchable:** specifies the boolean value that can be set to make the power plant dispatchable. The default value is set to true.

Table 4.6 summaries the default values for the power producer. These values were obtained from the US government website [77]

4.4 Pollution Measurement Unit

Here we would like to describe the GWP and GHG emission of the power grid systems that we are interested in studying. Global warming produced by gases is measured in terms of GWP. Each GHG has different GWP.

The GWP of a GHG is defined as the ratio of the time-integrated radiative forcing

Gas	Global Warming Potential
CO_2	1.0
CO	2.2
CH_4	10
N2O	180
HCFC-22	410
CFC-11	1300
CFC-12	3700

Table 4.7: GWP of different gases [14]

from the instantaneous release of 1 kilogram (kg) of a trace substance relative to that of 1 kg of a reference gas [80]. The reference gas used is carbon dioxide (CO_2) and hence GWP of all gases are represented as CO_2e (Carbon dioxide equivalent) or GHG emission. We use CO_2e and GHG interchangeably. The GWP for various greenhouse gases is shown in Table 4.7. The Chlorofluorocarbon (CFC) has the highest GWP and can cause greater warming of earth's atmosphere per kg of its emission. Although CO_2 has GWP of 1, emission of gases other than CO_2 is comparatively less. CO_2 accounts for more than 70% of the emissions [14].

CO_2 is primarily emitted from burning fossil fuels in a coal station. GHG emission in g/kWh between the year 1971 to 2010 is shown in Figure 4.2. The projection for the year 2020 is also shown. There is a steady decrease in the average emission of GHG. Several reasons contribute to the average decrease in GHG emissions, they are:

- **Efficient power production technology:** Due to technological advancement, the efficiency of the power plant has increased over these years. Conversion from heat energy of fossil fuel to electrical energy is much more efficient.
- **Increasing use of Renewable energy:** There is an increase in the use of renewable energy like wind and solar in recent years. The increase in use has

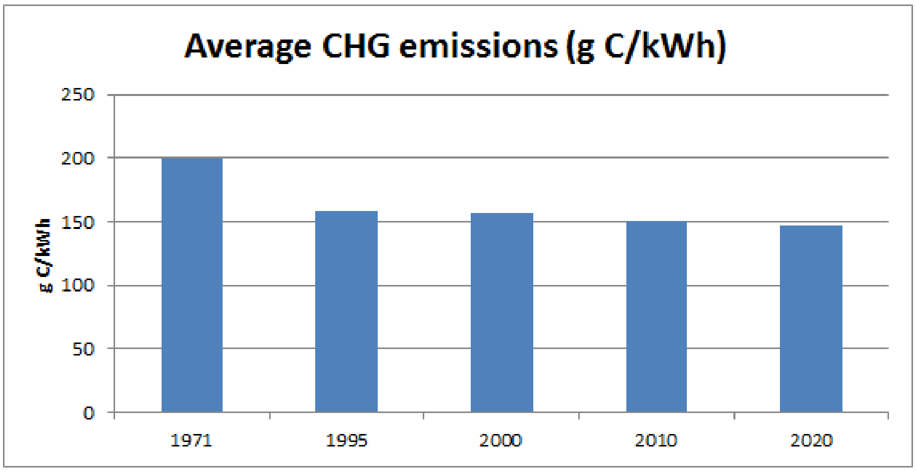

Figure 4.2: CO_2 emission (g/kWh) [8]

replaced part of the energy generated from fossil fuels.

- **Efficient consumer technology:** The consumer electronics have undergone a major change in recent years. Intelligent scheduling of electrical appliances during non-peak hours reduced dependency on the peaking power plant.

- **Switching to low carbon fuel:** Emerging CCGT technology that uses methane as fuel. CCGT produces less carbon emission per kWh than a conventional power plant.

The average GHG for various power generation technologies is shown in Figure 4.3. The average GHG emission varies through construction, operation and decommissioning of a power plant. Accounting for emissions from all phases of the project (construction, operation, and decommissioning) is called carbon lifecycle approach. Technologies like coal plants and gas turbines (Natural Gas / Oil) emit most of their carbon during the operation phase. Some technology like hydro emits most of the GHG during construction and decommissioning phase of the project. Nuclear, hydro and wind technologies emit the least carbon in its entire life cycle. The significant variation in CO_2 emissions of coal power plants is mainly due to the different types of coal used during operation. High-quality coal produces a smaller amount of CO_2. Solar PV has a large variation in CO_2 due to variation in the technology used in the

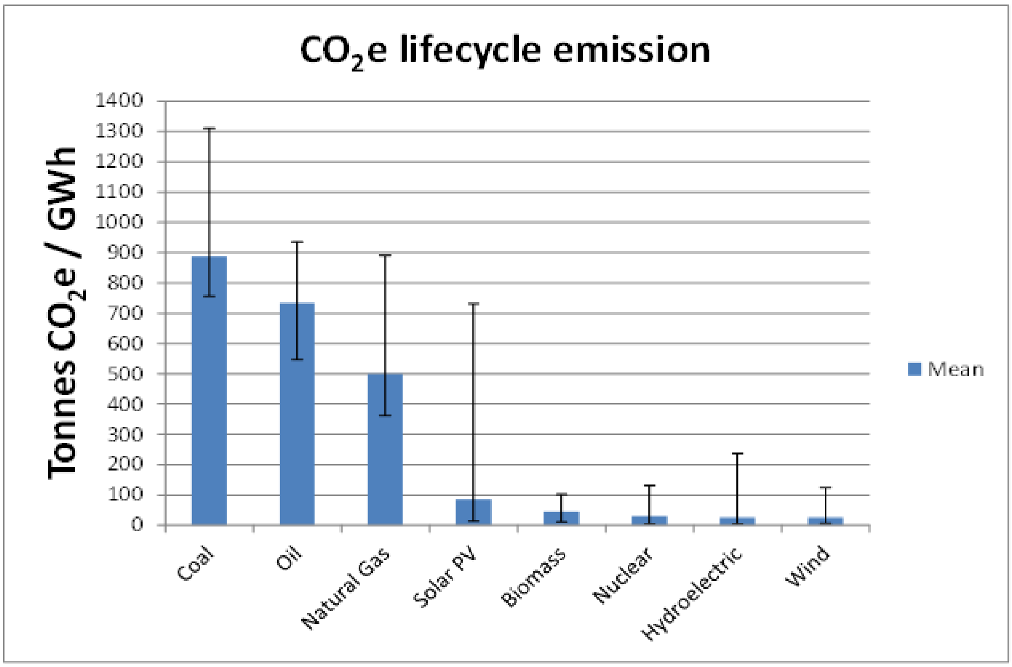

Figure 4.3: CO_2 emission lifecycle of different power generation technology [8]

Storage Technology	**GHG emissions(tonnes CO_2e/MWh)**
CAES	19.4
Pumped Hydro Storage	35.7
Lead acid battery(Pb-A)	125.3
Vanadium redox battery(VRB)	161.4

Table 4.8: CO_2 emission lifecycle of storage technology

production of Solar PV. Some solar PV has a better efficiency of converting sunlight into electrical energy but emit higher GHG during the manufacturing process.

The life cycle of CO_2e for BES is given in Table 4.8. The CAES has the least amount CO_2 emission of 19.4 CO_2e per MWh. However, it is the least efficient among BES technology. There is a loss of approximately 96 % during CAES operation. Chemical batteries have the highest carbon emission but have more use cases than PHS and CAES.

4.5 Summary

In this chapter, we discussed about various components that form the power grid. We also looked in detail at the terminologies and parameters that are associated with power grid modeling. We established a standard for measuring GHG emissions. In the next chapter, we will provide implementation details of our simulation tool.

Chapter 5

GridSim: Design and Implementation

This chapter provides an overview of various design decisions of our proposed simulation tool and its implementation details. An overview of the architecture is presented, followed by implementation details of architecture including back-end services, UI, and middleware is provided. A brief user manual is provided in the end which can be used as a quick start guide for working with GridSim.

5.1 Architecture of the Framework

Based on our design goals and current software development trends, we have designed the architecture that can meet our requirements. The proposed components contain five essential elements namely Simulation Engine, Search Analytics, Messaging Bus and Data Store as shown in Figure 5.1. Sensors are external to the framework and can communicate with the simulation engine using Advanced Message Queuing Protocol (AMQP) [81]. Every component of GridSim uses open source software. We briefly describe how these components help us to achieve the intended design goals.

- **Search Analytics:** Search analytics provides data analysis service to help users perform various statistical measures. It also provides intuitive UI to make custom graphs. Its helps to separate the actual simulation engine execution

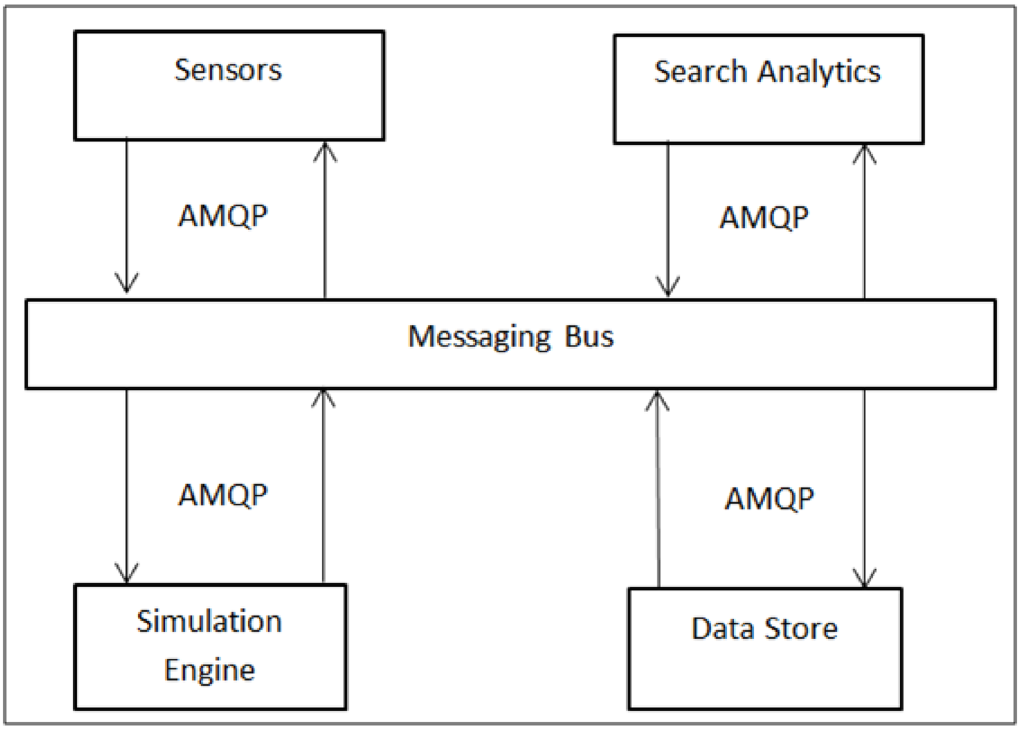

Figure 5.1: Architecture of proposed simulation framework [9]

from the trace data thus maintaining the separation of concern.

- **Messaging Bus:** Messaging bus is the core that connects various components. It provides the backbone to integrate the simulation engine, data store, search analytics and sensors. It uses AMQP as the data exchange format. This helps us to achieve separation of concerns as well as support integration for other services.

- **Data Store:** Data store services help us to store data of the simulation run. The data store is used by the search analytical service to generate graphs and other meaningful results.

- **Simulation Engine:** The simulation engine is the core of framework that simulates the given scenario. The simulation engine consists of various components which will be explained in later sections.

In the following section, we look into the various considerations and implementation of the components.

5.2 Data Store

The data store service is used to store data generated by each simulation run. The data store service is responsible for serialization of the object. The data store is implemented using a Not Only Structured Query Language (NoSQL) database since the data generated by each simulation run can be different and there is no complicated relationship between the data generated. This supports our design goal of easy extensibility. Some advantage of using NoSQL over Structured Query Language (SQL) are:

- **Schema-less:** In NoSQL columns(attributes) can be added in fly. The data can be structured, semi-structured or unstructured. This helps the simulation to cope up new attributes added to the model.
- **Better query performance:** Generally, NoSQL gives better performance over SQL when no relational queries are performed.
- **Object oriented support:** Since NoSQL provides store data without relationship, the object associated with the model can be directly stored with the usage of ORM library (Object-relationship mapping)

The NoSQL data store is a MongoDB instance [82]. MongoDB is a document-oriented database, that stores object models as a document. A document is a key-value pair of the object attributes and its associated data. MongoDB can store huge volumes of data and query without performance degradation when compared to relational databases. It supports good integration with the Elasticsearch engine.

5.3 Search analytics

The most important requirement of a search analytic service is that we envision the ability to access large amount of data in near real-time and agility for data growth and updates. A near real-time search engine with standardized API is its main attraction. Most databases that store large volumes of data, require some sorting, filtering and other such capabilities to segregate and organize that data. Then it can be easily searched and queried. In this case, an offline analysis is the only solution. A simulation application would greatly benefit by the presence of a search analytics service that provides on-going, live support for growing near-real-time data. Such repositories are in practice now.

For example, Elasticsearch used by thousands of organizations worldwide including Netflix, Facebook, GitHub, etc., has such characteristics. Elasticsearch can be used to perform near real-time search, data analytics, and visualization [83]. It is an open source software, and that makes it easier to integrate with any application. In our simulator, we use MongoDB as our database storing all the events occurring during the simulation and Elasticsearch to provide support for data analytics. Each event is associated with a time-stamp and is stored on our servers in Javascript Object Notation (JSON) format. By querying the events using the appropriate message, we can get real-time analysis.

We use Elasticsearch in our proposed framework for the following reasons:

- **Scalability:** When it comes to data analytics on a massive scale, elastic search provides incredible support. Elasticsearch can be run as a single instance or multiple instances and is transparent to other services using it.
- **Visualization:** Elasticsearch provides great visualization capability with the help of Kibana [84]. Kibana provides real-time summary and charting of data. Users can create custom graphs and visualization without the need for programming.
- **RESTful API:** Since Elasticsearch is a RESTful server, the most widely used mode to communicate with it is through its REST API. A client typically opens a connection with the Elasticsearch server, posts a JSON Object as a request

and receives a JSON object as a response. This is very useful because there is no restriction on the type of client, the programming languages used. Any client which can communicate with HTTP requests can communicate with the Elasticsearch server.

5.4 Messaging Middle-ware

There are various standards and protocols for building message-oriented middleware systems. One of the most popular middleware is the Java Messaging Service (JMS) [85]. JMS provides a standard API for the Java platform. JMS also provides many services for interoperability within and outside the Java platform. Integration with other languages such as Ruby, Scala, etc. is possible but very tricky. Therefore, there was this necessity for a messaging standard that will assure interoperability among different platforms and services. AMQP emerged out of this need [86–88]. At the time of writing this thesis, AMQP, and its various open source implementations were in practice in some of the most critical systems running in the world, especially in the financial industry.

AMQP is an important protocol heavily used in recent years. It was developed by John O'Hara of JP Morgan Chase Inc. and is a binary wire transmission protocol. AMQP originated in the financial industry as a solution to the problem of seamlessly connecting different processing platforms together. In order to attain this effortless interoperability, AMQP boasts of a well-defined, structured set of rules or behavior for sending and receiving messages. These rules use a combination of techniques including store and forward, publish and subscribe, peer to peer, request/response, clustering and transaction management among many. Because of these the protocol has become valuable for communication across various operating systems, programming platforms, integration services and hardware devices without compromising on performance and security [88].

RabbitMQ is an open source implementation of the standard AMQP and is written in Erlang [89]. It provides support for all major operating systems and is also available in languages such as Python, Java, Ruby and .NET. RabbitMQ is very extensible and provides a number of plugins to allow communication with other web protocols such as HTTP, XMPP, SMTP and STOMP [88]. A complete list of the advantages and disadvantages of using a message-oriented middleware is discussed in detail here [90].

We use RabbitMQ as our messaging middleware based on the architecture proposed in [91]. It stores messages in queues and acts as a broker between two types of processes, the producers and consumers. There are two core units that form RabbitMQ namely, Queues and Exchanges/Router. In simple terms, every message that is passed through RabbitMQ has to be placed in a queue. The main function of the router is to route the messages from the appropriate producer to the appropriate consumer. Each message consists of a simple header, specifying where it is heading to. The router doesn't read or process the message, it simply delivers the message to the appropriate queues. The consumers, on the other hand, can either subscribe to a particular message or keep polling to see if a message is received. Figure 5.2 shows a simplified architecture of the components involved in the RabbitMQ messaging system [90].

The producers in RabbitMQ generate messages which are then pushed to the exchanges. The exchanges then apply some routing rules on these messages and push each message to the appropriate queues, thus providing a delivery service. The messages can either be directly delivered, or it can be delivered because of an existing subscription system. The routing choices simply depend on the value of the routing key which is available in the header part of the message. This header is constructed by the producer itself. If a particular message is to be sent to more than one queue, then the exchanges take the responsibility of duplicating the message and delivering it to the queues. Consumers always must have a permanent connection with their corresponding exchanges, so that the exchanges may be aware of the exact details of the queues the consumers have subscribed to.

We chose RabbitMQ as our messaging service mainly because of two reasons:

1. It supports a standard messaging protocol (AMQP) because of which we are not confined by any proprietary client-specific messaging protocol.

2. All the messages are collected by the RabbitMQ; this type of message storage pattern is very similar to a push-style data flow. All the messages move from where they are produced to where they are consumed in a fluid manner, without having to periodically pull messages at various end points.

In our simulator, we also have a common queue that stores all incoming messages to all exchanges in their order of arrival. This common queue is what mining repository is subscribed to. All operations inside RabbitMQ are done in memory. All the messages in our simulator are time-stamped and their order is maintained consistently throughout the simulation.

5.5 Simulation Engine

The simulation engine is the heart of the entire framework. The simulation engine uses NetBeans Platform as a base framework and has several modules as shown in Figure 5.3. The components are written as separate NetBeans modules which help us to achieve the goal of separation of concern. In the following sections, each of components is explained in detail.

5.5.1 User Interface Components

Intuitive UI is one of the core design principles of the proposed framework. In this section, we briefly describe the various UI components that the user can interact with and their implementation details. The windowing system used in this framework is provided by the NetBeans platform API.

- **Designer Window :** The designer window, shown in Figure 5.4 is used to design various simulation scenarios. Users can drag/drop grid components from

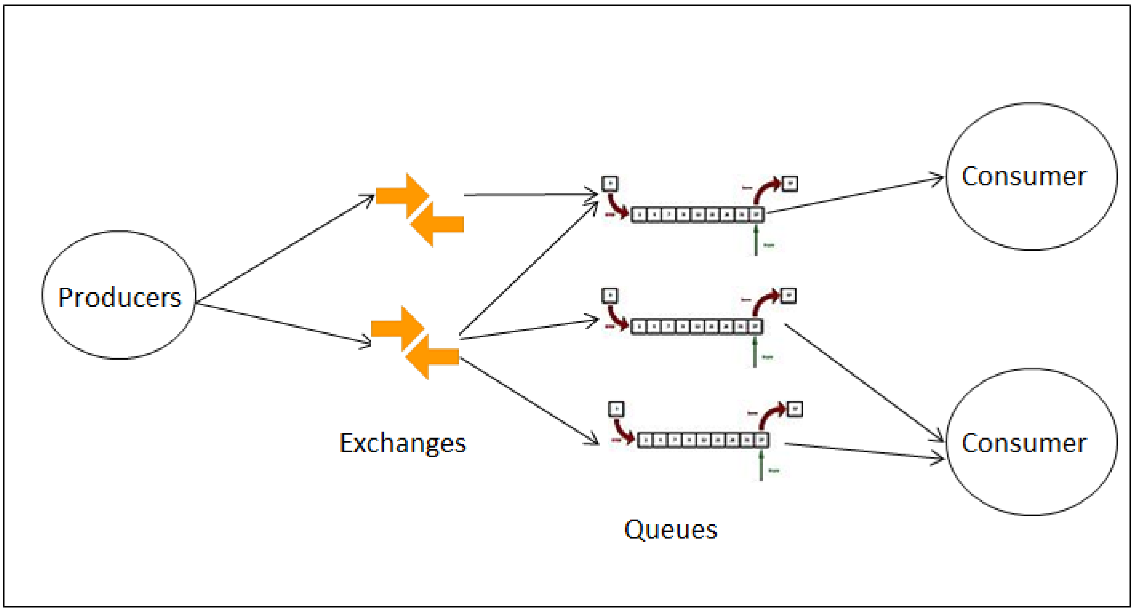

Figure 5.2: RabbitMQ Architecture

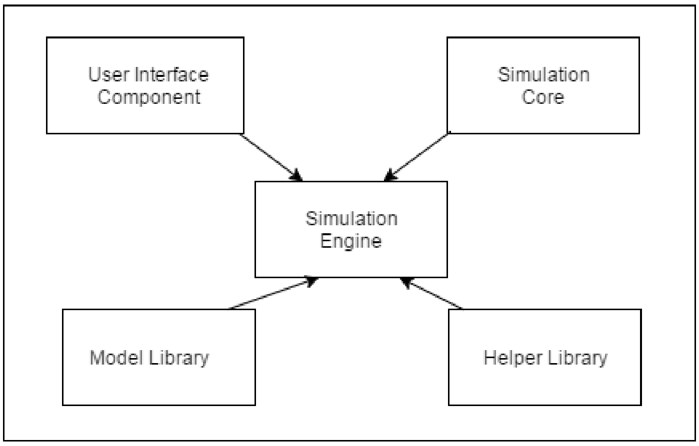

Figure 5.3: Simulation Engine Components

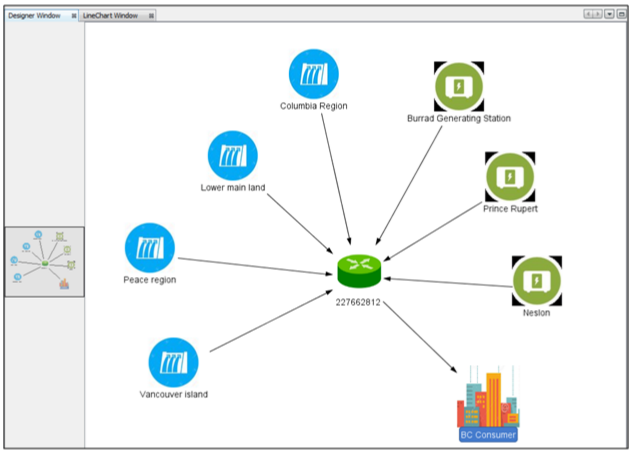

Figure 5.4: Designer Window

the palette window. The components added to the designer window can be removed using context sensitive menu. The components can be connected using edges that represent the flow of electricity. Like components, the edges can be deleted by using the context sensitive menu. The designer window can be zoomed in/out and scrolled. A scenario that is designed can be saved from the options in the file menu. The designer window uses Netbeans platform visual API as the base component. The modeled scenario is converted into a graph data structure using Java Universal Network/Graph Framework (JUNG) [92].

- **Palette Window :** The Palette Window shown in figure 5.5 has various grid components that can be added to the designer window. The user can drag/drop components from the Palette onto the designer window. Each grid component is internally mapped onto a node of a graph data structure and each node is internally mapped to the associated model.

- **Context Sensitive Menu :** Each component added to a designer window provides a context sensitive menu as shown in Figure 5.6. The context menu can be opened by right clicking on a particular grid component. The delete node is used to delete a particular node and properties is used to open up a property window for that particular node.

- **Property window :** The property window, shown in Figure 5.7 is used to edit

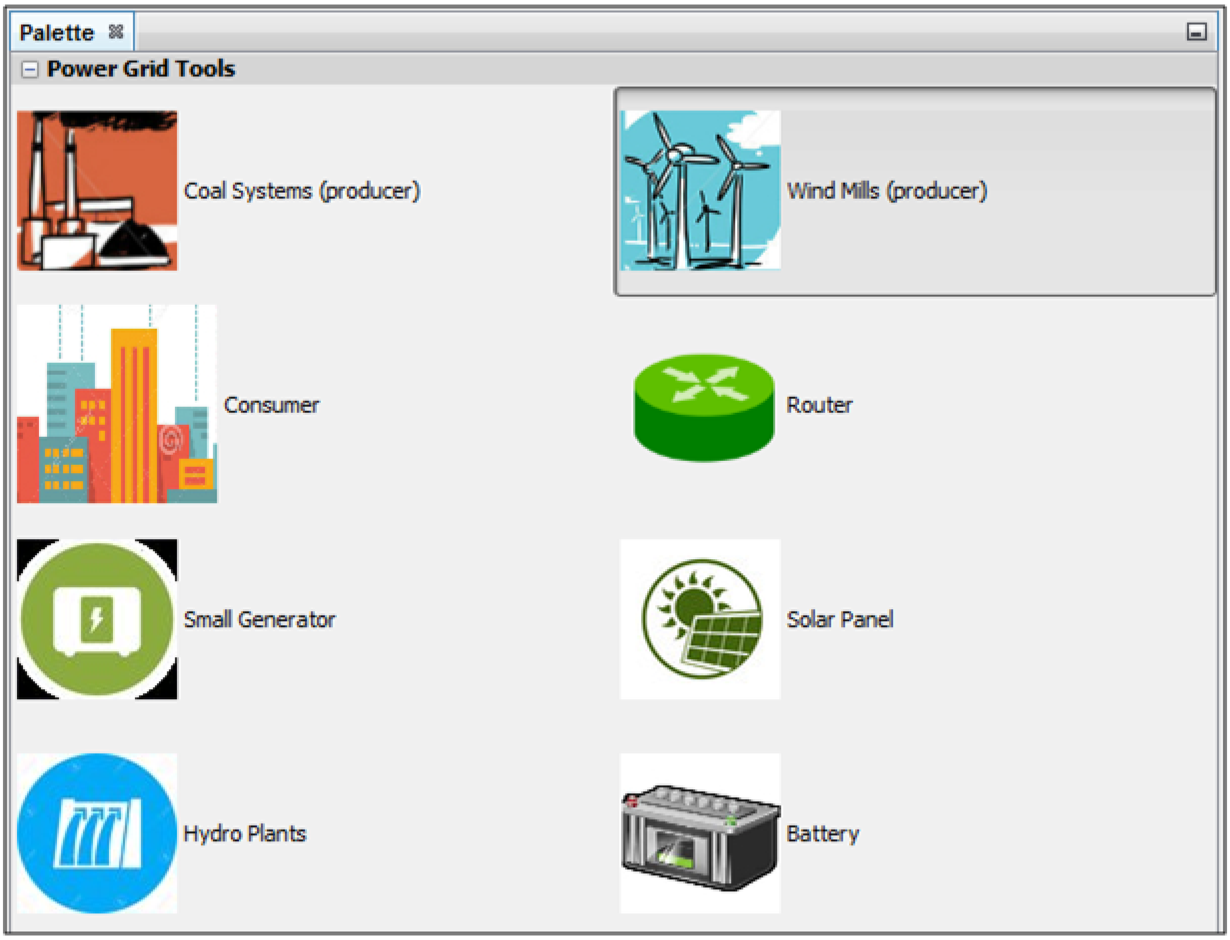

Figure 5.5: Palette Window

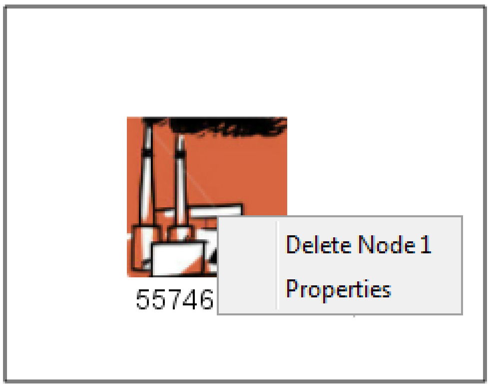

Figure 5.6: Context Sensitive Menu

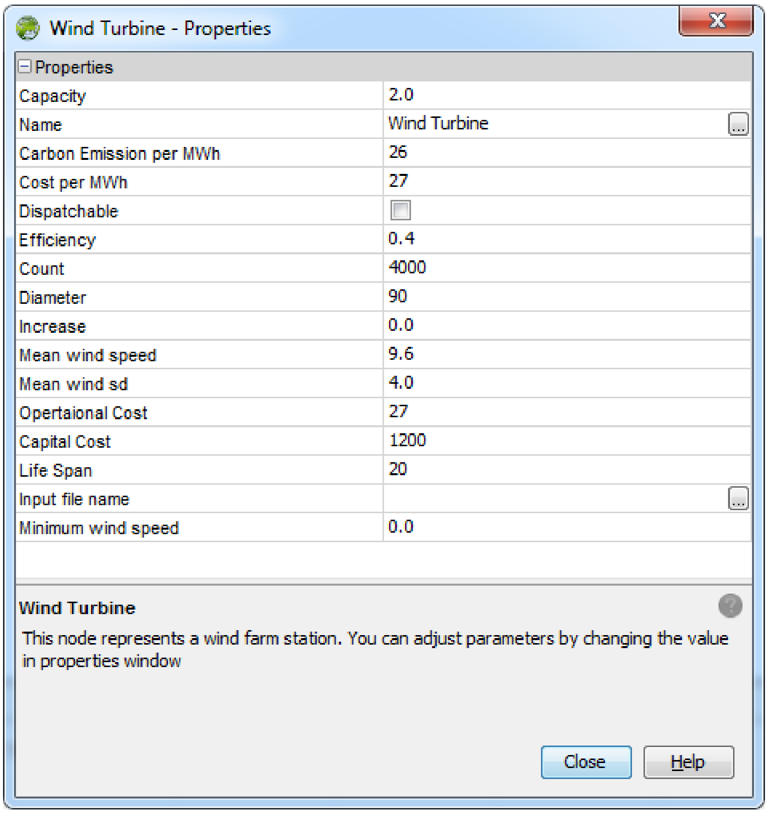

Figure 5.7: Property Window

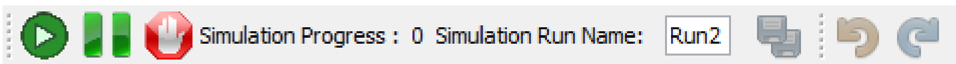

Figure 5.8: Toolbar

properties associated with a particular grid component . There is a default value for each attribute associated with the model. The user can use the property window to edit the property of a particular model.

- **Toolbar :** The toolbar shown in Figure 5.8 is used to control the start, stop and pause the simulation. It has control to save the current scenario.

5.5.2 Model Library

The model library is a separate NetBeans module that stores the details of various models of grid components. The models are Java classes that can be exported as a package to be used with other simulation tools. New components/models can be added to the library by extending the various interfaces provided in the package. The details of models are described in the next chapter. The model library also has a package for "control strategy" that can be associated with a distribution station (Routers). A new control strategy can be attended if the user wants to extend the framework.

5.5.3 Helper Library

The helper library contains helper functions for the simulation framework. It has helper methods to Read/Write JSON files. It also provides necessary support for object serialization/de-serialization. It has functions for connecting with Elasticsearch, RabbitMQ and query their status.

5.5.4 Simulation Core

The simulation core is the run time that performs the simulation. The simulation engine is based on time-stepped simulation. The simulation core initializes the simulation by reading the configuration files. It checks the status of various services before performing the simulation. It is also responsible for capturing the state generated by the model and passing it to the data store service.

At each time step, the model's particular method defined in the interface is called by the simulation core. The simulation core accesses the model based on the control strategy defined by the user. The simulation core performs the simulation for the time scale given in the input configuration file. The scale can vary from hourly to years. The input attributes required for simulating various time-scale should be provided by the model.

5.6 User Manual

We provide a brief overview of the system requirements for GridSim, followed a user manual. We also provide an overview of the software layout for development

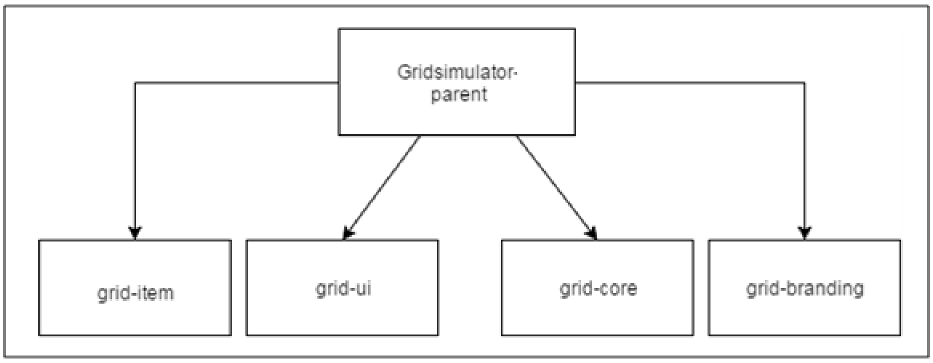

Figure 5.9: GridSim NetBeans module

purposes.

5.6.1 System requirements

The GridSim was tested with the following configuration in Windows 7 and Mac OSX:

System requirements: 1 GB Ram, 2.2 GHz processor.

Software requirement: RabbitMQ, Elasticsearch, Kibana, JRE or JDK 1.8 (JDK for development), Eclipse/ Netbeans and Maven(for development)

5.6.2 Working with GridSim

The simulator package comes with an installer for Mac OSX and Windows. Before running the simulator, the configuration file /resource/configuration.properties needs to be edited. The properties in the file should point to URLs of RabbitMQ and Elasticsearch. Once setup, the simulator can be launched by doubling the GridSim.exe (which in turn invokes .jar files). The following steps are involved in performing a simulation using the GridSim for integration study.

1. First, the user has to input the data and set the parameters necessary for a particular scenario. For example to perform integration study of wind energy into the existing grid system, he/she needs to collect data related to wind patterns

and speeds for the particular location.

2. Next, the user can use the designer window to design the scenario. The user can drag and drop various grid components from the palette window. At least one producer, consumer, and control unit should be part of the designed scenario.

3. The user then needs to open the property of the particular components whose properties the user wishes to edit. For example if the user wants to change the input file for the wind speed, he/she needs to right- click on the windmill icon in the designer window and then select edit. The property window will open. He/She can enter the location of the wind speed data file for the windmill.

4. Once the parameters have been set, he/she can then press the Run button on the simulation toolbar. Once the simulation has been completed, he can view the result in Kibana.

5. Kibana has several pre-written queries that can be used to visualize the results.

This is the typical workflow for a user. However, there can be other tasks involved which can alter the workflow.

5.6.3 Software Organisation

The project is composed of four NetBeans modules, shown in the Figure 5.9, each implementing a particular functionality of the simulation tool. The pom.xml has all the required dependencies to begin development. All the grid component models are located in the grid-item NetBeans module. The grid-item module is a separate NetBeans module that stores the details of various models of grid components and helper library. The models are Java classes that can be exported as a package to be used with other simulation tools. New components/models can be added to the library by extending the various interface provided in the package. The model library also has a package called control unit which has all the control strategies.

A new control strategy can be attended if the user wants to extend the simulation tool. It has helper functions for parsing JSON data, serialization/deserialization of JSON data. The helper library contains all the helper functions for the simulation tool. It has helper methods to Read/Write JSON files. It also provides necessary support for object serialization/de-serialization. It has functions for connecting with Elasticsearch, RabbitMQ and queries their status. Grid-UI modules contain all the required UI components of the simulation tool including designer windows, graphs, toolbars and configuration settings window. The Grid-core module contains the core of the simulation tool which includes the simulation engine.

5.7 Summary

In this chapter, We examined in detail the various backend components of GridSim namely the simulation engine, the middleware, and various UI available to interact with the tool. We also provide a small user manual that can be used as a guide for operating the software.

Chapter 6

GridSim: Simulation and Analysis

In this chapter, we present a few integration studies that we conducted using GridSim to illustrate its use. We chose the province of British Columbia (BC) in Canada and Tamil Nadu (TN) in India for this demonstration study. The rationale for choosing these provinces is that both of them have some interesting similarities and differences. For example, they are similar in terms of energy production and consumption, but very different in climatic conditions. BC has a cold climatic condition, whereas TN has a hot climatic condition. BC's bulk of the energy production comes from Hydro (renewable energy), and TN has the highest installed wind capacity in India, at 40 % of the total India's renewable energy [93]. However, TN's bulk of the energy production comes from the thermal power plant that uses coal as the energy source. These similarities and differences made us choose these two provinces as the candidates for integration study.

The primary objective of this study is to estimate the amount of GHG emitted for the provinces of BC and TN for the 2015 and future. We also performed integration of renewable energy like the wind into BC's energy system and measured the GHG emissions, cost and feasibility. To be more specific, we have devised the following question for the province of BC and TN that we would like to answer using our simulator[1].

- What is the current amount of GHG emission with the present capacity of energy generation and consumption for BC and TN?
- What will the GHG emission trend be with respect to the increase in energy consumption for BC and TN?
- It is predicted that BC's energy demand will grow by 40% by the year 2035 [15] and TN's by 500% in the next 35 years [94]. What will the GHG emission be for the predicted increase in energy consumption?
- Suppose consumer electronics become intelligent and schedule their energy consumption(smart grids) to reduce the peak demand. What will be its effect on GHG emissions for BC?
- What will be the GHG emission if the CCGT is replaced with wind turbines in the year 2035 for BC?
- What will be the cost of electricity with the various class of wind farms for BC?

6.1 Scenario Assumptions

We use a simple electricity model [11]. The following assumptions are made to perform the simulation. These assumptions are not the limitations of our simulation tool.

- The cost and power loss associated with transmissions is set to zero.
- The temporal resolution used for wind and load data is 1 hour.
- The simulation does not take into account the reliability and technical constraint aspects of the power grid.

[1]The simulation experiments were performed only for demonstration of GridSim.

- The simulation time span used is one year.
- A control strategy that will optimize the dispatch order that will produce the least carbon emission was used.
- The direction of the wind was not considered, and it is assumed that the wind direction is always perpendicular to the wind turbines. This is a valid assumption as modern wind turbines have a yaw drive which orients the wind turbine into the wind direction.

6.2 Model Parameters

The parameters for our simulation are given in Table 6.1.

Technology	**Carbon Emission in Kg per MWh**	**Cost per MWh ($)**	**Capacity factor (Mean)**	**Capacity factor (Standar deviation)**
Coal Station	800	95	0.75	0.2
Nuclear Station	29	95	0.9	0.1
Diesel (Peaking power plant)	800	220	NA	NA
CCGT	400	79	NA	NA
Hydro	26	74	0.5	0.2
Wind turbine	26	operational - 27, capital - 1200	NA	NA

Table 6.1: Parameters for energy producers

Due to unavailability of model parameters specific to countries[2], the parameters were obtained from the US government website [77] and [95] and may vary between countries. All the costs specified are LCOE expect for wind turbines. The wind turbine cost is specified as capital and operational cost. The life expectancy of the wind turbine was set to 20 years [96].

[2]The choice of parameters affects the accuracy of experiments

BC site name	**Type**	**Capacity MW**
Columbia Region	Hydro	5946
Lower main land and coast	Hydro	1997
Peace region	Hydro	3424
Vancouver island	Hydro	459
Burrard Generating Station	CCGT	950
Prince Rupert	CCGT	46
Fort Nelson	CCGT	73
Total		12895

Table 6.2: BC production capacity [15]

6.3 BC's Power Grid System

British Columbia (BC) is a beautiful western province in Canada with a population of more than 4 million people. Currently, the primary source of energy in BC is hydropower plants, and there are five primary sites that generate electricity. The additional requirement for energy is met using a peaking power station or imported from other provinces. The current generating capacity of BC is 12895 MW [15]. Table 6.2 shows the generating capacity of the various plants in BC. The Columbia region has the highest capacity of hydro with 5946 MW, followed by the Peace region. The CCGT generators are split into three regions and are operated only when the hydropower plants cannot meet the energy demand.

The hydropower plant capacity is 11826 MW and CCGT capacity is 1069 MW which contributes 8% of the total generating capacity. The hydropower plants are non-dispatchable, and CCGT acts as the peaking power plant.The capacity factor of hydropower plant was set to a Gaussian distribution with mean 0.5 and standard deviation of 0.2. The value was derived from the assumption that a 11826 MW hydropower plant produces an average of 48000 GWh of electrical energy per year [15].

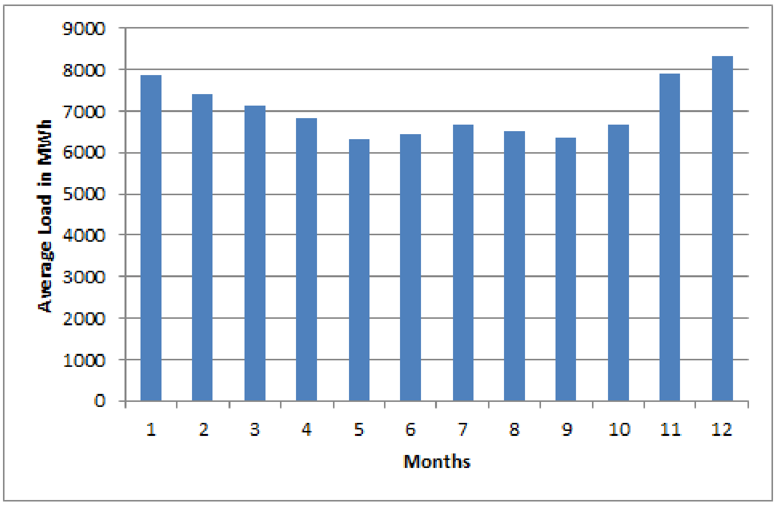

Figure 6.1: Histogram of monthly consumption for the year 2015

6.4 Data and simulation experiments for BC

Although the simulation can take any valid input parameters for simulation, we use historical wind and load data to build the scenario. This helps us to perform a valid integration study on BC's power grid system.

- **Load Data:** The load data was obtained from BC Hydro, a main electric distributor [97] for the province of BC, for the year 2015(Jan-Dec) and averaged over a period of one hour. The BC load data has consumption for 8760 hours as an excel sheet. The file was converted into CSV(Comma- Separated Values) and then into JSON format. Although the simulator supports CSV format, JSON is preferred as it maps to and from objects with much more convenience.

  The BC power consumption on a monthly basis is shown in Figure 6.1. The average consumption per day is 168897 MWh, and total consumption is 61,647,759 MWh, which is approximately 61,648 GWh. The consumption is high in the month of January and December; it gradually decreases towards the middle of the year. This is mainly due to cold winters, where heating of indoor spaces becomes a necessity. In the month of July, the increase in consumption can be attributed to the use of air conditioners.

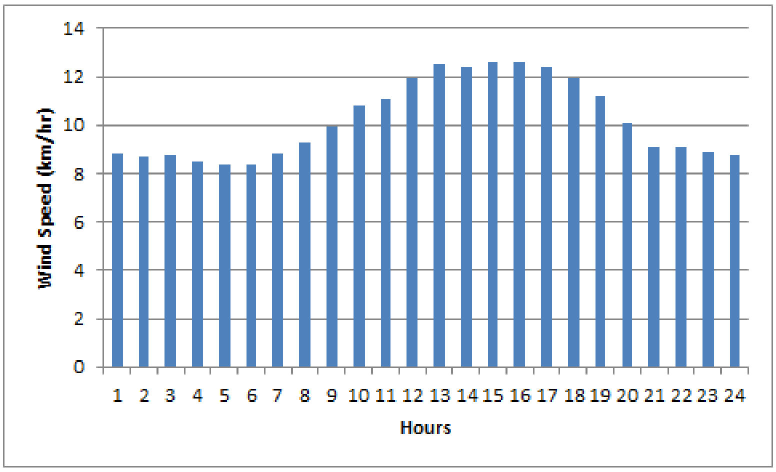

Figure 6.2: Histogram of Prince George hourly wind speed for the year 2015

- **Wind Data:** The wind data was obtained from Environment Canada [98] for the city of Prince George (PG)[3]. The data contains monthly wind data for 2015(Jan-Dec) which is averaged hourly. The data for several months was aggregated into JSON file. Since air density values were not available,the air density was set to the standard value of 1.225 kg/m^3.

  As per the wind data of Prince George, the average wind speed is 10 km/h. An average of 10 km/h qualifies Prince George to be in the class 1 category of wind classification [99]. The hourly average wind speed, shown in figure 6.2, is high during 11 to 18 hours of a day which coincides with the peak demand of BC.

6.4.1 Experiment 1

In Experiment 1, we would like to answer the following question *"What is the GHG emissions share with current capacity of British Columbia (BC) and load data?"* The GHG emission and cost per MWh for the year 2015 was estimated by running a simulation using GridSim. The simulation parameters given in Table 6.1 were used and were derived from [12], [95], and [100] . Figure 6.3 shows the relative contribution of GHG emission and electrical energy produced. The CCGT produces only 12% of

[3]The city of Prince George is considered a wind shadow. Accurate simulation should use wind data at the erection site.

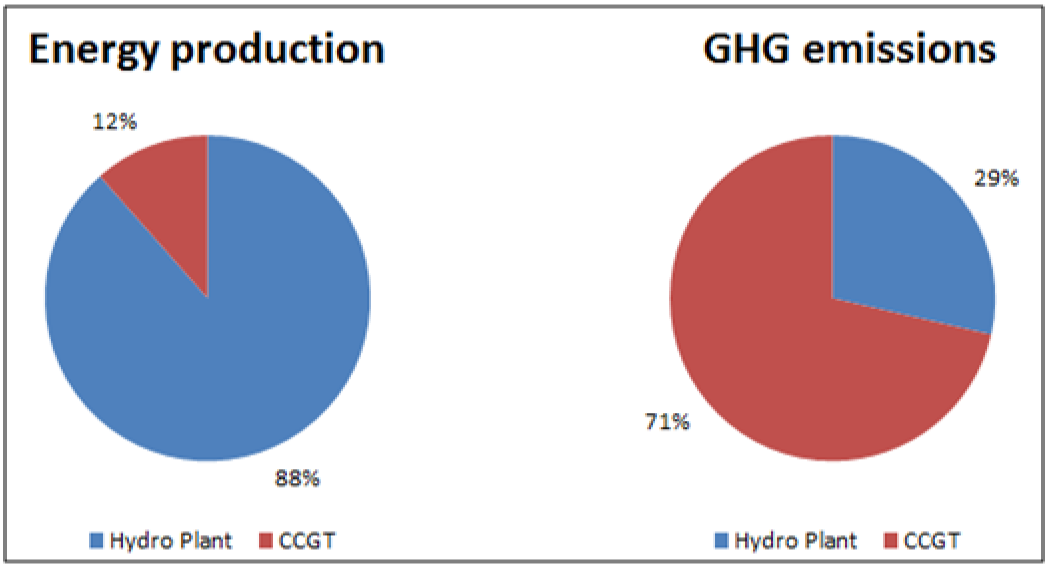

Figure 6.3: Electrical energy produced and GHG emissions in 2015 with hydro plant and CCGT

the total energy but emits 71% of the total GHG emissions. The average cost per MWh of electrical energy was estimated to be \$ 71.5.

6.4.2 Experiment 2

In Experiment 2, we would like to answer the following question *"What will be the GHG emission trend with respect to the increasing energy consumption?"* To estimate the emission trend of GHG with respect to increase in energy demand, a simulation using parameters given in Table 6.1 was performed by increasing the energy consumption from 0 to 40%. The capacity of CCGT is set to -1 to match any increase in energy demand. Figure 6.4 shows the carbon emission trend with respect to increase in energy consumption. The steep increase in GHG emission, when there is 5% increase in energy demand, causes a relative increase in the use of CCGT to meet the additional energy demand. Also, the amount of GHG emissions doubles when there is a 10% increase in energy consumption.

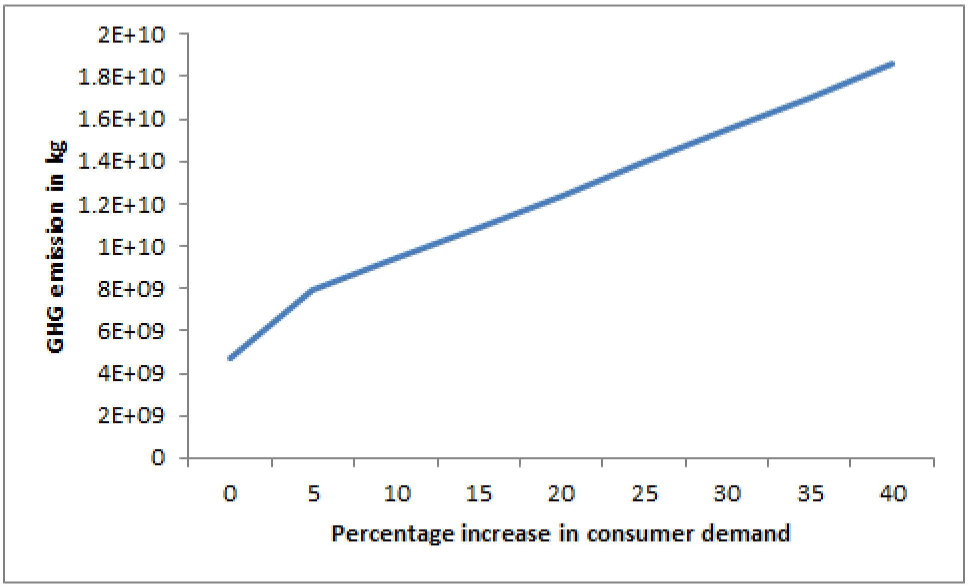

Figure 6.4: Increase in energy demand Vs. GHG emission

6.4.3 Experiment 3

In Experiment 3, we would like to answer the following question *"What will be the GHG emission in 2035 when additional energy demands(40% increase) is met with additional hydro plants and CCGT?"* To answer this question, we ran the simulation with 40% increase in energy demand. We included future energy projects of BC Hydro which consist of two turbines of 500 MW for Mica Dam and 1100 MW for Peace River. We assume that the CCGT is used to generate the remaining energy requirements, and its capacity will increase to 2000 MW. The mean of capacity factor of the hydropower plant was increased to 0.6 to compensate for technological advancements in the hydropower plant. Also, the carbon emission associated with CCGT was reduced to 350 kg per MWh. These parameters were derived from [12], [95] and [100].

The simulation result for 40% load increase is shown in Figure 6.5. The hydropower plant contribution to the total energy generated is reduced to 84% and accounts for 25% of carbon emission. The CCGT emits 75% of the total GHG emissions. The average cost per MWh of electrical energy is increased to $77. The carbon emission has increased by 60% from 2015 to 2035.

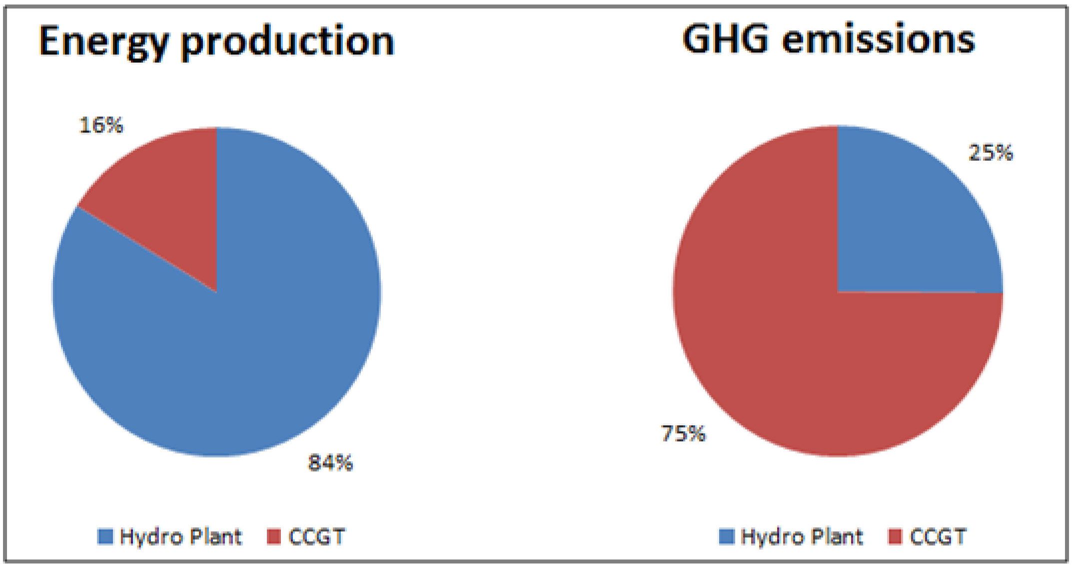

Figure 6.5: Electrical energy produced and GHG emissions in 2035 with hydro plant and CCGT

6.4.4 Experiment 4

In experiment 4, we would answer the question *"What will be the impact of efficient scheduling of consumer demand(smart grid) on carbon emission?"* This experiment was designed to demonstrate the importance of scheduling the load to decrease energy consumption. To answer this question, we simulated this scenario by using a Gaussian distribution for consumer load with mean 9852 MWh and standard deviation of 1000 MWh. The mean was obtained from BC's load data with 40% increase in energy demand. The simulation estimates a 7.5% decrease in carbon emissions when compared estimated GHG emissions in 2035 without scheduling.

6.4.5 Experiment 5

In experiment 5, we would answer the question - *"Suppose, BC Hydro plans to replace the CCGT with wind energy to reduce carbon emission. What will be the reduction in emission? What will be the cost of electrical energy?"* To answer these questions, a simulation with wind farms replacing CCGT was performed.

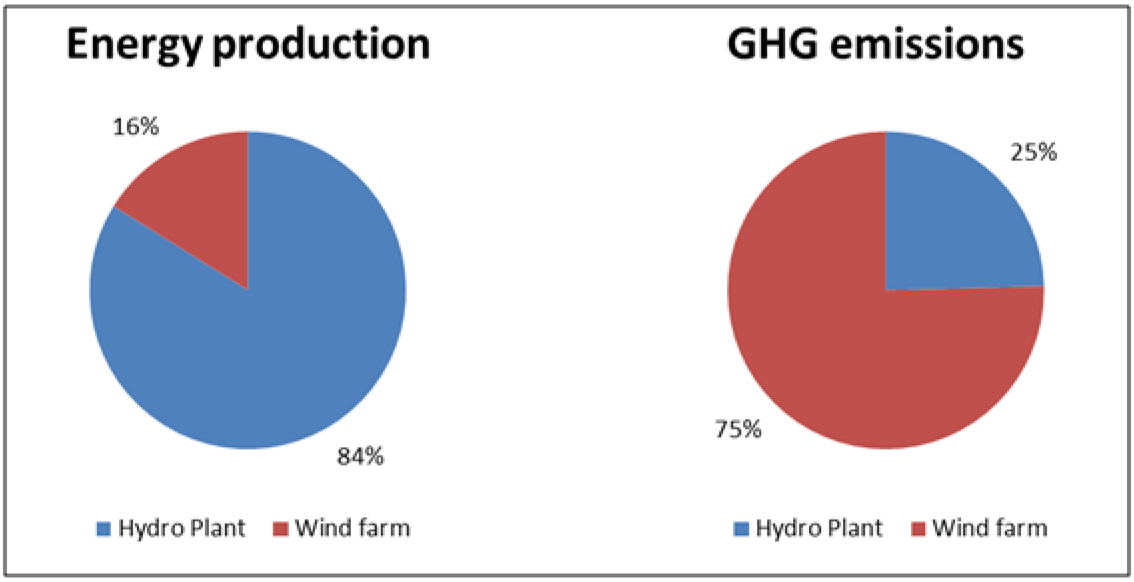

Figure 6.6: Electrical energy produced and GHG emissions in 2035 with hydro plant and wind farms at class 1 location

An initial simulation was conducted to estimate the average power that can be produced with a 2 MW (90 m rotor diameter) wind turbine. The efficiency of the wind turbine was set to 0.4. This simulation helped to estimate the amount of wind energy capacity required to replace the CCGT of 2000 MW. The average power that can be produced from the available wind data was estimated to be 157 kW. So to replace the 2000 MW CCGT, approximately 12800 wind turbines are required. The wind turbines are not dispatchable and any excess energy produced is curtailed.

The simulation result for replacing 2000 MW CCGT power plant with wind turbines is shown in Figure 6.6. The percentage of energy produced from wind farms is 16% but emit 75% of carbon emission. Also, the amount of GHG emission is about 2% more than the using CCGT. This can be mainly attributed to the poor wind speed. The average cost per MWh of electrical energy is increased to $257. This makes wind energy unfavorable for replacing CCGT. Figure 6.7 shows the comparison GHG emissions using various technologies. The bar graph compares the current emission(2015) to the predicted total emissions of 2035 using various strategies. Meeting the future energy demand with CCGT alone produces the most GHG emissions,

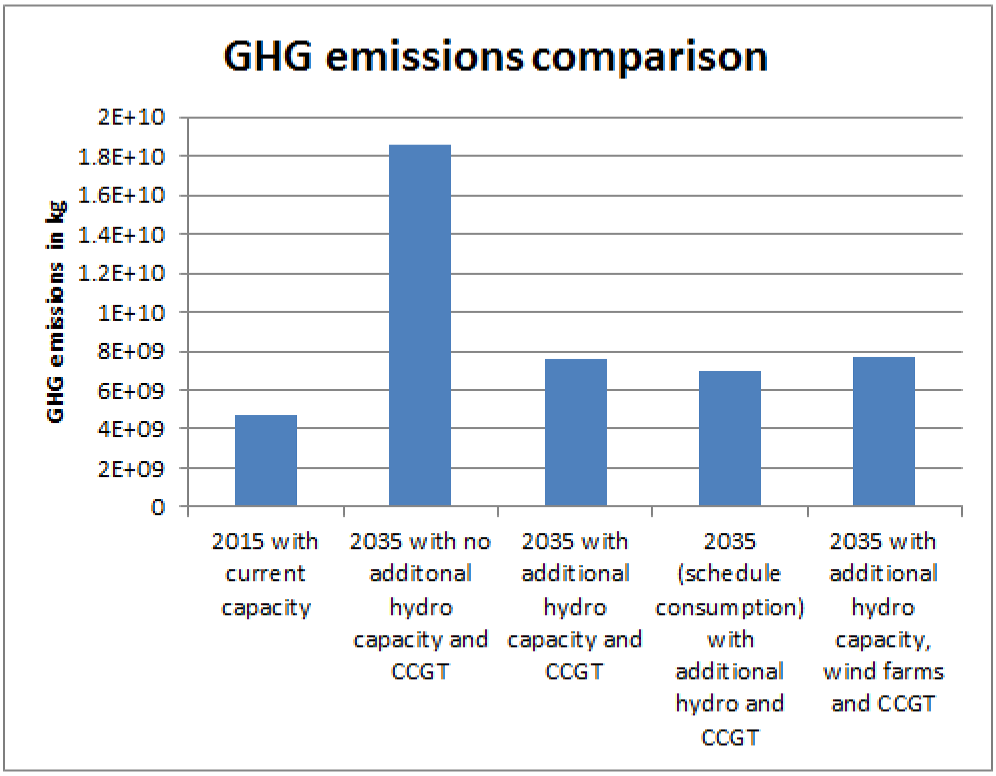

Figure 6.7: GHG emission comparison for the year 2035 with different technologies.

followed by wind turbines. The fact that emissions are higher for wind turbine is due to poor quality of wind available in siting area, so additional energy needs should be compensated using CCGT. The scheduling of energy consumption in the consumer end produces the least carbon emission for 2035. Also, the amount of GHG emission increases from 2015 to 2035 by at least 60% .

6.4.6 Experiment 6

In experiment 6, we would answer the question *"What will be the cost of electrical energy and reduction in carbon emission if average wind speed is in class 7 wind classification (7.5 m/s)?"* Although wind speeds in siting location cannot be changed, these experiments help us to understand the sensitivity of unit cost of electricity(per MWh) to the siting location of wind turbines. In order to answer this question, we need to convert current wind speed data into class 7 wind speed data. To convert the wind speed data to class 7, we need an average increase of 170% in wind speed

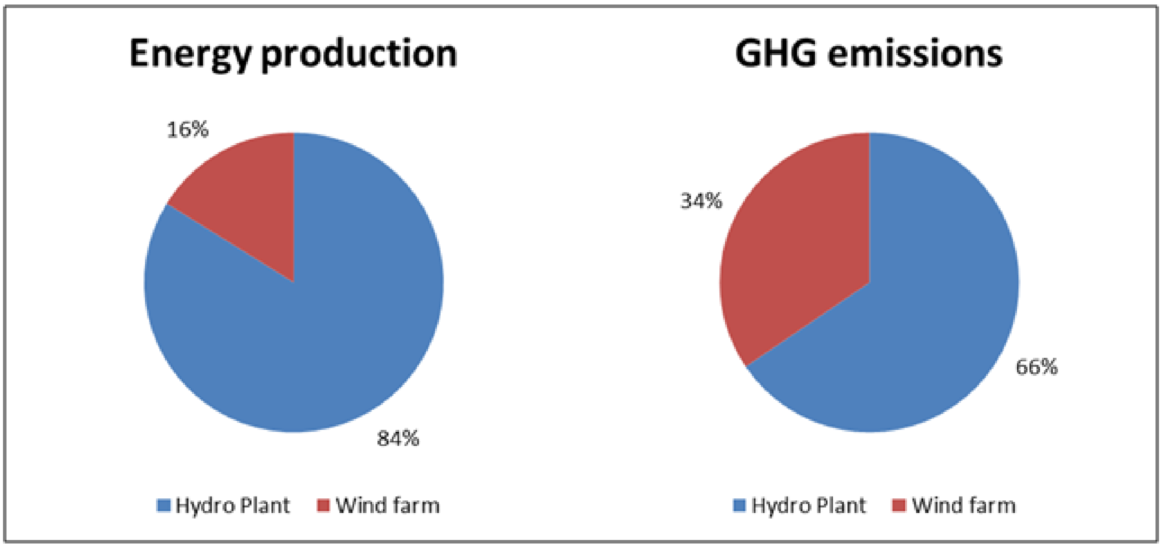

Figure 6.8: Electrical energy produced and GHG emissions in 2035 with CCGT and wind farms at a class 7 location.

(computed manually). The new data generated from existing wind data has an average of 7.5 m/s wind speed which is highly favorable for wind turbines installation. An initial simulation was done to estimate the average power that can be produced with a 2 MW (90 m rotor diameter) wind turbine. The efficiency of the wind turbine was set to 0.4. The average power that can be generated from the available wind is 909 KW. So to replace the 2000 MW CCGT power plant will require approximately 2000 wind turbine.

The simulation result for replacing 2000 MW CCGT power plant with wind turbines at a class 7 location is shown in Figure 6.8. The percentage of energy produced from the wind farm is 16% and emits 36% of carbon emission. Also, the amount of GHG emission is decreased by 61% when compared to using CCGT. This is mainly due to favourable wind speed. The average cost per MWh of electrical energy is increased to $96 when compared to $77 using CCGT due to a high capital cost of installing wind turbines. A class 7 wind location makes wind energy highly favorable for replacement of CCGT.

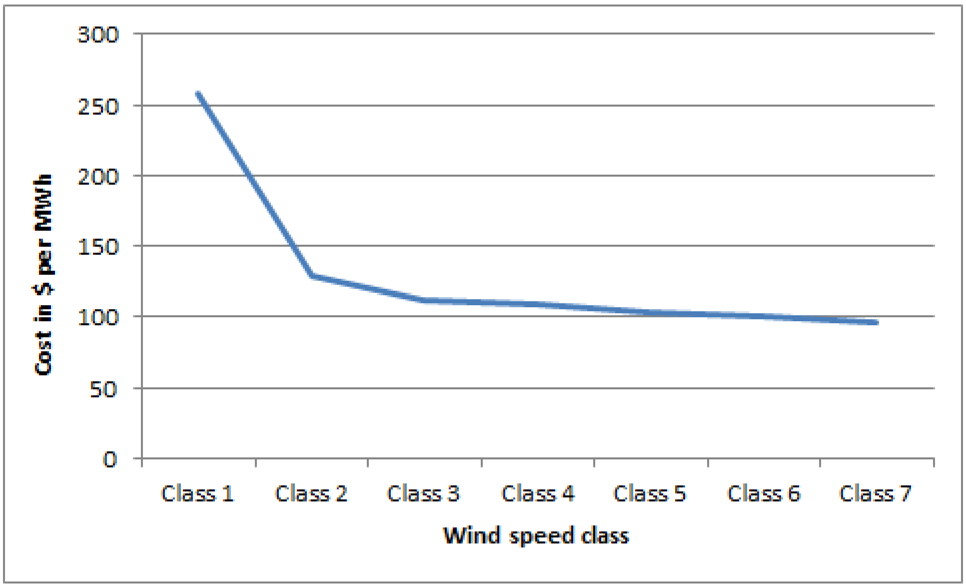

Figure 6.9: Cost per MWh vs wind speed class

We also ran experiments to estimate the cost of electricity with the various classes of wind speeds. The electricity cost declines as the wind class level increases as shown in the Figure 6.9 . The cost is very high when wind farms are located at class 1 location since the power generated per wind turbine is less and more wind turbines need to be installed to meet the energy demand. The cost remains almost constant ($100 per MWh) from class 4 to class 7 due to curtailment of excess energy produced during high-speed wind.

6.4.7 Implication

BC Hydro plans to meet the future energy demand using hydro capacity, and it claims that this plan will be environmental friendly. However, the simulation results expose the inconsistency of the claim in that there is a more than 60% increase in carbon emission from the year 2015. Since the bulk of GHG is emitted from CCGT which is only operated during peak energy demand, better scheduling of consumer load is a good option for BC as shown by the result in experiment 4. Integration of wind energy in BC is not a good option if the wind speed available is less than class 2. Replacing CCGT with other renewable energy can cause a further decrease in energy

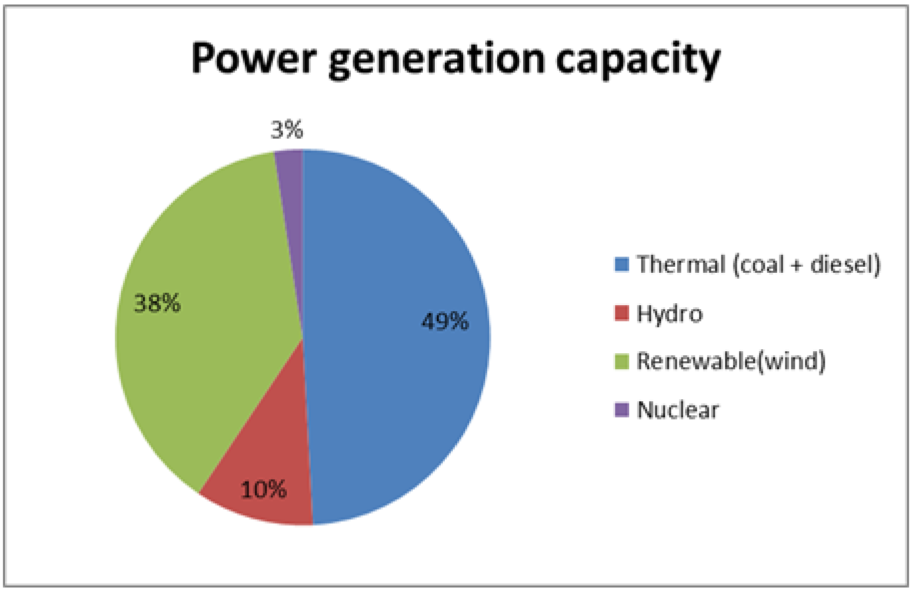

Figure 6.10: TN's power generation capacity share

demand, but the cost of electricity may increase.

6.5 TN's Power Grid System

Tamil Nadu is one of the 29 states of India located in the south with a population of 77 Million and has an area of 130,060 square km. The main source of power generation in TN is thermal coal-fired power plants. The capacity of thermal power plants is 10411 MW (coal station + diesel peaking power plant) followed by wind energy with a capacity of 8000 MW [93]. The installed capacity of hydro is 2182 MW and nuclear is 900 MW. Figure 6.10 shows the relative contribution of each power generation technology to total generation capacity. Tamil Nadu has the largest renewable energy resource compared to any other state in India.

6.5.1 Data and simulation experiments for TN

The data for the simulation of scenarios in TN was obtained from the government of Tamil Nadu website TEDA [93] and the book titled "A Roadmap to Tamil Nadu's Electricity Demand-Supply by 2050" [94]. Since the hourly load data was not available, the values were generated from a Gaussian distribution from Table 6.3. The

Year	Average Consumption in MWh	Peak Load (MW)	Variance
2016-2017	12500	19000	3250
2021-2022	18000	26330	4165
2030-2031	27104	34270	3583
2040-2041	48539	61370	6415.5
2050-2051	86926	109900	11487

Table 6.3: TN's average consumption and peak load

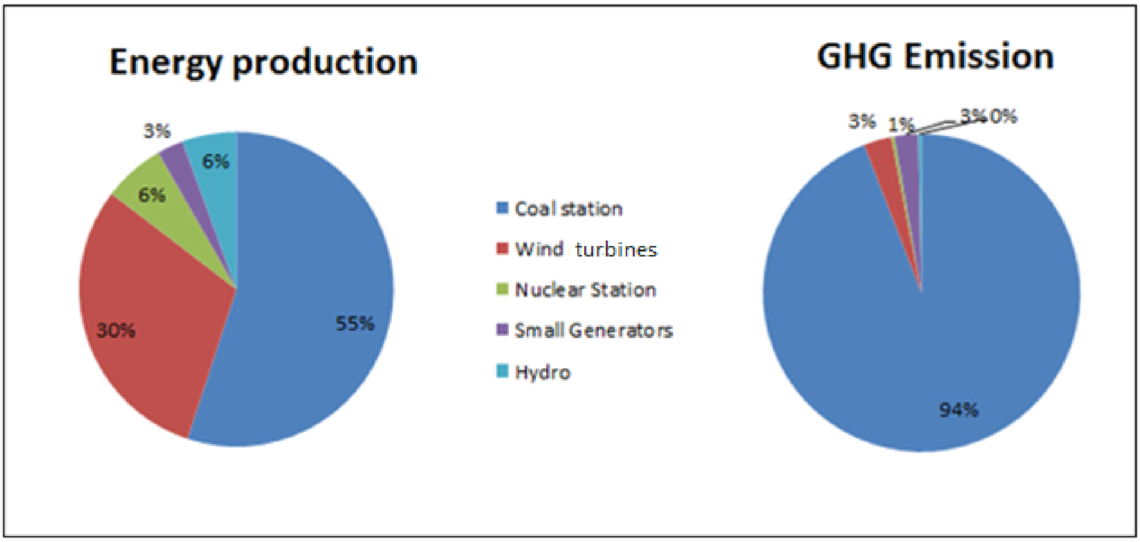

Figure 6.11: TN's energy and GHG share

data was derived from [94].The mean for Gaussian distribution was set to average consumption per hour, and the variance in energy consumption was assumed to be half of the difference between average energy consumption and peak load.

6.5.2 Experiment 7

In this experiment, we have answered the following question: "What is the actual contribution of each energy source to the total production and their GHG emissions?" The percentage of energy production from various sources and their contribution to GHG emission is shown in Figure 6.11.

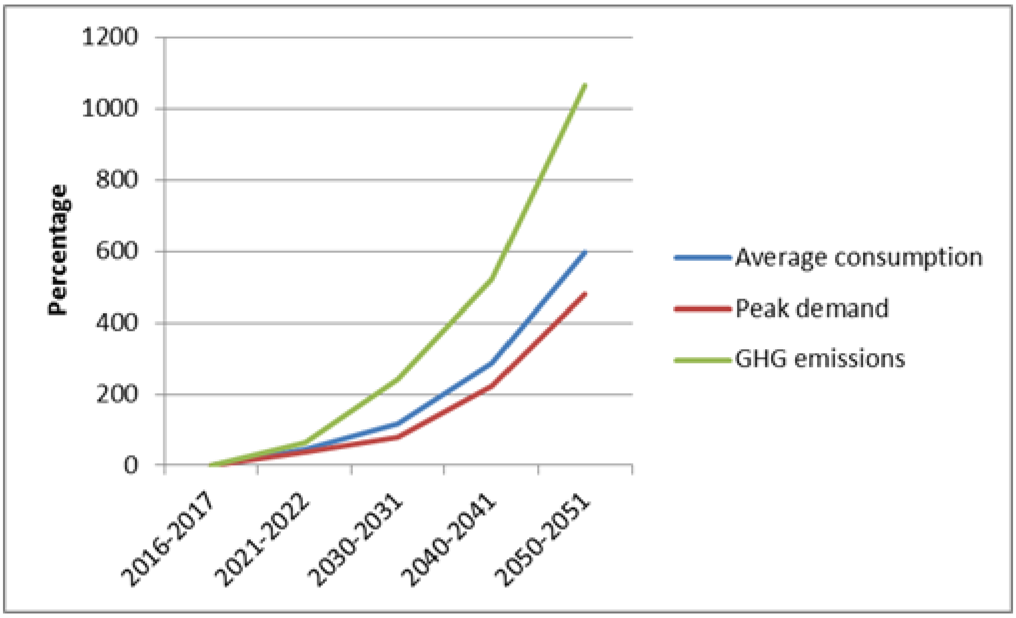

Figure 6.12: TN's GHG trend for 2050

The result shows that the coal station contributes to 94% GHG emission but only 55% to the total energy production. Although the installed capacity of wind is 38%, it contributes only 30% to the total energy production due to variability associated with the wind. The GHG associated with the wind and small generators (peaking power plant) is 3%. The simulation estimates that the GHG emission of TN is 1200% more than GHG emission of BC.

6.5.3 Experiment 8

In this experiment, we will answer the following question: "What would be the future GHG emission if the same proportion of technology was used to meet future energy demand?" This experiment provides future insight into the GHG emission for the state of Tamil Nadu. The input for consumer demand was obtained from Table 6.3. The average consumption per hour was obtained from the total predicted energy consumption for various years. The variance associated with the energy consumption was calculated at one-half of the difference between peak load and average consumption. The result of the experiment is shown in 6.12.

The increase in the percentage of GHG emission with respect to average consumption increase and peak demand increase is shown in Figure 6.12. Although the initial increase in energy demand does not cause a huge difference in the increase in GHG emission, there is a significant difference from the year 2040. This can be mainly attributed to heavy dependence the coal-powered thermal power plant to meet the future energy demand.

6.5.4 Implications

TN's heavy dependence on coal is a severe threat to the environment in the future. Due to a growing economy of the state, there is a 500% increase in energy demand in 2050. This will cause the GHG emission to increase by 1200%. Proper scheduling of the load will have a small impact in GHG emission, yet, in our view, it is an important step in reducing GHG. Since the impact of GHG emission is very severe on environment and health, the government should take all necessary actions to meet the future energy demand in an environmentally friendly manner. With the availability of stable sunlight for about 8 hours a day throughout the year and to some extended guaranteed wind power most of the year, Tamil Nadu is in a very good position to become a self-sufficient green energy state. Economically, it can bring jobs related to green energy production and management.

6.6 Summary

In this chapter, we demonstrate the use of GridSim on real world data. We predicted the carbon emission for the future and performed wind energy integration studies using existing and simulated wind speed data for the province of BC and Tamil Nadu. The above experiments, we believe, demonstrated some of the capability and use cases of our tool. Similarly, with carefully designed experiments GridSim can answer most of the questions discussed in Chapter 1, section 1.7.

Chapter 7

Conclusion and Future Directions

This chapter provides the summary of research presented in this thesis. The main contribution of the thesis is GridSim that can be used to perform grid integration studies. We, then, discuss some of the limitations of GridSim and future directions for improving it. Finally, I reflect on my research experience at UNBC.

7.1 Summary of the Research

The primary research objective of this thesis has been to develop a simulation tool for grid integration, which we believe could be useful to answer some of the "big questions" that we listed in Chapter 1. I soon realized that it is more challenging than we initially thought. It required a good understanding of the three fields – computer science, modeling and simulation, and grid systems. For grid systems, I had to understand the current trends in energy production, electrical power grid technologies, and its impact on the environment such as GHG emissions. I also had to carefully investigate various tools and frameworks available for electrical grid modeling and simulation and understand their use and limitations. With that knowledge, I started to prepare the requirement specification document. At this stage, the main challenge was getting the specification for the "right software framework" for modeling and simulation of grid system intended for grid integration study.

Once I decided on my thesis topic, I started to think about what kind of software framework I ultimately wanted to design and implement. I started with the analysis of the system, and that provided several key insights into the design aspects of the system. It included research into the existing trend of software development and technologies that can help to achieve the design goals of the framework. Design goals were used to narrow down the choice of the software technologies (language, middleware, database, etc.) that we used to design and implement GridSim. The implementation phase of the framework included a detailed study of grid components and their characteristics. Finally, we had to demonstrate the use of GridSim for some real scenario.

The selection of case studies also involved some research and investigation. We chose two provinces – one from Canada and one from India. The rationale for the selection was given in the Simulation chapter. The thesis presented a very limited case study. GridSim is powerful enough to model and simulate more complex scenarios. However, as is the case with any software framework and tool, GridSim can be improved and expanded in several ways. We have listed some limitations here. Currently, GridSim:

- Does not support all types of grid components. For example, it supports only one type of storage technology.
- Models its components only at coarse-grained level. The accuracy of modeling the components could be improved by incorporating the primitives necessary for fine-grained modeling. This would closely reflect the real system. For example, nuclear radiation from the nuclear power plant was not considered in GridSim.
- GridSim is mainly focussed on integrating units from a power production perspective. There are several simulators focussed on a power consumption perspective. The possibilities of integrating GridSim with other simulation tool/frameworks that deal with the consumer end of a power grid can be investigated.

- GridSim has options for very few control strategies. More control strategies that support optimization constraints can be included.
- Needs to be installed in the system along with other dependencies in order to run. A cloud-based service will simplify the process of running the simulation.
- Uses Kibana to generate graphs. The graphs generated using Kibana cannot be easily converted into image files. It lacks support for creating gray-scale graphs.

Addressing these limitations could be possible opportunities for future work.

7.2 Learning Experience

The experience and the skills developed through this thesis are very rich. I came to UNBC without any research experience. I had some industry experience of software development, and that was helpful in terms of maintaining a good work ethic and work habits. I soon realized that research is an entirely different venture. Compared to industry, the requirements and specifications are often fuzzy. Even choosing a research problem to focus on was difficult. There were many interesting problems that I wanted to work on. Next, I learned to read research papers. It is quite different from reading a textbook. With the explosion of literature on the internet, the number of papers I had to skim through and select to read was initially overwhelming. Slowly, I learned to choose and read research papers better.

Throughout my thesis work, in addition to thinking about solving technical issues, I had to face the problem of deciding what I wanted in my thesis and what I could leave out. An interesting aspect of my thesis is that it is interdisciplinary by nature. I had to learn about grid systems on my own. From the computer science perspective, my thesis involves software design, modeling and simulation, data analytics, and distributed computing. It certainly expanded the breadth of my knowledge and also taught me how to focus deeper.

Finally, after completing my work, I had to write a thesis. Through this experience, I learned how difficult it is to write a good technical document. Through the evolution of the document, my writing skills have improved a lot. This experience has increased my confidence in writing such a document in the future and also helped me to realize the importance and appreciation of such documents.

Bibliography

[1] Global Smart Energy. The electricity economy: New opportunities from the transformation of the electric power sector. *White paper for the Global Environment Fund http://www. globalenvironmentfund. com*, 2008.

[2] B Liscouski and W Elliot. Final report on the august 14, 2003 blackout in the united states and canada: Causes and recommendations. *A report to US Department of Energy*, 40(4), 2004.

[3] Statistical review of world energy 2015, (accessed May 12, 2016). http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

[4] E. K. Hart, E. D. Stoutenburg, and M. Z. Jacobson. The potential of intermittent renewables to meet electric power demand: Current methods and emerging analytical techniques. *Proceedings of the IEEE*, 100(2):322–334, Feb 2012.

[5] Powermatcher, (accessed May 12, 2016). http://fpai-ci.sensorlab.tno.nl/builds/powermatcher-documentation/master/html/architecture-powermatcher.html.

[6] S. Rahman, M. Pipattanasomporn, and Y. Teklu. Intelligent distributed autonomous power systems (idaps). In *Power Engineering Society General Meeting, 2007. IEEE*, pages 1–8, June 2007.

[7] National Academy of Sciences, National Academy of Engineering, and National Research Council. *America Energy Future: Technology and Transformation*. The National Academies Press, Washington, DC, 2009.

[8] Ralph EH Sims, Hans-Holger Rogner, and Ken Gregory. Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. *Energy policy*, 31(13):1315–1326, 2003.

[9] O. Villa, A. Tumeo, S. Ciraci, J. A. Daily, and J. C. Fuller. A high performance computing network and system simulator for the power grid: Ngns. In *High Performance Computing, Networking, Storage and Analysis (SCC), 2012 SC Companion:*, pages 313–322, Nov 2012.

[10] US EIA. Updated capital cost estimates for utility scale electricity generating plants. *US Energy Inf. Adm*, 2013.

[11] Hossein Safaei and David W Keith. How much bulk energy storage is needed to decarbonize electricity? *Energy & Environmental Science*, 8(12):3409–3417, 2015.

[12] U.S. Energy Information Adominstration. Levelized avoided cost of new generation resources in the annual energy outlook 2015 (us energy information administration, 2015).

[13] Lazard's - levelized cost of storage analysis, (accessed May 28, 2016). https://www.lazard.com/media/2391/lazards-levelized-cost-of-storage-analysis-10.pdf.

[14] Daniel A Lashof and Dilip R Ahuja. Relative contributions of greenhouse gas emissions to global warming. 1990.

[15] Transmission data, (accessed May 12, 2016). https://www.bchydro.com/energy/in-bc/our_system/generation/our_facilities.html.

[16] Nic Waller and Alex Aravind. *Modeling and Simulation of Adaptive Distributed Power Generation System*. 2010.

[17] Energy Outlook. International energy outlook. *Outlook*, 2016.

[18] Alexandra Von Meier. *Electric power systems: a conceptual introduction*. John Wiley & Sons, 2006.

[19] Hermann W Dommel and William F Tinney. Optimal power flow solutions. *power apparatus and systems, IEEE transactions on*, (10):1866–1876, 1968.

[20] James A Momoh, ME El-Hawary, and Ramababu Adapa. A review of selected optimal power flow literature to 1993. part ii: Newton, linear programming and interior point methods. *IEEE Transactions on Power Systems*, 14(1):105–111, 1999.

[21] David I Sun, Bruce Ashley, Brian Brewer, Art Hughes, and William F Tinney. Optimal power flow by newton approach. *power apparatus and systems, ieee transactions on*, (10):2864–2880, 1984.

[22] Harald Andruleit, Hans Georg Babies, Jürgen Meßner, Sönke Rehder, Michael Schauer, and Sandro Schmidt. Annual report, reserves, resources and availability of energy resources 2011. *German Mineral Resources Agency (DERA), Hanovre*, 2012.

[23] D.J.C. MacKay. *Sustainable Energy–without the Hot Air*. Without the Hot Air Series. UIT, 2009.

[24] Bert Metz, Ogunlade R Davidson, Peter R Bosch, Rutu Dave, and Leo A Meyer. Contribution of working group iii to the fourth assessment report of the intergovernmental panel on climate change. 2007.

[25] US Reducing. greenhouse gas emissions: How much at what cost. In *McKinsey & Company and The Conference Board December 2007 (www. mckinsey. com/clientservice/ccsi/pdf/US_ghg_final_report. pdf)*, 2008.

[26] Mark Z Jacobson and Gilbert M Masters. Exploiting wind versus coal. *Science*, 293(5534):1438, 2001.

[27] R David Richardson and Gerald M McNerney. Wind energy systems. *Proceedings of the IEEE*, 81(3):378–389, 1993.

[28] J. Ekanayake and N. Jenkins. Comparison of the response of doubly fed and fixed-speed induction generator wind turbines to changes in network frequency. *IEEE Transactions on Energy Conversion*, 19(4):800–802, Dec 2004.

[29] J.P Painuly. Barriers to renewable energy penetration; a framework for analysis. *Renewable Energy*, 24(1):73 – 89, 2001.

[30] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galvan, R. C. PortilloGuisado, M. A. M. Prats, J. I. Leon, and N. Moreno-Alfonso. Power-electronic systems for the grid integration of renewable energy sources: A survey. *IEEE Transactions on Industrial Electronics*, 53(4):1002–1016, June 2006.

[31] M. H. Okba, M. H. Saied, M. Z. Mostafa, and T. M. Abdel-Moneim. High voltage direct current transmission - a review, part i. In *Energytech, 2012 IEEE*, pages 1–7, May 2012.

[32] D. Povh. Use of hvdc and facts. *Proceedings of the IEEE*, 88(2):235–245, Feb 2000.

[33] J.P. Deane, B.P. Ó Gallachóir, and E.J. McKeogh. Techno-economic review of existing and new pumped hydro energy storage plant. *Renewable and Sustainable Energy Reviews*, 14(4):1293 – 1302, 2010.

[34] Anya Castillo and Dennice F. Gayme. Grid-scale energy storage applications in renewable energy integration: A survey. *Energy Conversion and Management*, 87:885 – 894, 2014.

[35] Mary Black and Goran Strbac. Value of bulk energy storage for managing wind power fluctuations. *Energy conversion, ieee transactions on*, 22(1):197–205, 2007.

[36] Septimus Van der Linden. Bulk energy storage potential in the usa, current developments and future prospects. *Energy*, 31(15):3446–3457, 2006.

[37] Bruce Dunn, Haresh Kamath, and Jean-Marie Tarascon. Electrical energy storage for the grid: a battery of choices. *Science*, 334(6058):928–935, 2011.

[38] Bruce Dunn, Haresh Kamath, and Jean-Marie Tarascon. Electrical energy storage for the grid: a battery of choices. *Science*, 334(6058):928–935, 2011.

[39] Willett Kempton and Jasna Tomi. Vehicle-to-grid power fundamentals: Calculating capacity and net revenue. *Journal of Power Sources*, 144(1):268 – 279, 2005.

[40] Y. Ota, H. Taniguchi, T. Nakajima, K. M. Liyanage, J. Baba, and A. Yokoyama. Autonomous distributed v2g (vehicle-to-grid) considering charging request and battery condition. In *2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe)*, pages 1–6, Oct 2010.

[41] Benjamin K. Sovacool and Richard F. Hirsh. Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electric vehicles (phevs) and a vehicle-to-grid (v2g) transition. *Energy Policy*, 37(3):1095 – 1103, 2009.

[42] Pierluigi Siano. Demand response and smart grids- a survey. *Renewable and Sustainable Energy Reviews*, 30:461–478, 2014.

[43] Hamid Gharavi and Reza Ghafurian. *Smart grid: The electric energy system of the future*. IEEE, 2011.

[44] April EPA. Inventory of us greenhouse gas emissions and sinks: 1990-2009. Technical report, EPA 430-R-11-005, 2011.

[45] Spyros Chatzivasileiadis, Damien Ernst, and Göran Andersson. The global grid. *Renewable Energy*, 57:372–383, 2013.

[46] James G March. Handbook of organizations. 1965.

[47] Vidyadhar G Kulkarni. *Modeling and analysis of stochastic systems.* CRC Press, 1996.

[48] Harold Stanislaw. Tests of computer simulation validity: what do they measure? *Simulation & Games*, 1986.

[49] Anu Maria. Introduction to modeling and simulation. In *Proceedings of the 29th Conference on Winter Simulation*, WSC '97, pages 7–13, Washington, DC, USA, 1997. IEEE Computer Society.

[50] Banks Jerry. *Discrete-event system simulation.* Pearson Education India, 1984.

[51] Gilbert M Masters. *Renewable and efficient electric power systems.* John Wiley & Sons, 2013.

[52] Gregor Giebel, Poul Sørensen, and Hannele Holttinen. Forecast error of aggregated wind power. *Tradewind, Deliverable D*, 2, 2007.

[53] The network simulator - ns-2, (accessed May 12, 2016). http://www.isi.edu/nsnam/ns/.

[54] Omnet discrete event simulator - home, (accessed May 12, 2016). https://omnetpp.org/.

[55] Steffen Schütte, Stefan Scherfke, and Martin Tröschel. Mosaik: A framework for modular simulation of active components in smart grids. In *Smart Grid Modeling and Simulation (SGMS), 2011 IEEE First International Workshop on*, pages 55–60. IEEE, 2011.

[56] Vincenzo Liberatore and Ahmad Al-Hammouri. Smart grid communication and co-simulation. In *Energytech, 2011 IEEE*, pages 1–5. IEEE, 2011.

[57] Michael Tiller. *Introduction to physical modeling with Modelica*, volume 615. Springer Science & Business Media, 2012.

[58] Martin Lévesque, Da Qian Xu, Géza Joós, and Martin Maier. Communications and power distribution network co-simulation for multidisciplinary smart grid experimentations. In *Proceedings of the 45th Annual Simulation Symposium*, ANSS '12, pages 2:1–2:7, San Diego, CA, USA, 2012. Society for Computer Simulation International.

[59] H. Kellerbauer and H. Hirsch. Simulation of powerline communication with omnet++ and inet-framework. In *Power Line Communications and Its Applications (ISPLC), 2011 IEEE International Symposium on*, pages 213–217, April 2011.

[60] K. Mets, T. Verschueren, C. Develder, T. L. Vandoorn, and L. Vandevelde. Integrated simulation of power and communication networks for smart grid applications. In *2011 IEEE 16th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, pages 61–65, June 2011.

[61] Marc Snir, Steve Otto, Steven Huss-Lederman, David Walker, and Jack Dongarra. *MPI-The Complete Reference, Volume 1: The MPI Core*. MIT Press, Cambridge, MA, USA, 2nd. (revised) edition, 1998.

[62] Barbara Chapman, Gabriele Jost, and Ruud Van Der Pas. *Using OpenMP: portable shared memory parallel programming*, volume 10. 2008.

[63] Homer renewable energy microgrid software | distributed power and microgrid design support, (accessed May 12, 2016). http://homerenergy.com/software.html.

[64] GridLAB-D, (accessed May 12, 2016). http://www.gridlabd.org/.

[65] J Koen Kok, Cor J Warmer, and IG Kamphuis. Powermatcher: multiagent control in the electricity infrastructure. In *Proceedings of the fourth international joint conference on Autonomous agents and multiagent systems*, pages 75–82. ACM, 2005.

[66] Hyacinth Nwana, Divine T. Ndumu, Lyndon C. Lee, and Martlesham Heath. Zeus: An advanced tool-kit for engineering distributed multi-agent systems, 1998.

[67] Frank Buschmann, Kelvin Henney, and Douglas Schimdt. *Pattern-oriented Software Architecture: On Patterns and Pattern Language*, volume 5. John Wiley & Sons, 2007.

[68] Friedrich Steimann, Philip Mayer, et al. Patterns of interface-based programming. *Journal of Object Technology*, 4(5):75–94, 2005.

[69] I. Stojmenovic. Simulations in wireless sensor and ad hoc networks: matching and advancing models, metrics, and solutions. *IEEE Communications Magazine*, 46(12):102–107, December 2008.

[70] P. S. Magnusson, M. Christensson, J. Eskilson, D. Forsgren, G. Hallberg, J. Hogberg, F. Larsson, A. Moestedt, and B. Werner. Simics: A full system simulation platform. *Computer*, 35(2):50–58, Feb 2002.

[71] K.C. Divya and Jacob Østergaard. Battery energy storage technology for power systems-an overview. *Electric Power Systems Research*, 79(4):511 – 520, 2009.

[72] Ryan Wiser, Mark Bolinger, et al. Wind technologies market report, 2008.

[73] US Energy Information Administration. Assumptions to the annual energy outlook 2012.

[74] Eric Lantz, Ryan Wiser, and Maureen Hand. The past and future cost of wind energy. *National Renewable Energy Laboratory, Golden, CO, Report No. NREL/TP-6A20-53510*, 2012.

[75] S Tegen, M Hand, B Maples, E Lantz, P Schwabe, and A Smith. Cost of wind energy review. *Golden, Colorado, National Renewable Energy Laboratory (NREL)*, 2010.

[76] Ilja Pawel. The cost of storage–how to calculate the levelized cost of stored energy (lcoe) and applications to renewable energy generation. *Energy Procedia*, 46:68–77, 2014.

[77] Monthly generator capacity factor, (accessed May 12, 2016). http://www.eia.gov/todayinenergy/detail.cfm?id=14611l.

[78] Amy Sopinka and G Cornelis van Kooten. Is bc a net power importer or exporter. Technical report, Department of Economics Working Paper, University of Victoria, Victoria, Canada, 2012.

[79] US Energy Information Administration. Energy and climate change- world energy outlook special report 2015.

[80] Thomas F Stocker. *Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 2014.

[81] Stefan Appel, Kai Sachs, and Alejandro Buchmann. Towards benchmarking of amqp. In *Proceedings of the Fourth ACM International Conference on Distributed Event-Based Systems*, pages 99–100. ACM, 2010.

[82] Mongodb, (accessed May 12, 2016). https://www.mongodb.com/.

[83] Oleksii Kononenko, Olga Baysal, Reid Holmes, and Michael W. Godfrey. Mining modern repositories with elasticsearch. In *Proceedings of the 11th Working Conference on Mining Software Repositories*, MSR 2014, pages 328–331, New York, NY, USA, 2014. ACM.

[84] Kibana: Explore, visualize, discover data | elastic, (accessed May 12, 2016). https://www.elastic.co/products/kibana.

[85] The jms api programming model - the java ee 6 tutorial, (accessed May 12, 2016). http://docs.oracle.com/javaee/6/tutorial/doc/bnceh.html.

[86] Michele Albano, Luis Ferreiro, Luis Pinho, and Abdel Alkhawaja. Message-oriented middleware for smart grids. *Computer Standards and Interfaces*, 38:133 –143, 2015.

[87] Stefan Appel, Kai Sachs, and Alejandro Buchmann. Towards benchmarking of amqp. In *Proceedings of the Fourth ACM International Conference on Distributed Event-Based Systems*, DEBS '10, pages 99–100, New York, NY, USA, 2010. ACM.

[88] John O'Hara. Toward a commodity enterprise middleware. *Queue*, 5(4):48–55, May 2007.

[89] Rabbitmq - messaging that just works, (accessed May 12, 2016). https://www.rabbitmq.com/.

[90] Nicolas Nannoni. Message-oriented middleware for scalable data analytics architectures. 2015.

[91] Warren Smith and Shava Smallen. Building an information system for a distributed testbed. In *Proceedings of the 2014 Annual Conference on Extreme Science and Engineering Discovery Environment*, XSEDE '14, pages 35:1–35:8, New York, NY, USA, 2014. ACM.

[92] Jung, (accessed May 12, 2016). http://jung.sourceforge.net/.

[93] Government of Tamil Nadu, (accessed May 12, 2016). http://teda.in/.

[94] Sharma S. A roadmap to tamil nadu electricity demand-supply by 2050, free book culture, (accessed May 12, 2016). http://mitramaadhyama.co.in/.

[95] Report World Nuclear Association(WNA). Comparison of lifecycle greenhouse gas emissions of various electricity generation sources.

[96] R.H. Crawford. Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield. *Renewable and Sustainable Energy Reviews*, 13(9):2653 – 2660, 2009.

[97] Load data, (accessed May 12, 2016). https://www.bchydro.com/energy-in-bc/our-system/transmission/transmission-system/balancing-authority-load-data/historical-transmission-data.html.

[98] Historical data, (accessed May 12, 2016). http://climate.weather.gc.ca/historical-data/ search-historic-data/e.html.

[99] Cristina L Archer and Mark Z Jacobson. Evaluation of global wind power. *Journal of Geophysical Research: Atmospheres*, 110(D12), 2005.

[100] Daniel Weisser. A guide to life-cycle greenhouse gas (ghg) emissions from electric supply technologies. *Energy*, 32(9):1543–1559, 2007.