A design method for Hybrid Power Systems

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Abstract

One upcoming method to improve the efficiency of renewable energy systems is the Hybrid Power System. The hybrid power system incorporates multiple renewable sources in order to achieve a stable power output and sufficient power quality for any system.

This thesis first provides an introduction to energy storage systems, wind turbine and hybrid power systems. This introduction includes different turbine schemes, power electronics schemes and circuits to interface them with the grid. The introduction to hybrid power system includes examples and explainations of various energy storage systems, different topologies including control strategies. This thesis then proposes a step-by-step method in designing a Hybrid Power System.

This thesis then ends with a feasibility study of taking the author's Depart of Electronic, Electrical and Computer Engineering Department off-grid by using the proposed, novel design method. Simulink Simpowersystems simulation was implemented, which proved insufficient. This was then supplemented by an Excel Spreadsheet.

Acknowledgements

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Without their unwavering patience, confidence and hope, this thesis would not have come to fruition. This is without a doubt, for them, despite all odds.

Table of Contents

Table of Figures

Glossary

Abbreviation	**Description**
AA-CAES	Adiabatic CAES
AP	Active Power
BESS	Battery Energy Storage Systems
BCRRE	Birmingham Centre for Railway Research and Education
BS	Bulk storage
CAES	Compressed-Air Energy Storage
CE	CO_2 / Carbon emissions
CEERE	Centre for Energy Efficiency & Renewable Energy
DFIG	Doubly-Fed Induction Generator
DG	Distributed Generation
DoD	Depth of Discharge
EECE	Electronic, Electrical and Computer Engineering
ESD(s)	Energy Storage Device(s)
ESS	Energy Storage Systems
EU	European Union

FC(s)	Fuel Cell(s)
FF	Fossil Fuels
GloW	Global Warming
HPRS	Hybrid Power Renewable Systems
HPS(s)	Hybrid Power System(s)
IG	Induction Generator
Li-Ion	Lithium-Ion
LL	Load Levelling
NaS	Sodium-Sulfur batteries
NiCd	Nickel Cadmium
NiMh	Nickel Metal Hydride
NREL	National Renewable Energy Laboratory
PE	Power Electronics
PHP	Pumped Hydro Power
PMSG(s)	Permanent Magnet Synchronous Generator(s)
PQ	Power Quality
RAPS	Remote Area Power Supply System
RE	Renewable Energy
RG	Renewable Generation
RP	Reactive Power
RS	Renewable Sources
SMES	Superconducting Magnetic Energy Storage
SOC	State of Charge
SU	Supercapacitor & Ultracapacitor
TES	Thermal Energy Storage
WPD	Wind Power Density
WT	Wind Turbine

Chapter 1 – Introduction

1.1 Needed: Energy miracles.

Humanity is facing three interconnected crises: Climate change, abundant and clean energy and drinkable water (1). Global warming (GloW) is the rising of planet's surface temperature. This rise in surface temperature has distorted the globe's Planetary Energy Balance, resulting in changes to the ocean currents and winds that move heat around. As a result, the world's climate is changing (2).

The primary cause for GloW is the rise of CO_2 emissions (CE). CO_2 traps the sun's energy in the atmosphere, which is known as the 'Greenhouse Effect'. And as greenhouse gas emissions continue to rise, more heat is trapped and is unable to be released back into space.

A primary source of CO_2 emissions are due to the burning of fossil fuels (FF), such as coal, petroleum and natural gas (3). Unfortunately, at this stage, a high percentage of the world's energy comes from FF. As living standards rise, so do the nation's appetite for energy. Today, the maximum power consumed worldwide at any given moment is about 12.5 Terawatts (1,4). It is projected that the world marketed energy consumption grows by 53% from 2008 to 2035 (5).

In the power generation sector, renewable energy (RE) is the next wave of innovation. Renewable sources allows power generation from small to utility scale from renewable sources such as wind, wave and sun with near zero carbon emissions. There was a study done by the University of Oxford that stated the United Kingdom has the largest wind resource in Europe (6), and a separate study that ranked energy systems according to their impact on GloW, pollution, wildlife and other concerns (7). The very best options were wind, solar, tidal, hydro and geothermal. The poorer options are nuclear power, coal with carbon capture, ethanol, oil and natural gas. One other event that sparked a further interest in RE is the recent Japan quake. It caused a meltdown in a nuclear power plant, and an explosion of concern over the safety of nuclear energy (8).

However, the variability of renewable sources causes power generation problems. The natural resource might not be available at the time when customer demand is high, and vice versa. To answer this challenge, energy storage devices (ESD) were integrated into existing power systems (1,9). Also, implementing a combination of different, but complementary renewable sources (i.e. wind blows by night and sun shines during the day), will help to compensate for power demand at given times.

As for the transport sector, the most used power generation method is the Combustion Engine (10). Until now, not much headway has been made in terms of hybrid transportation. However, the Railway Research Centre for Research and Education (BCRRE) in the University of Birmingham is taking the lead in hybrid railway and power generator technology. Such promising technologies for vehicles are hydrogen, fuel-cells and batteries. One recent breakthrough of BCRRE is the successful design and construction of UK's first hydrogen-powered locomotive.

The reality is, until carbon emissions are reduced to zero, GloW will continue (11). It takes the combined effort and teamwork of every nation on Earth to seek a consensus on an international strategy to combat GloW. While the transition from FF to renewable sources will take decades, it is showing a lot of promise. Experimental technologies such as hybrid power systems (HPS) are making brilliant headways. HPS shows promising signs in expanding the boundaries of RE. While there are still many hurdles to overcome, such as cost, political will, and social impact, HPS is slowly coming into the world's limelight (4).

It is also the subject of discussion and research topic in this thesis.

1.2 Overview of research problem

Until now, as HPS are being implemented in many fields, it is still very difficult to properly define a step-by-step method of designing and developing HPS. This is so as different ESDs have different operational characteristics of their own, and therefore, require different control techniques to optimise its performance. Also, the variable nature of both the renewable energy source and load demand still makes determining a profitable complement between cost and capacity a challenge.

It is imperative for a standardised method of designing a HPS to be formed as the future performance and profitability of the HPS depends heavily on the key decisions that were made during the design phase. Therefore, the design phase will have to take into consideration critical HPS attributes such as optimised sizing of WT and ESD capacities and power transmission topology.

This thesis undertakes this challenge of forming a step-by-step method of designing and developing a HPRS. This method covers the analysis of procured data for renewable source and customer load demand, individual power sizing of ESD and renewable generator and power transmission topology. And a feasibility study on bringing the University of Birmingham's School of Electronic, Electrical and Computer Engineering (EECE) building 'off-the-grid'. On-site wind and load demand data across one day were used in this study.

1.2.1 Objectives

The objectives and specifications of this research were undertaken and correlate with each of the chapters. This correlation is shown below:

Objective	Description	Chapter
1	Literature review on current wind turbine technologies and future trends.	3
2,3	Literature review on energy storage devices and hybrid power renewable system. Compare & Contrast the pros & cons of each energy storage device from different perspectives.	2,4
4	Develop a strategy to design and using the developed strategy to design a HPRS.	5
5	Implement the developed method in a case study. This case study tests the feasibility of a HPRS successfully powering the University of Birmingham's EECE department, enabling it to be self-sustaining while off-grid.	6

1.3 Research methodology

Literature review

To set out to fulfil Objectives 1 – 4, an intense literature review was undertaken to consolidate as much information as possible on the current trends and concepts of wind power, energy storage and hybrid renewable generation. The sources of information include IEEE Xplore, PhD Theses, Conference proceedings, lecture notes and textbooks.

Developing design method

Chapter 5 is by far the toughest as it involves consolidating vast amounts of methods and information into an easily followed step-by-step process. Various other methods proposed by researches and research institutes such as National Renewable Energy Laboratory (NREL) and Sandia National Laboratories were studied very closely. However, such research institutes have the means (i.e. softwares) to fully investigate this issue. This thesis presents a method to do so without the aid of optimisation softwares, such as HOMER.

Case study

A suitable case study was identified and used to implement the newly formed method in order to test its effectiveness. Suitability of a case study depends on the conditions stated on the design and development method.

Simulation methodology

A simulation model will be implemented in Matlab and Simulink using the SimPowerSystems toolbox.

1.4 Thesis structure

Chapter 1	States the motivation of the research, background, the problem, and solution.
Chapter 2	Gives a literature review of the importance of ESDs, the current trends in the market, categorises ESDs to different power scales, and explaining ideal characteristics and costs of ESD in different applications and needs.
Chapter 3	Gives a literature review of current Wind Turbine (WT) technology,

	introduction to wind power concepts, including different WT PE configurations and future trends.
Chapter 4	Provides a short introduction to Hybrid Power Renewable Systems (HPRS), while discussing the basic HPRS topology and control strategies.
Chapter 5	Presents a step-by-step Design and Development method of constructing a HPRS from the ground up.
Chapter 6	Presents a case study of implementing a HPRS system at University of Birmingham's EECE building.
Chapter 7	Conclusions from simulations and literature review. This section includes future work.

Chapter 2 – Energy Storage Systems

This chapter introduces the idea of Energy Storage Devices (ESDs). It starts by explaining the necessity of ESDs by painting a picture of the variability of RS and explains the cause behind grid voltage instability, which is Reactive Power (RP). It then moves on to state the benefits of ESDs in today's RE sector, and how RE would not fulfil its potential until ESDs is integrated. Various examples of today's ESDs which are implemented in HPRS are sorted according to categories (bulk, distributed generation and power quality), and a description of how they function is also investigated. Examples of how energy storage systems are used in other sectors, e.g. transportation, are also described according to different systems. Finally, the ideal characteristics of ESDs are described, along with illustrations of how they differ depending on different categories and types.

2.1 Variability, Reactive Power and the need for Storage

Currently, RE's increasing penetration into power systems comes largely from wind and solar generation. Not only is RE becoming more palatable to grid operators, RG is now possible in remote areas with large potential for renewable resources. And while the annual growth of RE is impressive, it is still uncertain if RE may still contribute mightily to the grid without putting it at risk (12).

This is so as renewable sources (RS) are inherently variable. As wind and solar farms are now capable of producing large amount of power (The largest wind farm in the world, the London Array is capable of producing 630 MW), engineers must grapple with the voltage instabilities introduced into the grid. The variable nature of RS peaks and troughs in irregular episodes, independent to consumer demand (13). This is a huge challenge because generation and demand must be matched on a minute-to-minute basis. Therefore, the concern of maintaining existing security and reliability of electrical production supply was raised (14). Power flow consists of both Active Power (AP) and Reactive Power (RP). These two power components arise when an AC wave flows through the grid, the current is either always leading or lagging the voltage wave. Inductive components within the network cause the current to lag voltage, while capacitive components causes the current to lead the voltage.

AP is the power that is consumed by consumers, and measured in Watts. RP is the product of voltage and the out-of-phase AC component of the current. RP is absorbed by energetic electric or magnetic fields, e.g. coils in motors and transformers. RP control can also be done by a type of WT drivetrain known as Doubly-Fed Induction Generator (DFIG) (15). As WT can be very far from grid connections, power is transferred via transmission lines, which are inductive in nature.

AP and RP determine how the voltage peaks and trough in the network. If voltages fall too low, inductive loads such as motors and transformers will draw too much current. Thus, overheating and causing damage to the equipment.

Declining voltages in a grid is a function of the consumption of both AP and RP. If a big load consumes too much reactive power, the voltage will drop. As reactive loads are inductive, which causes current to lag voltage, grid operators must feed in RP that leads voltage. By flooding in the reverse, voltage stability is maintained (12).

As a commitment to EU's energy 20/20/20 policy, RG will have to be increased. This creates the need to move towards a more integrated and flexible electricity system (16,17). Therefore, in order for these new RG sources to become reliable as primary sources of energy replacing FF, ESS is a crucial factor. Below are some of the short and long term benefits that energy storage provide (18-22):

- Spinning reserves
- Load levelling and shifting
- Reactive power support
- Deferring distribution asset upgrade ("Buying time" for utility operators)
- Electricity prices control (Purchasing electricity during off-peak periods and storing it for high demand periods)
- Increases the overall efficiency of the power system
- Voltage and Frequency control
- Cope with the adverse effects of widespread and uncontrolled customer-owned DG

2.2 Current technological status of ESDs

Energy storage has been in use for a long time and in many different forms. ESD finds ready application in a diverse range of markets, from traction and propulsion, remote area power supplies (RAPS) and electrical power systems. Due to the economic and electrical benefits, next wave of innovation, and legislations, many states and countries have implemented laws that require the utilities to increase their RE portfolios.

ESDs can be used for three applications or categories: Bulk Energy Storage (BS), Distributed Generation (DG) and Power Quality (PQ) (18,23). Each category will have different operational requirements. Some ESDs were designed by the manufacturer to operate in multiple categories, and some are meant to specialise in just one. This is due to the limitations in either power output or storage capacity. This idea will be investigated further below:

Table 1 - Application category requirements (23)

Application Category	Discharge Power Range	Discharge Time Range	Stored Energy Range	Representative Applications
Bulk Energy Storage	10-1000 MW	1-8 hrs	10-8000 MWh	Load levelling, spinning reserve
Distributed Generation	100-2000 kW	0.5-4 hrs	50-8000 kWh	Peak shaving, transmission deferral
Power Quality	0.1-2 MW	1-30 secs	0.028-16.67 kWh	End-use power quality and grid reliability

Bulk energy storage includes ESDs that may provide services up to 10 MW for at least 8 hours. Storage for distributed generation includes applications that will deliver between 100 kW and 2MW for 0.5 to 4 hours. Whereas, technologies that are suitable for PQ applications are required to deliver up to 2MW at short intervals (bursts): a few 50 Hz cycles to a minute.

ESS works on a very simple idea. It takes any surplus energy currently in the grid, transform it into another form, and only feed it back to the grid when its needed. The surplus energy can be stored in one (or more) of these three forms: Chemical, Kinetic and Potential.

Examples of Chemical forms of ESS are Battery Energy Storage Systems (BESS), and Hydrogen Storage systems, based on electrolysers, hydrogen tanks and fuel cells. An example of a Kinetic form of storage is Flywheels. Finally, Potential forms of storage include Compressed-Air Energy Storage (CAES), and Pumped Hydro Storage (HPS). Profit or savings from providing this service comes from two ways: Ensuring that overall HPRS efficiency is increased, and using off-peak power electricity to store energy and sell it back to the grid at peak times (24).

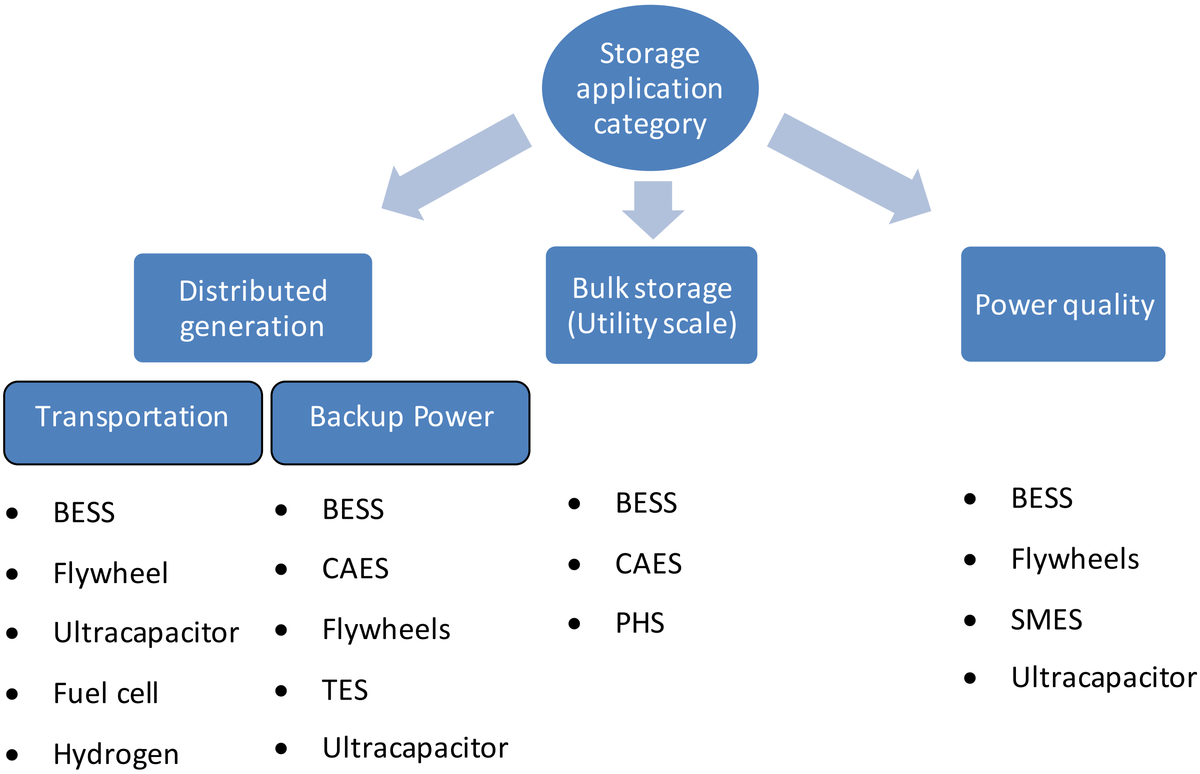

Figure 1 - ESS Application Categories diagram (18,23)

2.3 *Today's Energy Storage Devices*

In this section, various examples of ESDs and how they function will be covered. Each ESD covered will be divided into their respective application category (Bulk Storage, Distributed Generation or PQ). Some ESDs' application category will overlap. However, differences in terms of storage capacity and costs will be highlighted. To start off, a graph showing the different ESDs according to the fields of application is shown below:

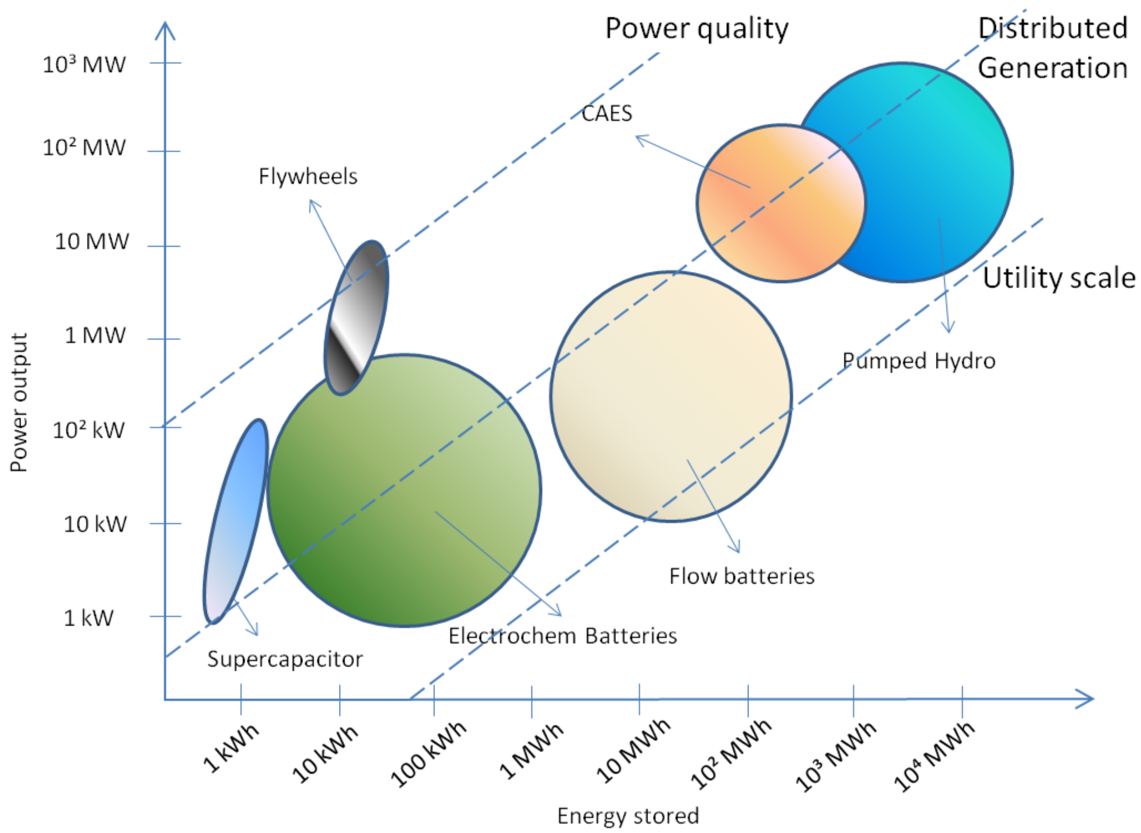

Figure 2 - Power Output vs Energy Stored, divided into 3 sections of varying application categories

(20)

The figure above has 3 divisions: 10^{-3} hours, 1 hour and 10^{3} hours. These 3 time frames describe the typical operational requirement for the 3 application categories of Power

Quality, Distributed Generation (Bridging Power) and Bulk Storage respectively. Most of the ESDs shown above will be described in the next section.

2.3.1 Bulk Energy Storage Systems (Utility scale)

Storage at the bulk-scale is also known as Energy Management (25). There are certain functions for utility scale ESDs to meet. The main one is Load Levelling (LL). LL is a demand-side management practice that alters the pattern of energy use such that peak demand is shifted to periods of low demand. LL on a utility scale involves storage periods for seasonal, weekly and daily time periods. It does not help with voltage transients across a very small period of time from a few seconds to minutes.

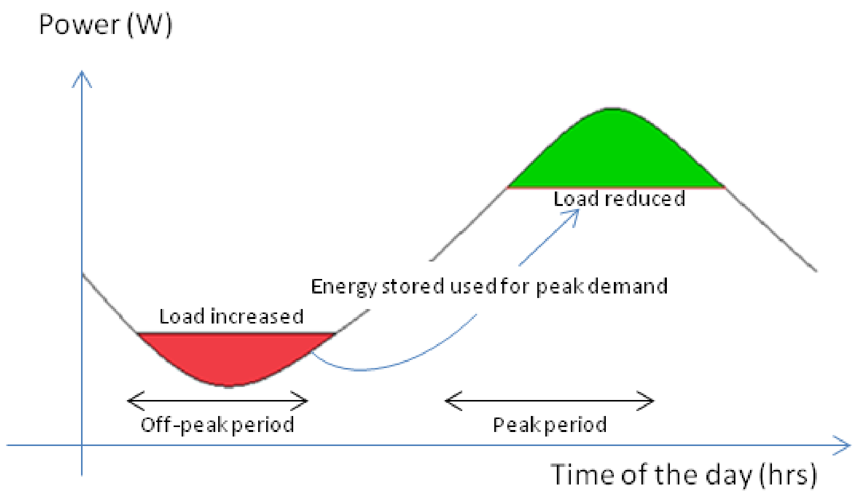

Figure 3 - Load Levelling (26)

Load levelling provides many benefits that would interest utility operators and investors. Such benefits that are well-known are the investment deferral of generation, decommission old power plants with high emissions, and reduce Transmission & Distribution (T&D) losses. Up to 50% losses of T&D can be saved when loads are shifted from periods of high demand to periods of low demand on a 70-80% efficiency HPS (26).

a. Pumped-Hydro Power

One type of Hydropower generation is called 'pumped-hydro' storage (PHP). It is a mature technology, readily available and is currently the most used for high-power applications (20). To this date, PHP provides a total of 100GW combined in this world (27). It works based on a very simple idea. It involves two bodies of water with different elevations. The body with higher elevation will have more potential energy (PE). In PHP, PE is stored in the form of water in the higher reservoir, and relies on gravity to convert potential energy into kinetic energy as water flows to the lower reservoir. The kinetic energy of the water is used to drive turbines, which generates electricity (16).

In times of low demand, typically at night, water is pumped with off-peak electricity generated by coal-fired and nuclear power plants to the upper reservoir (23). At times of high demand, typically during the midday, water from upper reservoir is released to flow down to the lower reservoir, which turns several rotors, which in extension, turns the generators. Electricity generated at this time is sold back to the electricity grid. In this way, PHP operates as a reversible cycle of consumption and production of electricity. PHP has a roundtrip efficiency of about 70-80%, and their capacity is limited only to the size of the reservoirs. So PHP storage is capable of storing power up to a few days (18).

The major drawback to this design is the large area of land needed for construction, the elevation needed between them, and with an adequate geological structure or 'container' for water storage.

b. Compressed-Air Energy Storage (CAES)

CAES is a hybrid form of storage that is one of the trendsetting ESDs. The main advantage of CAES is the medium with which it uses to function- Air, which is readily available in abundance and it is free. This attribute immediately puts it as the cheapest ESD to operate. For a CAES system with typical 70% overall efficiency, energy related cost is at \$3/kWh, while Operation & Maintenance (O&M) cost at \$2.5/kW-yr (23,28) (More cost data will be provided later).

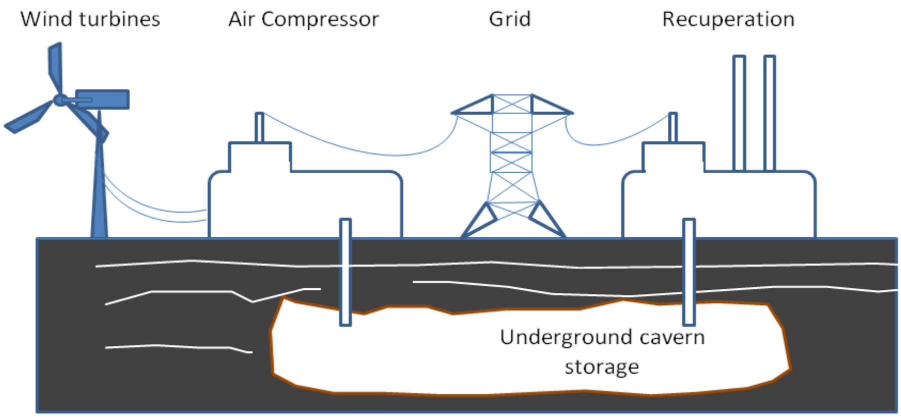

Figure 4 - Schematics of Compressed-Air Energy Storage system (29)

CAES exploits a very important characteristic of air, which is its 'elastic energy'. CAES is divided into 3 major components: an air compressor (which is driven by a motor), an air motor and a storage medium. It works by using off-peak or surplus power to collect air from the atmosphere and the air compressor pre-compresses it into a storage medium, in the form of Potential Energy. Storage medium may range from natural geological formation, abandoned salt mines, or vessels. Air storage is usually about 40-70 bars in vessels and about 100 bars in a geological 'container'. At times when demand exceeds generation, stored energy from the storage will be heated up, and then channelled to the air motor. This air motor converts potential energy into kinetic energy, and the kinetic energy is used to turn a shaft connected to a power generator. The stored air is then released back into the atmosphere (16,28).

c. Battery Energy Storage Systems (BESS)

Batteries are an established means for storing electricity in the form of chemical energy. It has been used as an ESD for over a century. They are modular and quiet (22). Larger batteries are sometimes grouped together. Such a system is called Battery Energy Storage System (BESS), and can be housed in a nearby building, close to the need of the consumers, within a very short construction time (14). Below is a short overview the current major types of batteries.

There are many types of batteries out there and the five main types are Lithium-Ion (Li-Ion), Lead Acid, Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH) and Redox Flow Batteries. Probably the most familiar one will be Lithium-Ion batteries, which are found in the 3C's sector: cameras, cell phones, and computer, and until recently, electric cars. Li-Ion batteries have the highest energy density and the lowest self-discharge rate of all the battery types. The main drawbacks of Li-Ion batteries are the high cost for production, and the high difficulty in producing a charging system (14).

The Lead-acid battery is the most matured of all battery types. It is the 'go-to' for most applications as it gives reasonable operational capability with low cost and low manufacturing difficulty. It's the common choice for power service provision in the range of 5V to 24V DC (30). In the 1970's, the overall design of Lead-acid batteries were improved with the addition of safety valves, sealed enclosures and a change of electrolyte.

Another battery type that has just recently come into the limelight is Sodium – Sulfur (NaS) batteries. NaS batteries were the first type of batteries to be designed specifically for utility-scale energy storage purposes. The exciting aspect of this battery is that it is currently the most promising candidate for utility-scale power applications. It has a very high energy density, low maintenance requirements, a long life cycle of 15 years and environmentally anti-contamination. NaS batteries have an operating temperature of 300 Celsius.

The final main type of battery is the Flow battery. A flow battery generates electricity when an electrolyte containing electroactive elements flow in a fuel cell that converts chemical energy into electricity. It stores energy in an electrolyte solution contained in tanks. The electrolyte circulates from these tanks through a cell, which generates electricity from the fluid. Recharging the flow battery involves replacing the electrolyte within the tanks. The most common type of flow battery is the Vanadium Redox Flow battery. It is a combination of Reduction and Oxidation.

2.3.2 Distributed Generation (DG) Energy Storage Devices

DG is also known as Bridging Power. The function of Bridging Power is to ensure continuity of supply from a scale of minutes or less when switching from one generation source to another (25). However, DG ESDs are much smaller in rated values and size. They are expected to be placed in areas close to consumers and in existing facilities. The objective of DG ESDs is to enable dynamic voltage control to reduce the cost of balance of plant.

a. Battery Energy Storage Systems (BESS)

Li-ion, Lead-acid and Nickel Cadmium batteries are used in several energy storage plants even at utility scale. Incorporating an ESD from utility scale to DG scale requires only the downscaling of the ESD capacity.

Just recently, Li-Ion batteries have got a huge break in its application with the first ever dynamic energy storage installation in the UK, commissioned by ABB (31). This turnkey project, titled DynaPeaQ® for ABB was deployed by UK Power Networks in Norfolk, and is placed in a 11kV distribution network. It comprises of 8 battery modules and is capable of storing up to 200kW of power for 5 minutes up to 1 hour.

b. Fuel Cells (FC)

For this application, hydrogen-based systems with either a FC or a combustion engine as the power unit is required. The hydrogen is the product of electrolysis of water, and stored in a gas tank. For smaller power applications, the Proton Exchange Membrane (PEM) type FC is generally used. Solid-oxide fuel cells are another type of FC that uses solid oxide material as the electrolyte. It has a wide range of applications including storage unit in vehicles and base power generation. The ceramics used in SOFC do not become ionically active until 500-1000^{o}C. This higher operating temperature makes SOFC suitable for applications with high heat absorption such as heat energy recovery, and is able to operate with a high efficiency of 60%.

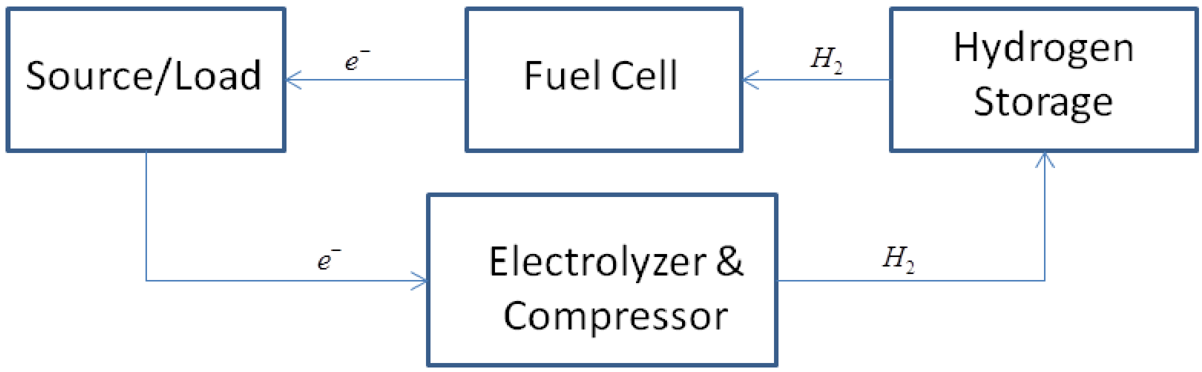

Figure 5 - Hydrogen Electrolyser in a Hydrogen Energy Storage System (23)

These operate on hydrogen and air at ambient temperature with very fast response time and high efficiency. Fuel cells can be used in decentralised production (residential areas, or low power stations), power reserves, and also centralised electricity production. The electrolysis unit is capable of operating at variable power input in a peak shaving operation (32).

2.3.3 Power Quality Energy Storage Systems

a. Supercapacitors or Ultracapacitors

The Supercapacitor or Ultracapacitor (SU) were developed in the 1960's. It is an electrochemical double layer capacitor (ECDL) separated by a dielectric. There are no chemical reactions involved in the working mechanism of SU. This greatly extends their life cycles because it could charge and discharge hundreds and thousands of times (18,22). Therefore, they are the ideal devices for PQ and short-term energy storage. Some SU are capable of providing 400kW and is able to discharge the stored power in 1 to 10 seconds.

The storage capacity of SU is the square of its voltage. The energy/volume ratio obtained is superior to that of a conventional capacitor (5 Wh/kg or 15 Wh/kg) with better discharge time constancy (power of 800-2000 W/kg). Therefore, the maximum operational voltage is limited to a few volts per element (2.5-3V for modules up to 1500F) (20). Therefore, SU has to be packed in series, to form a ‘module’ (each giving about 50-100kW), and additional modules are connected in parallel. Several modules have to be linked just to provide storage capabilities of normal power application voltages. Currently, the module voltage is limited to 200 to 400 Volts due to reliability issues (18,20,22-23).

b. Flywheel Energy Storage

For hundreds of years, pure mechanical flywheels were used to keep machines running smoothly between cycles. It was then in 1980’s when magnetic bearings for flywheels were developed, the potential for using flywheels as an ESD were then the subject of intense research (33). There are many benefits that make flywheels useful (18,20,22,33):

- High power and energy density
- State of charge can be easily measured (Calculated from rotational velocity)
- No maintenance requirements
- High cycling capability (Able to cycle between a range of a 10,000 to 100,000 cycles. Not affected by Depth of Discharge. Only limited by design fatigue.)
- High round trip efficiency of 85%.
- Fast response time to varying input

A flywheel stores energy in a rotating mass. The amount of kinetic energy stored as rotational energy is dependent upon inertia and the square of the angular velocity of the rotating mass. The flywheel is housed in a vacuum housing to eliminate any from friction-losses between the air and the rotating mass. Kinetic energy can be extracted and injected into the flywheel with an electrical machine that may operate as both a motor and a generator. When the electrical machine is acting as a motor, current is supplied to the stator winding, and it is converted into torque which falls across the rotating mass. This causes the mass to spin faster, and therefore, gain more kinetic energy. When the electrical machine is acting as a generator, kinetic energy stored in the rotor applies a torque, which is used to turn the generator shaft, thereby generating electricity.

2.4 Characteristics of energy storage techniques

It is necessary to critically analyse the fundamental characteristics of ESDs to establish a proper base for criteria comparison. For every ESD application, there are at least four "soft" characteristics that must be met. The main characteristics of storage systems on which the criteria is based on will be described below (20,34).

a) Storage capacity

   This is the maximum quantity of energy that the ESD may store after charging, measured in Wh (Watt-hours). It should be noted that not all energy stored will be discharged. The usable energy represents the limit of discharge depth, also known as the minimum-charge state).

b) Depth of Discharge

   Depth of Discharge (DOD) is the inverse of State of Charge (SOC). SOC describes the current percentage of energy remaining with respect to the rated capacity, i.e. full=100% and empty=0%. DOD's inverse representation is: full=0% and empty=100%. It can be used to determine the time needed to extract the stored energy.

c) Discharge time

This parameter describes the maximum power discharge duration, and is given by

$$(2.1)\ \tau = \frac{\text{Total energy stored}}{\text{Maximum charge or discharge power}} \quad (1)$$

This parameter depends on the DOD and operational conditions of the system.

d) Efficiency

This parameter is defined as, the ratio = (total joules of energy released from storage / total joules of energy stored). As a single storage system will comprised of many subsystems, the net cyclic efficiency is the concatenation of the efficiency values of each subsystem,

$$\eta = \prod_{j=1}^{J} \eta_j \quad (2)$$

where ‘j’ is the number of subsystems (j > 0), and η is efficiency, ‘J’ is the number of cycles (J > 1). Therefore, getting a ‘J’ number of cycles net efficiency requires the efficiency value of every subsystem, for every cycle.

e) Response time of an ESD

Fast response times are needed especially for Power Quality applications. This response time value should be within a factor of two (half) of the time required for the instantaneous output power to achieve 9% of its recommended maximum level, after the deliver-power command was received.

f) Mass and volume densities of energy

This characteristic represents the maximum amount of energy accumulated per unit volume of the ESD, and is defined

$$D = \frac{C}{V} \quad (3)$$

where D is the volumetric energy density, C is energy density, and V is rated geometric volume (geological footprint) (34).

g) Durability / Longevity /Cyclic life

This parameter refers to the number of times the ESD is capable of fully discharging after each recharge. ESDs are always given a cyclic life time value of *N*, where one cyclic life is one charge (SOC=100%) and one full discharge (SOC=0%).

h) Maintenance

ESDs must be designed in such a way that periodic maintenance can be done with ease and in a short time. It is also ideal to for maintenance periods to be as long as possible without compromising the ESDs performance.

i) Cost

The aim is to reduce the time when ESD gains will exceed expenditure. The capital invested and operational costs (maintenance, energy lost during cycling) play vital roles in deciding the financial worthiness of the investment. An analysis of the estimated durability of the entire system includes materials and environmental costs from fabrication to recycling, must be considered. Investment costs is generally calculated via

$$\text{Total Cost}, C_t = (aC_1 + aC_2)P_d \qquad (4)$$

C_1 is the unit cost per total energy capacity (in $/kWh), C_2 is the discharge power (in $/kWh), P_d is the nominal discharge power and *a* is autonomy (34).

j) Self-discharge

This is the portion of stored energy, which will dissipate after a given amount of time of ESD inactivity.

2.5 Summary

A broad overview of the demand matching challenge that is faced by the renewable industry was given and a technical explanation was given. The three main technological applications of ESDs were described, and examples of ESDs available today were investigated and sorted according to its application. Technological comparison between different ESD types was discussed through various graphs. And finally, the characteristics that form the comparison criteria for the most suitable selection of ESD for different types of applications were discussed.

ESDs are able to act as giant energy buffers to accommodate unequal instantaneous energy in the power system. In an ideal case, at any given instant, there should be zero net exchange between the energy sources and energy sinks for both real and reactive power (35). If this balance is not maintained, the equilibrium of voltage and frequency of the system will be disturbed. Therefore, the ESD should behave as an energy source or sink depending on the surplus or deficit power.

Chapter 3 – Wind Energy

This chapter is a literature review that investigates wind power as a whole. It was written to provide an up-to-date introduction to the reader. It starts off by giving a short exposure to the latest events and trends in the wind industry. Followed by a discussion of wind power concepts including the power contained in the wind and mathematical models, and wind system categories. This chapter then ends with the future direction of the wind industry.

3.1 Wind power today

Everything is achievable through technology and ingenuity. Mankind has long since turned wind power into good use, from milling grains to utility scale power generation. Just recently in September 2010, the world's largest offshore wind farm, Thanet has just been operational 12km off the shores of Kent (36). The wind farm has 100 WTs by Vestas, each with a nameplate rating of 3MW. Thanet is capable of powering 200,000 British homes at any given time. Such incredible applications are due to the fact that UK has the largest wind resource in Europe (6).

WTs work on a simple and genius idea, Lift. Lift is the concept that allows WTs to operate. Incoming wind imparts a force (torque) on the wind turbine rotors (the prime mover) and rotates it. In this way, WTs 'captures' the kinetic energy of the wind and converts it into mechanical power via the turbine rotors. The mechanical power is then converted into useful electrical energy via a generator. The power is then conditioned and power-factor corrected before being sent to the grid. Common generators used today are induction generators (IG) (i.e. Squirrel cage and wound rotor), synchronous generators and Permanent Magnet Synchronous Generators (PMSGs) (37). IGs are common for high powered generation i.e. off shore WTs, especially if it is based on the Squirrel-cage design. The squirrel-cage design boasts a low price, simple and robust mechanical operations and offers some degree of flexibility against variable incoming wind. PMSGs employing the gearboxless, direct-drive scheme are also slowly being applied to decentralised generation such as microgrid and Remote Area Power Supply System (RAPS) applications (37-39).

3.2 Wind power concepts

Wind energy has progressed into a matured state that it is now widely accepted as a utility generation technology. This wave of innovation is propelled by advancements in modern power electronics technology and concepts, especially with the invention of Pulse Width Modulation technique, and semiconductor devices such as the IGBT and multi-level converter topologies with high switching speeds and low switching losses.

To date, modern WTs can be classified into 2 different constructional designs. The first constructional characteristic that will meet the eye is the position of the axis of rotation of the wind rotor. Hence, WTs can be classified into Vertical-Axis WTs (VAWTs) and Horizontal-Axis WTs (HAWTs).

Main components of the WT are divided into 2 categories, the mechanical power and electrical power sides. The mechanical power side is responsible of converting the extracted power from the wind to electrical power. The electrical power side is responsible of converting the generated electricity to the appropriate voltage and frequency before transferring it to the grid. The electrical power side also consists of (depending on WT power generation scale, application and category) static-VAr compensators, dummy loads, capacitor banks, resistor banks and power factor correctors to maintain power quality before sending it off to the grid. The mechanical component components are housed in the Nacelle of the WT.

3.3 Energy and power contained in the wind

In the planning stages of a wind farm, it is important to know the average wind speed of a given location. The wind speeds at the location of interest is taken over many years. From the time series data of wind speed, it is then possible to determine the Wind Power Density (WPD) via Weibull Distribution. WPD is the calculation of the effective power of the wind at a given location, measured in Watts per square meter (W/m^2). This value is then used to justify the suitability of the location to build a wind farm.

Illustrated below is the idea to calculate the kinetic energy in the wind. Power is defined as the rate at which energy is converted, expressed as $J\ s^{-1}$, or Watts (W). The energy contained in the wind is its kinetic energy (40), given by,

$$\text{Kinetic Energy} = \frac{1}{2} m V^2 \tag{5}$$

Where *m* is mass of moving air, *V* is velocity in $m\ s^{-1}$.To calculate the extractable energy by the WT, take an imaginary circle that has an area that represents the actual swept area of the WT.

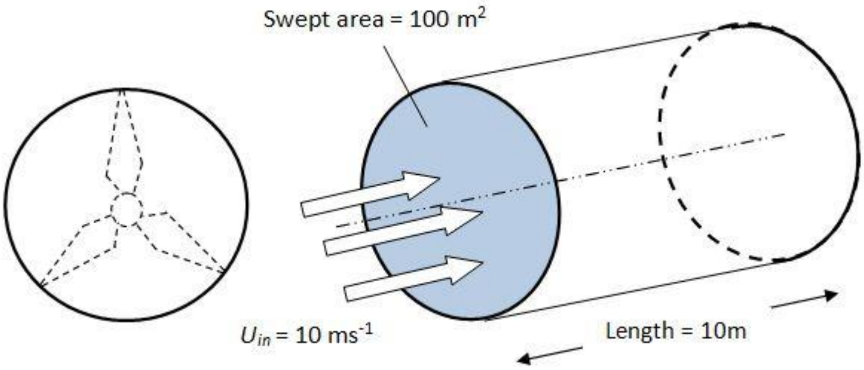

Figure 6 - The imaginary circle at the same swept area as a WT (left), and a cylinder of air passing the ring (right)

If the ring is taken to be 100 m^2, and incoming wind speed, U_{in} *or* V_{wind}, is 10 m s^{-1}. Therefore, a cylinder of air of 10m long will pass through the WT swept area every second. The volume of the cylinder of air is then 1000 m^3. Next, multiply this value by the air density, ρ of 1.2256 kg m^{-3}, to obtain the mass of air moving through the WT swept area. This is mathematically described below:

$$\begin{aligned} \text{mass of air per second} &= \rho \times \text{volume of air passing each second} \\ &= \rho \times \text{rotor swept area} \times \text{velocity} \\ &= \rho \text{AV} \end{aligned} \tag{6}$$

Therefore, substituting the above equality into the kinetic energy formula,

$$\text{K.E. per sec} = \frac{1}{2}\rho A V^3 \tag{7}$$

As Power is energy per unit time, therefore:

$$P = \frac{1}{2}\rho A V^3 \tag{8}$$

As with any power extraction process, there is a certain extraction efficiency value. Therefore, by taking P_{wind} and multiplying it with the extraction efficiency, called the Coefficient of Performance (or Aerodynamic Efficiency), C_p, a mathematical model of the WT rotor blades is formed. C_p is a function of Blade pitch angle, β, and WT tip speed ratio, λ.

$$P_{wind} = \frac{1}{2}\rho A V_{wind}{}^{3} C_P(\lambda, \beta) \tag{9}$$

Blade pitch angle refers to the angle between the chord of the blade and the reference line on the rotor hub, and is shown in the diagram below:

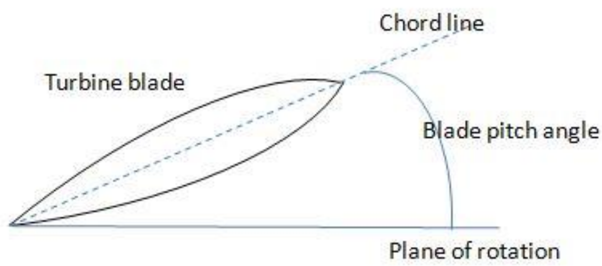

Figure 7 - Blade pitch angle and chord line

Also, via inspection, the corresponding Aerodynamic Torque equation based on the P_{wind} model is:

$$\mathrm{T_{wind}} = \frac{1}{2}\rho A V_{wind}{}^{3} C_P(\lambda, \beta)\frac{1}{\omega_{WT}} \tag{10}$$

Where ω_{WT} is the rotational velocity of the wind turbine rotors (41). C_p is also known as the Betz limit, and has a maximum value of 0.59. It means that only a maximum of 59% of power can be extracted from the resource. This limit shows that air is not forced to flow through the rotor but can flow around it instead (42). C_p is normally plotted against λ. λ is defined as,

$$\lambda = \frac{\Omega R}{V_{wind}} \qquad (10)$$

Where R is radius of the swept area of the WT blades and Ω is rotor angular velocity. This ratio provides a generalised representation of the WT rotor performance across all wind and rotational speeds. From the P_{wind} formula, the following factors of wind generation can be deduced (40):

a. Captured wind power is directly dependent upon the cube of wind speed
b. The area through which the wind is passing

As P_{wind} is dependent upon the cube of wind speed, any fluctuations or power generated will be in the magnitude of cube. Therefore, it is important to implement power limitation control. This can be done via Stall Control, Active Stall or Pitch Control techniques (43). After a certain wind speed is achieved (varies from turbine to turbine), the mechanical brakes will come into action and shut down the wind turbine. This wind speed is known as the Cut-out windspeed, C_{out}. This prevents any wear and tear or mechanical damage when wind speeds are very high. The Cut in windspeed, C_{in} is the minimum windspeed with which the WT will start to generate power.

3.4 Wind System Configurations

Since the steady development of WTs for the last 25 years, there are now four or five generations of WT technologies (44). WT technology is generally divided into 3 categories: (a) Category 1: Systems without power electronics (direct grid connection), (b) Category 2: Systems with partially rated power electronics (using small Power Electronics [PE] converter); and (c) Category 3: Systems with full-scale power electronics for interfacing with wind turbines (implementing a large PE converter) (43-48). Each category has different and specific operational characteristics. With these characteristics, the WT will require different components to function optimally. The distinguishable characteristics for each category are described below.

For Category 1 WTs, due to the absence of PE interface to the grid, aerodynamic control is implemented to limit the power generated and alleviate power fluctuations. Therefore, Cat. 1 WTs are also known either as Pitch, Stall, or Active Stall WTs. Aerodynamic control is used in conjunction with IGs, which are almost independent of torque variation to maintain a fixed speed. The IGs requires reactive power to operate, which can either be supplied by the grid, capacitor banks (reactive compensator) or ESD. Soft-starters are used to reduce the inrush current and alleviate flicker problems on the grid. The gearbox between the rotor and the generator is to increase the rotational velocity of the low-speed shaft to a higher-speed generator. It allows Cat. 1 WTs are attractive in terms of cost and reliability. However, they are slow to control the output active power, due to rotor blade and generator inertia. This makes for higher maintenance due to unwanted torque pulsations from gusts.

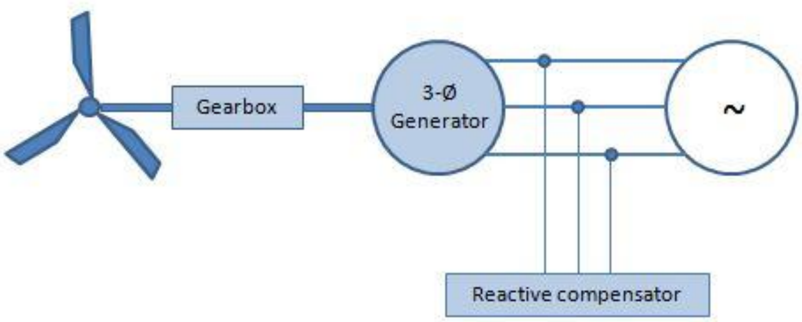

Figure 8 - Cat. 1 WT IG with direct grid-connection (45)

For Cat. 2 WTs, a medium-scale power converter with a wound rotor IG is implemented. Such a scheme is known as Doubly-Fed Induction Generator (DFIG) scheme. With PE and a wound rotor, this scheme allows for variable speed generation. The AC/DC/AC converter is divided into 2 parts, the Rotor-side Converter (C_{rotor}) and the Grid-Side Converter (C_{grid}). The rotor-side converter is used to control the wind turbine output power or reactive power at the grid terminals. The grid-side converter is used to regulate the voltage of the DC bus capacitor, while generating or absorbing reactive power. Hence, the DFIG scheme also allows for fast Active and Reactive Power control. When generator is operating super-synchronously, the generated power is delivered via both the rotor and stator. When the generator is operating sub-synchronously, power is delivered into the rotor from the AC grid. The DC Link circuit decouples the generator speed (and in extension, the rotor speed) from the grid frequency. This then widens the speed range and permits an effective wind-oriented rotor operation (49).

And for Category 3, a full-scale PC is integrated between the WT generator and grid. Synchronous generators (either conventional or permanent magnet synchronous) are employed in this case and these generators are able to output variable voltage and frequency powers that vary with wind speed. The rectifier and inverter will then convert the rated output and ensures it is grid compatible before channelling the power to the grid. The de-coupled power converter to the grid also enables fast active and reactive power control for the system. The negative side to this system is the more complex topology employed, and power losses during conversion processes.

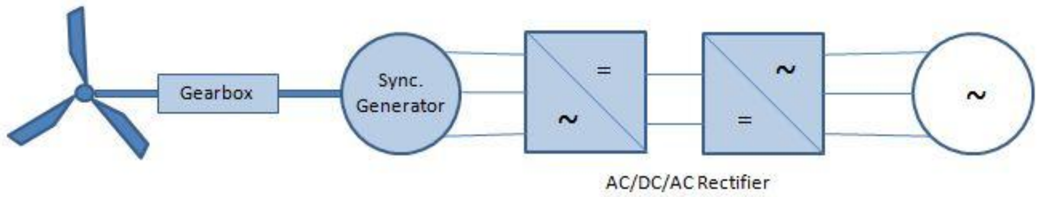

Figure 9 - General topology of a Synchronous generator integrated with full-rated PE (45)

3.6 Future trends

This section sheds a light on the trends in which today's wind industry is heading into. The future trends are listed and elaborated as below:

1. *Future transmission technology – Connecting wind power generation to the grid*

Currently, companies are heading in the direction of offshore wind farming. The main aim of this is to exploit the wind resource at sea, which has a more favourable energy balance compared to onshore. Generally, offshore WTs produce on average about 50% more energy than onshore WTs placed on flat-terrain (50). And with the benefit of less variation of wind speed (less turbulence), less fatigue loads will be placed on the WTs. Therefore, an offshore WT's life expectancy is higher than an onshore WT's at 25-30 years. However, it should be noted that assembling a WT at the shallow seabed does require higher cost and about 50% more energy than onshore WTs. This problem is then added on by transmission systems. Engineers are quick to innovate a solution for grid access. This solution came in the form of High-voltage DC (HVDC). HVDC is able to connect wind farms to the grid for secure and efficient power transmission to load centers. Currently, HVDC systems are more suited for power transmissions over distances of up to 100km at power levels in the range of 200 to 900MW (50). There are different types of HVDC transmission systems, but the one type that is gaining much attention by companies such as ABB and Siemens is Voltage-source converter (VSC)-based HVDC transmission system.

2. High power, multi-level, medium voltage converter topology

It is the goal of every engineer to optimise power extraction by increasing extraction efficiency (by increasing the nominal power of WTs) and decreasing the cost of generating each megawatt of power. One such method that has been gaining attention is multi-level converter topologies.

Multi-level converter topologies can be classified into 5 categories: diode clamps, bidirectional switch interconnection, flying capacitors, multiple 3-phase inverters, cascaded 1-phase H-bridge inverters. The advantages of using multi-level converters are reduced harmonic content in the input and output voltages, reduced electromagnetic interference, low demand for input filters and reduced number of commutations. For the same harmonic performance for a 2-level converter, the switching frequency used in a multi-level converter can be reduced to 25%, which reduces switching losses (51). Therefore, it can be then deduced that the efficiency of the converter is the ratio between switching frequency and conducting losses. However, one disadvantage of the multilevel converter with split DC-link is the voltage unbalance between the capacitors that integrate it (50).

Currently, the Power Electronic Building Blocks (PEBB) concept greatly simplifies the design process of any PE network. PEBB is a modular PE system that incorporates power devices, gate drives and other components into functional blocks. By grouping them into blocks, the designers addresses the device stress, switching speed, switching losses and thermal management with respect to the operational specifications (45).

3. Energy Storage Devices

As discussed earlier, ESD will improve the economic effectiveness of any RG method. One of the several kinds of ESDs that are being applied in wind farms are Li-Ion and Lead Acid batteries, hydrogen storage and CAES. One advantage of using BESS is the flexibility in which the power characteristics of the battery can be modified to suit selected applications. A very simple block diagram of how a WT is normally integrated with BESS is shown below. This integrated design will be discussed further in the coming chapters:

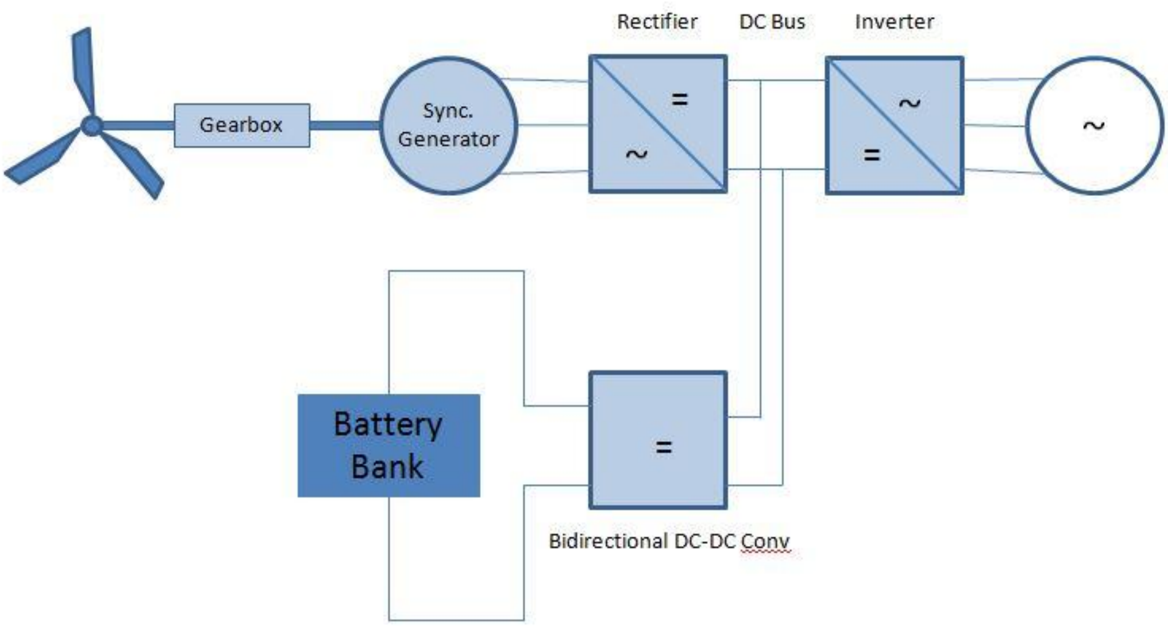

Figure 10 - WT integrated with BESS via a Bidirectional DC-DC Converter (45)

As wind penetration increases, the hydrogen storage option quickly becomes economical. This application is very lucrative as the hydrogen produced from electrolysis can be sold as vehicle fuel, which greatly reduces the usage of fossil fuels for personal transportations and encourages the market to shift from pure combustion engines to hybrid vehicles.

3.7 Summary

A review of the current news of the WT world is presented. This is followed up by an introduction to basic wind power concepts such as the different rotor axis, common components of the WT nacelle, the power contained in the wind and the maximum extractable power by the WT rotors. The next part, the technical portion of the discussion showcases the 3 categories in which any WT may be classified into: system without PE, system with partially rated PE and system with fully rated PE. This part of the discussion is then elaborated further by showing the PE topology for 2 out of the 3 categories. And finally, the future direction of the wind industry is touched upon.

Chapter 4 – Hybrid Power Renewable Systems

This chapter combines together the concepts (and in extension, benefits) described in chapters 2 and 3 and presents the concept of Hybrid Power Renewable Systems (HPRS) and it is the next step in RE generation. A brief introduction to the concept of HPRS is given. The generic topology of a HPRS is then introduced, along with its individual components and functions. This chapter then ends with a discussion of frequently employed control strategies in the industry.

4.1 Introduction to Hybrid Power Renewable Systems

HPRS is defined as systems that produce output power from two or more sources of energy (10,52-53), and usually consists of an additional energy storage system, power conditioners and a controller (54). The entire system is linked together through a bus bar. HPRS is used due to the fact that extracting energy out of a stand-alone variable source is not reliable. Multiple energy sources groups such as Wind and BESS integrated together, or Solar and Wind (complementary characteristics), or Wind, Diesel and Supercapacitor in a group is able to combine the benefits of each resource type, while compensating in terms of generation for any RE source that dipped from short to long terms. This hybridisation through multiple energy sources instantly combines all advantages of the employed generation techniques and sets itself as the 'Holy Grail' of Renewable Generation. Examples of advantages include a high degree of reliability of output power at 'grid quality', lower life-cycle cost, high technical performance, faster turnover rate for investment costs, can be easily designed to have integrated distributed networks (mini-grids), easily support growing fixed loads and easily retrofitted into diesel-based power systems (55). However, the main disadvantages of

HPRS are the additional investment cost due to batteries and PE and the overall complexity of the system. Also, there is a very limited experience of customers and suppliers with HPS as this field is relatively new. Finally, deciding on the proper HPS components is difficult as life-cycle economic analysis is required, which is based on detailed system simulations (56).

As HPS can be employed to extract both renewable sources and current fossil fuel combustion engines, this concept is applied not only into RE, but also into the transport sector (e.g. Toyota Prius and hybrid power trains) and autonomous decentralised generation. Placing a HPS in a rural area bypasses the need for extending existing power grid infrastructure to cater to the needs far away. HPS systems can be employed for power generation on all scales with all sorts of applications: from a hybrid car, to a decentralised generation and distribution network, to utility-scale generation applications. A single line diagram of a HPRS is shown below:

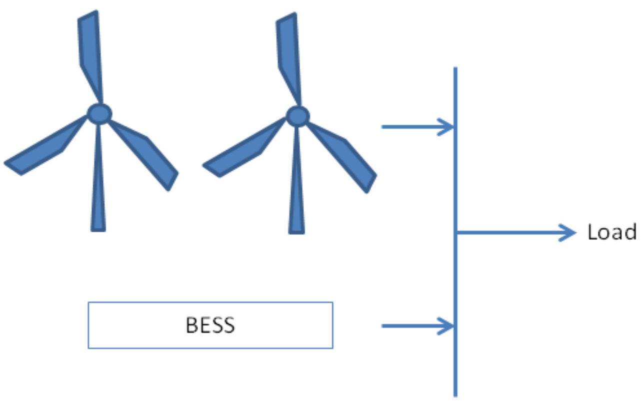

Figure 11 - HPRS employing Wind turbines and a BESS linked with a bus bar.

Generally, there are 3 main HPRS technological configurations which are classified by the type of bus bar the power generation components are coupled to. The 3 HPRS configurations (bus bar types or transmission configurations) are Pure DC Bus line, Pure AC Bus line, Hybrid AC/DC Bus line (53,55). Each category will be described below:

1. Pure DC Bus line

For HPRS incorporating the Pure DC Bus line structure, the power generators in the system are connected to the DC Busbar via rectifiers. DC Loads will be able to be interfaced directly. The battery supplies power to the DC loads in response to the surplus or deficit power based on the instantaneous demand. AC loads can be serviced via an inverter. There is much emphasis placed on the DC Bus line configuration recently as HVDC is able to greatly reduce transmission losses over a medium range of 50-75km (53,55,57).

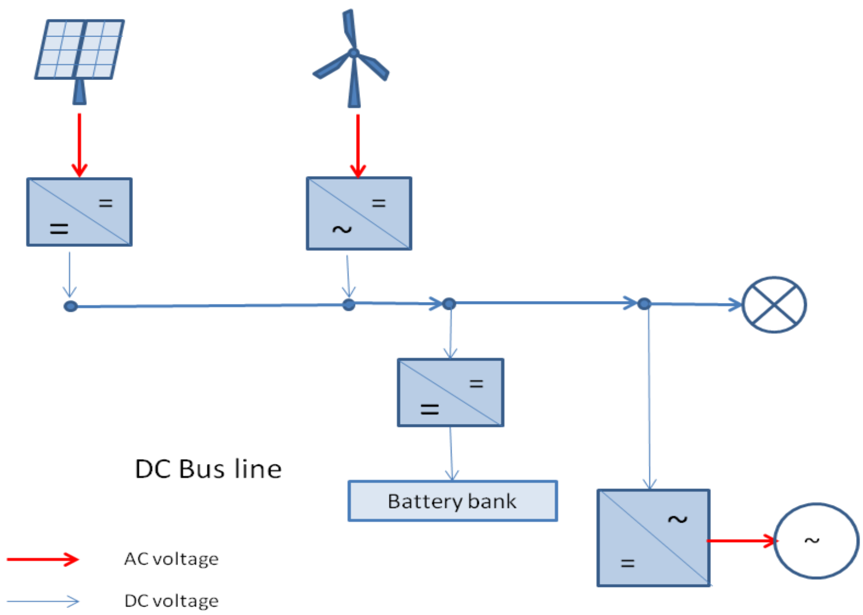

Figure 12 - Figure of a Pure DC Bus line HPRS configuration (55)

2. Pure AC Bus line

All power generating components are coupled to an AC Bus line. Components that output AC voltages may be connected directly to the AC bus line, or alternative, need an AC/AC converter to enable stable coupling. A bidirectional inverter controls the energy supply of the AC loads and the battery charging. Battery units connected to the AC Bus line are connected via a bidirectional inverter to supply or absorb power from the grid. Pure AC Bus line system is shown below:

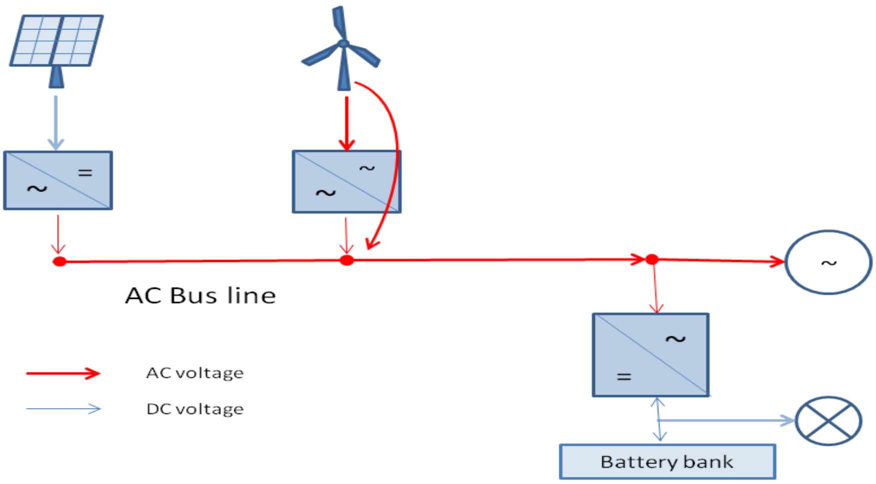

Figure 13 - HPRS incorporating an AC Bus line concept (55)

3. Hybrid AC/DC Bus line

As the name suggests, both an AC and DC bus bar is employed in this configuration. DC and AC generating components are connected at both sides of a master inverter, which controls the power flow to the AC loads. DC loads are supplied by the battery. While this setup will have a higher level of complexity, cost and control by integrating them both together, it is possible for both AC and DC bus bar to complement each other's weaknesses. The single line describing this configuration is shown below:

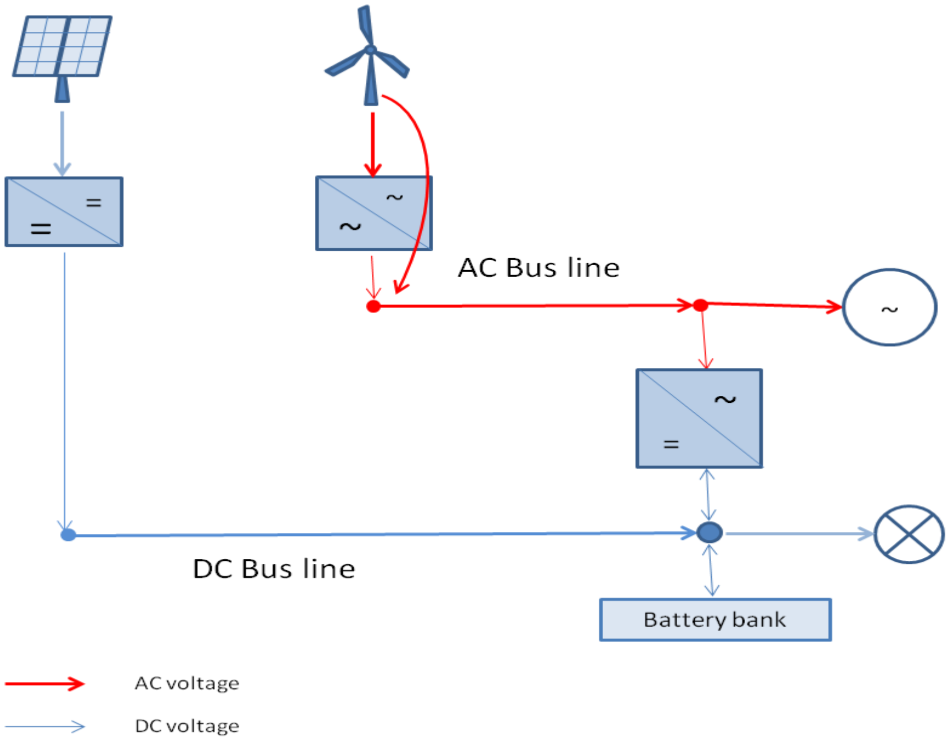

Figure 14 - Hybrid AC/DC Bus bar for HRPS (55)

Table 2 - Critical Comparison of DC Bus line, AC Bus line and Hybrid Bus line

	DC Bus line	AC Bus line	Hybrid Bus line
Power Generator Input	Connected via Rectifiers	Connected directly or with AC/AC Converter	Both AC and DC sources connected at Master Inverter
Load	Connected directly to DC Loads	Bidirectional Inverter controls AC Load and Battery charging	Master Inverter control power flow to AC Load
ESD	Connected directly to bus line	Connected to AC Bus line via Bidirectional inverter	Interfaced directly

4.2 Topology of a Hybrid Power System

As described, a HPS is a system that employs multiple generation sources to produce power to its output application. Hence, each generation source can be described as power plants.

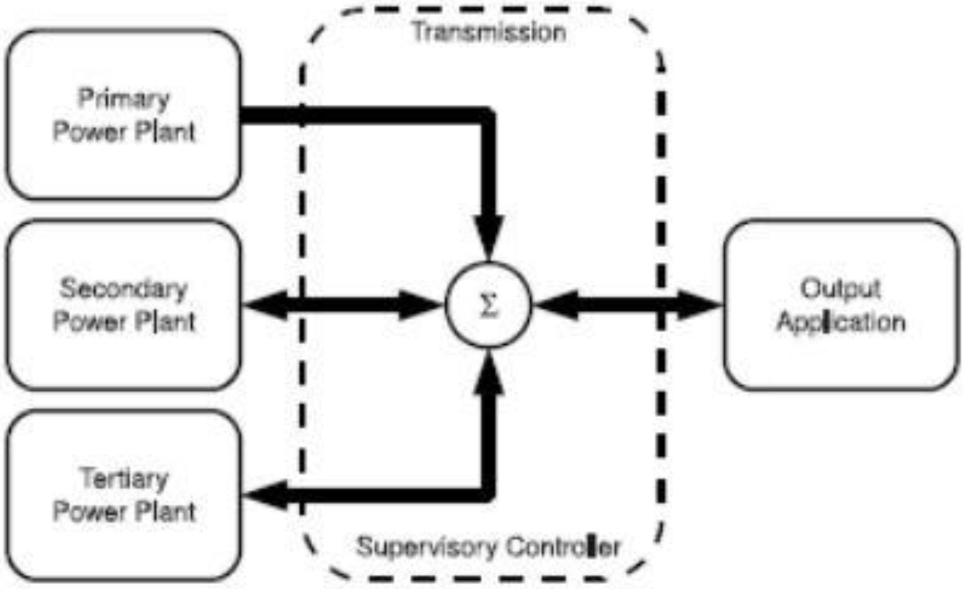

Figure 15 - Block diagram of a hybrid drivetrain topology (10)

The block diagram in Figure 15 was used as a template for HPS design in this thesis. For a system which consists of 3 power plants, the power plants may be called as Primary, Secondary and Tertiary power plants. Transmission schemes are used to link the output of different power plants and channel it to the intended output application.

In this thesis, a HPS is still generally considered as a concept. However, HPRS is used to specifically describe a HPS employed in the RE field. A hybrid drivetrain is used to refer to the entire system top-to-bottom: the entire HPS system and the interface to the output application. Each power plant will be discussed below.

Primary Power Plants (PPP) are the main energy source of interest for power extraction. Such energy sources here include Wind, Solar, Geothermal, Nuclear, Wave, Internal Combustion Engines and others. It should be noted that PPPs can be used to produce power. It does not function as a power sink in any case (10). There may be more than one primary source of energy in this plant, i.e. Wind combined with Solar.

Secondary Power Plants (SPP) are generally taken as ESDs. ESDs is able to augment the performance of PPP by increasing the capacity and generation efficiency of the HPRS system, provide reactive power support for the generators in the same HPRS, alleviate RG variability while ensuring output power quality is on par with the grid. Due to the nature of ESDs, SPPs are able to act as power sinks for surplus power in the grid by converting it into stored energy. Generally, ESDs in SPP are for long term energy storage purposes. For this case of the thesis, BESS is the SPP.

Tertiary Power Plants (TPP) have a very different role of all the power plant and is optimised for a different task. The function of TPP is dependent upon the first two plants, as the aim of TPP is to further complement the entire system. Examples of TPP components include short term ESDs such as Ultra-capacitors or resistor banks for energy dissipation purposes (10). Short term ESDs employed in the HPRS are aimed to alleviate short bursts of power fluctuations (in the range of seconds to minutes), that is not normally coped by the larger ESDs.

4.2.1 Control Strategies

CS is essential as they not only tell the system what to do next qualitatively, but also quantitatively and when to stop. The successful operation of the entire HPS operation depends on the successful operation of each individual component at low level. Hence, CS extends not only to the system-wide output of the entire system, but also down to each individual component.

In a complex system (i.e. HPRS), there are 2 fundamental types of control objectives to be met (10). These are:

- Output Control: Effective control of the system-wide HPRS output power
- Supervisory Control: The control of each of the individual power plants at low levels of the system

a. Output Control

Output Control relates the system-wide (High-level) output of the HPRS to the outside world according to the operational requirements. The operational requirements of Output Control are highly dependent upon 2 things: the duty cycle of the intended application, and component selection at the system design stage. Therefore, it is imperative to know the operational requirements of the intended application of the HPRS.

b. Supervisory Control

Supervisory Control is the low-level control strategy employed for individual power plants and transmission of a HPRS. As different power plants have different roles to play, hence each of the individual supervisory control will have different operational requirements to meet. For an HPRS, the supervisory control will have to take into consideration certain parameters: State of Charge (SOC) of the ESD, Depth of Discharge, ESD discharge rate, DC Link voltage testing, Bidirectional DC-DC Converter control to transfer power to the DC Link when there is a low voltage and output PWM Inverters.

4.2.2 System control strategy selection

As different systems have different tasks, operational requirements and conditions to monitor, each system will require the right CS to perform correctly. There are many ways to approach the right CS for a system. Rule based CS is generally more popular as it is easier to form conditional-action rules for systems to follow (10). The general thought process for a programmed system is: 'If' a rule is met by a predetermined set of conditions, the system will execute the following commands. This whole program is then run in a loop for continuous monitoring. Generally, CS can be classified into 2 broad categories: Deterministic and Fuzzy Logic.

Deterministic Control Strategies are formed by human observation and experience to monitor and react to measurable quantities such as shaft speed and State of Charge of ESD. However, deterministic CS does not consider the efficiency of the drivetrain as whole. There are several examples of Deterministic CS in use today and by far the most popular, simple and effective rule-based strategy is the Threshold based strategy. This threshold based strategy is used for the HPRS designed in this thesis.

Threshold-based strategy works by implementing thresholds in which if any monitored value crosses this threshold, a process in the system will be triggered. This strategy is frequently applied to ESDs. If there is unused power above the allowed threshold which maintains the grid frequency, surplus power is then channelled to be stored in the ESDs connected to the grid. If the power levels dipped below the specified threshold, then deficit power will be siphoned from the ESD back into the grid. A diagram describing the Threshold based rule is shown below. Other examples of Deterministic Control Strategies are Power Follower, Modified power follower and State machine (10).

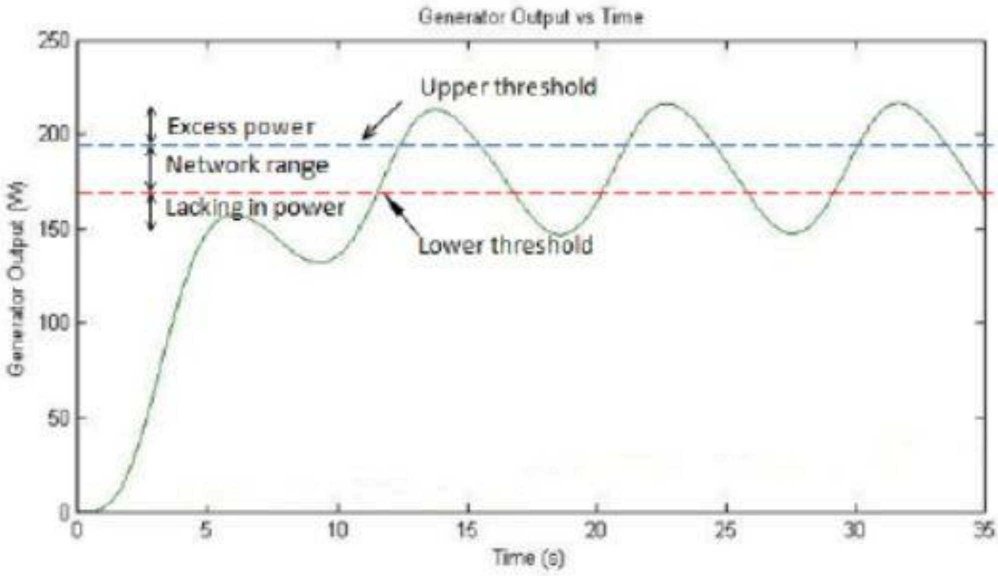

Figure 16 - Threshold based Deterministic Control Strategy (28)

Fuzzy Logic Control Strategies are considered as a combination of multiple rule-based Deterministic control strategies. Each Deterministic control strategy has their own task at hand, but each of them work hand-in-hand for the larger picture of the HPS (10). According to (58) and (59), fuzzy logic is much closer in spirit to human thinking and natural language than the traditional logical systems. This provides an interesting method of capturing the inexact nature of the real world. Therefore, it is especially useful due to their flexibility to tolerances of imprecise measurements. This method can be branched into Conventional, Adaptive and Predictive control (10).

4.3 Summary

An introduction to HPS was given to the reader and an explanation as to how HPS is the 'Eureka moment' of ESDs. Technical aspects of HPS were then gradually revealed with single-line system diagrams of actual real-world systems, and were classified into 3 categories: Pure DC Bus line, Pure AC Bus line and Hybrid AC/DC Bus line. Next, a template of a typical HPS system was presented and each individual power plant was then discussed. Control Strategies and its importance were then discussed and shown that the 2 HPS governing control strategies are called Output and Supervisory Control categories. The general Control Strategies frequently employed was then sub-divided into Rule-based Deterministic and Fuzzy Logic control. The Threshold based strategy (under the category of Deterministic control) was explained in more detail as it is used in this research. Needless to say, HPS shows a lot of promise not only in the RE field, but also in the transportation sector.

Chapter 5 – Designing a Hybrid Power Renewable System

There is still a lacking of a defined standard as to design a hybrid power system from the ground up while taking into consideration challenges and conditions from all sides. Designing a HPRS at a given location is not an easy task, and it comes with many challenges. From an investor's point of view, the PPP have to be the most abundant and cost effective, i.e. wind density at a flat plain. This is so as different power plant candidates and applications will have different associated costs (60). The SPP (typically an ESD) will then have to be able to complement the PPP. It is not easy to decide which kind of systems is best under which conditions and also the capacity sizing of the ESD, especially when high cost is at stake. Also, to decide on an on-line operating strategy requires knowledge of electricity market prices (spot prices), electricity market condition, demand forecasting and operation scheduling (61). Other conditions to take into consideration are available resource analysis, system design optimisation, cost breakdowns (O&M costs), policy analysis and operational analysis.

Presently, there are softwares to aid in the design of a HPRS. Examples of softwares currently in use are industrial grade HOMER, VIPOR and Hybrid2 by National Renewable Energy Laboratory (NREL) and Centre for Energy Efficiency & Renewable Energy (CEERE). The combined functions of those softwares will allow an investor to be able to determine the most cost-effective solution component selection for a hybrid power system for the desired application (such as rural electrification), and to optimise the performance between system components.

Here is a novel take on this challenge. This method will be applied in the next chapter for a case study of implementing a HPRS of Wind Turbine and BESS beside the Gisbert Kapp (GK) building (which houses the departments of Electronic, Electrical and Computer Engineering and Health Sciences). This case study is called 'The HPRS-GK case study'.

5.1 Design and Development

Designing and developing a product from scratch requires many phases, consideration of many conditions and operational specifications. The design of a HPRS involves 2 stages, Planning phase and Operational Planning phase.

5.1.1 The Planning phase

The planning phase is where initial development and motives of the system are first defined and tackled. Below are the steps that were used to build a HPRS beside the Gisbert Kapp building.

a. Data procurement

At the initial development level, it is important to procure as much generation source and load data as possible. The data that will typically be of interest to engineers (depending upon application) are the renewable source data and load profiles at a targeted location. It is proposed in this step-by-step method that the any analysis of data starts from the load profile.

1. Load profile

Load profile is defined as the power requirements for the demand-side converters over a given period of time (56). Load profiles vary each hour but it is predictable as user habits are similar day-by-day, or at times of special events i.e. half time in a World Cup game or at commercial breaks of a popular television series. Despite being somewhat predictable, there will be times when there are peak demand spikes. Therefore, a HPRS coupled with an ESD that is designed to handle the load 80-95% of the time is recommended (56). Daily demands can be logged by a data logger or a meter. If however, seasonal variations in load are suspected, long term data logging will be needed to reveal the seasonal load profile. Load profiles are important to decide the type of HPRS needed.

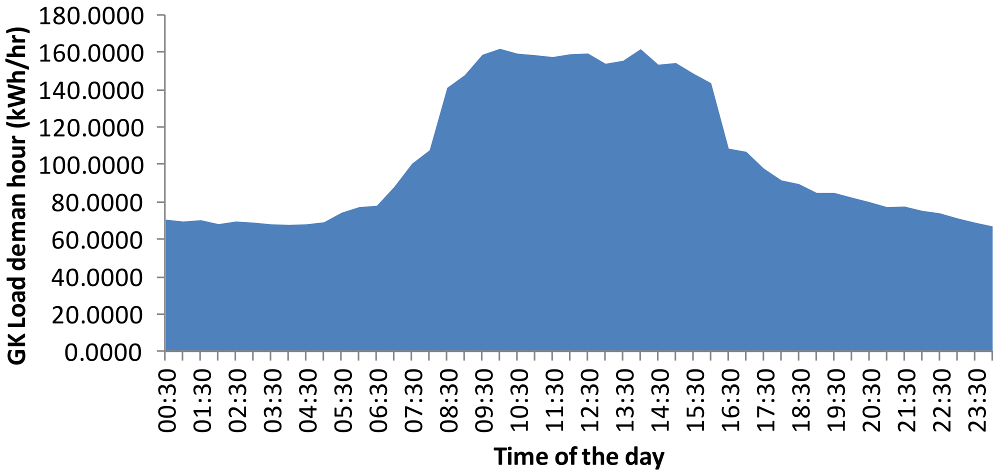

Figure 17 - Load demand of Gisbert Kapp building over time, sampled every half hour across 24 hours at 23/9/2010

2. Renewable source data

Renewable source data, i.e. wind speeds, wind density per meter squared and peak sun hours. Below is a partial screenshot of data that was provided by University of Birmingham's Birmingham Urban Climate Laboratory (BUCL). It shows the dates and different weather base stations that are placed all around Birmingham city. Below is the data that was taken by a base station very near to Gisbert Kapp building.

Energy source data is important to determine the reliability of the PPP and the annual output of the WT or the Capacity Factor. As the amount of power generated by the WT is to the cube of wind speed, it is a non-linear function. And as WTs generate power between the Cut-in and Cut-out wind speeds, knowing the proportion of time wind speeds are outside this range is also equally important. Wind speeds can be measured by anemometers or sonic anemometers housed at weather stations, at various frequencies ranging from every second (1 Hz) to once per minute. The wind speed may then be averaged over a period of time. Also, Weibull distribution is considered the de facto standard of modelling wind speed distributions (62). Wind speed data is also important to calculate the Wind Energy Flux, also known as the Wind Energy Density. Therefore, the 2 very important parameters to determine in a given location are Wind Energy Density and Wind Speed Frequency Distribution.

The 2 parameter Weibull Distribution is the standard method to calculate the wind speed frequency distribution in order to determine the annual output of the WT. The cumulative distribution function is given by,

$$\Pr(U \le V) = F(V) = 1 - \exp\left[-\left(\frac{V}{A}\right)^k\right] \tag{11}$$

Where U and V are wind speeds, A is scale parameter and *k* is the shape parameter. For wind frequency distributions, the shape parameter is recommended to be a value of 2.

The Wind Power Density (WPD) is a direction function of air density and wind speed. It is given by,

$$\text{Wind power density} = \frac{1}{2} \times \rho \times V^3 \quad (12)$$

As described later in section 6.1.1, the yearly mean wind speed at GK is 3.27m/s. Equating this into the Wind power density equation, gives 21.42 W/m^{-2}.

The WPD may be calculated from a 2 parameter Weibull function. The shape and scale parameters of the Weibull function may be estimated seasonally to calculate annual wind power output and the WPD.

b. System and individual power plant sizing

As HPRS uses both renewable generation and energy storage, not only are the benefits of both worlds brought together, but so do their weaknesses. As with any power generation system coupled with renewable generation, there will be 2 fundamental challenges associated with HPRS: Varying user load and varying renewable energy source.

1. Specifying and sizing a Primary Power Plant

It is a must that PPP's generation capacity must be able to meet the daily energy requirement or a certain percentage of the total energy required on a yearly basis (with the help of a backup generator). As renewable energy sources are variable in nature, the ESD will complement any dips and highs. As PPP works hand-in-hand with the SPP ESD, roundtrip efficiency of the ESD device must be considered as well.

As an example, using the data from Figure 16, the total consumer consumption for 23/9/2010 is 5044.8 kWh. Therefore, 5044.8 kWh is the energy that the HPRS of wind turbine coupled with BESS must supply. Assuming that the WT generator efficiency is 0.9, the wind generation will have to supply:

$$\begin{aligned} \text{Targetted amount} &= 5044.8 \div 0.9 \\ &= 5605.3 \text{ kWh} \end{aligned} \quad (13)$$

It should be noted that the WT generator should not only provide power to charge the BESS but also to provide the required output power to the grid.

2. Specifying and capacity sizing a Secondary Power Plant

In this case, the SPP will be an ESD. However, specifying an ESD is dependent upon the HPRS application and customer specifications. For high power load levelling purposes, characteristics of the HPRS needed are high storage capacity, high DOD, high cyclic efficiency, high mass and volume densities of energy, high cyclic life and low self-discharge rate. For a decentralised HPRS system, certain characteristics such as high storage capacity and mass and volume of energy density is not needed. However, other operational characteristics such as high discharge rate and fast response times are crucial to alleviate variations in power.

Sizing the capacity of the ESD or multiple ESD's is probably the toughest and most crucial aspect of designing a HPRS. Having the optimal size of ESD is a compromise between cost, storage capacity, power quality and reliability, cyclic life and profitability. The ESD must have the capacity to compensate for any deficit energy and to absorb any surplus energy. If capacity is too large, a larger cost will be associated with the HPRS construction. Vice versa, if capacity is too small, not all surplus energy will be absorbed and deficit energy compensated. Hence the HPRS will not be profitable. There are many qualitative methods currently to optimally size an ESD, such as the Duty Cycle Constrained Selection (DCCS) method (10), genetic algorithms, and using the peak demand value in the load profile as the capacity value for the ESD (63) (shown below). These methods have their respective strengths and weaknesses. Fortunately, industrial grade softwares such as HOMER are also used to aid in this design aspect.

If the Pwind is higher than Pdemand, the ESD is charged and vice versa. The capacity of the ESD is taken from the lowest point of Pwind below the Pdemand threshold. If the capacity starts from the highest discharge point, a constant deficit power will be able provided over a time range.

Continuing with the example above, the SPP for the HPRS of GK will be Li-Ion BESS. When selecting and sizing a BESS, there are 2 factors to consider: the system voltage and maximum charge rate of the BESS (56).

The WT generator in this case should be able to provide DC current up to the maximum allowable charge rate of the batteries.

Assume that battery capacity is 875 Ah at C_{100} rate and System voltage is 24 V. Capacity at 10 hour charging rate is 662 Ah. Therefore, maximum charging rate at C_{10} is 662/10 = 66.2 A. It can be deduced that the DC Link voltage should be able to provide 24V and at least 60 A.

3. HPRS Electrical Distribution Configuration

Once the primary and secondary power plants have been sized, the transmission configuration will then be specified. Traditionally, power system planning includes centralised generation and transmission planning. But today's power system requires generation and resource adequacy and transmission planning. Transmission goes hand-in-hand with resource adequacy planning as it is crucial that reliable transmission interconnect the generation with demand.

For different applications, different configurations of transmission configuration will bring the most benefits. As stated in chapter 4, the most efficient configuration of HPRS topology is the hybrid AC-DC bus line. Hence the configuration will be implemented in the upcoming GK-HPRS case study.

At this stage, a model of a HPRS should have been formed, which includes both PPP and SPP.

5.1.2 The Operational Planning phase

In the operational planning phase, this is where supervisory and system control strategies are selected. Supervisory control strategy controls each individual power plant via feedback loops and controlled - PWM converters. System (output) control strategies take into consideration outside world and directs the HPRS to react accordingly at a low level. It should be noted that different control strategies will affect the capacity sizing of the ESD differently.

a. System (output) control strategy

As stated in chapter 4, the simplest and most common system control strategy for a HPRS is the Deterministic Threshold-based control strategy. As providing power to any network requires the delicate balance of generation and demand, the mismatch in power can be measured. This difference will then be used as a reference value for PI converters to control the appropriate SPPs or ESDs.

However, as multiple ESDs with different characteristics may be integrated within a HPRS, firing the right one at the right time is equally important. Hence it is also the function of the system control strategy to use the appropriate ESD at the right time, balance the output of each ESD, and to deactivate any ESDs to be recharged.

As an example with respect to the HPRS-GK case study, this deterministic control strategy will be implemented.

b. Supervisory control strategy

Supervisory control only manages its own power plant with respect to control signals from system control strategy. Such supervisory control strategies for individual power plants are battery trickle charge control, WT DFIG maintaining the constant DC voltage at the DC Link and PWM control of the bidirectional DC-DC Converter at the battery side.

As system control strategy can be taken as the 'overseer' of system-wide functions, it can be put into simpler terms with a flow chart. Below is an example flow chart for a HPRS which is integrated with only one ESD, and not a combination of multiple ESDs. This flow chart shows how System control strategy is related to Supervisory control strategy. The black arrows in the flow chart represent System control strategy while the ones in red represent the supervisory control strategy.

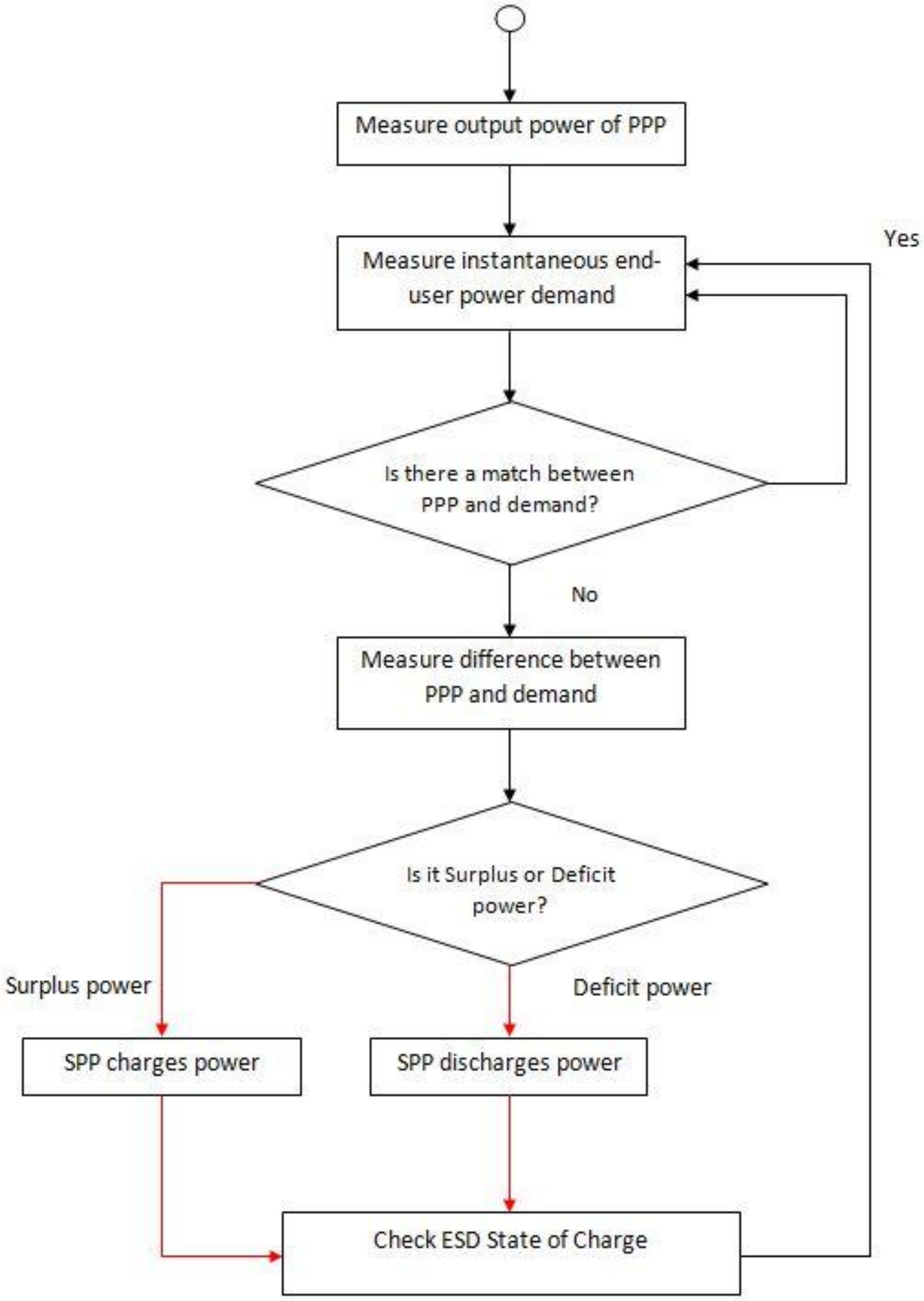

Figure 18 - HPRS flowchart.

5.2 The Novelty of the proposed method

This method proposed in this thesis was done based on several journal accounts of attempts at designing and constructing real world HPRS. A critical analysis was done on each account, and the strengths various techniques were applied here.

5.3 Summary

As a conclusion, this chapter has presented a novel step-by-step method to designing a HPRS in a given location. The entire process is divided into 2 sections, the Planning phase and the Operational Planning phase. The planning phase involves Data procurement to decide the reliability and resource capacity of the power plant. The procured data is then used to size and specify individual power plants. Operational control method is divided into System and Supervisory control. A flowchart was given to show how these 2 strategies relates to each other.

Chapter 6 – Case study: Hybrid Power Renewable System at University of Birmingham's Gisbert Kapp building

This chapter investigates and tests the step-by-step process of implementing a HPRS system from chapter 5.

A case study of simulating a HPRS system at Birmingham University's Gisbert Kapp (GK) was formed. The GK building houses both the Electronic, Electrical and Computer Engineering and Health Sciences departments. This simulation was formed as there was ample wind resource data that was taken very close to the GK building by a weather station (managed by Birmingham University's Birmingham Urban Climate Laboratory (BUCL)) and GK building power demand data (managed by Estates department). It was decided that a HPRS consisting of a WT and a Lithium-Ion BESS system will be implemented beside GK building.

In order to test the simulated HPRS system, wind resource and energy demand data for 1 day were procured from BUCL and Estates: 26 June 2011. These data procured are 1 minute averaged wind speeds recorded in the weather station at a height of 7 meters.

The energy demand data of GK that were procured were measured every half hour via 2 transformers from 12:30am to 12am the next day. The data from Estates also correspond to the above date.

6.1 Design and Development

HPRS design for this case study will be implementing the Design and Development method in Chapter 5. Using the block diagram in chapter 4, the HPRS drivetrain topology is:

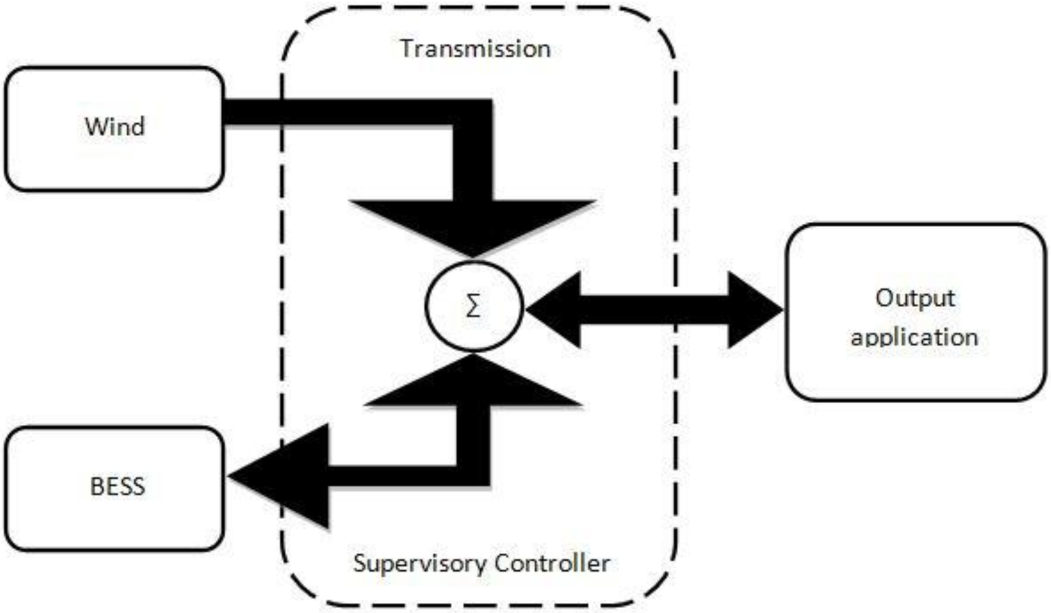

Figure 19 - HPRS drivetrain technology incorporating Wind and BESS

6.1.1 The Planning Phase

a. Data Procurement

As stated in the introduction to this case study, wind resource data and load demand profiles were procured from BUCL and Estates department.

1. Load profile

The following figure shows the subplots for the energy demand profile for GK for one day.

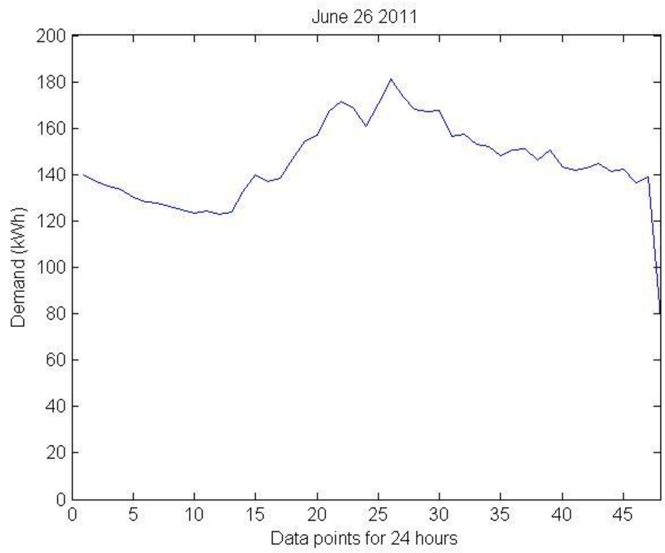

Figure 20 - Plot of load profile

Table 3 - Table of mean daily profiles

Date	Total daily energy consumption (kWh)	Total daily power consumption (kW)	Mean daily energy (kWh)	Mean daily load (kW)
26 June 2011	3477.7	6955.4	72.45	144.9

As the data above is in units of kWh, which is a unit of energy. But,

$$kW = \frac{kWh}{h} \tag{14}$$

Where *h* is time in unit of hours, *kW* is the rate of energy usage, or power demand. These readings were taken at intervals of 30 minutes (0.5 hours). However, the readings above are averaged power and it was assumed that this energy profile has a similar shape to the power profile. From the data above, it is now almost possible to start sizing the PPP. Therefore, a 200kW Norwin 29-STALL-200kW will be modelled for this research.

2. Renewable source data

Figure below shows the plotted timeseries data that was procured on .

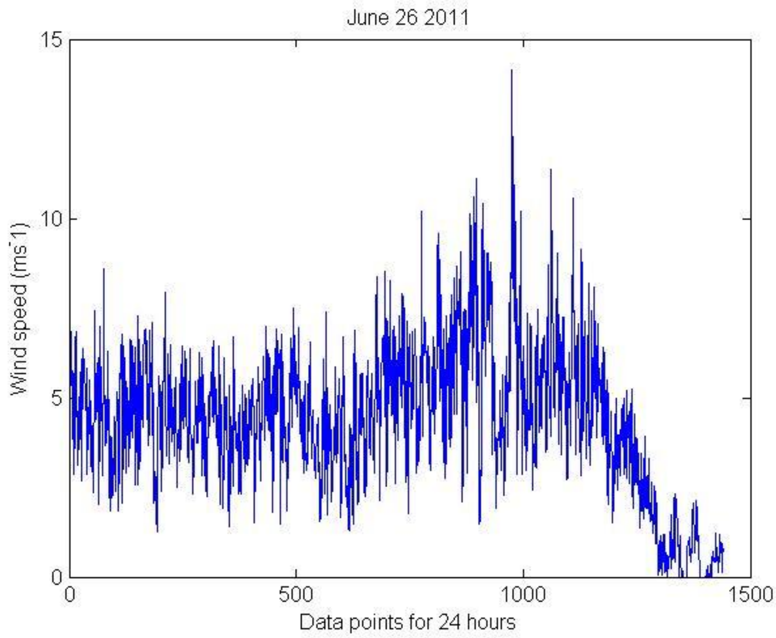

Figure 21 - Figure showing the wind speed profile

This implementation was done by using REUK.co.uk's built in annual power generated tool (64). This tool is able to calculate a WT's annual electricity output with wind speeds that is modelled by the Weibull Distribution.

Based on data points provided by BUCL over a year, the average wind speed at GK is:

Wind site	Wind Turbine	Year mean wind speed (m/s)	Wind power density (W/m^2)
Gisbert Kapp building	**C&F 100**	**3.2700**	**58.53**

However, this data was taken by a weather station at 7m height. It is also known that wind has different speeds at different heights. Therefore, this value will have to be extrapolated to the WT tower height.

There are 2 methods in which the wind speeds can be extrapolated to a different height (62,65): the Wind Power Profile Law and Log Wind Profile. Both methods produce almost the same results, and the Wind Power Profile Law will be chosen due to its simplicity and flexibility. The Wind Power Profile Law, which is also known as the One-seventh Power Law is as below:

$$u_x = u_r \left(\frac{z_x}{z_r} \right)^{\alpha} \tag{15}$$

Where u_x is wind speed at the target height, u_r is the reference wind speed at a known height, z_x is the target height, and z_r is the reference height and α is assumed to be at a constant of 1/7 or 0.143.

Using this formula, all data that were procured for the entire year was extrapolated to the Northern Power® 100 hub height of 43m. Hence, the new extrapolated mean wind speed is:

Wind site	Wind Turbine	Mean wind speed (m/s)	Wind power density (W/m^2)
Gisbert Kapp building	**C&F 100 (x2)**	**4.1491**	**119.55**

With the new extrapolated mean wind speed at a height of 43m, the new Weibull Distribution curve can be calculated with REUK.co.uk's power calculator tool.

The predicted annual turbine output is 182,039 kWh. Also, the wind power density is 119.55 W/m^2. This is expected of urban wind speeds due to obstacles such as buildings and trees. A wind power density of 119.55 W/m^2 is considered as Class 2 by National Renewable Energy Laboratory (NREL) (66). According to the organisation's calculations, Class 3 is the ideal class for wind generation.

b. *System and Individual power plant sizing*

1. Specifying and sizing a Primary Power Plant

The Primary Power Plant in this case will be wind. As shown in Chapter 5, the wind turbine output will be calculated based on the daily load. The largest load will be taken as the reference value:

$$\begin{aligned} &\text{Daily load} = 3477 \text{ kWh and Generator } \eta = 0.9 \\ &\text{Energy required} = 3477 / 0.9 \\ &= 3863.33 \end{aligned} \tag{16}$$

The wind generator will have to supply a total of 3863.33 kWh daily. Increasing the rated power output of the WT will dramatically increase the cost of the system.

It is therefore recommended that GK should not fully rely on a PPP coupled with a SPP. It should still rely on conventional grid base load sources alongside a PPP and SPP.

2. Specifying and capacity sizing a Secondary Power Plant

The battery should supply the average load of a depth of discharge of 60% for 1 hour. 60% DoD is assumed to be the maximum safe level discharge of the battery. As this wind turbine scheme with the DC Link does not require the BESS voltage to be same voltage, 300V will be provided by the battery. Therefore, calculation for battery rating is as follows:

$$\text{Battery rating} = \frac{144.9\text{kW} \times 1\text{hr}}{300 \times 0.6} \\ = 800Ahr \tag{17}$$

Therefore, 25 800Ah 12V batteries connected in series were considered.

6.1.2 The Operational Planning Phase

a. System (Output) control strategy

For the system's output control strategy, the common and simple Deterministic Threshold-based control strategy (as discussed in Chapter 4). Based on the WT topology, the DC link voltage affects the duty ratio of the PWM. Therefore, the DC link voltage will be maintained via PI controllers (which control the charge and discharge rate of the BESS) at a target voltage based on the instantaneous output and thresholds.

b. Supervisory control strategy

As discussed in chapter 4, Supervisory control strategy is the control methods at the component level. For this case study, the PPP is the WT and SPP is the BESS.

Wind Turbine supervisory control. As the WT has a direct-drive (gearbox-less) system, supervisory control of the aerodynamic system is needed. However, simulating an aerodynamic system is beyond the scope of this research.

BESS supervisory control. However, for the BESS system, a charging system is needed. A charge controller is important to manage the delicate chemical reactions during the charging process, which will cause undesirable reactions to occur. Among the effects of overcharging are electrolysis of water and generation of hydrogen and poisonous gasses, and deformation of cases of sealed batteries, which destroys the battery (67). However, simulating a battery charge controller is beyond the scope of this research.

WT PE supervisory control. Based on the WT PE topology, it is an AC/DC/AC converter which consists of an uncontrolled rectifier and a PWM-controlled voltage-source inverter separated by a DC Link.

6.2 Mathematical modelling and Simulation

6.2.1 Input wind speed modelling

The wind data that was acquired from BUCL was loaded into Matlab workspace in Time Series format. Data was extracted from the massive BUCL depository and placed into Matlab-readable notepad format. The time series was saved in the workspace, and the From Workspace block was used to invoke the data.

6.2.2 Wind Turbine modelling

Throughout the course of the research, several models of WTs across different sources were investigated. The models that were investigated are: built-in Simulink WT model, built-in Simulink DFIG Wind Farm demo (involves built-in Simulink WT model), Aalborg University's Wind Turbine blockset, and the author's own WT model from his Bachelor study years. As a WT consists of the Rotor, the Generator, and the PE i.e. Rectifier and Inverters, this section will be sub-divided accordingly.

a. Wind Turbine rotor modelling

As stated in chapter 3, the mathematical model of WT rotor is:

$$P_{\text{wind}} = \frac{1}{2}\rho A U_{\text{in}}{}^{3} C_P(\lambda, \beta) \quad (18)$$

Screenshot to follow:

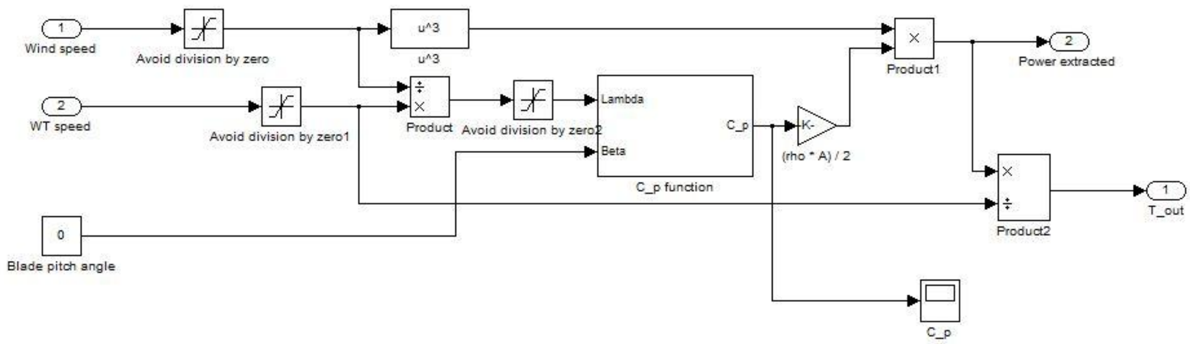

Figure 22 - WT Rotor model Simulink implementation

In the model, two 'Avoid Division by zero' blocks were used. These blocks impose a ranged limit on which the values may enter the block, while avoiding Zero-Crossing Errors. C_p function describe the Coefficient of Performance of the Wind turbine, given by the equation

$$C_p(\lambda,\beta) = c_1(c_2/\lambda_i - c_3\beta - c_4)e^{-c_5/\lambda} + c_6\lambda \quad (19)$$

Where coefficients c_1 to c_6 are $c_1 = 0.5176$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = 21$, $c_6 = 0.0068$. These values were taken from Simulink's Documentation (15). T_out is the Torque output of the WT.

b. Wind Turbine generator modelling

The Permanent Magnet Synchronous Generator was used as the WT generator. The mathematical model used is from the Simulink SimPowerSystems model depository. The machine parameters are tabled below:

PMSG	
Stator resistance	0.016 Ohm
Armature inductance	0.0007 H

Magnetic Flux	1.04 Vs
Pole pairs	6
Rated power	100kW

Below is a screenshot of the wind turbine model:

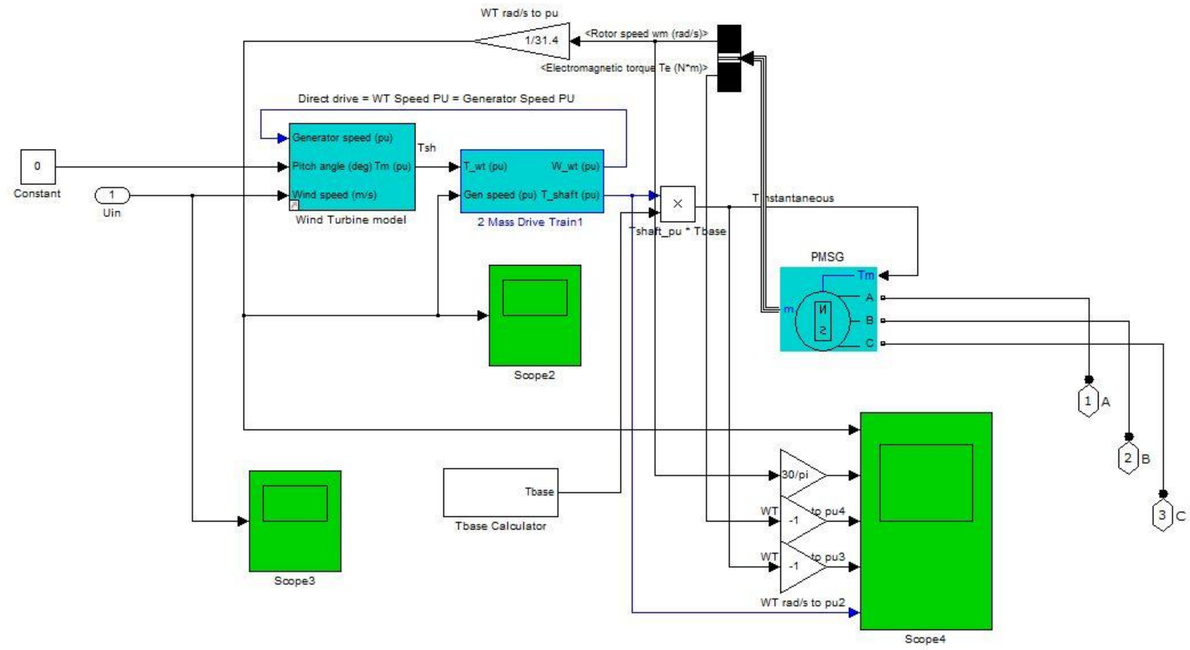

Figure 23 - WT model with PMSG

The 2 Mass Drive Train describes mathematically the transfer of torque from the rotor to the generator through the shaft. The PMSG block models a PMSG and is a built in Simpowersystem toolbox component, whereas the T_base calculator calculates the Base Torque of the WT based on base Power and base Rotational Velocity. This block is used to convert the torque signal from the 2 Mass drive train block from PU to actual value.

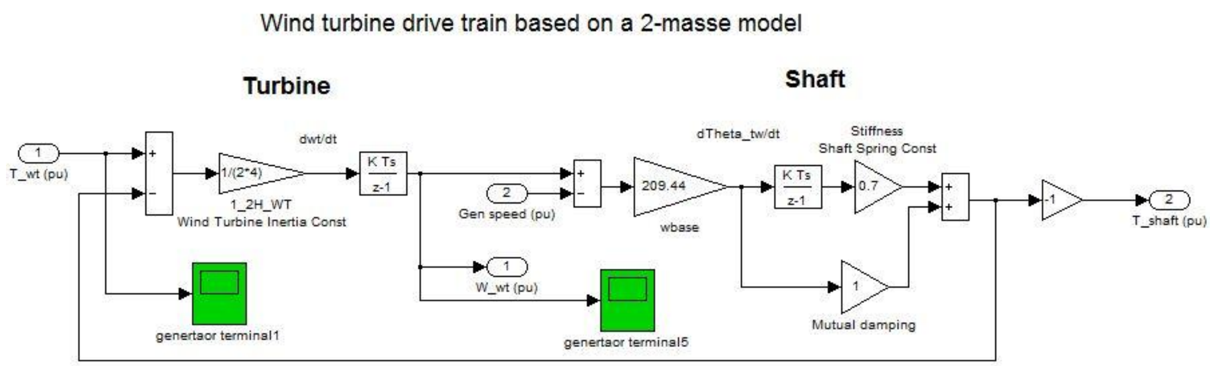

Figure 24 - Figure of a 2 Mass Drive Train block

c. *Wind Turbine AC-DC-AC Converter modelling*

In this WT scheme, power generated from the PMSG will be fed into an AC-AC Converter.

Moving on to the DC Link parameters, the relation between DC Link voltage and the output AC Voltage of 3-Phase PWM inverter is given by:

$$V_{LL} = \frac{\sqrt{3}}{2\sqrt{2}} k V_{DC} \qquad (20)$$

Where *'k'* is modulation index of the PWM Inverter, and V_{LL} is the Fundamental phase-phase RMS voltage of the AC side. As V_{LL} is set as the on-site grid voltage of 415 V_{RMS}, and k was set as 1, the V_{DC} was found to be 680 V. This value was then used to calculate the capacitance of the DC Link capacitor. The capacitance was found via the ratio of stored energy in the capacitor to the nominal power rating of the converter:

$$\frac{W_c}{P_{nom}} = \frac{\frac{1}{2} C V_{DC}{}^2}{P_{nom}} = 0.5\left(\frac{1}{f_{grid}}\right) \qquad (21)$$

This ratio is usually a fraction of a cycle, over here this fraction is taken to be 0.5 cycle. This shows that the calculated capacitance value will be able to supply nominal power to the inverter for half a cycle, when the inverter is disconnected from the rectifier. As f_{grid} is 50Hz, V_{DC} is 680V, and $Pnom$ is 100kW, the capacitance was found to be 8650μF.

The inverter was controlled by using a basic PWM Signal Generator outputting signals at 3000 Hz. This circuit was based on a DC Bus bar, as compared in Table 2.

The screenshot of the AC-DC-AC model is shown below:

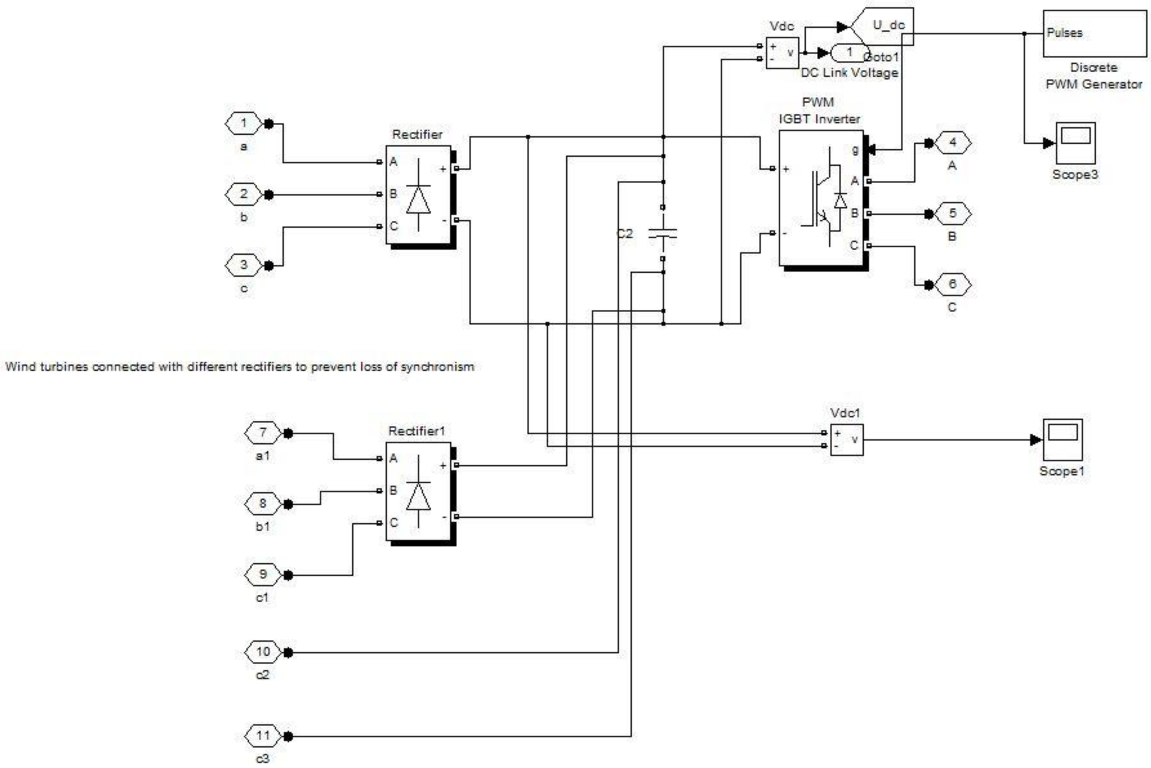

Figure 25 - Screenshot of AC-AC Converter with DC Link

d. Consumer varying load demand modelling

The load demand of EECE building was first saved in the TimeSeries format. A challenge then occurs with inputting a varying load into the system. This was achieved by using the Three-phase Dynamic Load block from Simulink to input the varying loads.

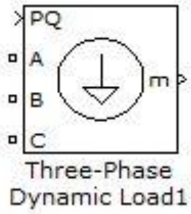

Figure 26 - The Three-phase Dynamic Load block

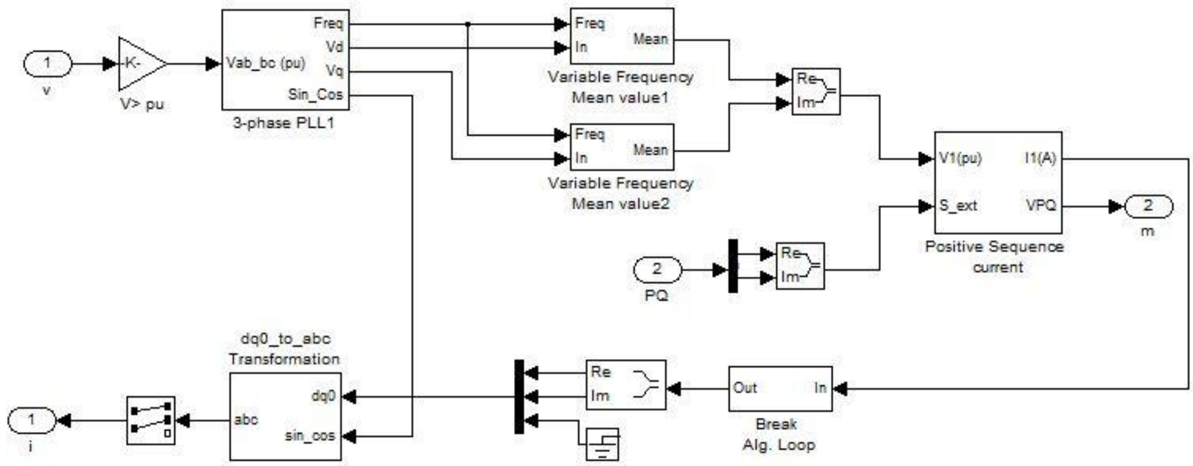

Figure 27 - Under the mask of the 3-phase Dynamic Load Block

The 3-phase dynamic load block implements a 3-phase, 3 wire dynamic load where the active and reactive powers vary as a function of a positive-sequence voltage. When terminal voltage of the load is higher than a specified minimum, the active and reactive powers behave as below:

$$P(s) = P_0(\frac{V}{V_0})^{n_P} \frac{1+T_{p1}s}{1+T_{p2}s}$$
$$Q(s) = Q_0(\frac{V}{V_0})^{n_q} \frac{1+T_{q1}s}{1+T_{q2}s} \quad (22)$$

Where V_0 is the initial positive sequence voltage, P_0 and Q_0 are initial active and reactive powers, V is positive voltage, n_p and n_q controls the nature of the load, T_{p1} and T_{p2} are time constants controlling dynamics of active power, and T_{q1} and T_{q2} are time constants controlling reactive power.

This requires an 2 column timeseries input of PQ values whereas the data acquired was in kWh. It was also assumed that GK has a power factor of 1, and does not absorb Reactive Power.

6.2.3 Hybrid Power System modelling

a. BESS modelling

The Battery Energy Storage System was modelled with the Simulink Battery block. This block provides an accurate and easy to implement model for batteries. As a simple means of sizing the battery capacity, it is required to be able to supply nominal power for 1 hour. The benefit of having a Bidirectional DC-DC Converter to control the voltage of the DC Link is that the battery voltage can be lower than the V_{DC}.

To keep the simulation model simple, Lithium-Ion batteries were chosen. This is so as a different type of battery charge control has to be implemented in order to successfully charge a Lead-Acid type battery.

b. Bidirectional DC-DC Converter modelling

The PE component that separates any HPS from other systems is the Bidirectional DC-DC Converter. The schematic of this simple Bidirectional DC-DC Converter is shown below:

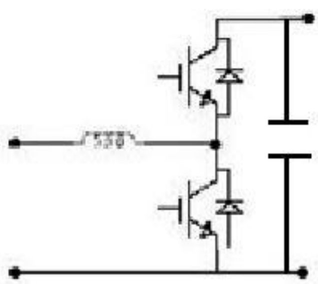

Figure 28 - Schematic of DC-DC Converter

While this converter is easy to emplement, there are several flaws to this converter type. It lacks a good efficiency rating, and could only support a voltage of 3 times its rated value. Parameters to the IGBTs were set to support a voltage of V_{DC}. The challenge of implementing this converter is the control system.

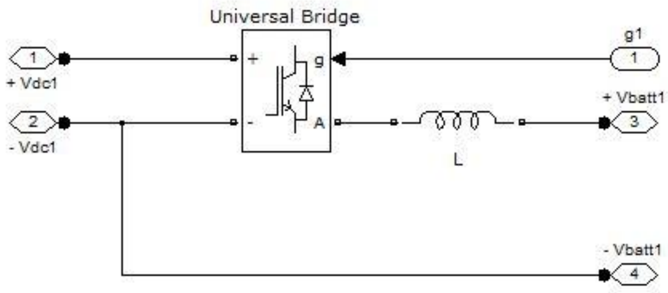

Figure 29 - Implementation of DC-DC Converter

The control system is implemented via 2 control loops, and takes into account the DC Link voltage, and the BESS current and a feed forward loop of battery voltage. The control loops seek to implement the equation of:

$$V_{OUT} = L\left(\frac{di_{batt}}{dt}\right) + V_{batt} \tag{23}$$

The output signal is then sent to the PWM Generator. This implementation is shown below:

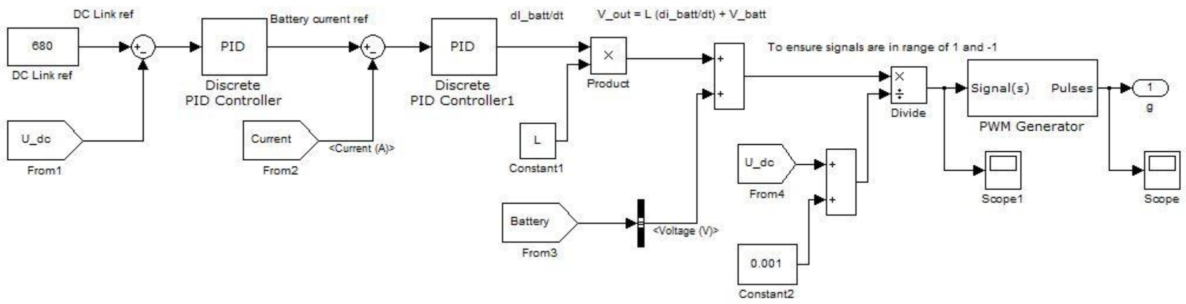

Figure 30 - Control loop of the Bidirectional DC-DC Converter

The DC Link reference voltage is compared with the measured DC Link voltage, and the error is fed into a PID Controller. This signal, which is now the Battery Current reference value, is then compared with the instantaneous Battery Current signal. This provides the rate of change of battery current, which is then multiplied by L.

The design of Inductance L is a compromise between size, current ripple, and control performance for both boost and buck operations of the DC-DC Converter. Assuming constant battery voltage, the inductance ripple current Δi_L is given by:

$$\Delta i_{L\max} = \frac{V_D}{4fL} D(1-D) \tag{24}$$

Where D is the duty ratio of the PWM. Maximal ripple is taken to be 0.5D, and the ripple current is proportional to the DC bus voltage and can be decreased by increasing the switching frequency or the inductance. Inductance L was then calculated to be 14mH.

c. L-C Filter modelling

As the PWM has a high switching frequency of 3000Hz, this will cause unwanted high frequency harmonics in the AC voltage. This causes a power quality problem in the AC voltage which will be sent to the consumer. The L-C filter will be used to eliminate the unwanted harmonics.

Calculation of the L-C filter is based on the equations below(68):

$$K = \left[\frac{\left(k^2 - \frac{15}{4}k^4 + \frac{64}{5\pi}k^5 - \frac{5}{4}k^6 \right)}{1440} \right]^{\frac{1}{2}}$$

$$L_f = \frac{V_0}{I_0 f_s} \left\{ k \frac{V_{DC}}{V_{0,avg}} \left[1 + 4\pi^2 \left(\frac{f_r}{f_s} \right)^2 K \frac{V_{DC}}{V_{0,avg}} \right] \right\}^{\frac{1}{2}} \quad (25)$$

$$C_f = K \frac{V_{DC}}{L_f f_s^2 V_{0,avg}}$$

Where k is the modulation index of the PWM, and is set to 1. V_0 is the load voltage, which is 415 V, I_0 is the nominal current, which is set at 10A, f_r is the fundamental frequency at 50Hz and f_s is the switching frequency of 3000Hz, $V_{0,avg}$ is the total harmonic voltage of the load, and is assumed to be at 5% of V_0, and L_f and C_f is the inductance and capacitance of the filter respectively. Via calculations, $K = 0.158579, L_f = 80mH, C_f = 7.22\mu C$.

A final model is shown below (with and without subsystem groupings) will be shown in Appendix A.

6.3 Simulation Results

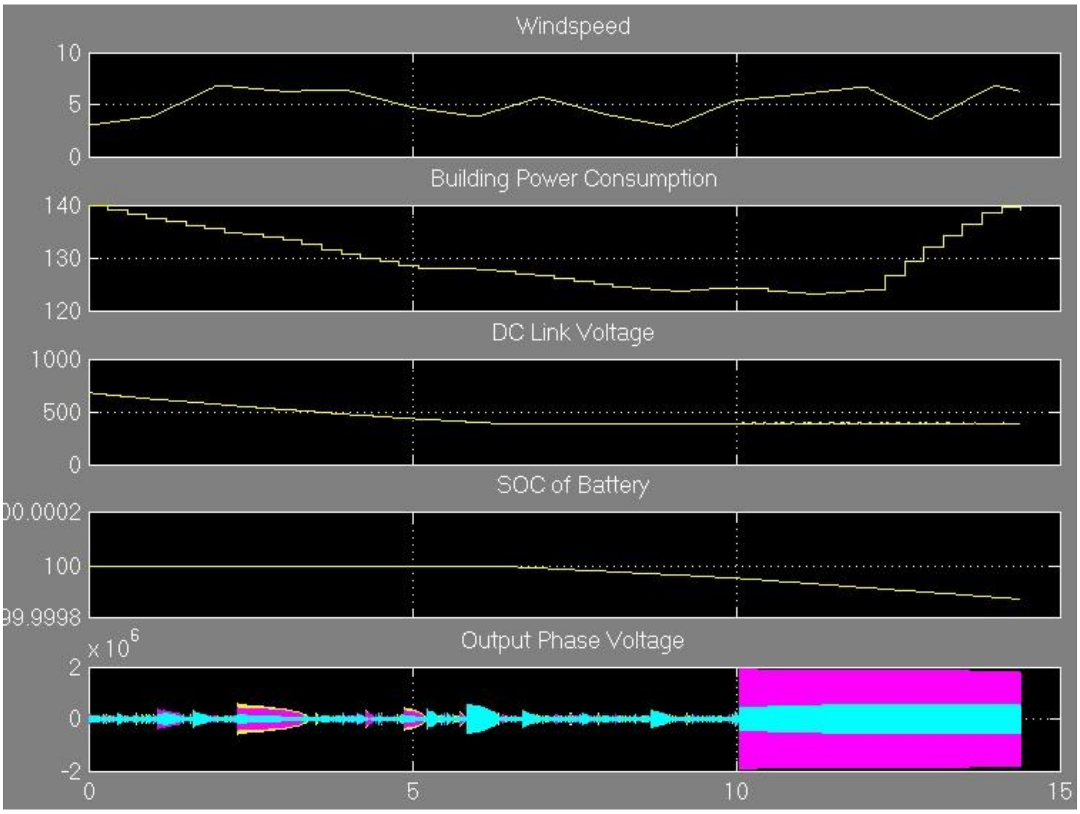

Figure 31 - Simulink simulation results

The figure above shows the simulation results of the programmed model. Unfortunately, due to the amount of data of each individual component (i.e. DC Link, PWM, Filters), the simulator could not cope with the huge amount of data. While it was planned to simulate for 24 hours, the model has simulated each component on a millisecond basis. As shown in the figure above, the SOC of the battery decreased very slightly to maintain the DC Link voltage when the power consumption has increased along with a slight drop in the windspeed. This shows that the choice of wind turbines was only able to maintain the DC Link voltage of 460V with the available wind speed. Also, the battery voltage decreased very slightly as 14 seconds of simulation time is too short for the battery to react toward changes in voltages. It is also noted that there is a huge increase in Output Phase Voltage from 10 seconds onward. This is due to the output filter causing resonance problems. One possible solution for this is to implement a dump load or dampening resistor.

As the model is too complex for Simulink, this research was continued on in Microsoft Excel.

6.4 Simulation via Microsoft Excel

This research was continued in Microsoft Excel. A spreadsheet was made to supplement the previous Simulink research. In this spreadsheet, mathematical models were kept simple and linear.

Date	Time	Windspeed	Extrapolated Windspeed	Power Generated (W)	GK Demand (W)	Power Difference	Average Power Used	ESD Energy	ESD Output	State of Charge (%)	Combined Power
26-Jun-11	00:00	4.01	5.15	42244	67300	-25056		240000	216000	100	258244
		3.03	3.89	18170	67300	-49130					
		5.03	6.45	82879	67300	15579					
		3.96	5.08	40562	67300	-26738					
		3.52	4.52	28585	67300	-38715					
		2.11	2.71	6127	67300	-61173					
		2.67	3.43	12461	67300	-54839					
		4.64	5.96	65336	67300	-1964					
		4.54	5.83	61163	67300	-6137					
		2.66	3.41	12252	67300	-55048	-30322	209678	188710.2	87.4	200962.3
	00:30	1.93	2.48	4718	70900	-66182					
		3.37	4.32	24910	70900	-45990					
		4.94	6.34	78840	70900	7940					
		4.04	5.18	42943	70900	-27957					
		3.11	3.99	19629	70900	-51271					
		4.51	5.78	59840	70900	-11060					
		2.35	3.02	8509	70900	-62391					
		2.60	3.34	11480	70900	-59420					
		1.56	2.01	2499	70900	-68401					

Figure 32 - Screenshot of Excel spreadsheet

The screenshot above shows an excerpt of the spreadsheet. Full spreadsheet will be in Appendix A.

The first column is Date, followed by Time. Time is based on the sample rate for GK Demand. The 3rd and 4th columns are the Windspeed and Extrapolated Windspeed respectively. As the data obtained was timed averaged to be 1 minute, it is not necessary as GK Demand is sampled every half hour. Therefore, windspeed datapoints were taken every 3 minutes. The extrapolated windspeed is calculated to the height of CF 100 Wind turbine. The 5th column of Power Generated by WT measures the power generated based on the WT Power equation. This value is then multiplied by 0.9, which represents the WT Generator itself. However, the final value is multiplied by 2 as its taken as the sum of 2 CF 100 Wind Turbine. The next column shows GK Demand, and Power Difference was calculated between each Power Generated datapoint and the GK Demand. However, to simplify the model further, average power used is timed every half hour. ESD Energy was then calculated based on the maximum energy that was sized in Chapter 6.1.1 section b, where:

$$\begin{aligned} \text{Energy contained} &= \text{Battery Rating} \times \text{Voltage} \times \text{Quantity} \\ &= 800\text{Ahr} \times 12\text{V} \times 25 \\ &= 240000\text{J} \end{aligned} \tag{26}$$

Each time the ESD outputs energy, an efficiency value is used to represent the Bidirectional DC-DC Converter between the DC Link and the ESD. SOC of the ESD was calculated via a linear relationship of ESD Output divided by Total Energy Contained. And the final column of Combined power is the sum of Power Generated and ESD Output.

This spreadsheet was done across 2 days.

6.5 Spreadsheet Results

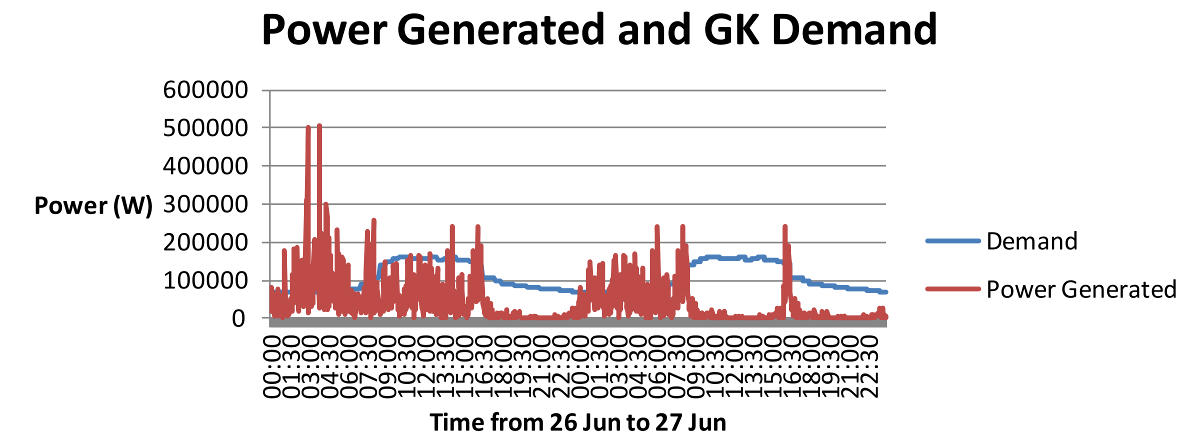

Figure 33 - Figure showing discrepency between the Power Generated and GK Demand

In figure 33, due to the variability and really small wind power capacity the area surrounding GK, WTs are only able to compensate for half of the time.

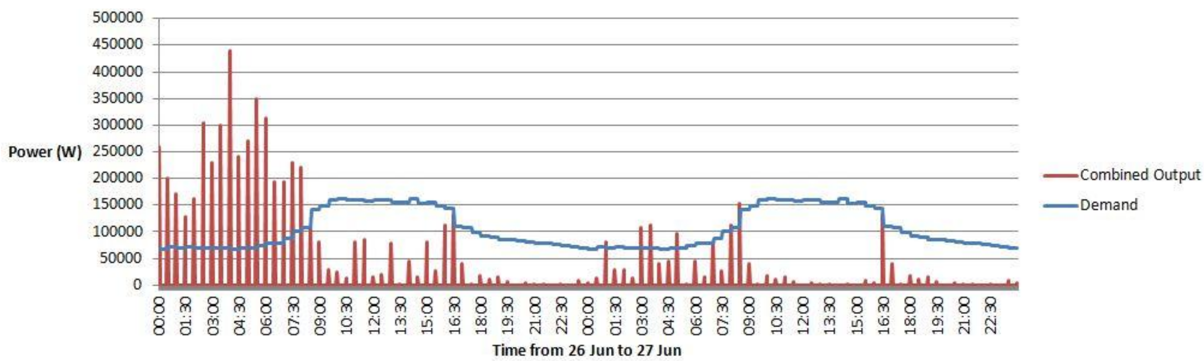

Figure 34 - Figure showing the discrepency between Combined Output and GK Demand

In figure 34, this shows clearly the combined output between the ESD and WTs against GK Demand. From this graph, it can be seen that the generation of WT is more than ample between 00:00 and 08:00. During this time, there is ample wind power and battery SOC is at 100%, with low demand. At this point, GK will be able to profit by feeding in extra energy into the power grid with the Feed-in Tariff system. Also, at 09:00 onwards, generation is at a low point. The ESD will then be able to compensate for any deficit power. However, due to the size of the ESD, it is only able to compensate up to 16:30. However, as the SOC of the ESD is 0%, this carries forward until the next day. The ability of the ESD suffers then.

Chapter 7 – Conclusions and Future Work

7.1 Conclusions

This thesis has presented this method in designing a hybrid power system that is applicable in an urban environment. This method was applied in a feasibility study in turning the Electronic, Electrical and Computer Engineering Department of University of Birmingham into a self-sustaining building. A building will be successfully be self-sustaining if its own HPS is able to generate constant phase voltages and frequency out of renewable resources, while taking into consideration consumer power demand.

However, certain conclusions on urban self-sustainability may still be drawn from the concepts and design method that were used in this research. The main challenge of urban self-sustainability is the lack of availability of renewable sources. This is apparent as the wind data used in this research was not adequate for the wind turbines used to generate rated power, and a BESS with a capacity of aiming to supply the GK load of 6 hours had to be implemented. This then raises the question of applying multiple renewable sources i.e. solar. However, this is not a cost effective solution as each renewable energy device will have its own efficiency rating.

Based on the idea of this research, it is challenging to take an urban building off-grid. If this challenge is accepted, it is therefore recommended for the building the take advantage of the power grid, as both a tertiary power plant and a dump load. This step ensures the following: 1) reduces the load imposed on the grid at Peak Times – which allows for a reduction in the cost of balancing; 2) surplus power from the ESD will be able to be fed back into the grid once the SOC is at maximum for Feed-In Tariffs; 3) the power quality of the building will be constant – due to the tertiary power plant compensating for any drop in power from both the WT and the ESD.

7.2 Future works

This section provides the author's views on suitable follow-up work to further refine this simulation model and HPS design process. The key follow on research areas can be summarised as supervisory control strategies and parameter extraction.

The first step would involve suitable techniques for accurate parameter extraction for components used in this simulation. Also, for energy analysis to be performed over a very long period of time, ideal filters and generators will be used instead. This reduces simulation times drastically and uses less computer memory.

Another key area is the supervisory control strategies currently used for HPS design. One such control strategy that is at the early stages of research at University of Birmingham is the Duty Cycle Constrained Selection (DCCS). This method is a qualitative approach which is based on the premise of the output duty cycle of which the HPS is subjected to. By analysis of the intended HPS application and possible output duty cycle, it is then possible to closely specify the power sources and capacity servicing that purpose. The benefit of this method will be able to reduce the need for complex modelling for an optimised system.

The next step is step is that other renewable sources such as solar will be used in order to further test this simulation, along with the addition of system components of a dump load, and inverters that are capable of injecting negative current into the gird. This allows the HPS' functionality to be expanded by enabling it to supply power to multiple unbalanced loads in parallel. Therefore, multiple buildings will be islanded. This is the basis for a micro-grid approach in reduction of loads to the power grid.

Lastly, this simulation will be done across a longer period of real world data, while incorporating multiple seasons and days. This will show the effectiveness of the chosen ESD capacity in different times of the year.

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Appendix A

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Title:	A Design Method for Hybrid Power Systems
Course:	Master of Research in Electronic, Electrical and Computer Engineering

Spreadsheet on simulation of a hybrid renewable system for Gisbert Kapp (23 Sept 2010)

Date	Time	Windspeed	Extrapolated Windspeed	Power Generated (W)	GK Demand (W)	Power Difference	Average Power Used	ESD Energy	ESD Output	State of Charge (%)
26-Jun-11	00:00	4.01	5.15	42244	67300	-25056		240000	216000	100
		3.03	3.89	18170	67300	-49130				
		5.03	6.45	82879	67300	15579				
		3.96	5.08	40562	67300	-26738				
		3.52	4.52	28585	67300	-38715				
		2.11	2.71	6127	67300	-61173				
		2.67	3.43	12461	67300	-54839				
		4.64	5.96	65336	67300	-1964				
		4.54	5.83	61163	67300	-6137				
		2.66	3.41	12252	67300	-55048	-30322	209678	188710.2	87.4
	00:30	1.93	2.48	4718	70900	-66182				
		3.37	4.32	24910	70900	-45990				
		4.94	6.34	78840	70900	7940				
		4.04	5.18	42943	70900	-27957				
		3.11	3.99	19629	70900	-51271				
		4.51	5.78	59840	70900	-11060				

		2.35	3.02	8509	70900	-62391				
		2.60	3.34	11480	70900	-59420				
		1.56	2.01	2499	70900	-68401				
		3.21	4.12	21686	70900	-49214	-43395	166283	149654.7	69.3
	01:00	2.53	3.25	10590	69900	-59310				
		2.53	3.25	10590	69900	-59310				
		6.48	8.31	177648	69900	107748				
		2.99	3.83	17390	69900	-52510				
		3.01	3.87	17866	69900	-52034				
		2.32	2.97	8114	69900	-61786				
		2.76	3.53	13658	69900	-56242				
		2.78	3.56	13988	69900	-55912				
		4.06	5.20	43552	69900	-26348				
		2.57	3.29	11023	69900	-58877	-37458	128825	115942.7	53.7
	01:30	4.34	5.57	53322	70600	-17278				
		4.32	5.55	52771	70600	-17829				
		4.35	5.58	53840	70600	-16760				
		3.03	3.88	18117	70600	-52483				
		5.58	7.16	113730	70600	43130				
		3.90	5.00	38717	70600	-31883				
		6.55	8.40	183217	70600	112617				
		4.78	6.13	71338	70600	738				
		5.40	6.93	102968	70600	32368				
		4.08	5.23	44265	70600	-26335	2628	131453	118308.1	54.8
	02:00	6.43	8.24	173324	68500	104824				
		5.26	6.75	95005	68500	26505				
		6.57	8.43	185493	68500	116993				
		3.14	4.03	20299	68500	-48201				
		5.27	6.76	95711	68500	27211				
		5.75	7.38	124047	68500	55547				
		4.83	6.19	73372	68500	4872				
		4.43	5.68	56595	68500	-11905				
		4.23	5.43	49508	68500	-18992				

		6.19	7.94	154545	68500	86045	34290	165743	149169.1	69.1
	02:30	4.76	6.11	70402	69900	502				
		3.56	4.57	29495	69900	-40405				
		4.07	5.23	44167	69900	-25733				
		6.22	7.98	157260	69900	87360				
		6.06	7.78	145507	69900	75607				
		7.83	10.05	313561	69900	243661				
		7.57	9.71	282902	69900	213002				
		7.22	9.27	246144	69900	176244				
		9.15	11.74	500381	69900	430481				
		2.68	3.44	12559	69900	-57341	110338	240000	216000.0	100.0
	03:00	4.52	5.80	60479	69300	-8821				
		5.92	7.59	135314	69300	66014				
		3.95	5.07	40256	69300	-29044				
		4.58	5.88	62876	69300	-6424				
		3.62	4.64	30883	69300	-38417				
		5.73	7.35	122950	69300	53650				
		3.88	4.98	38094	69300	-31206				
		5.85	7.50	130702	69300	61402				
		6.85	8.79	209947	69300	140647				
		5.05	6.48	84322	69300	15022	22282	240000	216000.0	100.0
	03:30	5.04	6.47	83574	68400	15174				
		4.96	6.36	79704	68400	11304				
		4.92	6.31	77839	68400	9439				
		5.44	6.98	105098	68400	36698				
		5.98	7.68	139822	68400	71422				
		3.40	4.36	25605	68400	-42795				
		9.18	11.78	505318	68400	436918				
		5.88	7.55	132994	68400	64594				
		4.72	6.05	68642	68400	242				
		7.00	8.98	223947	68400	155547	75854	240000	216000.0	100.0
	04:00	4.98	6.39	80527	68100	12427				
		4.36	5.59	54100	68100	-14000				

		5.75	7.38	124371	68100	56271				
		3.32	4.26	23946	68100	-44154				
		4.66	5.97	65929	68100	-2171				
		5.29	6.79	96750	68100	28650				
		5.58	7.16	113363	68100	45263				
		7.70	9.88	298550	68100	230450				
		7.42	9.52	266515	68100	198415				
		3.37	4.33	25088	68100	-43012	46814	240000	216000.0	100.0
	04:30	6.87	8.81	211791	68400	143391				
		4.89	6.27	76143	68400	7743				
		3.68	4.72	32579	68400	-35821				
		6.34	8.13	166301	68400	97901				
		4.19	5.37	48014	68400	-20386				
		4.46	5.72	57793	68400	-10607				
		4.95	6.35	79271	68400	10871				
		5.67	7.27	118940	68400	50540				
		4.04	5.18	43039	68400	-25361				
		4.37	5.61	54473	68400	-13927	20434	240000	216000.0	100.0
	05:00	4.61	5.91	63994	69500	-5506				
		3.40	4.36	25673	69500	-43827				
		3.73	4.79	34006	69500	-35494				
		5.74	7.37	123659	69500	54159				
		7.09	9.09	232501	69500	163001				
		2.62	3.37	11801	69500	-57699				
		6.38	8.19	169948	69500	100448				
		3.46	4.44	27056	69500	-42444				
		6.02	7.73	142788	69500	73288				
		5.89	7.56	133742	69500	64242	27017	240000	216000.0	100.0
	05:30	3.11	3.99	19572	74600	-55028				
		4.59	5.89	63289	74600	-11311				
		6.25	8.02	159622	74600	85022				
		6.15	7.89	152011	74600	77411				
		4.55	5.83	61325	74600	-13275				

		2.67	3.42	12363	74600	-62237				
		4.84	6.21	74104	74600	-496				
		5.45	7.00	105912	74600	31312				
		3.18	4.08	20945	74600	-53655				
		5.31	6.81	97741	74600	23141	2088	240000	216000.0	100.0
	06:00	5.99	7.68	140243	77600	62643				
		3.44	4.41	26497	77600	-51103				
		3.15	4.04	20338	77600	-57262				
		3.04	3.90	18369	77600	-59231				
		3.16	4.05	20533	77600	-57067				
		4.86	6.23	74934	77600	-2666				
		2.82	3.62	14695	77600	-62905				
		4.05	5.19	43231	77600	-34369				
		3.68	4.72	32473	77600	-45127				
		2.60	3.34	11507	77600	-66093	-37318	202682	182413.8	84.5
	06:30	3.38	4.33	25133	78300	-53167				
		4.68	6.01	66997	78300	-11303				
		1.60	2.05	2665	78300	-75635				
		3.48	4.46	27433	78300	-50867				
		3.35	4.30	24623	78300	-53677				
		4.60	5.90	63537	78300	-14763				
		3.41	4.37	25809	78300	-52491				
		3.67	4.71	32235	78300	-46065				
		3.93	5.05	39738	78300	-38562				
		4.21	5.40	48566	78300	-29734	-42626	160056	144050.1	66.7
	07:00	4.23	5.42	49298	88500	-39202				
		4.46	5.72	57987	88500	-30513				
		2.76	3.54	13718	88500	-74782				
		3.87	4.97	37859	88500	-50641				
		3.57	4.58	29744	88500	-58756				
		4.96	6.37	79897	88500	-8603				
		4.14	5.31	46181	88500	-42319				
		4.11	5.27	45183	88500	-43317				

		2.93	3.76	16380	88500	-72120				
		5.70	7.31	120775	88500	32275	-38798	121258	109132.1	50.5
	07:30	7.03	9.02	226839	100800	126039				
		6.79	8.71	204207	100800	103407				
		3.24	4.16	22278	100800	-78522				
		5.30	6.80	97189	100800	-3611				
		6.70	8.59	196103	100800	95303				
		3.32	4.26	23838	100800	-76962				
		3.03	3.89	18152	100800	-82648				
		1.63	2.10	2850	100800	-97950				
		3.94	5.05	39860	100800	-60940				
		5.63	7.22	116315	100800	15515	-6037	115221	103698.9	48.0
	08:00	7.35	9.43	259252	108000	151252				
		2.89	3.71	15832	108000	-92168				
		4.20	5.38	48290	108000	-59710				
		3.10	3.98	19497	108000	-88503				
		4.81	6.17	72554	108000	-35446				
		5.04	6.47	83773	108000	-24227				
		5.21	6.69	92427	108000	-15573				
		4.88	6.27	76096	108000	-31904				
		4.25	5.45	50107	108000	-57893				
		3.71	4.77	33463	108000	-74537	-32871	82350	74115.0	34.3
	08:30	3.32	4.26	23860	141400	-117540				
		2.58	3.31	11244	141400	-130156				
		4.03	5.18	42879	141400	-98521				
		3.62	4.65	31063	141400	-110337				
		3.02	3.88	18009	141400	-123391				
		3.11	3.99	19572	141400	-121828				
		5.78	7.42	126196	141400	-15204				
		5.03	6.45	83028	141400	-58372				
		6.09	7.81	147242	141400	5842				
		4.97	6.38	80284	141400	-61116	-83062	0	0.0	0.0
	09:00	4.20	5.39	48428	148200	-99772				

		4.44	5.70	57327	148200	-90873				
		5.37	6.88	100866	148200	-47334				
		5.06	6.49	84372	148200	-63828				
		3.21	4.12	21686	148200	-126514				
		4.94	6.34	78888	148200	-69312				
		5.47	7.02	107081	148200	-41119				
		3.62	4.65	31063	148200	-117137				
		5.32	6.83	98460	148200	-49740				
		3.54	4.55	29075	148200	-119125	-82475	0	0.0	0.0
	09:30	5.14	6.60	88856	159100	-70244				
		4.04	5.18	43103	159100	-115997				
		6.01	7.71	141936	159100	-17164				
		4.98	6.38	80478	159100	-78622				
		4.75	6.10	70092	159100	-89008				
		4.34	5.57	53543	159100	-105557				
		4.62	5.93	64579	159100	-94521				
		6.04	7.75	144072	159100	-15028				
		3.70	4.74	32952	159100	-126148				
		3.36	4.32	24866	159100	-134234	-84652	0	0.0	0.0
	10:00	3.06	3.92	18697	162300	-143603				
		2.27	2.91	7610	162300	-154690				
		4.51	5.79	59959	162300	-102341				
		3.89	4.99	38538	162300	-123762				
		3.67	4.71	32393	162300	-129907				
		3.74	4.80	34143	162300	-128157				
		2.89	3.70	15701	162300	-146599				
		2.39	3.06	8861	162300	-153439				
		4.90	6.29	76847	162300	-85453				
		2.74	3.52	13437	162300	-148863	-131681	0	0.0	0.0
	10:30	5.12	6.56	87413	159700	-72287				
		3.33	4.27	24141	159700	-135559				
		5.39	6.91	102055	159700	-57645				
		3.57	4.58	29769	159700	-129931				

		6.16	7.91	152902	159700	-6798				
		5.33	6.84	98961	159700	-60739				
		5.51	7.06	109030	159700	-50670				
		6.32	8.11	165123	159700	5423				
		6.22	7.97	156805	159700	-2895				
		4.97	6.37	79946	159700	-79754	-59085	0	0.0	0.0
	11:00	4.76	6.11	70402	158900	-88498				
		3.52	4.52	28488	158900	-130412				
		5.52	7.08	109923	158900	-48977				
		1.26	1.61	1297	158900	-157603				
		5.61	7.20	115264	158900	-43636				
		3.34	4.28	24250	158900	-134650				
		4.82	6.19	73189	158900	-85711				
		5.28	6.77	96093	158900	-62807				
		4.93	6.32	78124	158900	-80776				
		5.07	6.50	85075	158900	-73825	-90689	0	0.0	0.0
	11:30	5.53	7.09	110402	157900	-47498				
		6.31	8.10	164419	157900	6519				
		6.31	8.09	163716	157900	5816				
		4.21	5.40	48740	157900	-109160				
		4.68	6.00	66868	157900	-91032				
		3.43	4.41	26451	157900	-131449				
		3.80	4.87	35785	157900	-122115				
		2.08	2.67	5869	157900	-152031				
		3.03	3.89	18224	157900	-139676				
		2.87	3.68	15361	157900	-142539	-92316	0	0.0	0.0
	12:00	4.21	5.40	48705	159400	-110695				
		6.00	7.70	141018	159400	-18382				
		4.57	5.87	62466	159400	-96934				
		3.22	4.13	21787	159400	-137613				
		3.54	4.54	28977	159400	-130423				
		4.52	5.79	60119	159400	-99281				
		4.54	5.83	61244	159400	-98156				

		4.40	5.64	55527	159400	-103873				
		6.40	8.21	170908	159400	11508				
		3.16	4.05	20591	159400	-138809	-92266	0	0.0	0.0
	12:30	5.85	7.51	130970	159800	-28830				
		5.17	6.63	90210	159800	-69590				
		5.57	7.14	112694	159800	-47106				
		3.16	4.05	20611	159800	-139189				
		3.98	5.10	41118	159800	-118682				
		3.36	4.31	24689	159800	-135111				
		3.90	5.00	38717	159800	-121083				
		5.21	6.68	92374	159800	-67426				
		2.67	3.42	12391	159800	-147409				
		4.92	6.31	77555	159800	-82245	-95667	0	0.0	0.0
	13:00	5.87	7.53	131912	154300	-22388				
		3.06	3.92	18642	154300	-135658				
		2.68	3.44	12615	154300	-141685				
		3.48	4.46	27457	154300	-126843				
		3.42	4.39	26106	154300	-128194				
		1.59	2.04	2636	154300	-151664				
		4.87	6.24	75258	154300	-79042				
		5.18	6.65	90788	154300	-63512				
		2.48	3.19	10011	154300	-144289				
		1.07	1.37	802	154300	-153498	-114677	0	0.0	0.0
	13:30	1.37	1.76	1691	155900	-154209				
		1.89	2.42	4410	155900	-151490				
		1.72	2.21	3347	155900	-152553				
		3.04	3.90	18297	155900	-137603				
		3.68	4.72	32526	155900	-123374				
		3.92	5.03	39376	155900	-116524				
		6.51	8.36	180543	155900	24643				
		3.00	3.84	17548	155900	-138352				
		4.44	5.70	57250	155900	-98650				
		4.07	5.22	44070	155900	-111830	-115994	0	0.0	0.0

	14:00	3.20	4.11	21464	162100	-140636				
		2.93	3.75	16346	162100	-145754				
		5.04	6.46	83524	162100	-78576				
		7.19	9.23	242786	162100	80686				
		5.28	6.78	96366	162100	-65734				
		4.11	5.27	45348	162100	-116752				
		4.82	6.18	72962	162100	-89138				
		3.78	4.84	35167	162100	-126933				
		1.71	2.19	3243	162100	-158857				
		2.88	3.69	15538	162100	-146562	-98825	0	0.0	0.0
	14:30	2.60	3.34	11494	153800	-142306				
		4.50	5.77	59403	153800	-94397				
		2.20	2.83	6974	153800	-146826				
		5.50	7.05	108437	153800	-45363				
		5.00	6.42	81697	153800	-72103				
		5.51	7.06	108971	153800	-44829				
		4.02	5.16	42466	153800	-111334				
		2.77	3.56	13913	153800	-139887				
		5.62	7.21	115696	153800	-38104				
		5.00	6.42	81648	153800	-72152	-90730	0	0.0	0.0
	15:00	2.73	3.51	13334	154700	-141366				
		2.39	3.07	8962	154700	-145738				
		3.09	3.96	19253	154700	-135447				
		3.69	4.73	32765	154700	-121935				
		2.85	3.66	15137	154700	-139563				
		3.29	4.22	23303	154700	-131397				
		1.12	1.44	920	154700	-153780				
		2.49	3.20	10121	154700	-144579				
		4.29	5.51	51607	154700	-103093				
		3.44	4.41	26566	154700	-128134	-134503	0	0.0	0.0
	15:30	3.77	4.83	34944	149000	-114056				
		5.53	7.09	110163	149000	-38837				
		4.73	6.07	69298	149000	-79702				

		5.43	6.97	104693	149000	-44307				
		3.51	4.50	28126	149000	-120874				
		4.72	6.06	68860	149000	-80140				
		6.47	8.30	176909	149000	27909				
		4.72	6.06	68773	149000	-80227				
		5.64	7.23	117061	149000	-31939				
		5.54	7.11	111303	149000	-37697	-59987	0	0.0	0.0
	16:00	5.07	6.51	85227	143900	-58673				
		4.09	5.24	44526	143900	-99374				
		7.18	9.22	242078	143900	98178				
		4.19	5.38	48152	143900	-95748				
		6.05	7.76	144430	143900	530				
		5.47	7.02	106847	143900	-37053				
		5.86	7.52	131441	143900	-12459				
		6.64	8.52	191137	143900	47237				
		6.51	8.35	179796	143900	35896				
		5.89	7.55	133266	143900	-10634	-13210	0	0.0	0.0
	16:30	4.71	6.05	68380	108900	-40520				
		3.95	5.07	40256	108900	-68644				
		3.33	4.28	24185	108900	-84715				
		3.79	4.86	35475	108900	-73425				
		2.90	3.71	15848	108900	-93052				
		2.05	2.64	5660	108900	-103240				
		4.20	5.39	48393	108900	-60507				
		4.30	5.52	51969	108900	-56931				
		4.10	5.26	45051	108900	-63849				
		3.92	5.03	39376	108900	-69524	-71441	0	0.0	0.0
	17:00	1.38	1.77	1724	107200	-105476				
		2.06	2.65	5735	107200	-101465				
		3.94	5.06	40012	107200	-67188				
		1.74	2.24	3453	107200	-103747				
		3.30	4.23	23367	107200	-83833				
		3.29	4.22	23282	107200	-83918				

		2.44	3.13	9524	107200	-97676				
		1.56	2.00	2461	107200	-104739				
		1.95	2.50	4843	107200	-102357				
		0.98	1.26	620	107200	-106580	-95698	0	0.0	0.0
	17:30	1.48	1.89	2100	98200	-96100				
		2.53	3.25	10603	98200	-87597				
		2.90	3.73	15997	98200	-82203				
		1.84	2.36	4069	98200	-94131				
		2.38	3.06	8839	98200	-89361				
		1.48	1.90	2130	98200	-96070				
		1.22	1.57	1192	98200	-97008				
		1.88	2.41	4340	98200	-93860				
		2.01	2.58	5320	98200	-92880				
		2.93	3.76	16430	98200	-81770	-91098	0	0.0	0.0
	18:00	2.66	3.41	12266	91900	-79634				
		2.78	3.56	13958	91900	-77942				
		2.12	2.72	6250	91900	-85650				
		1.91	2.44	4516	91900	-87384				
		1.26	1.61	1291	91900	-90609				
		1.18	1.52	1076	91900	-90824				
		1.57	2.02	2537	91900	-89363				
		0.74	0.94	259	91900	-91641				
		3.25	4.17	22464	91900	-69436				
		2.46	3.15	9688	91900	-82212	-84469	0	0.0	0.0
	18:30	1.23	1.58	1210	89900	-88690				
		1.50	1.93	2213	89900	-87687				
		2.19	2.81	6889	89900	-83011				
		1.61	2.07	2741	89900	-87159				
		1.74	2.24	3453	89900	-86447				
		0.91	1.17	491	89900	-89409				
		1.78	2.28	3653	89900	-86247				
		2.06	2.64	5710	89900	-84190				
		0.98	1.25	611	89900	-89289				

		2.81	3.61	14555	89900	-75345	-85747	0	0.0	0.0
	19:00	2.96	3.80	16992	85200	-68208				
		1.65	2.12	2929	85200	-82271				
		2.66	3.42	12349	85200	-72851				
		1.61	2.06	2701	85200	-82499				
		1.10	1.41	862	85200	-84338				
		2.65	3.40	12128	85200	-73072				
		1.88	2.42	4368	85200	-80832				
		2.97	3.81	17060	85200	-68140				
		2.00	2.56	5194	85200	-80006				
		2.10	2.70	6066	85200	-79134	-77135	0	0.0	0.0
	19:30	1.33	1.71	1544	85200	-83656				
		0.84	1.08	393	85200	-84807				
		1.33	1.71	1544	85200	-83656				
		0.95	1.22	558	85200	-84642				
		1.80	2.31	3822	85200	-81378				
		0.89	1.15	465	85200	-84735				
		1.29	1.65	1386	85200	-83814				
		1.00	1.28	643	85200	-84557				
		0.79	1.01	322	85200	-84878				
		0.72	0.92	244	85200	-84956	-84108	0	0.0	0.0
	20:00	0.80	1.02	331	82700	-82369				
		0.26	0.33	12	82700	-82688				
		0.17	0.22	3	82700	-82697				
		0.02	0.02	0	82700	-82700				
		0.53	0.67	95	82700	-82605				
		1.96	2.51	4881	82700	-77819				
		1.13	1.45	937	82700	-81763				
		1.72	2.21	3341	82700	-79359				
		0.99	1.27	640	82700	-82060				
		1.64	2.10	2871	82700	-79829	-81389	0	0.0	0.0
	20:30	1.86	2.38	4190	80300	-76110				
		1.28	1.64	1367	80300	-78933				

		1.24	1.60	1257	80300	-79043				
		0.75	0.97	279	80300	-80021				
		2.06	2.64	5710	80300	-74590				
		0.37	0.48	33	80300	-80267				
		0.88	1.13	448	80300	-79852				
		0.82	1.05	360	80300	-79940				
		1.81	2.32	3867	80300	-76433				
		1.04	1.34	739	80300	-79561	-78475	0	0.0	0.0
	21:00	0.91	1.16	486	77600	-77114				
		0.60	0.77	141	77600	-77459				
		1.27	1.63	1344	77600	-76256				
		0.66	0.84	185	77600	-77415				
		1.23	1.57	1207	77600	-76393				
		1.23	1.57	1207	77600	-76393				
		0.88	1.13	445	77600	-77155				
		1.56	2.00	2475	77600	-75125				
		1.55	1.98	2414	77600	-75186				
		1.14	1.46	958	77600	-76642	-76514	0	0.0	0.0
	21:30	1.77	2.28	3647	77900	-74253				
		1.04	1.33	733	77900	-77167				
		0.82	1.06	364	77900	-77536				
		0.93	1.19	520	77900	-77380				
		0.61	0.78	147	77900	-77753				
		1.40	1.80	1804	77900	-76096				
		1.19	1.52	1087	77900	-76813				
		0.67	0.86	196	77900	-77704				
		1.02	1.31	691	77900	-77209				
		0.53	0.68	99	77900	-77801	-76971	0	0.0	0.0
	22:00	1.69	2.17	3153	75600	-72447				
		1.72	2.21	3335	75600	-72265				
		1.48	1.89	2100	75600	-73500				
		2.56	3.28	10920	75600	-64680				
		1.23	1.57	1207	75600	-74393				

		1.38	1.77	1713	75600	-73887				
		1.18	1.51	1068	75600	-74532				
		1.71	2.19	3238	75600	-72362				
		1.99	2.56	5171	75600	-70429				
		1.37	1.75	1661	75600	-73939	-72243	0	0.0	0.0
	22:30	1.29	1.65	1389	74300	-72911				
		1.31	1.68	1455	74300	-72845				
		1.13	1.45	940	74300	-73360				
		1.46	1.88	2041	74300	-72259				
		0.79	1.01	316	74300	-73984				
		0.91	1.17	492	74300	-73808				
		1.81	2.32	3880	74300	-70420				
		2.38	3.05	8750	74300	-65550				
		2.55	3.28	10869	74300	-63431				
		0.66	0.85	190	74300	-74110	-71268	0	0.0	0.0
	23:00	1.29	1.65	1389	71600	-70211				
		1.47	1.88	2058	71600	-69542				
		1.20	1.54	1137	71600	-70463				
		2.52	3.24	10503	71600	-61097				
		2.03	2.61	5472	71600	-66128				
		2.33	2.99	8241	71600	-63359				
		2.77	3.55	13868	71600	-57732				
		2.39	3.07	8917	71600	-62683				
		2.04	2.61	5513	71600	-66087				
		2.24	2.87	7341	71600	-64259	-65156	0	0.0	0.0
	23:30	3.55	4.56	29272	69300	-40028				
		3.02	3.87	17938	69300	-51362				
		1.11	1.42	888	69300	-68412				
		1.52	1.95	2294	69300	-67006				
		3.40	4.36	25718	69300	-43582				
		2.31	2.96	8041	69300	-61259				
		2.65	3.40	12128	69300	-57172				
		1.04	1.33	726	69300	-68574				

		2.03	2.61	5480	69300	-63820				
		1.68	2.15	3070	69300	-66230	-58744	0	0.0	0.0
27-Jun-11	00:00	4.01	5.15	42244	67300	-25056				
		3.03	3.89	18170	67300	-49130				
		5.03	6.45	82879	67300	15579				
		3.96	5.08	40562	67300	-26738				
		3.52	4.52	28585	67300	-38715				
		2.11	2.71	6127	67300	-61173				
		2.67	3.43	12461	67300	-54839				
		4.64	5.96	65336	67300	-1964				
		4.54	5.83	61163	67300	-6137				
		2.66	3.41	12252	67300	-55048	-30322	0	0.0	0.0
	00:30	1.93	2.48	4718	70900	-66182				
		2.58	3.31	11244	70900	-59656				
		4.03	5.18	42879	70900	-28021				
		3.62	4.65	31063	70900	-39837				
		3.02	3.88	18009	70900	-52891				
		3.11	3.99	19572	70900	-51328				
		5.78	7.42	126196	70900	55296				
		5.03	6.45	83028	70900	12128				
		6.09	7.81	147242	70900	76342				
		4.97	6.38	80284	70900	9384	-14476	0	0.0	0.0
	01:00	4.20	5.39	48428	69900	-21472				
		4.44	5.70	57327	69900	-12573				
		5.37	6.88	100866	69900	30966				
		5.06	6.49	84372	69900	14472				
		3.21	4.12	21686	69900	-48214				
		4.94	6.34	78888	69900	8988				
		5.47	7.02	107081	69900	37181				
		3.62	4.65	31063	69900	-38837				
		5.32	6.83	98460	69900	28560				
		3.54	4.55	29075	69900	-40825	-4175	0	0.0	0.0

	01:30	5.14	6.60	88856	70600	18256				
		4.04	5.18	43103	70600	-27497				
		6.01	7.71	141936	70600	71336				
		4.98	6.38	80478	70600	9878				
		4.75	6.10	70092	70600	-508				
		4.34	5.57	53543	70600	-17057				
		4.62	5.93	64579	70600	-6021				
		6.04	7.75	144072	70600	73472				
		3.70	4.74	32952	70600	-37648				
		3.36	4.32	24866	70600	-45734	3848	3848	3463.2	1.6
	02:00	3.06	3.92	18697	68500	-49803				
		2.27	2.91	7610	68500	-60890				
		4.51	5.79	59959	68500	-8541				
		3.89	4.99	38538	68500	-29962				
		3.67	4.71	32393	68500	-36107				
		3.74	4.80	34143	68500	-34357				
		2.89	3.70	15701	68500	-52799				
		2.39	3.06	8861	68500	-59639				
		4.90	6.29	76847	68500	8347				
		2.74	3.52	13437	68500	-55063	-37881	0	0.0	0.0
	02:30	5.12	6.56	87413	69900	17513				
		3.33	4.27	24141	69900	-45759				
		5.39	6.91	102055	69900	32155				
		3.57	4.58	29769	69900	-40131				
		6.16	7.91	152902	69900	83002				
		5.33	6.84	98961	69900	29061				
		5.51	7.06	109030	69900	39130				
		6.32	8.11	165123	69900	95223				
		6.22	7.97	156805	69900	86905				
		4.97	6.37	79946	69900	10046	30715	30715	27643.5	12.8
	03:00	4.76	6.11	70402	69300	1102				
		3.52	4.52	28488	69300	-40812				
		5.52	7.08	109923	69300	40623				

		1.26	1.61	1297	69300	-68003				
		5.61	7.20	115264	69300	45964				
		3.34	4.28	24250	69300	-45050				
		4.82	6.19	73189	69300	3889				
		5.28	6.77	96093	69300	26793				
		4.93	6.32	78124	69300	8824				
		5.07	6.50	85075	69300	15775	-1089	29626	26663.1	12.3
	03:30	5.53	7.09	110402	68400	42002				
		6.31	8.10	164419	68400	96019				
		6.31	8.09	163716	68400	95316				
		4.21	5.40	48740	68400	-19660				
		4.68	6.00	66868	68400	-1532				
		3.43	4.41	26451	68400	-41949				
		3.80	4.87	35785	68400	-32615				
		2.08	2.67	5869	68400	-62531				
		3.03	3.89	18224	68400	-50176				
		2.87	3.68	15361	68400	-53039	-2816	26809	24128.3	11.2
	04:00	4.21	5.40	48705	68100	-19395				
		6.00	7.70	141018	68100	72918				
		4.57	5.87	62466	68100	-5634				
		3.22	4.13	21787	68100	-46313				
		3.54	4.54	28977	68100	-39123				
		4.52	5.79	60119	68100	-7981				
		4.54	5.83	61244	68100	-6856				
		4.40	5.64	55527	68100	-12573				
		6.40	8.21	170908	68100	102808				
		3.16	4.05	20591	68100	-47509	-966	25843	23259.1	10.8
	04:30	5.85	7.51	130970	68400	62570				
		5.17	6.63	90210	68400	21810				
		5.57	7.14	112694	68400	44294				
		3.16	4.05	20611	68400	-47789				
		3.98	5.10	41118	68400	-27282				
		3.36	4.31	24689	68400	-43711				

		3.90	5.00	38717	68400	-29683				
		5.21	6.68	92374	68400	23974				
		2.67	3.42	12391	68400	-56009				
		4.92	6.31	77555	68400	9155	-4267	21576	19418.6	9.0
	05:00	5.87	7.53	131912	69500	62412				
		3.06	3.92	18642	69500	-50858				
		2.68	3.44	12615	69500	-56885				
		3.48	4.46	27457	69500	-42043				
		3.42	4.39	26106	69500	-43394				
		1.59	2.04	2636	69500	-66864				
		4.87	6.24	75258	69500	5758				
		5.18	6.65	90788	69500	21288				
		2.48	3.19	10011	69500	-59489				
		1.07	1.37	802	69500	-68698	-29877	0	0.0	0.0
	05:30	1.37	1.76	1691	74600	-72909				
		1.89	2.42	4410	74600	-70190				
		1.72	2.21	3347	74600	-71253				
		3.04	3.90	18297	74600	-56303				
		3.68	4.72	32526	74600	-42074				
		3.92	5.03	39376	74600	-35224				
		6.51	8.36	180543	74600	105943				
		3.00	3.84	17548	74600	-57052				
		4.44	5.70	57250	74600	-17350				
		4.07	5.22	44070	74600	-30530	-34694	0	0.0	0.0
	06:00	3.20	4.11	21464	77600	-56136				
		2.93	3.75	16346	77600	-61254				
		5.04	6.46	83524	77600	5924				
		7.19	9.23	242786	77600	165186				
		5.28	6.78	96366	77600	18766				
		4.11	5.27	45348	77600	-32252				
		4.82	6.18	72962	77600	-4638				
		3.78	4.84	35167	77600	-42433				
		1.71	2.19	3243	77600	-74357				

		2.88	3.69	15538	77600	-62062	-14325	0	0.0	0.0
	06:30	2.60	3.34	11494	78300	-66806				
		4.50	5.77	59403	78300	-18897				
		2.20	2.83	6974	78300	-71326				
		5.50	7.05	108437	78300	30137				
		5.00	6.42	81697	78300	3397				
		5.51	7.06	108971	78300	30671				
		4.02	5.16	42466	78300	-35834				
		2.77	3.56	13913	78300	-64387				
		5.62	7.21	115696	78300	37396				
		5.00	6.42	81648	78300	3348	-15230	0	0.0	0.0
	07:00	2.73	3.51	13334	88500	-75166				
		2.39	3.07	8962	88500	-79538				
		3.09	3.96	19253	88500	-69247				
		3.69	4.73	32765	88500	-55735				
		2.85	3.66	15137	88500	-73363				
		3.29	4.22	23303	88500	-65197				
		1.12	1.44	920	88500	-87580				
		2.49	3.20	10121	88500	-78379				
		4.29	5.51	51607	88500	-36893				
		3.44	4.41	26566	88500	-61934	-68303	0	0.0	0.0
	07:30	3.77	4.83	34944	100800	-65856				
		5.53	7.09	110163	100800	9363				
		4.73	6.07	69298	100800	-31502				
		5.43	6.97	104693	100800	3893				
		3.51	4.50	28126	100800	-72674				
		4.72	6.06	68860	100800	-31940				
		6.47	8.30	176909	100800	76109				
		4.72	6.06	68773	100800	-32027				
		5.64	7.23	117061	100800	16261				
		5.54	7.11	111303	100800	10503	-11787	0	0.0	0.0
	08:00	5.07	6.51	85227	108000	-22773				
		4.09	5.24	44526	108000	-63474				

		7.18	9.22	242078	108000	134078				
		4.19	5.38	48152	108000	-59848				
		6.05	7.76	144430	108000	36430				
		5.47	7.02	106847	108000	-1153				
		5.86	7.52	131441	108000	23441				
		6.64	8.52	191137	108000	83137				
		6.51	8.35	179796	108000	71796				
		5.89	7.55	133266	108000	25266	22690	22690	20421.0	9.5
	08:30	4.71	6.05	68380	141400	-73020				
		3.95	5.07	40256	141400	-101144				
		3.33	4.28	24185	141400	-117215				
		3.79	4.86	35475	141400	-105925				
		2.90	3.71	15848	141400	-125552				
		2.05	2.64	5660	141400	-135740				
		4.20	5.39	48393	141400	-93007				
		4.30	5.52	51969	141400	-89431				
		4.10	5.26	45051	141400	-96349				
		3.92	5.03	39376	141400	-102024	-103941	0	0.0	0.0
	09:00	1.38	1.77	1724	148200	-146476				
		2.06	2.65	5735	148200	-142465				
		3.94	5.06	40012	148200	-108188				
		1.74	2.24	3453	148200	-144747				
		3.30	4.23	23367	148200	-124833				
		3.29	4.22	23282	148200	-124918				
		2.44	3.13	9524	148200	-138676				
		1.56	2.00	2461	148200	-145739				
		1.95	2.50	4843	148200	-143357				
		0.98	1.26	620	148200	-147580	-136698	0	0.0	0.0
	09:30	1.48	1.89	2100	159100	-157000				
		2.53	3.25	10603	159100	-148497				
		2.90	3.73	15997	159100	-143103				
		1.84	2.36	4069	159100	-155031				
		2.38	3.06	8839	159100	-150261				

		1.48	1.90	2130	159100	-156970			
		1.22	1.57	1192	159100	-157908			
		1.88	2.41	4340	159100	-154760			
		2.01	2.58	5320	159100	-153780			
		2.93	3.76	16430	159100	-142670	-151998	0	0.0	0.0
	10:00	2.66	3.41	12266	162300	-150034			
		2.78	3.56	13958	162300	-148342			
		2.12	2.72	6250	162300	-156050			
		1.91	2.44	4516	162300	-157784			
		1.26	1.61	1291	162300	-161009			
		1.18	1.52	1076	162300	-161224			
		1.57	2.02	2537	162300	-159763			
		0.74	0.94	259	162300	-162041			
		3.25	4.17	22464	162300	-139836			
		2.46	3.15	9688	162300	-152612	-154869	0	0.0	0.0
	10:30	1.23	1.58	1210	159700	-158490			
		1.50	1.93	2213	159700	-157487			
		2.19	2.81	6889	159700	-152811			
		1.61	2.07	2741	159700	-156959			
		1.74	2.24	3453	159700	-156247			
		0.91	1.17	491	159700	-159209			
		1.78	2.28	3653	159700	-156047			
		2.06	2.64	5710	159700	-153990			
		0.98	1.25	611	159700	-159089			
		2.81	3.61	14555	159700	-145145	-155547	0	0.0	0.0
	11:00	2.96	3.80	16992	158900	-141908			
		1.65	2.12	2929	158900	-155971			
		2.66	3.42	12349	158900	-146551			
		1.61	2.06	2701	158900	-156199			
		1.10	1.41	862	158900	-158038			
		2.65	3.40	12128	158900	-146772			
		1.88	2.42	4368	158900	-154532			
		2.97	3.81	17060	158900	-141840			

		2.00	2.56	5194	158900	-153706				
		2.10	2.70	6066	158900	-152834	-150835	0	0.0	0.0
	11:30	1.33	1.71	1544	157900	-156356				
		0.84	1.08	393	157900	-157507				
		1.33	1.71	1544	157900	-156356				
		0.95	1.22	558	157900	-157342				
		1.80	2.31	3822	157900	-154078				
		0.89	1.15	465	157900	-157435				
		1.29	1.65	1386	157900	-156514				
		1.00	1.28	643	157900	-157257				
		0.79	1.01	322	157900	-157578				
		0.72	0.92	244	157900	-157656	-156808	0	0.0	0.0
	12:00	0.80	1.02	331	159400	-159069				
		0.26	0.33	12	159400	-159388				
		0.17	0.22	3	159400	-159397				
		0.02	0.02	0	159400	-159400				
		0.53	0.67	95	159400	-159305				
		1.96	2.51	4881	159400	-154519				
		1.13	1.45	937	159400	-158463				
		1.72	2.21	3341	159400	-156059				
		0.99	1.27	640	159400	-158760				
		1.64	2.10	2871	159400	-156529	-158089	0	0.0	0.0
	12:30	1.86	2.38	4190	159800	-155610				
		1.28	1.64	1367	159800	-158433				
		1.24	1.60	1257	159800	-158543				
		0.75	0.97	279	159800	-159521				
		2.06	2.64	5710	159800	-154090				
		0.37	0.48	33	159800	-159767				
		0.88	1.13	448	159800	-159352				
		0.82	1.05	360	159800	-159440				
		1.81	2.32	3867	159800	-155933				
		1.04	1.34	739	159800	-159061	-157975	0	0.0	0.0
	13:00	0.91	1.16	486	154300	-153814				

		0.60	0.77	141	154300	-154159				
		1.27	1.63	1344	154300	-152956				
		0.66	0.84	185	154300	-154115				
		1.23	1.57	1207	154300	-153093				
		1.23	1.57	1207	154300	-153093				
		0.88	1.13	445	154300	-153855				
		1.56	2.00	2475	154300	-151825				
		1.55	1.98	2414	154300	-151886				
		1.14	1.46	958	154300	-153342	-153214	0	0.0	0.0
	13:30	1.77	2.28	3647	155900	-152253				
		1.04	1.33	733	155900	-155167				
		0.82	1.06	364	155900	-155536				
		0.93	1.19	520	155900	-155380				
		0.61	0.78	147	155900	-155753				
		1.40	1.80	1804	155900	-154096				
		1.19	1.52	1087	155900	-154813				
		0.67	0.86	196	155900	-155704				
		1.02	1.31	691	155900	-155209				
		0.53	0.68	99	155900	-155801	-154971	0	0.0	0.0
	14:00	1.69	2.17	3153	162100	-158947				
		1.72	2.21	3335	162100	-158765				
		1.48	1.89	2100	162100	-160000				
		2.56	3.28	10920	162100	-151180				
		1.23	1.57	1207	162100	-160893				
		1.38	1.77	1713	162100	-160387				
		1.18	1.51	1068	162100	-161032				
		1.71	2.19	3238	162100	-158862				
		1.99	2.56	5171	162100	-156929				
		1.37	1.75	1661	162100	-160439	-158743	0	0.0	0.0
	14:30	1.29	1.65	1389	153800	-152411				
		1.31	1.68	1455	153800	-152345				
		1.13	1.45	940	153800	-152860				
		1.46	1.88	2041	153800	-151759				

		0.79	1.01	316	153800	-153484				
		0.91	1.17	492	153800	-153308				
		1.81	2.32	3880	153800	-149920				
		2.38	3.05	8750	153800	-145050				
		2.55	3.28	10869	153800	-142931				
		0.66	0.85	190	153800	-153610	-150768	0	0.0	0.0
	15:00	1.29	1.65	1389	154700	-153311				
		1.47	1.88	2058	154700	-152642				
		1.20	1.54	1137	154700	-153563				
		2.52	3.24	10503	154700	-144197				
		2.03	2.61	5472	154700	-149228				
		2.33	2.99	8241	154700	-146459				
		2.77	3.55	13868	154700	-140832				
		2.39	3.07	8917	154700	-145783				
		2.04	2.61	5513	154700	-149187				
		2.24	2.87	7341	154700	-147359	-148256	0	0.0	0.0
	15:30	3.55	4.56	29272	149000	-119728				
		3.02	3.87	17938	149000	-131062				
		1.11	1.42	888	149000	-148112				
		1.52	1.95	2294	149000	-146706				
		3.40	4.36	25718	149000	-123282				
		2.31	2.96	8041	149000	-140959				
		2.65	3.40	12128	149000	-136872				
		1.04	1.33	726	149000	-148274				
		2.03	2.61	5480	149000	-143520				
		1.68	2.15	3070	149000	-145930	-138444	0	0.0	0.0
	16:00	4.71	6.51	85227	143900	-58673				
		3.95	5.24	44526	143900	-99374				
		3.33	9.22	242078	143900	98178				
		3.79	5.38	48152	143900	-95748				
		2.90	7.76	144430	143900	530				
		2.05	7.02	106847	143900	-37053				
		4.20	7.52	131441	143900	-12459				

		4.30	8.52	191137	143900	47237				
		4.10	8.35	179796	143900	35896				
		3.92	7.55	133266	143900	-10634	-13210	0	0.0	0.0
	16:30	1.38	6.05	68380	108900	-40520				
		2.06	5.07	40256	108900	-68644				
		3.94	4.28	24185	108900	-84715				
		1.74	4.86	35475	108900	-73425				
		3.30	3.71	15848	108900	-93052				
		3.29	2.64	5660	108900	-103240				
		2.44	5.39	48393	108900	-60507				
		1.56	5.52	51969	108900	-56931				
		1.95	5.26	45051	108900	-63849				
		0.98	5.03	39376	108900	-69524	-71441	0	0.0	0.0
	17:00	1.48	1.77	1724	107200	-105476				
		2.53	2.65	5735	107200	-101465				
		2.90	5.06	40012	107200	-67188				
		1.84	2.24	3453	107200	-103747				
		2.38	4.23	23367	107200	-83833				
		1.48	4.22	23282	107200	-83918				
		1.22	3.13	9524	107200	-97676				
		1.88	2.00	2461	107200	-104739				
		2.01	2.50	4843	107200	-102357				
		2.93	1.26	620	107200	-106580	-95698	0	0.0	0.0
	17:30	2.66	1.89	2100	98200	-96100				
		2.78	3.25	10603	98200	-87597				
		2.12	3.73	15997	98200	-82203				
		1.91	2.36	4069	98200	-94131				
		1.26	3.06	8839	98200	-89361				
		1.18	1.90	2130	98200	-96070				
		1.57	1.57	1192	98200	-97008				
		0.74	2.41	4340	98200	-93860				
		3.25	2.58	5320	98200	-92880				
		2.46	3.76	16430	98200	-81770	-91098	0	0.0	0.0

	18:00	1.23	3.41	12266	91900	-79634				
		1.50	3.56	13958	91900	-77942				
		2.19	2.72	6250	91900	-85650				
		1.61	2.44	4516	91900	-87384				
		1.74	1.61	1291	91900	-90609				
		0.91	1.52	1076	91900	-90824				
		1.78	2.02	2537	91900	-89363				
		2.06	0.94	259	91900	-91641				
		0.98	4.17	22464	91900	-69436				
		2.81	3.15	9688	91900	-82212	-84470	0	0.0	0.0
	18:30	2.96	1.58	1210	89900	-88690				
		1.65	1.93	2213	89900	-87687				
		2.66	2.81	6889	89900	-83011				
		1.61	2.07	2741	89900	-87159				
		1.10	2.24	3453	89900	-86447				
		2.65	1.17	491	89900	-89409				
		1.88	2.28	3653	89900	-86247				
		2.97	2.64	5710	89900	-84190				
		2.00	1.25	611	89900	-89289				
		2.10	3.61	14555	89900	-75345	-85747	0	0.0	0.0
	19:00	1.33	3.80	16992	85200	-68208				
		0.84	2.12	2929	85200	-82271				
		1.33	3.42	12349	85200	-72851				
		0.95	2.06	2701	85200	-82499				
		1.80	1.41	862	85200	-84338				
		0.89	3.40	12128	85200	-73072				
		1.29	2.42	4368	85200	-80832				
		1.00	3.81	17060	85200	-68140				
		0.79	2.56	5194	85200	-80006				
		0.72	2.70	6066	85200	-79134	-77135	0	0.0	0.0
	19:30	0.80	1.71	1544	85200	-83656				
		0.26	1.08	393	85200	-84807				
		0.17	1.71	1544	85200	-83656				

		0.02	1.22	558	85200	-84642				
		0.53	2.31	3822	85200	-81378				
		1.96	1.15	465	85200	-84735				
		1.13	1.65	1386	85200	-83814				
		1.72	1.28	643	85200	-84557				
		0.99	1.01	322	85200	-84878				
		1.64	0.92	244	85200	-84956	-84108	0	0.0	0.0
	20:00	1.86	1.02	331	82700	-82369				
		1.28	0.33	12	82700	-82688				
		1.24	0.22	3	82700	-82697				
		0.75	0.02	0	82700	-82700				
		2.06	0.67	95	82700	-82605				
		0.37	2.51	4881	82700	-77819				
		0.88	1.45	937	82700	-81763				
		0.82	2.21	3341	82700	-79359				
		1.81	1.27	640	82700	-82060				
		1.04	2.10	2871	82700	-79829	-81389	0	0.0	0.0
	20:30	0.91	2.38	4190	80300	-76110				
		0.60	1.64	1367	80300	-78933				
		1.27	1.60	1257	80300	-79043				
		0.66	0.97	279	80300	-80021				
		1.23	2.64	5710	80300	-74590				
		1.23	0.48	33	80300	-80267				
		0.88	1.13	448	80300	-79852				
		1.56	1.05	360	80300	-79940				
		1.55	2.32	3867	80300	-76433				
		1.14	1.34	739	80300	-79561	-78475	0	0.0	0.0
	21:00	1.77	1.16	486	77600	-77114				
		1.04	0.77	141	77600	-77459				
		0.82	1.63	1344	77600	-76256				
		0.93	0.84	185	77600	-77415				
		0.61	1.57	1207	77600	-76393				
		1.40	1.57	1207	77600	-76393				

		1.19	1.13	445	77600	-77155				
		0.67	2.00	2475	77600	-75125				
		1.02	1.98	2414	77600	-75186				
		0.53	1.46	958	77600	-76642	-76514	0	0.0	0.0
	21:30	1.69	2.28	3647	77900	-74253				
		1.72	1.33	733	77900	-77167				
		1.48	1.06	364	77900	-77536				
		2.56	1.19	520	77900	-77380				
		1.23	0.78	147	77900	-77753				
		1.38	1.80	1804	77900	-76096				
		1.18	1.52	1087	77900	-76813				
		1.71	0.86	196	77900	-77704				
		1.99	1.31	691	77900	-77209				
		1.37	0.68	99	77900	-77801	-76971	0	0.0	0.0
	22:00	1.29	2.17	3153	75600	-72447				
		1.31	2.21	3335	75600	-72265				
		1.13	1.89	2100	75600	-73500				
		1.46	3.28	10920	75600	-64680				
		0.79	1.57	1207	75600	-74393				
		0.91	1.77	1713	75600	-73887				
		1.81	1.51	1068	75600	-74532				
		2.38	2.19	3238	75600	-72362				
		2.55	2.56	5171	75600	-70429				
		0.66	1.75	1661	75600	-73939	-72243	0	0.0	0.0
	22:30	1.29	1.65	1389	74300	-72911				
		1.47	1.68	1455	74300	-72845				
		1.20	1.45	940	74300	-73360				
		2.52	1.88	2041	74300	-72259				
		2.03	1.01	316	74300	-73984				
		2.33	1.17	492	74300	-73808				
		2.77	2.32	3880	74300	-70420				
		2.39	3.05	8750	74300	-65550				
		2.04	3.28	10869	74300	-63431				

		2.24	0.85	190	74300	-74110	-71268	0	0.0	0.0
	23:00	3.55	1.65	1389	71600	-70211				
		3.02	1.88	2058	71600	-69542				
		1.11	1.54	1137	71600	-70463				
		1.52	3.24	10503	71600	-61097				
		3.40	2.61	5472	71600	-66128				
		2.31	2.99	8241	71600	-63359				
		2.65	3.55	13868	71600	-57732				
		1.04	3.07	8917	71600	-62683				
		2.03	2.61	5513	71600	-66087				
		1.68	2.87	7341	71600	-64259	-65156	0	0.0	0.0
	23:30	3.55	4.56	29272	69300	-40028				
		3.02	3.87	17938	69300	-51362				
		1.11	1.42	888	69300	-68412				
		1.52	1.95	2294	69300	-67006				
		3.40	4.36	25718	69300	-43582				
		2.31	2.96	8041	69300	-61259				
		2.65	3.40	12128	69300	-57172				
		1.04	1.33	726	69300	-68574				
		2.03	2.61	5480	69300	-63820				
		1.68	2.15	3070	69300	-66230	-58745	0	0.0	0.0