Building a Smart-Grid bottom-up with Smart Autonomous Entities

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Final Year Project April 2013
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DECLARATION

I hereby declare that this project is entirely my own work and that it has not been submitted as an exercise for a degree at this or any other university

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Name  Date
I would like to thank Dr. Donal O'Mahony, my supervisor, for his continuous support and guidance throughout this project. I would also like to thank my class mates for their advice and camaraderie.

Also a word of thanks to my family for their support, advice, guidance and reading abilities.
Abstract

Electrical grids have been in use for over a hundred years. During the majority of this time, power has been supplied by carbon intensive generators using fuels such as coal, gas and peat. These generators have the advantage of supplying a steady and predictable output to the grid. Recently the types of generators being connected to the grid have changed, to include renewable sources such as wind and solar power. This adds complexity as supply is no longer predictable and capable of producing on demand.

To solve the issues that are arising with these new energy sources will require for more intelligent use of the resources available, both in terms of generation capabilities and the distribution network.

This project will examine the issues affecting future grid development and examine some solutions to these. The project aims to build a working emulator of an electrical grid. This emulator will operate according to protocols based on current real world practices and future operational proposals.
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1 Introduction:

1.1 Motivation:

Electrical grids have been in place since the industrial age. While most of the infrastructure has been updated and expanded since then, some aspects of its usage are only beginning to change. Over time the types of generators on the grid have been predictable and controllable large scale generators, such as coal, peat and gas plants. This created a model with variable demand being balanced by controllable generation.

But the recent push towards renewable energy usage is changing that model. With sources such as wind and solar power entering the energy mix, the supply of power to the system now contains large variable inputs.

This has led to the idea of the smart grid, which will allow for greater use of variable renewable energy sources and the more efficient and cost effective use of the electricity distribution network. The exact details of how the smart grid will function are not fully know and a large body of research and testing is currently underway.

1.2 Goal:

The goal of this project is to develop an emulator of an electrical grid. This will be capable of running simulations of a grid operating under real world conditions.

The emulator will need to operate to strict protocols, which reflect the current and future policies that have been identified for successful grid operation. It will be necessary to develop the policies for the grids operation based on an analysis of how current grids operate and how they will be affected by future developments.

1.3 Report Structure:

This report is divided into four main sections.

1. The first is a discussion of how grids operate today, the policies that are driving the direction of their development and the issues that lie ahead for grids into the future.
2. The second section details the design of the emulator, this specifies the policies by which the emulator operates and identifies the key entities involved.
3. The third section discusses the implementation of the emulator, based on the described design.
4. The fourth section contains an analysis of a simulation and discusses how the results reflect on the design specification.
2 State of the Art:

2.1 Introduction:
Before designing an emulator of an electrical grid, an analysis of real world grid operation and development is required. In the chapter that follows is a discussion outlining how grids have traditionally operated, the policies that are influencing their development and the challenges that grid operators will face, in implementing a smart grid into the future.

2.2 Operation of Traditional Electrical Grids:
Below follows a discussion of the operational practices employed in Ireland, the specific timeframes and figures relate to the Irish operation, which is relatively small compared to other grids around the world, but the general ideas of this discussion would hold in most other world grids.

2.2.1 Grid Operation:
Today the electrical grid is a complex system, where matching supply and demand is the primary objective. The grid system connects generators of power with consumers who use this power. The electrical grid functions as the link between the two groups and manages the power flow ensuring that supply and demand match.

The management of the power flow in the grid system is performed by Transmission System Operators (TSO) or System Operators (SO). The TSO or SO are responsible for ensuring the safe, reliable and economic operation of the electrical grid. This role includes scheduling power generation, real time balancing of supply and demand and fault management. In most grid structures there exists one TSO, thus creating a monopoly. As a result the TSO is generally subject to state regulation. In Ireland the TSO is Eirgrid, formerly ESB National Grid (ESBNG), and in Northern Ireland the TSO is the System Operator of Northern Ireland (SONI).

While the TSO is responsible for the operation of the electrical grid, they are not responsible for physically installing, maintaining and updating the grid infrastructure. This role falls to the Transmission and distribution system owner. In Ireland this role is performed by ESB Networks and by Northern Ireland Electricity in Northern Ireland, both of which are subsidiaries of the ESB group.

2.2.2 Operating Parameters:
When analysing the state of the grid there are three main parameters to consider, power, voltage and frequency. Of these the most critical parameter with the shortest tolerance in variation is frequency. This means that frequency is used by TSOs as an indicator of the current state of the grid, and this influences what decisions are made in the real time operation of the grid. Across Europe it is a requirement that all power systems maintain an operating frequency of 50Hz ± 0.5Hz. Each member TSO generally works to tighter requirements, for example in Ireland the system is maintained at 50Hz ± 0.2Hz.

Frequency can initially be a confusing parameter when associated with an electrical grid, but the principle is much simpler than might be expected. Consider a simple example: - think of a ratchet where you turn the handle and lift or move a load. In this system there is a load (demand) that is moved by energy being exerted to turn the handle (supply). If the load increases and the same energy is applied to the handle, then the handle will rotate at a slower rate, thus the frequency falls. To maintain a constant frequency the energy exerted must increase. If the load were to become lighter but the energy remained the same, the handle would turn faster, thus the frequency would increase, to maintain a constant frequency the energy used must also be reduced. In an electrical grid, all the traditional generators, coal, gas, peat, nuclear, hydro, etc all have turbines that rotate. These turbines turn at a specific RPM that results in the frequency produced being of the desired value. If the load on the system increases with no extra generation supplied, the RPM of each turbine reduces, and vice versa for a drop in system demand.

As a result when an imbalance occurs on the grid, this can be seen as a frequency change. As demand outstrips supply the frequency will reduce, a low frequency event, and when supply
outstrips demand the frequency will increase, a high frequency event. A low frequency event can be rectified by increasing generation or reducing the system load and a high frequency event can be rectified by decreasing supply or increasing the load on the system.

2.2.2.1 Operational Reserve:

To allow TSO’s to make adjustments to both supply and demand in response to frequency events, whose causes may last from fractions of a second to hours at a time, an operating reserve is required. This operating reserve is broken down into three main types; primary, secondary and tertiary reserve. These all work at different intervals after a frequency incident occurs, to try and rectify the frequency problem by correcting the imbalance between supply and demand. Figure 2-1 shows how and when the different forms of operating reserve are triggered. The following discussions describe the different types of operating reserve, specifically the Irish operation[1], but these different types of operating reserve are used across all grids.

2.2.2.1.1 Primary Operating Reserve:

Primary operating reserve is used from incident occurrence to fifteen seconds after the incident occurs. This is the most critical part of the system reserve as it reacts immediately to any frequency events. There are two main types of primary reserve, inertial and fast response.

Inertial reserve is the kinetic energy associated with a generator whose rotational speed changes with a change in frequency. This Kinetic energy can then be fed into, or withdrawn from the grid system to help alleviate the imbalances.

Fast response operational reserve is generally triggered by governor control at predefined frequency levels. It is supplied by steam based generators and pumped storage units which are operating below their maximum output. Steam plants cannot increase generation this suddenly and maintain the new level indefinitely. This drop in steam pressure will result in an unloading phase being triggered, where the plant’s output will reduce until the boiler pressure is returned to its standard operational level. For low frequency events, power consumers can also be tripped off, this includes storage facilities that were draining power e.g. the Turlough Hill pumped storage facility located in the Wicklow mountains.

2.2.2.1.2 Secondary operating Reserve:

Secondary operating reserve is used from fifteen seconds until roughly ninety seconds after the frequency event has occurred. This reserve is used to return the system frequency to its ideal level of 50Hz.

This response is provided by power plants operating below their maximum levels, TSOs generally keep a number of plants in this state as it allows them to be throttled up or down, depending on the variation in system demand. Pumped storage can also be used in this case, the storage facility can be used to increase system load in times of high frequency events and can be used to generate electricity in low frequency events. The key element here is that secondary response can be activated in a very short space of time. These output changes are generally performed manually via notification from the TSO to the facility in question.
2.2.2.1.3 Tertiary Operating Reserve:
Tertiary operating reserve operates from ninety seconds after the frequency event onwards. This reserve is generally only called upon in the case of major events occurring such as power plant failure or system demand varying from the forecast by a considerable amount. According to the Eirgrid code, and assuming a similar system prevails, there are four main types of tertiary operational reserve.

- Band 1 Tertiary Operating Reserve: this is used for the period of ninety seconds to five minutes after the frequency event.
- Band 2 Tertiary Operating Reserve: this reserve is used for a longer period, being available to run from ninety seconds to twenty minutes after a frequency event.
- Replacement Reserve: is used for much longer periods of time, it can be activated within ninety seconds of a frequency event and remain operational for up to twenty four hours after the event occurrence.
- Contingency Reserve: this reserve must be capable of operating up to twenty four hours ahead of real time.

Tertiary demand is generally met by generators in standing reserve, this means that they are not currently generating power, but are capable of a fast start. Examples of such generating plants are hydro, diesel and gas turbine plants. The Tertiary reserve is generally used to give load following capabilities to the TSO and ensure that at peak demand a generator failure will not result in a system failure.

All the different elements that can provide reserve capabilities can be summaries as either static or dynamic reserve. The main distinction here is that dynamic reserve reacts in response to frequency change, whereas static reserve is triggered at preset frequency levels to trip or trigger on.

2.2.3 Managing Grid Imbalances:
The SO or TSO are responsible for maintaining balance between supply and demand on the national grid. When solving the issue of changing supply and demand, a number of factors are taken into account. In determining the appropriate type of operating reserve to use TSOs consider the length of time this imbalance will occur for, the reason for the imbalance and the available operating reserve.

2.2.4 Scheduling and Transmission:
To allow the system to operate successfully the SO or TSO must predict the demand and arrange for adequate generation and reserve facilities to be available to meet this demand. Below follows a discussion of how this is achieved in Ireland today, but while these practices relate to the Irish grid, the overall principles are applicable to most other developed grids.

Eirgrid are the Irish TSO, they must cooperate and coordinate power supply with SONI, the Northern Ireland TSO. This is because these two systems are connected and power can flow in either direction across the border. When operating the scheduling and daily distribution of electricity, Eirgrid do so with three main themes as their primary concern. This is the operation of the grid in a safe, secure and economic fashion.

Operating the grid safely requires Eirgrid to consider the safety of consumers of electricity, the safety of those who work on the system and the safety of equipment and plant that is connected to the system.

Security is concerned with the maintaining of the electricity supply, Eirgrid must endeavour to avoid blackouts or disruption to consumers. There are a number of different factors that could result in the security of the power being jeopardised; these include unanticipated failure of a large generating facility or the failure of an element in the transmission system, such as transformers or transmission lines. To give system operators the ability to deal with issues such as this, extra power plants are scheduled to run, some running below their maximum output. This allows the system operator to increase or decrease their output to meet the current demand. Security of supply is the key aspect to maintaining a reliable electricity supply across the grid.
Operating the grid in an economic manner involves a balancing act between ensuring there is enough reserve to handle unforeseen events and not operating more plants than are necessary. Plants operating as reserve must be paid for operating in this state, even if they are not used to provide reserve for this operating window. To achieve this, Eirgrid publish a unit commitment programme which is updated several times a day, this acts as a schedule detailing which power plants are to be operational and the length of time they shall be operational for. This is based off demand and wind generation predictions.

2.2.4.1 Scheduling:
Scheduling involves planning the system generation and reserve requirements based on the predicted demand. This is achieved by issuing a schedule which details the MW output for each plant in thirty minute intervals over a thirty hour period. Traditional power generators are not the only facilities considered in this schedule, as power from interconnectors and reserve power requirements are also detailed.

Scheduling can generally be divided into long and short term operational planning and scheduling. Long term scheduling generally occurs from one year ahead of time, up to a week ahead of time, whereas short term scheduling generally occurs between a week and a day ahead of time.

Long term scheduling is generally concerned with planned outages during the year, these occur when plants are taken offline for resource or maintenance reasons. These outages are planned and coordinated to ensure the necessary generation and reserve capabilities are available at all times. These plans may need to be altered during the year for issues such as resources, forced outages, overruns and other such issues. Any entities requiring outage time, beyond that stated in the annual outage plan must be negotiate this with Eirgrid. Eirgrid will negotiate with the entities in question and come to a solution that allows system safety, security and economy to remain, but also allow entities to address issues.

Short term scheduling is performed with a number of factors in mind. A daily schedule is released at 16:00 and an updated version at 01:00 for the following day. As the schedule approaches real time a number of factors can be more accurately predicted and hence a more refined schedule can be released. Let's examine some of the factors Eirgrid consider when making a short term schedule.

- System Demand: predictions are relatively accurate a week ahead of time, but weather conditions can alter this demand.
- Reserve Requirements: Eirgrid must ensure an adequate level of reserve power is available.
- Wind: wind predictions are constantly being updated and wind can vary quite significantly from predicted patterns as variable weather conditions impact on the system.
- Hydro Energy Limits: these limits are generally forecast a day in advance and quite unlikely to change in real time.
- Interconnector limits: these are physical limits which occur due to infrastructure, available generation on either side of the interconnector and any outages that occur.
- Generation Constraints:
  - Curtailment: this occurs when demand falls below predicted levels or during a failure. Curtailment is used to stop overloading occurring on the system.
  - Spinning Reserve: This is where plants are run below their maximum output, so they can be called upon to provide extra power in the event of a generation facility failure or other significant loss of power within the system.

2.2.4.2 Dispatch:
The dispatch of power on the grid relates to the real time matching of supply and demand. This is achieved by using the schedule as a guide and by making decisions taking safety, security and economic operation into consideration. This is the stage where operators must respond to generator failures, transmission system failures and variations in wind generation and system demand from their predicted values.
The real time operation of the system is performed by Eirgrid in the National Control Centre (NCC) in Dublin. It is from here that all decisions regarding balancing supply and demand are made. A software tool called Electronic Dispatch Instruction Logger (EDIL) is used to send instructions to generators and these generators can then use this system to advertise their availability. A range of other software packages are used for reserve management, wind forecasting, contingency analysis and other issues. All these systems provide information to the engineers in the NCC who can then make better informed decisions around what actions to take to maintain system balance.

Scheduling and dispatch are fundamental stages in the operation of the electric grid. Scheduling insures that the necessary demand and reserve are in place to meet the projected demand and dispatch deals with ensuring that supply matches demand in real time. Dispatch is affected by issues such as demand deviation from the projected levels, wind generation deviating from the forecast and unforeseen plant failure, on both the generation and transmission system. Eirgrid are responsible for scheduling and dispatch operations in the Republic of Ireland and operating the National Control Centre in Dublin.

2.2.5 Grid Shut Down and Restoration:
For a number of reasons, including those discussed above, blackouts can occur on the grid. This represents the worst case scenario and can have severe consequences for users of the system, be they residential, commercial or industrial clients. As such when a failure occurs, the system must be returned to normal service as quickly as possible, with the chance of reoccurrence being very low. To help in these situations an alert system and procedure for system restoration exists. In this section follows a discussion of how grid operators deal with scenarios that could lead to blackouts and how blackouts are handled when they occur. The details of the following discussions are taken from the Eirgrid Grid Code version 4 from 2011 [2].

2.2.5.1 System Alerts:
If the grid were to enter a state of system emergency, Eirgrid would send out alerts to that effect to generators, transmission offices and distribution offices. These alerts can take four forms an amber, red, blue or other previously agreed alert structure. These alerts are communicated to all parties involved via the "Electronic Alert System" or verbally if this system fails, the receipt of each alert must also be acknowledged by each entity. Below follows a brief discussion of what each of the three main alerts are used for and what events they can represent.

2.2.5.1.1 Amber Alert:
This alert is the lowest priority alert available to system operators. This alert signifies that a single event exists, which has a high probability of causing a system issue to arise. This issue may cause voltage, power or frequency to deviate significantly from their ideal values.

2.2.5.1.2 Red Alert:
Red alerts are more serious than amber alerts. These alerts are issued for three main reasons;
- The voltage or frequency has deviated outside acceptable levels
- The probability of there being insufficient generation available to meet demand is very high
- A user has been disconnected from the system.

2.2.5.1.3 Blue Alert:
This is the most serious of the three standard alerts that a TSO can issue. A blue alert is issued in the case of total or partial failure of the grid.
These alerts can be issued nationally or within a local distribution area. But the goal is to alert all stakeholders that will be affected, that these issues are occurring. These alerts are an important part of grid operation, as they allow all the parties involved in the supply of power to the grid to take corrective action.

2.2.5.2 System Restoration:
If there was to be a failure within the system, irrespective of the size of the disturbance, a procedure for returning power to the affected areas is required. In any failure scenarios, Eirgrid are responsible for coordinating the system restoration effort. All stakeholders involved must listen for and respond to all instruction from Eirgrid in this regard.

As this represents such a serious scenario, adequate planning and preparation must take place. As such Eirgrid organise to run simulated blue alert scenarios with stakeholders throughout the year. This simulation is run while the stakeholder is offline, if possible.

2.3 Future Grids:
This section discusses some of the key issues influencing the development of electrical grids into the future. These discussions describe the issues, and some of the solutions being proposed.

2.3.1 Distributed Generation:
Traditional grids contain a small number of large power generating facilities, but in recent years this has started to change. This is due to the emergence of smaller generating facilities, which come in the form of small scale wind farms, solar panel installations on rooftops and other local generators. As smaller installations of power generation are connected to the grid at a local level, the methods employed in operating the grid need to change. The grid now contains a mixture of large and small scale generators connected to the grid at different voltage levels and this is posing new challenges in grid development.

Distributed generators supply power to the grid on lower voltage lines than traditional grids, this raises a number of issues. Power is transmitted over long distances on high voltage lines, this reduces the power loss which occur during transmission. This means distributed power connected on low voltage lines must not be transmitted over long distances to consumers, as the losses would be unacceptably high. Another option is to install the necessary infrastructure to raise the voltage of these connections to allow for distribution over large distance. But this has an added expense associated with it. The system is not designed to manage supply on low voltage lines entering the grid in this way. This means new control systems need to be implemented to allow for system operators to manage this power supply and maintain system equilibrium.
ESB Networks are responsible for the building, maintaining and updating of the national grid infrastructure in Ireland. They have been conducting tests on the new technologies that will be required to develop the grid into the future. They have had great success in this area and won the 2011 Power Grid International prize for "Best Grid Integration of Renewables Project" [3] for its smart grid demonstration project in conjunction with EPRI and ERC. The project focuses on the need for approximately 50% of the countries wind capacity to be connected to the grid at distribution voltages, to allow Ireland meet its wind integration targets. The project is broken into three subprojects, A, B and C. Project A is concerned with the control of reactive power, using voltage control at the wind farm, project B focuses on the control of the wind farm voltage rise by using voltage regulation close to the demand and project C involves the use of low cost substations which allow medium voltage wind connections to the grid. The graphical grid structure shown above in Figure 2-2 summarises the project undertaken by ESB.

This demonstration project allowed ESB Networks to test different solutions aimed at addressing some of the issues involved in connecting distributed generation to the grid. Through projects like this, ESB Networks are ensuring that the grid infrastructure can cope with power being supplied to the distribution network, and that this power can be managed appropriately to ensure system stability. It is through grid development such as this, that Ireland will be able to increase its use of renewable energy into the future.

The result of distributed generation; is local communities being powered predominantly by local power sources and the more traditional energy sources are being used to supplement these local generators. This creates an entirely new grid model, that requires new management strategies, technology and infrastructure to maintain the expected quality of service. As small scale generation becomes more prominent around the world, these issues will become more prevalent as countries attempts to promote the use of renewable energy.

2.3.2 Variable Renewable Energy Generation:
In traditional grids large scale generation facilities can provide relatively static and controllable outputs. This means the variability in balancing the supply and demand has traditionally been only on the demand side. With variable renewable energy sources such as wind and solar being integrated into the system, variability will also exist on the demand side. This will increase the amount of reserve required to maintain system balance.

2.3.2.1 Wind:
Wind energy raises some interesting issues, it is not only variable, but its peak times generally correspond to low system demand times. This complicates the integration of wind energy into the grid. But while these issues make wind integration harder, the potential of wind is vast and some research suggests that 400 terawatts of power could be harvested from wind, this compares favourably to the current world usage of 18 terawatts.[4]

Peak wind generation times generally coincide with low system demand times. This can be seen in Figure 2-3 (left). In this graphic it can be seen that the turquoise line, representing wind, has peaks in the morning and late at night but drops off considerably during the day. While the blue line, representing consumers, is relatively static with rises during the afternoon and evening, when wind generation is at its lowest. This means that wind
energy can at times be generating more energy than the system can use. This can be dealt with in two ways, the first is to curtail wind generation and the second is to store this energy for use at a later date. Both approaches are used today, but the storage option is seen as a more favourable option, but storage has its own drawbacks. Presently large scale storage is restricted by taking up large land areas and there are also efficiency issues.

As wind has such an unpredictable pattern and will make up a significant percentage of the total energy mix, prediction has become a very important tool. At present in Ireland, Eirgrid forecast the expected wind generation and the need to adjust for deviations from this prediction. Eirgrid provide live wind generation and prediction information online, they also provide system demand data. The below graphics show the wind generation in blue and the forecast values in purple (right) and the system demand (left) for the 9th of March 2013. It is obvious that the predictions are not perfect and Eirgrid must deal with these discrepancies by increasing output or reducing output from other power sources. The discrepancies can be quite large as seen on this graphic, for example at approximately 03.00 wind generation is roughly 275MW higher than was predicted. This is a significant amount of power considering the system demand at that time was 2300MW, meaning the discrepancy represents 12% of the overall system demand.

2.3.2.2 Solar:

Solar power also offers a huge potential around the world, not just in exceptionally hot and sunny regions. Solar panels can be used in desert areas which allows for previously unusable land to provide energy. Solar also has the advantage of peak power generation occurring during the day at similar times to when generation levels peak.

This energy source has been successfully utilised across a range of countries from US states such as California, which have large areas of desert lands, to countries with more moderate climates such as Germany. According to a report last year the European installed photovoltaic capacity has increased from 185 MW in 2000 to 52 GW by 2011, this represents an increase of 28000% in eleven years. [5] In 2011 alone 21.5GW of photovoltaic generation capacity was added in Europe. In the US
the total solar capacity increased by 76% in 2012[6], California is the state with the most photovoltaic installations. But interestingly large scale utility companies in California are currently still focused on generation from fossil fuels, this means most of the solar generation is coming from small scale generators.

2.3.3 Electric Vehicles:

Electric vehicles (EV) could be both a help and a hindrance to grid operators. EVs represent a significant new load to the grid, which will increase a nation’s power demands and could affect peak demand levels. But each car has one or more batteries and if a large number of cars were plugged into the grid, this combined storage capability could be a very useful tool for grid operators to use as extra operating reserve.

IBM are looking at this problem and see the batteries as presenting a solution to some of the problems with variable renewable energy generation. [7] If cars are plugged into the grid for periods of the day while their owners are at work, then this distributed battery capacity could be used to store extra power generated by wind and solar plants. But this isn’t as simple as it sounds, as cars would constantly be moving around and reconnecting and disconnecting from the grid. This means while the batteries of cars can be a help to the grid, to utilise them will take new and innovative development of the grid. The smart grid will be key to this with constant communication between charging stations and system operators essential in utilising this resource.

From the perspective of the increased system demand from electric vehicles, Deloitte examined how the penetration of electric vehicles would impact on the US national grid[8]. The findings were rather encouraging, they believe that to achieve President Obama’s goal of 1 million EVs on the road by 2015, no significant infrastructure or generating investment was required as a direct result of EVs. They suggested no investment to this end would be required in the next ten years. But they did identify one key area where investment is needed, "The last mile". This infrastructural investment is concerned with EV charging clusters on low voltage, distribution lines. This report is encouraging as the capital investment required for EV charging appears to only be required on the distribution network in the locality of the charging area.

One major issue is who will pay for all this infrastructure and the power used to charge the cars. This is a very topical issue at present, the initial idea was EVs would be charged by their owners at their place of residence. But as cars can often spend hours parked at office blocks, park and ride facilities, hospitals, schools, etc, it makes sense to plug the car into the grid at these locations. At present the infrastructure is being paid for by a mix of EV manufacturers and electric grid operators, for example in the US Tesla is establishing a charging network for use by only Tesla car owners. [9] But the issue of who pays for the electricity is still unclear, especially in public locations. But many of these locations presently charge at the meter for power.

Electric Vehicles present grid developers and operators with some exciting opportunities and many challenges. They have the potential to add vast amounts of storage capacity to the grid, but will also increase demand, and require some infrastructural investment. The issue of who will pay for this is still not fully resolved and there is a "Chicken and the Egg" dilemma developing, where the infrastructure will only be built if the number of EVs on the road is sufficiently high enough, but customers will only buy EVs if the infrastructure is there to support them.
2.3.4 Grid Hierarchies:
With grids moving towards this new model, distributed power generation and local supply powering local communities, the management of the grid needs to be updated. This new model makes local areas less reliant on more traditional energy sources, as their demand can at times, be met by local generation. This in itself creates a hierarchy within the grid, the national grid can be considered the parent of these local communities. But communities and local power generation can vary drastically in size and some communities could be subdivided further, creating more layers in the hierarchy. The result of this is the concept of Mega-, milli-, micro- and nano-grids [10]. These grids naturally form a hierarchical system, with distributed power and management techniques used to maintain a high quality of service to consumers. Below follows a discussion of these different types of grids and how they might be used.

2.3.4.1 Mega-Grids:
These grids are the largest grids and represent the upper most layers of the electrical grid hierarchy. This would include transmission lines and large scale generation plants such as the Moneypoint coal and oil plant in Kilrush, County Clare. This grid would supply power across the country that would filter down through the lower levels of the hierarchy to help maintain balance in the overall system.

2.3.4.2 Milli-grids:
These grids contain generation and loads, but are characterised by containing some of the traditional distribution network and are on the utility side of the grid. As such these grids are subject to statutory regulations. They are often referred to as micro-grids in error, but can be distinguished from these grids by their distribution network content. In Ireland each counties infrastructure could be considered a milli-grid. They would be managed by Eirgrid in the same manner as mega-grids, but they could be used to distributed power from local sources to the local community.

2.3.4.3 Micro-grids:
When considering the idea of grid hierarchies, the micro-grid is the fundamental element usually discussed. As such the name gets used in circumstances where the term milli-grid or nano-grid would actually be more appropriate. Micro-grids are characterised by having local control, and crucially, they are on the customer side of the grid. This means that there is one, metered connection between a micro-grid and a milli-grid and they are not governed by statutory regulations. An example of this would be a data centre, these facilities have a connection to the national grid with onsite generation available as well. The electricity is managed locally by the data centre staff and they can set standards for the local electrical system and make decisions as to which energy sources to use.

2.3.4.4 Nano-grids:
Nano-grids are a relatively new idea from an electrical grid perspective. But these grids have technically been in existence for a long time, just never considered in this manner. Nano-grids are very different to the preceding layers, they typically use DC current as opposed to the AC current used on the main electrical grid. The key principles involved are that nano-grids make autonomous decisions of power management between entities on a small scale.

An example of a nano-grid is the modern laptop. It contains the ability to connect to an external power source, it has storage capabilities from its battery and has loads represented by its hardware and external devices such as a USB drive, USB mouse and others. The role of the grid is not to control each of these devices, merely manage the power flows between them. The decisions are predominantly taken with regards to energy prices and this decides whether devices are operational or not and what energy sources are used.[10]

Systems like this provide secure, reliable electricity and fully functional communications capabilities between entities. They work on a very small scale, typically across an office floor or a small building.
Figure 2-6 shows how all of these grids could possibly link up to supply power in a secure manner. The grey dots represent consumers, with blue areas representing nano-grids, red areas representing micro-grids and green areas representing milli-grids. Then the main traditional grid is the Mega grid which sits at the top of this hierarchy.

2.3.4.5 Islanding:
Creating hierarchies introduces the prospect of "Islanding" off or isolating sections of the grid, this can be performed for a number of reasons. This can offer a new form of fault handling and reduce the severity of blackouts. For example if a section of the system is demanding too much power and to try and match that demand would jeopardise other sections of the grid, the rogue section can be disconnected from the grid until its demand has been reduced to acceptable levels. The advantage of the hierarchical structure, with distributed generation at different levels of the grid, is that "islanded" sections of the grid can be self sufficient for a period of time. An example of this can be seen in modern day hospitals, where during blackouts they switch to back-up power and can survive in isolation from the grid for a considerable length of time.

This hierarchical structure allows for the distributed control of the electrical system. It will allow for better fault isolation and allow for the identification and isolation of over-drawing bodies. For current grids to move to this model will require a major policy and infrastructure change. A system such as this would allow for distributed power to be connected and managed in a successful manner.

2.4 Policy:
As electricity supply is a public utility, government policy dictates the direction taken in the development of the grid. Presently there is a global movement from traditional fossil fuel generation to more renewable sources of generation. But each country and region is approaching the problem in a different way and developing policies to reflect their individual approach.
The European union has established the 20-20-20 goals which reflect targets for a range of issues including employment, R&D, education, fighting poverty and, more importantly for this report, climate change. Europe is targeting a 20%-30% reduction in its greenhouse gas emissions from 1990 levels, a 20% increase in energy efficiency and 20% of total energy consumption will be supplied from renewable sources. This is detailed in the 2009 Renewable Energy Directive(2009/28/EC) from the European Union. To achieve the goal of 20% of energy coming from renewable sources, each individual country was assigned a target that they must achieve by 2020. Figure 2-7 shows a graph displaying the targets for each country and the intermediate goals assigned. Some interesting countries to look at are Sweden, who began with just short of 40% of their energy from renewable sources, the UK who began with only about 3% renewable energy usage. The big contributors will be the Swedish, Portuguese, Latvians, Finish, Danes and Austrians. While some of the slower adopters are the UK, Slovakia, Montenegro and Lithuania. Ireland has a mandatory target of 16% which puts it in the middle ground.

The Irish government has issued targets in response to these European goals. Ireland plans to achieve the 16% target by 2020 for the countries total energy consumption. But in addition to this, Ireland has set out three goals for the electricity, transport and heating and cooling sectors. Ireland has set a target of 40% of electricity generation, 10% of transport energy and 12% of heating and cooling energy to come from renewable sources.[11] This 40% will be broken into 37% from wind and the remaining 3% coming from hydro, biomass, landfill gas and other sources. To aid in the achievement of these targets, Europe set interim targets for 2010. Ireland was tasked with achieving 13.2% of electrical energy from renewable sources, by 2009 Ireland had achieved 14.4%.[11] This corresponds to 5.5% of total energy being used coming from renewable sources.[12]

While Irelands targets are a major leap forward from the mandatory targets, they are not the most ambitious around Europe. Denmark has set a target of 50% for its electrical energy to come
from wind energy alone and has a target of 35% of total energy consumption to be supplied from renewable sources. If Ireland achieves its goal for 37% of electrical energy to be supplied by wind, it will not become a world leader in wind generation. However it will be elevated from being part of the middle group of wind using countries, to being amongst the top wind users worldwide. Ireland will be behind the likes of Denmark (50% goal), but in line with countries like Spain (40% goal). The main difference between Ireland and other countries deploying wind at these scales, is how isolated the grid currently is. The Irish grid contains relatively low levels of interconnectivity with other grids when compared with the likes of Denmark, Spain and others. This makes achieving these targets much harder, as Ireland cannot depend on power from other nations to supplement its wind generation.

In the US there is no single unifying renewable energy goal at a national level. But individual states are setting policies to encourage renewable generation. At a national level political issues are halting any national level binding goals or targets. This is because with republicans and democrates controlling one parliament house each, neither can implement drastic change. With democrats pushing for more renewable energy generation, and republicans pushing more oil drilling within the U.S., policies on these issues are not passing through the houses to implement any change. The only issue they agree upon is the need to reduce Americas dependency on imported oil.[13] As a result of this any policies within the U.S., exist solely on a state by state basis.

Figure 2-8 contains a graphic showing which states have mandatory policies and targets (green), voluntary targets (yellow) and no targets (white). California is one of the more progressive states in terms of setting enviromentally friendly energy goals. Their current goal is to generate 33% of their electricity from renewable sources by 2020. Most states operate policies that require each utility company to achieve a specific percentage target of their energy supply from renewables. This has led to the introduction of renewable energy credits. These credits allow companies achieving high percentages of renewable generation, to sell their surplus credits to companies that are struggling to meet targets. This is seen as a help to utilities with renewable infrastructure currently under construction. [14]
2.5 Ireland:

2.5.1 The smart grid:

The above graphic illustrates the projects and research initiatives that are currently being undertaken in Ireland. All of these projects focus on aspects of the smart grid which will be necessary for the successful implementation of a smart grid across the island of Ireland. The project and research areas can be broken down into five main topic areas as seen above. Below is a discussion of the projects currently being undertaken and their significance.

2.5.1.1 Smart users:

Users of the system play a critical role in determining the load on the system. For the smart grid to function correctly user behaviours need to change and users need to become more actively aware of the impact they have on power demand and how they can help in the systems operation. Today many people, particularly residential users, are not engaged with this process.

In 2009 the CER, SEAI, Bord Gais Energy and ESB Networks were trialling smart meters with 6,500 residential and commercial users. In 2010 time of use pricing and a new detailed billing system, containing detailed usage information, were introduced to the trial. A subset of the total test groups were provided with in home monitors and others were given web access. This system could allow for electricity suppliers to offer their customers prepay energy sales, similar to deals available from mobile phone operators, thus giving users more control over their energy usage and costs.

To help achieve the transport goals for 2020 the government has identified electric vehicle adoption as a key area for development. To achieve the 2020 goal the government set out to achieve a total of 6,000 electric vehicles being on the road by 2012. To encourage the population to adopt electric vehicles the government introduced a grant system in 2011 of up to €5,000 for people buying electric vehicles. New electric vehicles are also exempted from paying vehicle registration tax for three years after purchase. But electric vehicles need a large infrastructure of charging points, this system is being implemented by ESB Networks and contains 1,500 public charging points and 2,000 domestic charging points.

Commercial applications are being implemented across the country. Some companies are readjusting their demand in response to price, allowing them to save money and help to alleviate large peak power demands on the grid. Many firms are now implementing smart control systems that attempt to run the building in an efficient and more cost effective manner. Some Irish firms provide smart solutions to businesses, for example Glen Dimplex provide storage heaters, which can
be used by Eirgrid to add extra load to the grid when wind generation increases and this load can be removed when generation drops.

2.5.1.2 Smart generation:
To incorporate the extra renewable energy sources into the grid it will be necessary for the grid to operate with a higher penetration of renewable with variable power supply. Ireland is attempting to connect larger volumes of variable renewable supply than any other country and thus faces unique and previously unseen problems. Wind is the predominant source of renewable energy being targeted to make the 40% target achievable. Below is a discussion of the direction wind generation is taking in Ireland and some of the issues being faced and solutions being trialled.

2.5.1.2.1 Wind:
Ireland has a vast wind generation capacity from both on and offshore wind farms. Ireland is actively increasing its wind generation capacity, to help meet its renewable energy penetration targets. Currently Ireland can supply up to 50% of the system load from wind energy, but to meet the government’s target of 40% of annual electricity from renewable sources, the system will need to be expanded to support up to 75% of the system load being supplied from wind.[15] This equates to 6,000 MW of installed wind power, which is quite large considering the peak demand is less than 5,500. [3]

This may seem strange, but a recent article in the Scientific American[16] on a study from the University of Delaware found that in the analysis of a period of four years, it was feasible to provide power for up to 99.9% of the time using a mix of onshore wind, offshore wind and solar energy. They discovered that a 90% supply rate from renewable was achievable using onshore and offshore wind, but to gain the extra 9.9% solar power was required. In this set up the system required storage, but only enough for a number of days, instead of weeks. This study claimed that tripling the wind infrastructure was not as farfetched as it may at first seem, as coal power plants use three units of coal for every one unit of electricity. The conclusion was in order to use large volumes of wind energy you require more wind capacity than the system will ever demand.

While this research was not part of the policy making process in Ireland, it does support the plan to integrate what appear to be excessive levels of wind capacity onto the grid. This will allow wind energy to supply a large percentage of the country's energy demands.

**Figure 2-10 Projected Wind Capacity and System Demand**

![Graph showing annual electricity demand vs. wind generation](image)

SEAI have conducted research and published a report on the possible usage and development of wind generation in Ireland from 2011 to 2050.[17] Ireland realistically has the potential to generate more electricity from wind than the country consumes by 2030. This is illustrated in Figure 2-10, which shows the projected energy demand in yellow and the projected wind generation capacity in purple. These projections are based on an annual investment rising steadily to a peak of between €6 and €12 billion per annum by 2040. But SEAI fail to mention
where this investment will come from. Looking at current trends, investment would come predominantly from the private sector, but this would be dependent on state guarantees on minimum selling prices. But if this was achieved, between 2025 and 2030 Ireland’s wind capacity could outstrip the countries demands. Thus Ireland has the opportunity to become an exporter of wind energy. SEAI estimate that Ireland could contribute 5% of the total wind energy generated across Europe by 2050. To achieve this Ireland would need to increase the installed capacity to between 11 and 16 GWh/yr of onshore and 30 GWh/yr of offshore wind generation by 2050. This is estimated to be worth up to €15 billion annually to the economy. With these returns requiring annual investment of €6 - €12 billion a year, the potential exists for large profits to be made. This means the government should be able to encourage a large amount of investment from the private sector.

2.5.1.3 Smart Operations:
Operating a grid with a large increase in generation from variable renewable sources raises many issues. In this area projects are currently underway to examine the smart operation of wind farms, how smart meters can help all parties involved in the system and how commercial entities can play a role in the system operation.

2.5.1.4 Smart Networks:
Ireland needs to upgrade its infrastructure in order to meet its goals for integrating renewable energy sources onto the grid. The infrastructure also requires updating to ensure that Ireland maintains a high level of reliability within the system.

Eirgrid are in the process of planning and implementing the grid 25 programme. This programme aims to double the capacity of the Irish grid by 2025. To achieve this requires a €4 billion investment. The graphic (right) shows the spread of this investment across the republic. This investment is predominantly aimed at the high voltage transmission network for securing reliable transmission of bulk energy across the country. This investment is required to address a few key issues being faced by the Irish grid. These include larger wind integration and reliability of supply.

Self healing grids represent a major support to allow grids to remain operational or restart within a short time after a fault. This involves allowing the system to activate switches autonomously to try and redirect power around a fault, thus restoring power to affected areas. ESB Networks are currently piloting this technology. This technology also aids system operators in locations where the fault has occurred and this aids ground crews in repairing these faults in a more timely manner.

2.5.1.5 Smart Pricing:
Smart pricing shall play a major role in any future smart grid. Money is a big motivator and TSOs can use financial incentives to help change users behaviours to follow patterns that lead to the system working in a more controlled and stable manner. Encouraging people to perform non time-critical tasks during periods of high wind generation or low system demand would be of great help to TSOs as it would help reduce peak demands and increase minimum demands. For example a family may turn on their dish washer after dinner, but they don’t require the clean dishes until the following morning. If the dishwasher was programmed to run whenever the price of electricity was low, then a TSO could effectively turn this load on or off by increasing or reducing the price of electricity. Thus the machine would not run during the evening peak as people arrive home from
work, but over night when system demand is low and prices would fall accordingly. New smart appliances are presently being developed internationally with this type of functionality.

As mentioned above a smart metering trial has taken place in Ireland. The goal of the study was to use the information from the study groups, which were chosen to give a good representation of the entire population, to analyse the costs and benefits involved in rolling out a smart meter network across the country.

Eirgrid already run some time pricing for industrial customers. These customers are financially incentivised to lower their demand between 5 and 7 pm during the winter, the Irish annual peak time. Some industrial users make their load available for use in Short Term Active Response (STAR), where their load can be disconnected from the network for a short period of time. The Powerhouse initiative run by Eirgrid encourages industrial users to lower their demand when the system demand is approaching the maximum available supply. Industry is financially incentivised to partake in these schemes.

Ireland is investing heavily in the electrical infrastructure to ensure it meets its 2020 energy targets. Ireland is trying to increase the percentage of electrical energy that is being generated from renewable sources, predominantly wind. When analysing this there are two different figures to examine, the first is the total amount of power generated from wind and the other is what percentage this represents with respect to the total national generation. Ireland is too small to realistically become one of the largest generators of wind power in the world. But what they are aiming to achieve is to become part of a group of nations, such as Spain, Denmark and Portugal, who have a high percentage of their total energy generation coming from wind power. To achieve this will require a mix of public and private investment to the tune of billions of Euros per year. This investment is required at all levels of the grid and in new generating plants, predominantly renewable plants.

2.5.2 Smart Metering:

![Image](image-url)

**Figure 2-12 Irish Smart Metering Plan**

### 2.5.2.1 Planning:

The above graphic describes the four phased plan to implement a smart meter system throughout Ireland. In order to achieve a smart metering system in Ireland the Commission for Energy Regulation (CER) established a steering and working group to guide the project through the four phases outlined in the graphic. Both of these groups are chaired by CER representatives and contain members from a number of different parties involved in the electricity and gas systems in Ireland. These parties include the Department of Communications, Energy and Natural Resources (DCENR), the Sustainable Energy Authority of Ireland (SEAI), Bord Gais Networks, Bord Gais Energy, The Economic and Social Research Institute (ESRI), Electric Ireland and ESB Networks.[18]
2.5.2.2 Stimuli used in the trial:
The trial utilised smart meters to introduce a number of new measures for customers, these measures fit under the headings of time-of-use pricing and demand side management information. [18]

- **Time of Use Pricing:** variable pricing was introduced to reflect the variable cost of electricity on the Single Electricity Market. This was used to encourage participants to perform non time critical power usage at times of lower demand on the system.
- **Bi-Monthly/Monthly Detailed Billing:** The detailed billing was achievable with the smart meter data, it allowed for more detailed cost analysis and time of use information. The bill also included personalised and motivational text messages and historic comparison information.
- **In-Home Displays:** These monitors were linked to the smart meter and allowed users to view current power usage, set daily budgets and make daily, weekly or monthly comparisons of usage.
- **Annual Load Reduction Incentives:** Participants were set a percentage energy usage target, which if met would result in a cash reward. This was an annual target.
- **Web Access:** This gave participants access, through a web account, to their cost and consumption information. This was made available to all SME participant and residential customers could request an account.

These stimuli are similar to those used in other studies performed in other countries. Some countries trialled other options beyond what the Irish trial tested, such as critical peak pricing, but the Irish trial used a good mix of stimuli representative of those used in trials across the world.

2.5.2.3 Findings from consumer behavioural trials:
Below is a discussion of the conclusions from this trial. These conclusions are from the CER report published after the trial results were analysed.[18]

2.5.2.3.1 Response to time of use pricing and demand side management stimuli:
- Consumers were found to reduce their annual power usage by 2.5% and reduce their peak usage by 8.8% on average.
- The combination of bi-monthly billing, with a detailed electricity usage statement and an in house monitor, proved to be the most successful combination for reducing peak demand. Participants in this group reduced their peak electricity consumption by 11.3% on average.

The overall theme of the results found, that consumers managed to lower their demand at peak times to moving non time critical power usage to off peak times. Overall there was no combination of stimuli that significantly outperformed the others in terms of overall power consumption reductions.

2.5.2.3.2 Demographic, behavioural and experimental conclusions:
- 82% of the participants made some change to their electricity usage and 74% of these stated they had made a major change in their electricity usage.
- The in-house display was identified as an important aid to making changes by participants. 91% of participants rated it important in their shift away from peak time usage and 87% rated it as important in shifting to night time usage.
- The major factor inhibiting participants shifting appliance usage to night time was concerns with regards to safety and the inconvenience.

Overall it was found that the majority of participants achieved some savings in their electricity costs and the peak demand on the grid was reduced. The average annual energy saving per household was 2.5% and a peak demand reduction of 8.8%. If this was achieved nationally, this equates to an annual electricity generation cost reduction of €150 million. [19] If this was passed on to consumers, there would be significant savings to be made. The trial demonstrated that on
average a household could save €25 a year, but if the savings from a reduction in energy costs were to be passed onto consumers this figure could become much large.

2.5.2.4 Other Trials:
In this section a summary of the methods used and the results from five other smart meter trials are presented with a discussion on the differences in results. [20] Most of these trials used a combination of, time of use (TOU) pricing and critical peak pricing (CPP). CPP overrides the TOU prices at times when peak demand is very high and this price will more accurately reflect market conditions.

- TOU and CPP pricing introduced
- TOU only participants saw peak demand fall by 5.7%
- TOU and CPP participants saw peak demand fall by 25.4%
- Average annual saving of 6%

**Country Energy, NSW, Australia: (Started 2004)**
- TOU and CPP pricing introduced
- Peak demand fell by 30% in initial stages of trial, but effect reduced over time

**Energy Australia Strategic Pricing Study: (2006 –2007)**
- TOU and CPP pricing introduced
- Peak demand reductions due to CPP events of 5.5% - 7.8%

**California State-Wide Pricing Pilot: (2003 –2004)**
- TOU and CPP pricing introduced
- CPP caused 13%-27% reductions during a CPP event
- Load shifting effect nullified by end of year two

**SINTEF Energy Research, Norway: (2001-2004)**
- TOU pricing introduced
- Average peak load reduction of 8%-9%

2.5.2.5 Conclusions:
Comparing these results together, some patterns emerge. Time of use pricing on its own causes a peak demand drop of 5% - 9%, but some studies have shown that the effects of time of use pricing can wear off over time. This means that customers seem to be very involved and aware of their power usage initially, but eventually return to old habits. Ireland had similar success with time of use pricing as seen in the other trials, but didn’t implement any type of critical peak pricing structure.

Annual reductions in overall power usage are low, ranging from 2% - 6%. This is to be expected, as the smart meter is predominantly being used to encourage users to reduce their peak time usage. Thus users are generally using the same volume of power, but they are simply moving the time of this demand to other times of the day. To achieve usage reductions requires stimuli being presented to the user. This helps to get a more engages response from the user and the savings appear to be greater for greater stimuli usage. This means that user stimuli play an essential part in achieving demand reductions through smart meter usage. This means that major savings can be made by utilities who no longer need to build extra generators to deal with annual peak demand. These plants are only used for a few hours a year to meet this peak demand and effectively are unused at other times. In Australia this is thought to drive up to 25% of retail prices. [21]

Thus in conclusion the Irish study has not discovered any new headline grabbing smart meter effects, but has merely reaffirmed the international trend applies in Ireland. It also has come up to ten years after other trials were completed. But the trial has been deemed a success and the role out plan continues. As the trial was run using volunteer participants and over one year, it will be
interesting to see if smart meters will achieve similar savings on a national level. The reasons why the trial results may not correspond to national results are that volunteers are generally more enthusiastic and willing to get more involved in the project, where nationally not everyone will be so enthusiastic. Also other studies, such as the California study above, show that the effects of smart meters and TOU pricing can subside over time.

2.6 Summary of key Smart Grid Issues:
After examining the traditional operation of electrical grids and the manner in which grids are currently developing, it is possible to extract a number of key features of grid development. In the future electrical grids will need to operate with higher concentrations of variable renewable generation, small scale generation connected at distribution voltages, smart meters, electric vehicles and hierarchies.

- **Variable Renewable Generation**: Adding this form of generation to the grid adds more variability to the supply and demand balancing act. This means that operators need more reserve available to quickly counteract imbalances in the system.

- **Distributed Generation**: Connecting power generation to the distribution network requires the grid infrastructure to be updated to accommodate this. This means variable supply is entering the distribution system and the power generated must be used locally as the voltage levels are too low for long distance transmission of this power.

- **Smart Meters**: This offers the chance to motivate consumers to alter their power usage by providing financial incentives, through time of use pricing, and by providing feedback to customers about their usage. The goal is to encourage consumers to reduce their power usage annually and also at peak times.

- **Electric vehicles**: These offer the prospect of a large distributed storage capacity on the grid, which could greatly aid in the penetration of renewable generation on the grid. Their load can also be scheduled across a predefined time period, rather than needing to draw power immediately from the time they are plugged-in. But issues still remain over who will pay for the infrastructure and how owners will be billed for using public charging points.

- **Hierarchies**: Establishing the grid in this manner allows for greater control in managing and isolating areas of the grid. It allows for fault isolation and also for “Islanding” to be employed to shed load from the grid during high demand times.

The development of the grid into the future will pose many challenges. The abilities to solve these will play a key role in the world goal of reducing global dependence on fossil fuels. This can only be achieved if renewable energy is successfully integrated into the grid and if consumers use electricity in a more intelligent manner.
3 Design:

3.1 Introduction:
This chapter will discuss the design of the smart grid emulator. This includes a discussion on the goals of how the system should function and what key aspects of the smart grid should be modelled. The key entities that will constitute the different parts of the grid will be outlined and their functionality described.

3.2 Goal:
The overall goal is to allow users to instantiate a number of entities that constitute the electrical grid today and have this operate as a real electrical grid would. On a high level there are three main aspects required; generation, consumption and a means of connecting and balancing these.

![Diagram of Consumption, Generation and the Grid that connects them](image)

Each of the sub-grids, which constitute the grid hierarchy, should operate as an autonomous entity which balances power supply and demand. This places the grid in the middle of suppliers and consumers, responsible for instructing these entities in taking appropriate action to maintain system balance.

The key goal is for the system to operate autonomously and respond to imbalances appropriately and in a manner which replicates real world behaviour.

3.2.1.1 Hierarchies:
To allow for better management of system resources and aid in the isolation of problems, "The Grid" section of Figure 3-1 will need to consist of a hierarchy of grid entities. This will required grid entities to not just connect to other types of entities, but also to other grids. To allow for a hierarchical structure to be implemented it will be necessary for each grid to be capable of connecting to the level above and accepting connections from the level below. This can easily be summarised as a parent child relationship. As seen from the discussions of grid hierarchies, above, the number of entities at the top of the hierarchy is low, while the lower end of the hierarchy contains many elements. This analysis is the reason for stipulating a tree like structure where a grid may connect to one parent grid, but accept connections from many child grids. This is illustrated, below, in Figure 3-2.
Power needs to flow through this hierarchy, to allow power from large generation facilities to filter down through the system to local consumers. To model this, grids need to be capable of drawing power from their parent, if their parent has extra generating capacity available. With generation capable of being connected at all levels of the grid, it is quite probable that a grid lower in the hierarchy may be required to provide power to a grid higher in the hierarchy. This means that power also needs to be capable of flowing from children to parents and is illustrated by the arrows in Figure 3-2.

Thus the grid hierarchy will consist of more entities at lower levels and allow power to flow both up and down the hierarchy. Consumers and generators will connect to this hierarchical grid structure at a number of different levels. This allows for more accurate modelling of the different size of consumers and generators that connect to real world grids.

3.3 User Operation:

The operation of the system should allow for users to operate the emulator with ease and also allow for realistic emulation of an electrical grid.

The system aims to emulate a true electric grid, where a large number of entities, possibly spread across a large geographical area, connect together. These entities must then communicate their ability to supply power or their current power demands to the grid hierarchy. Then the grid connecting all these entities must ensure that supply and demand remain balanced. To replicate this in software, entities of the emulator should be capable of running across a number of different machines. This allows for a community to run the different elements and interconnect their power supplies.

One could imagine a scenario where a large group of users wish to run a simulation with real data. This could be achieved if a real world power generator, such as the Arklow Bank Wind Farm in Co. Wicklow, were to run a generator entity on their systems and have its output match that of the real wind farm. Then other users could run their own grid entities and have them connect to this generator entity. This could be very useful for TSOs and research groups to run simulations to test the grids reliability and security.
The emulator needs to allow for users to run simulations where the underlying goal is to test the performance of the grid hierarchy under defined circumstances. This means the system should be capable of operating autonomously with specific inputs that can be changed manually. For example, a user should be able to increase or decrease a consumer's demand in order to test how the system would react to such a change. The system should then adjust to operate under these new specifications. The system should also allow for failure modelling, users should be able to create a scenario where a failure will occur and watch the system respond to this.

### 3.4 Autonomous Operation:

The system contains a number of entities, which connect together to supply and consume power. To manage the entire system and maintain balance between supply and demand, all of the entities must act autonomously. To achieve this, each entity must be capable of communicating its current state to other entities. This requires each entity to autonomously manage power flows between itself and other entities and respond to requests from other entities.

For each entity to operate autonomously some key objectives for the system need to be defined. These objectives will help define how the system responds to different scenarios. These objectives need to be defined based on the previous discussions about how grids operate and their future development. The objectives are listed below:

1. **Balance:** The grid hierarchies overall goal is to be in a balanced state. This means that all decisions must reflect this goal.
2. **Priorities renewable:** In the theme of current grid protocols, renewable energy sources should be given priority over non-renewable sources. This primarily affects the scenario where generation capacity is greater than demand and the grid has a choice of which generation source to use.
3. **Minimise failure impact:** The grid hierarchy is a highly interconnected system, failure in one section could ripple through and have disastrous effects throughout the hierarchy. This should be avoided and the fault should be isolated from the rest of the hierarchy.

#### 3.4.1.1 Power management:

As the link between generators and consumers, it is the responsibility of grid entities to maintain balance in the system. They are responsible for ensuring the correct output is supplied by generators to meet customers' demands. This means each grid entity must maintain a record of the power demands from its consumers and connected grids. To meet this demand it is then necessary for each grid entity to stipulate the output of power generation entities to ensure that this demand is met.

Handling imbalances in the system will be a key factor in the successful modelling of a real grid. Imbalances come in two forms, when supply is greater than demand and vice versa. In responding to these scenarios the grid entity needs to base its decisions on the objectives set out above.

For the scenario where demand is greater than supply, the system needs to take a number of steps to try and rectify the system imbalance. Each grid entity tries each of the following steps, until the system returns to a balanced state.
1. Increase power generation from previously curtailed variable renewable energy sources and "Base-Load" generators
2. Increase power generation from available generators
3. Draw power from parent (if entity has a parent)
4. Draw power from children (if entity has any)
5. Draw power from storage facilities
6. Reduce power being supplied to parent grid
7. Reduce power being supplied to children grids
8. Limit power to the connected consumer

It is clear to see that this ordering is important, reducing the power supplied to other grids and customers is used only as a last resort in solving imbalances. Also the grid first tries to use local generation sources before seeking help from further up or down the hierarchy. This promotes a self sufficiency first approach to balancing an individual grid, where the grid tries to meet demand by using generation connected to itself, before going up the grid, then down the grid hierarchy in search of power. This represents the need for power generated by plants connected to the grid at distribution voltages to be used locally, as it cannot be transmitted over long distances at these low voltage levels because of unacceptable losses. This also helps reduce the burden each grid entity places on the entities it is connected to. The idea of using the storage capacity so late in the process is that it is a short term solution and merely postpones the imbalance issues until the storage empties.

In dealing with an oversupply of power the grid must reduce the amount of power being supplied to the grid or increase power demand. In solving such issues the grid performs the following actions, continuing down the list until the system is returned to a state of equilibrium.
1. If any consumers, parent or child grids have had their ability to draw more power restricted, these restrictions are lifted.
2. Any storage units whose current state of charge is less than their maximum charge are supplied with the excess power.
3. If the grid is drawing any power from a child grid, this draw is reduced.
4. If the grid is drawing power from its parent grid, this draw is reduced.
5. Any generators attached to the grid have their power reduced.
6. Wind curtailment or "base load" generator shutdown.

As for the previous scenario, the order of the above list is crucial. The goal is to avoid curtailing power generation, thus the first option is to try and increase system demand. Failing this the grid first tries to stop any power flows to its children and parent grid entities. This is to reduce the demand on other grids in the system. The grid will then curtail its gas generation and finally its wind generation, this reflects current policy of incorporating as much wind energy as possible in the energy mix.

When deciding on the above lists a few key principles were taken into consideration. Each grids first target is to be self sufficient, thus ensuring it has as little impact as possible on other areas of the grid. This also reflects the need to use distributed generation within the local grid. Renewable energy generation is given priority over other forms of energy generation; this is in line with current grid practices as all system operators aim to increase the volume of renewable energy being supplied to the grid.

3.4.1.2 Fault Isolation:

This section primarily deals with the implications of objective three. The goal is that each fault can be isolated sufficiently so it has minimal impact on the rest of the grid hierarchy. To achieve this, the link between two different grid entities in the hierarchy, must have the ability to stop power flow between them. This is complicated by the recovery policy, even when a section fails and the power flow is stopped, the two grids need to maintain a communication channel. This will allow for the system to recover quickly and seamlessly after the problem has been rectified.
This policy is reflected in the steps set out in the power management section above. When the demand on a grid entity increases above its generation capabilities, the order of which power demands are stopped first is crucial. In the list above on page 33, steps six, seven and eight outline the order in which power consuming entities have their power supply cut off. To help ensure that faults do not ripple through the system and cause system wide failures, the last power consuming entities removed are the consumers connected directly to the grid entity in question. Whereas power demand from other grid entities connected to the current entity are stopped first. This means that for effective fault isolation each grid entity within the hierarchy needs to prioritise self preservation.

This is a two way policy though, while each grid entity should prioritise self preservation, it should also strive to reduce the demands it places on other levels within the hierarchy. This is expressed in the rules for when power demand is greater than current supply. Firstly the grid entity seeks to use the power sources directly connected to itself, before seeking power from other grid entities. Thus grid entities can help alleviate strain throughout the hierarchy by prioritising the use of local power over power from elsewhere in the hierarchy.

The self preservation policy and practice of using local power first, enable the hierarchy to isolate faults. With these policies, problems within the hierarchy should be successfully isolated to one grid entity within the hierarchy. Ensuring isolations such as this will help minimise power outages and ensure a more reliable power supply all round.

3.5 Communication:

To facilitate the operation of the emulator, entities require a sophisticated communications system capable of supporting multiple conversations between a variety of entities whose functions vary dramatically. In general the communications will contain three main parts; connection request, initialisation and normal operation.

The connection request phase of the communication needs to contain information pertaining to the physical connection. This information includes voltage levels, current type and other information regarding the physical specification of the two entities. This is required to ensure that a physical connection between the two entities is only accepted if it would not cause any physical damage to the hardware of either entity. Such damage could be caused if a consumer configured to receive electricity at 220 volts connected to a grid supplying power at 100kV.

The initialisation of the connection establishes the terms of the connection. These terms include the maximum and minimum current draw allowed, the price that electricity is being sold at and any other relevant terms required for establishing the rules for the interactions between the two entities. These terms can be renegotiated at a later date if this is required by either party, but before power can flow between the two entities, an agreement of terms needs to be established.

The normal operation phase regards the communications that occur during operation of the connection. This includes renegotiation of the terms of the connection and the setting of current power demand. If two entities agree to certain minimum and maximum power flows, but one entity needs to draw a demand outside of this range, they can simply start a new negotiation to try and get the power they require. Selling entities may also need to renegotiate connections as prices change depending on remaining capacity.
There are six types of communications that take place in the grid, the grid to each one of the entities and between one grid and another. The differences lie in which direction power is flowing and the key parameters involved in the transaction of power between the two entities. Communication will play a key role in the operation of the emulator, the system will use these communications to aid in making decisions regarding system operation. The idea of the autonomous communication is that it will allow operators to set criteria and the system will be able to operate itself within the limits of that criteria.

3.6 Key Entities:
To implement the smart grid emulator, four main entities are required. These are: grids, generators, consumers and storage entities. Below follows a detailed description of each entity and how that entity interacts with others in the system.

3.6.1 Generators:
From the discussion of the power sources being utilised on the grid in chapter 1, three types of generator are required for the emulator. One to represent "base load" power where output is constant and cannot be quickly changed, a "throttle-able" generator whose output can quickly be changed to any value between a maximum and minimum value and finally a variable energy source which represents unpredictable renewable energy sources.

3.6.1.1 "Base-load" generators:
This type of generator is used to supply a steady power flow and usually system operators do not vary its output at all, quite often its output takes a long time to change. This sort of power source is usually comprised of peat or coal plants. For the purposes of the emulator this power source is required to provide power to the transmission network at high voltage levels.

3.6.1.2 "Throttle-able" generators:
This type of generator is simply a generator whose output can quickly be throttled up or down within a maximum and minimum range. This type of generator allows for quick balancing of discrepancies in power supply and demand, it also plays a key role in grids that have generators whose output cannot be quickly altered, such as wind generators. When wind generators are used with unstable client usage the resultant difference between supply and demand can change frequently, thus generators with the ability to alter their output quickly are needed to make up this difference.

3.6.1.3 Variable output generators:
These generators are representative of unpredictable renewable energy sources such as solar and wind. Operators cannot control the output of these plants, only curtail their supply to the grid. Current policy dictates that renewable energies should be used as a priority, hence curtailment is seen as a last resort. To model this effectively it will be necessary to implement some form of variable supply, ideally taken from real data sources.

3.6.1.4 Generator operation:
Generators of all kinds need to connect to grids in order to get their power distributed to consumers. This means generators will communicate with grid entities regarding what its current output should be. This needs to be achieved via a request from the grid to set the power output to a specific value. Generators need to ensure that their demand remains within their limits and be able to respond to requests from grids. This communication needs to support intelligent decision making and negotiations between the two entities. The wind and base-load generators need to be capable of handling curtailment requests and gas generators need to be able to supply a value between their maximum and minimum, but also restrict the grid demanding more than the maximum.
3.6.2 Consumers:

Consumers represent a multitude of different real world entities, from households to large scale industrial users of electricity. The main characteristics of consumers are, they signify a drain on the system and they follow a variable demand.

In the context of this emulator consumers are being defined as an entity that solely demands power from grids. It should be noted that while some electricity customers do have generation and storage capacities and can act as a drain and a supply to the overall grid, this is not applicable to this entity. To model such a consumer on the emulator would be achieved by instantiating a grid and connecting a generator or storage entity and a consumer to this grid entity, this grid entity would then connect to the grid hierarchy. This small grid would then appear as a variable customer on the grid hierarchy with the ability to both draw power from and supply power to the hierarchy.

Consumers need to have communication capabilities with the grid entity they are connected to. This allows for negotiations regarding price and power flows to take place. The consumer also needs to constantly check if its demand is being met. The consumer should be able to handle small imbalances between supply and demand, as a real system should. But it should have some means of tripping once the degree of the imbalance increases to unsustainable levels. The failure should be an automatic process, but to restart after a failure should be manual. This is in line with the rules that were discussed above in the grid recovery section on page 15.

3.6.3 Storage:

Storage units give grids the opportunity to store excess power generation for later use, rather than curtailing this generation. The storage entity can represent a number of real world entities, it can represent pump storage facilities such as Turlough Hill in Co. Wicklow, Ireland or banks of batteries, common in backup systems in data centres.

The storage units have a maximum charge and a current charge. The key element that needs to be modelled is charging and discharging of the stored energy. Storage entities connect to grid entities and power can flow from the storage entity to the grid, providing the storage entity has not completely discharged all of its energy, or power can flow from the grid to the storage entity providing the storage entity is not fully charged.

3.6.4 Grids:

Grid entities are fundamental to the operation of an electrical system. They connect consumers and generators of power and control the flow of power through the system. To achieve this, requires grid entities to have the ability to communicate with all other entities in the system, including other grids. Grids need to use this communication to allow power to flow from generators to consumer and ensure that the balance between demand and supply is maintained. Allowing grids to connect and communicate with other grids will allow for the successful modelling of grid hierarchies.

As the middle man, grid entities will be the most connected element in the emulator. They require the ability to connect to any type of generator, accept connections from consumers and allow for connections from storage facilities.
3.7 The Emulator:

The diagram in Figure 3-5, illustrates how the six entities of the emulator link together and the direction of power flow throughout the system. The arrows represent the directions in which power can flow between each entity.

Each of the three generator entities can operate on their own with zero or more connections from grid entities. The grid entities can exist in isolation or operate as part of a larger hierarchy of grid entities. Each grid entity can connect with up to one parent grid and can have zero or more children grids connected. The grid makes connection requests to generators, but consumers and storage entities make connection requests to the grid entity. Storage and consumer entities cannot exist in isolation, they are assigned a grid to connect to at initialisation time and cannot disconnect from this.

Power flows within the system are managed by the grid hierarchy. Each grid entity is responsible for setting the desired output from each of its generators, while each generator ensures its outputs do not go above its total generating capacity. Consumers place demands upon their grid entity and will receive power from the grid. The consumer monitors the power it receives and if it varies greatly from its demand, the consumer will fail. Storage units can act as a load or a source of power for grids. They can help store excess generation from renewable sources, which can then be used during peak demand periods.

The grid is responsible for balancing the power demand from consumers with power supplied from generators. The grid operates a number of policies to ensure the system utilises its resources in the desired manner. These policies are based on the three main operating principles of balance, prioritise renewable energy sources and minimise failure impact. These principles mean the grid hierarchy will prioritise power generated from renewable sources when deciding what generators to use power from. Also the hierarchical structure is created to allow for the successful isolation of faults from impacting on the rest of the hierarchy.
4 Implementation:

4.1 Introduction:
This chapter details the implementation of the emulator, based on the design described above.

4.2 Libraries Used:
The emulator is written in Java. This was chosen for the availability of a large number of helpful libraries. This includes libraries for HTTP communication and fast GUI design. In this section some of the libraries used are discussed.

4.2.1 Apache HTTP Client:
This library is used to allow entities to make HTTP requests to websites. This ability is used by the consumer and variable output generator entities. They use the Apache HTTP Client library to get real time system demand and wind generation from online sources.

4.2.2 Swing:
The Swing library is used to design and implement the GUI for each entity of the emulator. The advantage of this library over some other options is the drag and drop GUI designing tool combined with the ability to edit the code. This made GUI development much faster for simple tasks, but still allowed the extra freedom software level design offers.

4.2.3 JFreeChart:
JFreeChart is a java library that allows for the design of a multitude of different charts. This library was chosen as the output charts can be displayed on java Swing GUIs. This library was used to display plots of the power supply to and demand of an entity over time. This allows for a much more in-depth analysis of the systems performance.

4.3 Communication:
Communication forms an integral part of the emulator. All of the entities which need to connect together to distribute power must use a clearly defined communications protocol. This ensures communication can take place autonomously, where each entity can interpret the messages being received and can ensure any message it sends will be correctly interpreted by the recipient. In this section the basic protocol is discussed, all communications between entities is derived from this basic protocol.

The protocol is based on two entities connecting together, with one entity supplying power to the other. This creates a consumer and supplier relationship within the communication. A Supplier has a socket server on which it listens for connection requests. This listener is identified by its IP address and a port number. Any Consumer wishing to connect to this Supplier must first make a connection request. This request contains information regarding the current type and voltage level the Consumer wishes to draw current at. If these match the configuration of the Supplier, the connection is accepted.

If the request is accepted by the Supplier, the Consumer sends an authorisation request. This contains information about the maximum and minimum current demand allowed and the price per unit the Consumer wishes to pay. The Supplier can accept or counter this offer and the two parties negotiate until an agreement is reached. Once these three parameters have been agreed, the Consumer can draw any current between the minimum and maximum value at the agreed price, by sending an adjustment request. This deal can be renegotiated by either entity at anytime, by sending a new authorisation request.

The Supplier of power needs to be able to limit the power demands of the Consumer. This is achieved by the Supplier setting a maximum value and not accepting any renegotiated values which go above this. The Consumer is programmed to accept any maximum value which the Supplier sends...
twice. Then the Consumers supply from the Supplier is set to this maximum value. The Consumer can continue to try and negotiate a higher rate, but until the Supplier is capable of supplying more power, these requests will be rejected. These constant requests allow for the Consumer to get extra power as soon as it is available. Once this maximum value has been set the Consumer can still reduce its draw if it needs to.
4.3.1 Communication commands and their formats:
The following are the possible commands that can be sent over the communication channel. The XXX symbol simply represents a value, for example in MAXA XXX, XXX represents the maximum current value allowed to be drawn by the consumer.

4.3.1.1 Connection Request:
CONNREQ ID: XXX V: XXX C: XXX (Consumer requests connection)
   ID: ID of the Consumer
   V: Voltage level
   C: "AC" or "DC"

CONNACK ID: XXX V: XXX C: XXX (Supplier accepts connection)
   ID: ID of the Consumer
   V: Voltage level
   C: "AC" or "DC"

CONNREJ R: XXX (Supplier rejects connection)
   R: "Incompatible_current"
    "Incompatible_voltage"

4.3.1.2 Connection Parameter Negotiation:
PAUTH MINA: XXX MAXA: XXX P: XXX (Consumer offer of terms of connection)
   MINA: Min current Consumer allowed to draw
   MAXA: Max current Consumer allowed to draw
   P: Price willing to pay per unit

PACK MINA: XXX MAXA: XXX P: XXX (Supplier accepts terms of connection)
   MINA: Min current Consumer allowed to draw
   MAXA: Max current Consumer allowed to draw
   P: Price willing to pay per unit

PREJ MINA: XXX MAXA: XXX P: XXX (Supplier rejects terms of connection and sends counter offer)
   MINA: Min current Consumer allowed to draw
   MAXA: Max current Consumer allowed to draw
   P: Price willing to pay per unit

4.3.1.3 Setting the current flow between entities.
PADJ A: XXX (Consumer adjusts current drawn to level XXX, Min <= XXX <= Max)
   A: the present current flow required

PADJ OK (Supplier adjusts and accepts change)

Below in Figure 4-1 the manner in which these commands come together to form the communications protocol is displayed. The diagram shows a communication between a supplier and a consumer. The communication commands are divided into four different types. The "Compatibility test" section allows the two entities to verify hardware compatibility before establishing a connection. The Consumer and Supplier negotiations represent the negotiations that occur to allow either party alter the terms of the connection. The adjustments section is where the Consumer sets their current demand between the agreed maximum and minimum levels.
### 4.3.1.4 Flow Chart of communications

**Compatibility Test:**

- **CONNREQ**
  - **Parameter Match**: Do Connection Parameters Match Supplier Parameters?
  - **Parameter Mismatch**: CONNREJ

- **CONNACK**
  - **Parameter Match**

**Parameter Negotiation (Consumer):**

- **PAUTH** (with new counter offer or repeated PREJ offer if acceptable)
  - **Suggested parameters acceptable for Supplier?**
    - Yes: **PAUTH** (with new parameters)
    - No: **PACK** (Repeat received offer)

- **PACK** (Repeat received offer)
  - **Supplier accepts offer**
    - **PREJ** (with counter offer)
  - **Supplier rejects offer**
    - **Suggested parameters acceptable for Supplier?**
      - Yes: **PAUTH** (with new parameters)
      - No: **PACK** (Repeat received offer)

**Adjustments:**

- **PADI OK**
  - **Current offer acceptable for Supplier**
  - **Current deal satisfactory for Supplier?**
    - Yes: **PAUTH** (with new parameters)
    - No: **PREJ** (with new parameters)

**Parameter Negotiation (Supplier):**

- **Pauth** (Repeat received offer)
  - **Consumer accepts new parameters**
    - **Authorise parameters acceptable for Consumer?**
      - Yes: **PAUTH** (with new parameters)
      - No: **PREJ** (with new parameters)

- **PREJ** (with new parameters)
  - **Suggested Offer OK for Supplier?**
    - Yes: **PAUTH** (with new parameters)
    - No: **PACK** (Repeat received offer)

---

*Figure 4-1 Communications Flow Chart*
In a renegotiation the Consumer can send one command, a PAUTH command. In this they stipulate their desired terms. The Supplier can accept this by sending a PACK command, or reject the offer with a PREJ command. The PREJ command contains the Suppliers counter offer. The Consumer can then accept this by sending a PAUTH with the parameters from the PREJ repeated, or can send a PAUTH with another counter offer. This continues until the Supplier receives an offer they can agree to and sends a PACK command. The Supplier started negotiations work in the exact same manner, except they are started by the Supplier sending a PREJ command after receiving a PADJ command.

The above graphic shows how the communication commands can be broken down into four main sections; connection request, client started negotiation, server started negotiation and normal operation. The three communication stages, connection request, initial negotiation and normal operation, described on page 35, all use these four types of commands. When two entities connect, the connection request stage uses the compatibility test commands to check hardware compatibilities. The initial negotiation corresponds to a consumer negotiation. The normal operation of the connection consists of the adjustment phase, with both client and server negotiations. These negotiations allow for either entity to alter the terms of power flow between them.

4.4 Entities:

4.4.1 Grids:

Grid entities are essential to the successful distribution of electricity from generators to consumers. They maintain balance between supply and demand by communicating with generators and consumer. The grid is capable of having connections with all other entities, and to allow for hierarchies, they can connect to other grid entities. The grid must buy power from generators and sell it to consumers, thus a method of calculating and communicating a selling price has been developed. The grid thus has two main functions; communication and power management.

**Power Management:**

In managing the power flows within the system and maintaining balance, the rules set out on page 32 must be implemented. The grid entity maintains a number of java ArrayLists, one for gas generators, Variable output or "base-load" generators, storage entities, child grids and consumers. These ArrayLists maintain a number of details specific to the current operation of the connection between the two entities.

Each grid entity manages power imbalances by having a constantly running thread. This thread sums the power supplies and demands and subtracts the two to calculate the imbalance. This thread then goes through the relevant steps from page 32, based on whether the imbalance is due to over- or under-supply of power. This thread then sleeps for 10ms, before starting again.

To limit the supply to a consumer this grid thread sets a "renegotiate" Boolean variable, associated with that entities ArrayList entry, to true. Then the communications threads will limit the power supplied to that entity. To limit the power from a generator is achieved in a similar manner. For a gas generator a variable of type double is used to set the desired draw from that generator, again this is stored in the ArrayList entry for that generator. This is then communicated to the generator via its communications thread. To limit the supply from a Variable output or "Base-Load" generator is achieved by setting a double value to the required supply and setting a Boolean "reduce" variable to true. This is again dealt with by the communications thread for that entity.

To indicate to an entity that it is no longer being limited in its ability to draw or supply power, the Boolean values are set to false. This then allows the entity to negotiate a higher maximum power flow value with the grid entity.
Communication:

As the main link between all entities each grid entity must be able to handle connection requests and make connection requests. The grid can handle connection requests from storage, consumer and other grid entities and the grid can make connection requests to one other grid and any generator. Each grid uses three PORTs on the system, the three ports are the PORTs equating to

\[
\begin{align*}
6000 + \text{Grid ID} \times 3, \\
6000 + \text{Grid ID} \times 3 + 1, \\
6000 + \text{Grid ID} \times 3 + 2,
\end{align*}
\]

where Grid IDs start at 0. For example grid 2 has an ID = GRID2 and uses PORTs 6000+(2*3)=6006, 6007 and 6008. The first PORT is used to listen for consumers connecting to the grid, the second is used for connection requests from other grid entities and the third PORT is used for connections from storage entities. When an entity makes a connection to the server, listening on one of these ports, a separate thread is started to communicate with the connecting entity.

The grid has the ability to communicate with every other entity in the emulator. In the description of each entity below, the specifics of the communication protocol between the entity and the grid are discussed. In this section the specific implementation of the communication between two grid entities is discussed.

When two grid entities connect one is the parent and one is the child. The child grid initiates the connection. The key parameters are the price the parent sells at, the maximum power the parent can supply (PMAX), the price the child sells at and the maximum power the child can supply (CMAX). These four parameters are negotiated in the normal manner using PAUTH and PREJ commands. There is no minimum value as the values operate on a negative to positive scale as shown in Figure 4-2. This means if power flow is negative the child is supplying power to the parent and vice versa. This means that the child maximum power parameter is negative and the parents positive. The power flow can then be set to any value between these two maximums. If one entity cannot supply power to the other, they simply set their maximum value to zero.

![Figure 4-2 Inter-Grid Communications: Parent Child Power Flow](image)

Power flow is a number between CMAX and PMAX
GUI:
The GUI contains two windows, in a tabbed interface. The first window is the control panel, which displays information about the real time state of the grid. It is through this panel that connection requests can be made to generators and other grids. The second window contains a graph showing supply and demand over time.

Figure 4-3 shows the control panel for a grid entity. There is a lot of information displayed on the window. The supply from generators, supply to consumers and power flows between this grid and its children and parent. The right side panes allow for the grid to make a connection request to a generator or parent grid. To connect to a grid the port number it listens on for connection requests is entered in the text box and the relevant button pressed, the same applies for connections to other grids.
The Graphical display for the grid entity contains a graph with time on the X-axis and power on the Y-axis. The demand is shown in red and the supply is shown in blue. The grid above can be seen to have remained in a balanced state over the period of operation.

4.4.2 Generators:
Three different types of generators were developed for this project; "Base-Load", "Throttle-able" and Variable output generators. The three types all share some common traits, generators can be started on their own with not connections. They listen for connection requests from grids and can accept connections from multiple grids.

The generator has a socket server listening on port (8000+ID number), for example GENE3 listens on port 8003. This server socket listens for connections from grids who wish to draw power from the generator. The following communications involve negotiations of pricing, current power flows and maximum and minimum power draw per grid. Each connection to the generator is handled in its own separate thread, thus each grid has its own, independent line of communication with the generator.

Each generator maintains a total of the amount of power it is supplying to the connected grid entities and ensures this does not rise above the maximum output of the generator. If this total rises above the generators maximum output then the generator will renegotiate the terms of the connection with each grid entity stipulating the maximum power that can be drawn. The "Base-Load" and variable generators must also listen for commands from grid to curtail their output. Ideally these plants would provide all of their available power to the grid, but if demand is less than their ideal output, curtailment must occur to maintain system balance.

In the sections below the specific implementations of each generator is discussed.
4.4.2.1 Variable output generators:

In the emulator the variable output generator is named a wind generator, but it simply models a generator whose output changes over time, such as wind and solar power sources.

**Power Management:**

The wind generator output follows a predefined set of values and updates to the next value at regular intervals. To reflect the real operation of wind, some real wind generation values are used. Eirgrid make the wind generation predicted output and actual output values freely available online. These are downloaded by the wind generator entity and used to model a varying output. To achieve this, the wind generator makes a http request to the Eirgrid website to download the wind generation data for a twenty-four hour period.

Below is the Eirgrid URL used, the wind generator sends a HTTP request to this URL. The response to the request is the wind generation prediction and actual values for the period between the start and end dates specified.


In performing this task the URL remains static except for two values, the start and end dates (yellow). The system can edit these to get information for any specified period of time. At present these values are not accessible to users through the GUI, and allowing users this freedom is left as future work.

These generation values are then processed and entered into a one dimensional array and the entity simply updates its output in intervals of 2 seconds to the next value. If the HTTP request fails for any reason, for example no internet connection, a text file is supplied which contains twenty four hours worth of data. The system then reads in these data values and operates as normal.

The wind generator must keep track of the power demands being placed on it and ensure that it does not attempt to supply more power than its current maximum capacity. To ensure this the generator maintains a thread, whose sole purpose is to sum the demands from all connected grid entities and set a maximum on these demands if their sum is greater than the total power available. These maximums are then communicated to the respective grids over the socket interface.

**Communication:**

The communication between a wind generator and a grid entity is a variation of the protocol described on page 42. In this scenario the wind generator sends the PADJ command to the grid stipulating the power it wishes to supply to the grid. The grid can then accept this by sending a PADJ OK message. The grid needs a method of limiting the power flow from the wind generator. This is achieved by the grid renegotiating the max and min power flow values and this limits the wind generators output to the specified maximum value. This represents the grids ability to curtail wind power when necessary.
GUI:
The wind generator has a tabbed GUI with two windows, shown below in Figure 4-5 and Figure 4-6. These windows provide users with information regarding the performance and state of the generator as well as the ability to examine performance over time.

The control panel contains detailed real time information about the current state of the generator. Shown in the top right area is information regarding the IP address and Port number the generator uses for socket communications. It is on this socket that the generator is listening for connection requests from grids. The bottom right area shows the grids which are connected and their current draw on the generator, wind generators ideally operate with the total draw from all connected generators being equal to the generator’s output. The left side of the control panel displays information regarding the selling price, the output from the generator and the generator’s ID. The Scaling bar is used to increase or decrease the output of the generator. This is achieved by multiplying the downloaded data from Eirgrid by a scaling value, whose value is defined by the position of the slider.
The graphical display for the wind generator, shown above in Figure 4-6, displays the ideal output and actual output of the generator over time. The total power supplied to connected grids is shown in red and the actual generated power available is displayed in blue. Examining the graph displayed above, it can be seen how the connected grids initially consumed all of the generated power. This was followed by a period of wind curtailment, where the connected grids consumed less power than was being generated. Finally the grids returned to consuming all available power from the generator.

4.4.2.2 "Base-load" generators:

This type of generator provides a steady and constant flow of power to the grid. The aim is to use base generation to supply less than the minimum power requirement of the system. Then other forms of generation are added, which can respond quickly to variations in demand, to make up the difference.

**Power Management:**

The "Base-Load" generator supplies a constant level of power to a grid entity. The grid entity can reduce this supply. The generator can reduce its output to anywhere between its constant value and zero, but the grid entity is discouraged from doing so. This only happens in a scenario where demand is below the supply of the generator. The generator must monitor the demands from the grid and ensure that its supply never goes above its desired output.

**Communication:**

The communication protocol between a grid and a "Base-Load" generator is the same as the protocol used between a wind generator and a grid entity. The power supply is stipulated by the generator and then the grid can accept this or curtail it.
The generator GUI consists of a tabbed interface, there are two tabbed windows, a control panel shown in Figure 4-7 and a graphical display shown in Figure 4-8.

The control panel allows for the user to view current information about the generator's state. The base load generator code is based on a wind generator, except its output is static and can be specified by the user. The user can alter the output by entering a new value in the text box beside the "BaseLoad" label and pressing the change button. The generator listens for connection requests from grids on the IP address and Port specified on the right hand side.

The graphical display shows a graph of power against time. Two series are represented on the graph, the desired output (blue) and the actual output (red). This interface can be helpful in...
analysing system events over time. In the above graphic it can be seen that the supply of power increased rapidly to the "Base-load" generators maximum output, once the grid had connected to the generator. After this there was a very short and small curtailment and this was followed by a period of steady and constant supply of power to the attached grid.

4.4.2.3 "Throttle-able" generators:

For implementation purposes this type of generator has been named a "gas generator", as a gas generator is an example of a real world generator of this type. The gas generator is different from the other two types of generator in that its output can be any value between its minimum and maximum output values.

Power Management:

The gas generator has an absolute maximum value it can supply, but it can quickly be adjusted to supply anything from its minimum up to its maximum value. It can supply multiple grids at once, while ensuring the sum of the outputs remains less than the total maximum. This means the generator needs a method of curtailing demand from grids.

Communication:

This generator has one communication, between itself and the grid entities that connect to it. The protocol used is the same as described on page 42. This means that each grid entity can specify its desired power draw between the present maximum and minimum values specified. Either party can renegotiate these values. The generator can set a limit to the power draw by restricting the grid entity from increasing this maximum value.

GUI:

The gas generator GUI is displayed below in Figure 4-9 and Figure 4-10. The GUI features a tabbed interface with two tabs. The first tab is a detailed control panel with real time information about the generator's current state. The second is a graph of Power against time and shows maximum output in blue and current output in red.

![Gas Generator GUI](Figure 4-9: Gas Generator: Control Panel)

The control panel, shown in Figure 4-9 shows information about the generator's state, output and connections, this also displays the Port and IP address, on which the generator is
listening for connection requests from grids. The title of the frame has a coloured background. This operates on a traffic light coloured sequence, which indicates how close the generator is to reaching its maximum output. Green represents current output being much lower than maximum output and red indicates current output is close to or equal to maximum output. It is from this window that users can change the maximum and minimum outputs by simply entering the new value in the text box and pressing the "Change" button.

![Power Matching Graph](image)

**Figure 4-10 Gas Generator: Graphical Display**

The second window, shown in Figure 4-10, shows a graph of the generators performance over time. This is a graph of power (Y axis) against time (X axis) and displays two series. The two series shown are maximum output (blue) and current output (red). This allows for a user to analyse the system performance over time and examine any abnormalities that occur.

### 4.4.3 Consumers:

Consumers represent a variable demand that is connected to a grid entity within the hierarchy. Consumers can be connected at any level of the hierarchy, but only have one connection to it. While a house is used as the icon for this entity, it is used to represent any demand on the grid. This demand can represent a small user, such as a house, or a large user, such as an industrial facility.

**Power Management:**

The demand is modelled by an array of data points which are cycled through. The actual present demand is the value of the current data point multiplied by a scaling factor which is defined by the slider in the GUI. These data points are taken from the real data available from the Eirgrid website. By making a HTTP request, using the Apache HTTP Client, to the below URL;


The URL is static except for the dates, highlighted in yellow, which can be specified. This allows for the use of data from different times of the year and the data can come from one twenty-four hour period or from over a period of a number of days.
The consumer cannot exist without being connected to a grid entity and will only ever be connected to this one grid entity. The consumer therefore operates one communication channel between itself and the grid entity.

The controller monitors the power being supplied to it by the grid entity and compares this to the consumers' current demand. A failure occurs if the difference between demand and supply goes above a preset threshold. While the system is in the failure state the demand of the consumer continues to loop as before, but the power flow between the consumer and the grid is zero. This is achieved by maintaining a Boolean value “failure”, which if true means the system has failed. If this value is true the consumer will demand zero power from the grid, and this continues until the system recovers. The system is recovered manually by a user pressing the "Recover" button. A failure can be rectified in two ways;

- more generation capacity is connected to the grid hierarchy, or
- the consumers demand is reduced using the slider.

If a recovery is tried while the demand is still above what the grid can supply, the consumer will fail again. The failure reoccurs immediately as the imbalance will still be too large for the consumer to cope with.

**Communication:**

The communication protocol between a consumer and grid entity is the protocol described on page 42. The consumer can draw any power level between the negotiated maximum and minimum values. The deal can be renegotiated by either entity and a grid can limit a consumers’ current draw by setting a maximum and not allowing the consumer to negotiate a deal which raises this.

The consumer is the part of the system which fails. There is no specific communication protocol for this. Instead this is reflected in the communication channel by the consumer setting its demand to zero. This will be accepted by the grid and zero power will flow between them. On recovery, from a communication perspective, the consumer simply requests to increase power flow to the levels of its demand.

**GUI:**

The GUI for a consumer contains two tabbed windows, the first displays the control panel and the second a graph of supply and demand over time. These are shown below in Figure 4-11 and Figure 4-12.

![Figure 4-11 Consumer: Control Panel](image-url)
The control panel, shown above in Figure 4-11, displays information about the grid the consumer is attached to and the current supply and demand. The MINA and MAXA represent the current maximum and minimum values which have been agreed between the grid and the consumer. The "Scaling" slider is used to set the scaling factor applied to the downloaded data. This allows users to operate consumers of different sizes, which allows for more detailed modelling of a real system.

The recover button is used to recommence power flow between the consumer and the grid, after a failure has occurred. The recover button is only enabled after a failure occurs and is disabled again after a successful recovery from the failure.

![Power Matching](image)

The graphical display in Figure 4-12 contains a graph of power against time. There are two series shown, consumer demand (red) and supply from grid entity (blue). In the above graphic the variable nature of the consumer is shown, also the supply from the grid constantly updated to match the changing power demand.

### 4.4.4 Storage:

Storage entities can both demand power from and supply power to the grid. The storage unit has a maximum charge it can hold.

**Power Management:**

The battery required the modelling of a rate of charge. This means a measure of time and charge are required. This is achieved by using the following instruction;

\[
\text{Current_Charge} = \text{current_flow} \times 0.1
\]

This is performed every time an updated message is received from the grid entity, which communicated with the storage entity every 100ms. The minus sign is due to a negative current flow representing the battery being charged.

This means the battery can, in theory, provide an infinite amount of power for an infinitesimally small period of time or provide a smaller amount of power for a longer period of time. The same applies when the battery is being charged; the time taken for the storage entity to charge is dependent on the magnitude of the power being supplied. This means that the discharge/charge time of the battery is dependent on the magnitude of the power flow between the entities.
Communication:

The communication protocol governing a connection between a storage entity and a grid entity is a variation on the protocol described on page 42. This is because power can flow in both directions. This is similar to the power flow between two grid entities, but the battery does not operate a maximum or minimum power flow. Instead the battery communicates its current charge and its maximum charge to the grid. The grid entity can then set the power flow to be positive or negative and set the magnitude of power required. The grid entity can set a negative power flow (charging battery) if the current charge of the storage entity is less than the maximum charge. The grid entity can draw power from the storage entity provided its current charge is greater than zero.

GUI:

The storage entity has a GUI consisting of two windows in a tabbed interface. The first is a control panel and the second is a graphical display. These are shown below in Figure 4-13 and Figure 4-14.

![Figure 4-13 Storage: Control Panel](image)

The control panel contains information about the current state of the system on the left. This includes a status bar used to indicate the current charge of the battery. The current flow displays the present current flow into the battery. A negative current flow represents the battery being charged and a positive current flow represents discharge. On the right hand side of the control panel is information about the connection to the grid. The "Capacity" section allows for a user to specify the batteries capacity by entering a value in the text box and pressing the "Change" button.
The graphical display features a graph of charge on the Y-axis against time on the X-axis. The current charge of the battery is displayed in blue and the maximum charge in red. It can be seen from the screen shot in Figure 4-14 how the battery charged quickly to its maximum and after a period began to discharge.

4.4.5 Controller:

The controller is the starting point for the emulator. It is responsible for starting all other entities in the emulator. It has three main parts; a GUI interface, the ability to start another java class in a separate process and communication capabilities used to instantiate each new entity. It must also keep an internal record of entities that have been started and what ports they are using. This information is used for instantiating entities with correct port numbers.

GUI:

The starting of any entity could be performed in two ways, via a command line or a GUI. The command line would allow for the stipulation of parameters in a very concise manner, but may be intimidating to users unfamiliar with command line interfaces. Whereas a GUI may be more
restricting, it offers a very user friendly interface for operating the system. From an accessibility perspective a graphical user interface was chosen. This is shown in Figure 4-15.

The grid and all three generator entities can be started in isolation, but storage and consumer entities must be connected to a grid. Therefore a drop down menu is used to select which grid the consumer or storage entity will connect to. This means a user must select a grid and then press the appropriate button to start a consumer or storage entity. If a grid is not selected or a grid does not exist, the button press will not perform any action and an error message is printed to the console.

**Operation:**

To allow for the emulator to run across multiple machines it is necessary for each entity to be run in its own process and JVM. This means that the controller is required to take any java class and be capable of starting it in its own process and JVM on a button press. To achieve this the Java ProcessBuilder class is used.[22] This class manages a number of process attributes and can start a java class in a new process with these attributes. This allows the controller to start a new java class in its own process.

The controller can start any of the six entities, subject to a number of constraints. The grid and all generator entities can all exist independently of any other entity and thus can be started by a simple button press. But the consumer and storage entities must be connected to a grid. This means that a grid must exist for these entities to connect to, before they can be started. The dropdown list on the GUI allows a user to select a grid and then by pressing the consumer or storage buttons, the selected entity will be started. This entity is then initialised with instructions to connect to the specified grid; this information includes the grid ID and the port number the grid is listening on for connections from this type of entity.

Grids are initialised with three PORTS, these ports start at 6000. To keep track of the next set of available PORTS an integer value is maintained with the value of the next available PORT, this is then incremented by three every time a grid entity is started. Each generator uses one PORT and a similar integer is maintained to keep track of the next available PORT.

Consumers and storage units are initialised with the ID and PORT number of the grid they are to connect to. To keep track of this, a hash-table of ID and PORT pairs is maintained. The ID is the key for this pairing. This allows for the user to select the grid from the dropdown list of grid IDs and the controller to establish the PORT that grid listens on, for connections from the respective entity. For consumers the PORT is the number that is paired with the ID key, for storage units it is this number plus two.

When the user presses the start consumer or storage entity button, the system records the grid ID selected. This ID is then used for instantiating that entity. The same approach is taken for instantiating a generator with its mode of operation. Depending on what generator is started, a String variable is set with the value "GAS", "WIND" or "BASELOAD". This value is then used to send an initialisation command to the generator, in response to its initialisation request. These approaches work on the assumption that a user will only start one entity in the length of time it takes for that entity to make an initialisation request to the controller.

**Communication:**

The controller must communicate with each entity it starts, to instantiate the new entity. To achieve this, the controller has a socket server interface, which listens on port 5050. All new processes that the controller starts send an initialisation request to this server. The server will respond with information regarding the ports the entity should use, its ID and some extra, entity
specific information such as its mode of operation. The entity then uses this information to initialise parameters, modes of operation and internal socket servers, for connecting to other entities. The entity then closes its socket connection to the controller. Below follows a detailed outline of the commands involved in the initialisation communications.

4.4.5.1 Initialisation Request:
INIT TYPE: XXX  
Type: Entity Type: "GRID", "GENERATOR", "CONSUMER" or "STORAGE"

4.4.5.2 Initialisation response:
INIT ID: XXX PORT: XXX  
ID: The ID for this grid
PORT: The first of its three sequential PORT numbers

INIT ID: XXX PORT: XXX OP: XXX  
ID: The ID of this generator
PORT: The first of its three sequential PORT numbers
OP: The mode of operation of this generator; "GAS", "WIND" or "BASELOAD"

INIT ID: XXX PORT: XXX GRID_ID: XXX  
ID: The ID for this consumer
PORT: The PORT number the grid it shall connect to, is listening for connections on
GRID_ID: The ID of the grid it shall connect to

INIT ID: XXX PORT: XXX GRID_ID: XXX  
ID: The ID for this storage
PORT: The PORT number the grid it shall connect to, is listening for connections on
GRID_ID: The ID of the grid it shall connect to
5 Testing:

In this chapter a simulation is performed using the emulator and the results are discussed to evaluate the performance of the emulator. The following simulation is devised to test the system performance and ensure it adheres to the three main principles of operation. To make this more relevant it has been based on the use of real infrastructure in Ireland.

5.1 The Simulation:

The simulation models three grids connected in a hierarchy, with one parent and two children. The parent is representative of the national grid and its two children are representative of the Munster and Leinster Grids. Connected at a national level are a consumer and a generator. The generator is a gas generator based on the Aghada plant in Co. Cork. The Munster grid contains a customer representative of Cork City and has local wind generation supplied by the Gneeves wind farm. The Leinster grid has a consumer based on Dublin City, storage capacity based on Turlock Hill, the pumped storage facility in Co. Wicklow, and a wind farm modelling the Arklow Bank wind farm.

The simulation will connect all of these entities together and allow the system to settle. The demand from Cork will be drastically increased, to the point where the grid hierarchy cannot supply that much power.

The result that should be expected is for the Cork City consumer to fail, but the Dublin City and national level consumption should not be affected.
Figure 5-1 Simulation design
5.2 Results:

In Figure 5-2 the National grid, it can be seen that the grid remains balanced at all times. The peak from the Cork demand can be seen highlighted in yellow. It is worth noting that the national grid never allowed supply to the Munster grid rise above what it could supply.

In Figure 5-3 The Leinster grid is shown. This grid can be seen to have suffered no effects from the demand peak from Cork. This grid was isolated from the fault.

In Figure 5-4 the Cork grid is shown. It can be seen where the spike in demand occurred, in red. The blue supply line never matched this and the consumer shut down shortly after the demand increase. After the load was removed, the system had no load upon it and supply and demand fell to zero.
The graphs for the National, Dublin City and Cork City consumers are shown here. The peak in the Cork demand is highlighted in yellow. It can be seen that the Supply to the grid attempted to match this new demand, but the Munster Grid could not support this new level and quickly the supply dropped. Once this imbalance rose above a predefined threshold, the Cork City consumer failed and reduced its demand to zero which is reflected in the supply series, in blue. The demand remained high during the failure and is shown by the red series.

The interesting result is in the analysis of Figure 5-6 and Figure 5-7. The supply and demand curves never diverged. This means that the supply to these two consumers was maintained during the Cork City high demand and after its failure.

From the Graphs above it can be seen that there was a spike in demand from Cork City which filtered up through the hierarchy, but this was quickly stopped and the Cork City consumer failed. The interesting result is that Dublin City and the National Consumer never failed to have their power requirements met. This means that the system successfully minimised the impact of the Cork failure and its effects were isolated from the rest of the hierarchy.
5.3 Evaluation:
The emulator was designed with three main operating principles in mind. These are; maintaining balance between supply and demand, prioritising the use of renewable energy sources over non-renewable sources and minimising the impact of one failure on the entire grid hierarchy.

In the above test the system was put through a number of scenarios that demonstrated all of these principles being applied in the management of the grid hierarchy.

- Examining the graphs before the failure shows that the system remained in a balanced state, with adjustments constantly being made to ensure balance.
- During the operation of the system the wind generators provided power to the Leinster and Munster grids, and only once demand went above what these could supply did power flow from the National Grid to its children grids.
- The massive demand from Cork City was quickly rejected by the entities in the hierarchy and the fault was isolated to the Cork City consumer in the Munster grid. Analysis of the Dublin City and National Consumer graphs show that while Cork City was experiencing a peak in demand and the grid tried to facilitate this, the supply to these customers never failed. Thus the impact of the failure was successfully isolated to the local grid rather than affecting the entire hierarchy.
6 After Word:

6.1 Evaluation:

The test above demonstrates that the emulator can successfully operate according to the three main principles that have been defined. The system successfully implements these on an entity level, each grid entity makes decisions based on these principles.

The emulator allows for the modelling of real world scenarios. It implements a complex communication structure which allows each entity to communicate effectively with another. Each entity is given a small degree of intelligence and the decision making process is performed by the grid hierarchy.

While these results are promising they show that renewable usage is not fully optimised. Renewable energy in Munster was not utilised to power Leinster before the gas generator at the national level was used. This means that wind curtailment occurred, even though a sufficient demand existed for the power in another part of the hierarchy.

To allow this to occur would require more in-depth communications between grid entities within the hierarchy. This would require grid entities to have a more in-depth knowledge of the types of power sources available from their children and parent grids, and not just that power is available.

6.2 Future Work:

The system needs further development to allow for the modelling of more complex scenarios.

The user interactions with the system need to be refined. The user interface is not optimally intuitive to use, especially when connecting entities. This process also needs to include the IP address and not just the PORT number on which the connection should take place. This will allow for the emulator to operate across a number of different machines.

The emulator needs another entity to be modelled, electric vehicles. These offer a new and previously unseen load to the grid. If this entity was implemented it would allow for more real world scenarios to be modelled and would allow for the testing of different policies with regards their charging times.

The system would benefit from the inclusion of more real world data being used for simulations. All generators and consumers could be given more freedom to model their outputs and demands on real world entities.

At present only power supply is modelled between entities. To allow for a more in-depth analysis and more accurate modelling to be achieved, voltage and frequency should be introduced. Currently the voltage levels and current types of each entity are 12v AC, the emulator should be expanded to have different interfaces for varying voltage levels and current types.

6.3 Final Word:

The development of the electrical grid into the future will require the solving of many complicated issues. Some of the key issues facing the development of the grid are;

- The integration of more variable renewable energy sources
- The connection of this generation at distribution voltages
- Smart metering
- Electric Vehicles
- Grid hierarchies

To solve these issues a wide body of research is currently underway. But as electrical grids are so vast and complex, building physical test infrastructures is impractical. Therefore ideas need to be tested on emulators before being put forward for implementation.
The goal at the beginning of this project was to implement an emulator of an electrical grid, capable of running simulations of real world scenarios. The emulator is designed such that the operation of the entities involved, is based on real world practices and future ideas. This project has taken these ideas and policies and implemented an emulator capable of simulating real world events. The intelligence is spread throughout the system with communication protocols designed to allow each entity within the system communicate effectively with one another.

This emulator still needs more development to allow for more complex scenarios to be modelled. New entities, such as electric vehicles, need to be modelled and more freedom to model different policies would add to the systems effectiveness.

Overall this project has been successful in achieving the goals that were initially set. The result of the project was the development of a software based emulator of an electrical grid. This emulator can be used to model different real world scenarios. The results of these simulations can be analysed in real time and users can make adjustments to try and rectify or introduce problems.
7 Bibliography


