Department of Mechanical and Aerospace Engineering

Investigation into Microgrid Energy Trading

Author:
Michael Karling
Supervisor:
Professor Joe Clarke

A thesis submitted in partial fulfilment for the requirement of the degree
Master of Science
Sustainable Engineering: Renewable Energy Systems and the Environment
2015

Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

The copyright of this thesis belongs to the author under the terms of the United Kingdom Copyright Acts as qualified by University of Strathclyde Regulation 3.50. Due acknowledgement must always be made of the use of any material contained in, or derived from, this thesis.

Signed: Michael John Alexander Karling   Date: Thursday 3rd September 2015

Abstract

This report focuses on microgrid energy trading and investigates its potential to encourage embedded generation. Embedded generation through the establishment of microgrids has been identified as a solution for sustainability challenges in the energy industry. Microgrids can alleviate pressure on the national grid as modern energy consumption rises. Microgrids provide a pathway to integrate cleaner energy without a major re-wiring of the national grid. This report highlights and explores issues that have been identified for microgrids when in energy deficit or surplus. Microgrid owners must pay capital loan costs and maintenance for their on-site generators. When a microgrid is in deficit, the additional cost for national grid energy can make on-site energy generation too expensive. Currently, if a microgrid produces too much energy the surplus can be wasted or it can be sold to the national grid. Government feed-in tariff schemes are being introduced around Europe to encourage the uptake of small scale renewables. However, the national grid was not designed for bi-directional power flow, the energy exported is generally small, sporadic and can have technical issues such as harmonics. There is concern that after the government directives expire, the power companies will not pay for microgrid energy as it is not in their interests to do so.

This report suggests that microgrid energy trading offers an alternative way to manage surplus and deficit issues associated with embedded generation. If microgrids over the same voltage network can exchange energy at a price below the national grid import rate, then more deficits can be met without using the national grid. Profits can be made from surplus generation without stepping up the voltage for export. The microgrid energy trading field has been entirely theoretical in its first few years as there are so few microgrids worldwide to trial. Therefore, a need was identified to create a software model to simulate a future scenario fit for trading; to investigate the factors that influence trade and identify the caveats to make trade viable. This report describes the development of this software, MGTrader, and summarises the findings of the simulations.

Energy trade among Microgrids is possible, integrating well in tandem with other smart-era concepts such as demand management or peak/off-peak price plans. Microgrid energy trading is encouraged by variability in sizes of microgrids in an area and by the diversity of supply types those microgrids utilise. Trading is best suited to smaller urban networks as some low voltage networks in rural areas are affected by the distance between microgrids. This report advocates for further work to follow up the encouraging findings of this project with more detail and through new approach.

Acknowledgements

I dedicate this work to my father; Robert Karling, who died on the 24th May this year after a short illness. He always demonstrated his sincere interest and gave support throughout my education.

Thanks to my supervisor Professor Joe Clarke for his support and guidance. The encouragement he provided during this project gave me the motivation necessary for this work during a difficult period of my life. A special thanks to Dr Paul Strachan and the rest of the staff on the Sustainable Engineering: Renewable Energy and the Environment course at Strathclyde.

Table of Contents

List of Figures

List of Tables

1 Chapter One: The Microgrid Energy Trading Concept

This section describes the micro-generation concept and explains why it has moved towards the forefront of the consciousness of the energy industry. Then the theory behind microgrid trading will be explained and the potential benefits laid out.

1.1 Background: Microgrids

A microgrid, in its most simple form, is a small-scale power network. This network can work independently and self-sufficiently but it also often operates as part of a wider grid. In practice, it is a small local area with the capacity to generate sufficient electric power to meet its own energy needs. Although microgrids have become a part of the science and engineering consciousness in recent times, it is not a new concept. At the close of the 19th century, there was great competition between engineers about how electrical infrastructure should look. Thomas Edison held the patent for direct current 'DC', which needed to be locally distributed to avoid losses. Edison argued that giving control to local communities and businesses over their electricity generation was the best way to ensure cheap growth and maintenance of the network while also suiting the American ideal of individualism. By 1900 around half of all electricity produced in the US came from small, isolated units (Galvin & Yeager, 2009). However, innovations in alternating current and three phase power has meant that the 20th century grids around the world were built on a national scale rather than locally. So if the microgrid concept is to return to prominence and remain there must be new systems in place to compliment it such as microgrid energy trading.

There are a number of reasons why Edison's dream did not materialise. Some were business related but others were to do with technology. Firstly, the generators available at the time were inefficient on a small scale compared to centralised power stations. Property owners did not like having noisy, work intensive, combustion-based generators when a silent wire from an off-site power station could provide the electricity more cheaply and with more security of supply. Also, the technology to monitor and regulate supply and demand was not available (Galvin & Yeager, 2009). In the 21st century, such technology does exist and generators are more passive devices. Moreover, microgrid energy trading could offer cheap security of supply, which this report shall investigate.

20th century grid structures are now struggling to cope and adapt to changes in the 21st century. Consumption of electrical energy continues to rise globally. In the UK, the difference between expected power supply and peak demand at Christmas is lower every year making worries of power outages become an ever more realistic threat (Sean Farrell, 2014). In the US in 2013, the national grid failed to maintain power for the Superbowl, the largest sporting event in the world, as a power outage stopped play for over 20 minutes in front of the eyes of the world (Pengelly, 2013). To make the challenge even greater, the low carbon movement means that the answer cannot be to build more fossil fuel power stations. Renewable energy, however, is not as dispatchable as other 'traditional' sources of power. There are problems with supply when the sun doesn't shine and the wind doesn't blow. Also, a coal, gas or nuclear power station can be placed wherever it is needed on the existing grid. Renewables are not so simple to integrate. The UK, renowned for its abundant wind resources, finds that this resource is located in the west of Scotland, protected national parks, and in offshore sites where there is little to no infrastructure capable of transporting the energy generated to where it is used. In Scotland, the Beauly-Deeny Line, approved in 2010 for £4.7bn., was a controversial but vital project connecting areas rich in wind and tidal power with the Central Belt.

The UK based 'Customer-Led Network Revolution' (CLNR) claims that to update our current grid in its current form would be too costly: 'We are left with a choice of; do we re-wire the UK, re-wire the grid, the overhead lines… at hundreds and hundreds of billions of pounds cost to us all. Or do we try to come up with a smarter grid, where we sweat the assets, make them work harder for us and use that legacy infrastructure and still enable the low-carbon transition' - Professor Philip Taylor, Academic Lead CLNR, Durham University (Consumer-Led Network Revolution, 2012). With the other alternative being microgrid energy systems, trading could make this alternative more viable.

Renewable Energy sources may represent a challenge to the existing grid in trying to supply thousands of homes from a small number of high output sites. However, they may represent a solution to one of the problems of the outdated Edison-style microgrids. Solar panels on a roof, for example, generate electricity during the day without significantly disrupting the property owner or users' lives. Small scale wind power generators, if positioned correctly, can also be non-intrusive and non-disruptive to a local area. Similarly, heat pumps underneath property or grounds electronically heat the premises in a 'passive' manner and in many cases are lower in carbon emissions than a gas boiler. With the UK government bringing in the Feed-In Tariff in 2010, there is also a business incentive to make money out of micro-generation. Another problem with the current grid is that there is no real competition. The national grid is a 'regulated monopoly' where 'there is no two way discussion about what is for sale and at what price…If you want electricity, take it or leave it on the conditions of the utility' (Galvin & Yeager, 2009). Micro-generation in some ways gives power back to the consumer. However, there is much to be done to facilitate this power shift in the energy industry. Setting up a viable microgrid energy trading system is one area that could encourage the shift which will be investigated this further in this project.

Another reason for the emergence of microgrids (illustrated in figure 1) and the return of the Edison mode of thinking is the development of energy monitoring and managing technology for consumers. These developments are due, in large part, to the invention of the internet. At the forefront of this technological shift is the Smart Meter. Smart Meters give real time feedback to the user about energy usage and its cost while also providing energy companies precise energy demand data. Within the existing grid network, this will allow accurate billing for users. It will also allow the suppliers to know more definitely how much gas or coal must be burnt to meet demand, helping

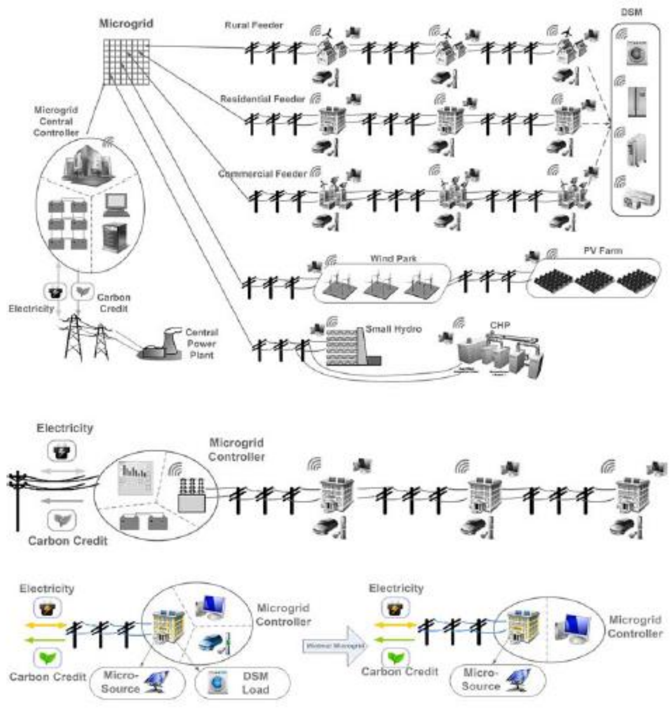


Figure 1.1 (a) Microgrid as a LV grid; (b) Microgrid as a LV feeder; (c) Microgrid as a LV house

Figure 1 Microgrid Illustration (Tao, 2014) prices and resource management. Users can also become more proactive about their energy use, switching non-essential systems off when demand and prices are high or choosing to perform certain electrical tasks when green electricity is more abundant. All these elements are useful and the UK government has set a target to roll out smart meters to every UK home by 2020 (USwitch, 2014). Moreover, the potential for smart meters within a microgrid system is even greater. Monitoring energy input and output to the national grid, managing energy storage within the microgrid, controlling electronic demand of the house by switching off or lowering output of certain household or business devices (such as lighting or air conditioning) could all be controlled using a smart meter as part of a microgrid management system (Privat, 2012). Moreover, within the context of this project, smart metering and cloud management of multiple grids offer an opportunity for energy sharing and, by adding an economic element, trade.

Figure 2 illustrates a small scale microgrid. A generator of some kind is an essential component of an electrical microgrid, whether it be photovoltaics, wind turbines, diesel generators or a combination of the above and other sources. Most definitions of a microgrid state that they must be able to act alone in a pseudo 'island mode' (Open Energy Information). The generators must be able to provide capacity to sustain the microgrid independently. Modern microgrids often feature some form of storage unit. This could involve a battery, an electric car or a hydrogen store; among others. These are charged when electricity is cheap or from a renewable source and then discharged when electricity is expensive, "dirty" or if the microgrid is cut off from the national grid. To monitor and manage the network, a control unit is installed. In modern applications, this is almost certainly a smart meter, which uses ICT to keep track of electrical loads and redistributes them effectively and efficiently. The importance of the smart meter and the network in modern microgrid thinking leads to the name 'smartgrid' being commonly used by the industry. Using that smart meter to facilitate trade will seamlessly allow for the microgrid owner to save or even make money for their energy use, which is why this report is important to investigate the viability of trade.

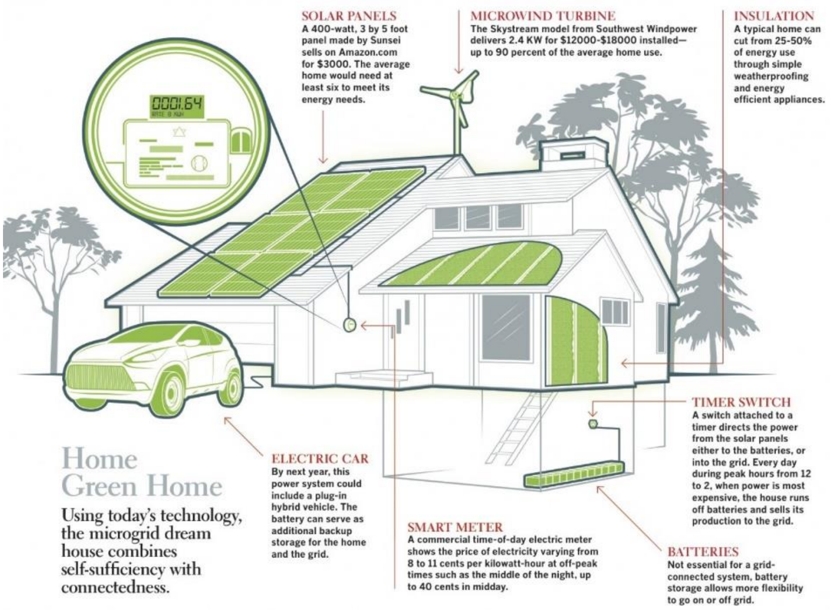


Figure 2 Example of a Single house microgrid (Fast Company, 2011)

The central idea behind the modern microgrid/smartgrid movement is simple. If we can all generate and store a little energy, and monitor, manage and communicate our energy usage with the rest of the grid, the demand on the national grid will greatly reduce. This will create a cheaper, more independent, "greener" and more abundant electricity market. The smartgrid revolution would have its drawbacks and resistance from special interests. However, smartgrids may well feature prominently in our future energy systems. This thesis will investigate a possible feature of distributed generation, microgrid energy trading, which could incentivise and increase the viability of smaller interactive power networks.

1.2 Microgrid Energy Trading Explained

Many definitions of microgrids state that they must be able to act independently in "island mode". However, microgrids need some form of reserve power source for when demand is not met by the on-site supply, especially in the case of microgrids that depend on fluctuating renewable resources. This can mean installing additional storage for when supply is not meeting demand, installing a dispatchable back-up generator or, as in most cases where available, a National Grid connection (Open Energy Information, n.d.). Conversely, microgrid owners require an outlet for excess power generated on site that isn't required within the grid itself. Simply discharging this "waste" energy will not make sense to a business or domestic property that has invested installing a generation capacity capable of meeting its demand at peak times (Galvin & Yeager, 2009).

Under the current system, microgrids import energy from the national grid when they cannot meet their own demand at the price negotiated with their energy provider. This price tends to be high, especially when considering the repayments and maintenance fees that need to be paid on the on-site installations (Ilic, Da Silva, Karnouskos, & Griersemer, 2012). When a microgrid generates a surplus of electricity, it can sell to the grid. Government policy in the UK sets a price per kilowatt hour for exporting energy to the grid that is locked in for a certain period in order to encourage cautious consumers to invest in small scale renewables (Galvin & Yeager, 2009). However, larger grids and non-renewable grids will find that export fees need to be negotiated privately with the grid. The problem is that the earnings from exporting energy are low because of a number of factors. Firstly, the process of reversing the national grid to accept energy from the low voltage network to the high voltage network is technically and logistically difficult at this moment (Ali, 2009). Secondly, there are technical issues such as harmonics and power factor to be considered when integrating the small scale energy with the national grid. Ultimately, it is not in the interests of the power companies to accept outside party’s sporadic, small, unpredictably quantified and technically challenging to integrate energy (Tao, 2014).

One solution to this is the possibility of energy trading between groups of local microgrids. If a group of microgrids pooled their surplus energy and made it available for other microgrids within the group to purchase at times of deficit, a trade price could be negotiated among the group that was better than national prices. Take an example of two microgrids, microgrid A is in deficit and microgrid B is in surplus. Rather than microgrid A buying from the grid for 10 pence/kWh and microgrid B selling to the grid for 3 pence/kWh they could agree to trade amongst one another for 7 pence/kWh, creating a better deal for both microgrids (Ali, 2009).

It is important to recognise that the possibilities are not limited to electricity trade, heat energy can also be exchanged in a similar fashion. A microgrid that generates heat can also trade its surplus to another local microgrid that is in deficit and would otherwise need to buy gas from the national gas network at a greater price than offered locally.

The benefits to such a system, if viable, are many. Firstly, a viable trading system would encourage diversity of supply. Diversity leads to security when it comes to energy both on a macro and micro level (MacKay, 2009). Such diversity cannot be achieved by singular microgrids in most cases as they do not have the space or resources to invest in multiple generators. In the context of multi-microgrid group looking to trade energy, different members of the group are incentivised to install different generation sources in order to benefit during trading. Table 1 shows the diversity of the UK national grid supply, this should be replicated on a micro level for trade to be truly successful.

Electricity Source	**TWh generated in 2013**
Coal	129.4
Nuclear	70.6
Gas	95.7
Total Renewables	*52.8*
Wind (onshore+off)	27.4
Hydro	4.7
Solar PV	2
Bioenergy (inc. co-firing)	18.7

Table 1 – UK national generation showing diversity of supply needed in microgrids (Department of Energy & Climate Change, 2014)

If all microgrids in an area use photovoltaics, the energy available in the pool when a microgrid is in deficit is likely to be negligible. However, through a diverse local energy generation pool, microgrids that have invested in solar energy can buy from wind energy or biomass based microgrids when solar resources are minimal, and vice-versa.

Combustion based energy sources such as Biomass CHP units also become more viable. Currently, biomass boilers only run well at their intended capacity (YouGen, 2014), with losses in efficiency if the output is adjusted to match the demand at a given time. In a microgrid trading circumstance the generator could run at capacity more often and contribute the excess to the pool for other grids to purchase.

One of the other potential benefits of pooling microgrid energy is that it may well improve the national grids feed in tariffs. By sending the surplus energy still available after local trading to the national grid, there is a greater chance the energy will be a useful contribution to the national grid. This is better than the grid receiving a relatively small amount of energy from here and there and therefore may lead to an increased feed-in tariff. Also the contributors to a pool may benefit from collective bargaining with the national grid, who may in turn wish to improve its pricing to lure microgrids away from local pools to increase its own customer base. Conversely it is possible that the national grid will make feed in tariffs unavailable to energy pools and increase the cost of energy when the microgrid pool does not meet its member's demands, or enforce a tax for using the low voltage network as a distribution network.

These possible permutations are speculative and will not be investigated further in this report, which is designed to focus on the viability of trading itself. However, it is important to realise the potential outcomes of creating a viable microgrid trading framework.

There is a limited amount of research into microgrid energy trading as it is a small and new field within the energy sector, much of the research related to it has been written within the past few years. The next section will review the existing research before defining the objectives and scope of the project.

1.3 Summary of Microgrid Energy Trading Research

Microgrid energy trading could be of great benefit in improving the economic viability and the balance of energy supply for consumers. It is highlighted that energy trading does exist already on the macro level between international transmission operators and international system operators so the creation of a smaller scale mechanism for energy trading is possible and beneficial (Luo, Satoko, Shin, & Davis, 2014).

There are two schools of thought with regards to the framework for microgrid energy trading: Peer to Peer and Intermediary/Centralised. "The centralised approach requires all information about energy generation and transportation costs to be available at the central controller" (Matamoros, Gregoratti, & Dohler, 2012). Matamoros et al. argue that this centralised approach is likely to be the best but only if privacy is not a concern. In a circumstance where a group of microgrids are operated by a single energy operator privacy is unlikely to be a problem however with multiple operators for each microgrid information may not be forthcoming. Luo et al. cite Keio University's solution of the Energy Virtual Network Operator (ENVO) as an example of a centralised controller. ENVO communicates with local microgrids and manages generation and demand information and makes collective schedules for Household Energy Management Systems. However, ENVO is redundant for energy trading without a delivery mechanism and energy storage devices (Luo, Satoko, Shin, & Davis, 2014). This is largely due to the fact ENVO is designed to shared resources rather than trade them using scheduling and predictive methods instead of reactive methods that look at the surplus/deficit values in real time (Tazoe, Matsumoto, Ishi, Okamoto, & Yamanaka, 2012).

Gregoratti and Matamoros highlight difficulties in power flow. The advantage of a centralised system of energy trading is that voltage control can be coordinated or solved using Newton-like descend methods at the expense of scalability and privacy (Gregoratti & Matamous, 2015). The problems of power flow are in general too complex to calculate an optimal solution and therefore suboptimal management solutions are often adopted, even where these methods approximate optimal solutions with high precision, loses are inevitable (Gregoratti & Matamous, 2015).

Many in the field believe that, at least until a framework can be established and the benefits made clear, peer to peer (or prosumer to prosumer (Cui, Wang, Nazarian, & Pedram, 2014)) is the preferable mechanism for trade. In this system, each microgrid would announce its surplus or deficit to the group and one of the other grids would sell or loan energy to that grid. In this way a minimal amount of information is shared between microgrids and each grid remains more independent (Luo, Satoko, Shin, & Davis, 2014). Issues of power flow can be addressed on a case by case basis rather than trying to maintain all local microgrids at a similar level (Gregoratti & Matamous, 2015). Gregoratti and Matamous go further by suggesting an algorithm that iterates energy requirements and cost until agreement is made between microgrids about the amount of energy that will be exchanged an the price it will cost to exchange it. This iterative process, it is argued, further protects a microgrid’s critical information.

In terms of the conclusions of the literature, the notion that microgrid energy trading, if established, will be a positive thing is universally agreed upon. However, there are differences in approach to coming to this deduction. Ideally, collective trading would be the most effective way to start an economically viable method to trade energy. With privacy concerns and scalability issues present in these intermediary-based approaches there has been research into peer-to-peer trading, which is acknowledged as a sub-prime solution. However, the economic viability of peer-to-peer trading converges on that of collective trading after a significant number of iterations over time (Gregoratti & Matamous, 2015).

The economic challenges of microgrid energy trading logistically are needed to be tackled just as much as the technical (Ilic, Da Silva, Karnouskos, & Griersemer, 2012). One suggestion is to have a stock market style approach. Where microgrids monitor energy prices in the market using collective smart metering and use predetermined maximum buy/minimum sell values to evaluate when to sell. This approach has its downsides, firstly the real world stock market has large input from the end user. In order to automate this system a highly complex model would need to be established with frequent, accurate and precise data collection about market conditions are needed which raises the cost of implementation (Ilic, Da Silva, Karnouskos, & Griersemer, 2012). Using set pre-negotiated prices for energy is the cheapest and simplest way to implement an economic model for energy trading. This system can mean that microgrids pay over or under the true market value of the energy they are trading. However, so long as the pre-negotiated price covers the levelised cost that takes into account generation cost, storage cost, and transfer cost, maintenance etc. and achieves at least, or undercuts, grid-parity with the costs of national grid electricity import (Luo, Satoko, Shin, & Davis, 2014) then the economics of microgrid energy trading are sound.

With the field of microgrid energy trading being so young there is much opportunity for improvement in the body of research available. The objectives of this thesis can now be defined.

1.4 Objectives

The biggest obstacle to microgrid energy trading research is that, with a few exceptions, microgrids do not exist. Therefore there is not the potential to conduct experiments one would wish to conduct in the real world to test the microgrid trading theory. This leaves two options, mathematical and computational modelling. Having evaluated literature on this topic, it is apparent that the theoretical trading mechanisms and the basic economic viability of microgrid energy trading have been investigated in detail. However, there is a lack of software available that can simulate energy trading with multiple degrees of freedom and realism for the user to experiment with. Therefore, it is the objective of this project to develop software that captures the essence of a real world trading environment for the purpose of simulation and investigation. The aim of this software would be to simulate a real world scenario of a single low voltage network with a group of microgrids within it that are able to trade.

The software will be able to explore the factors that make trading viable, such as diversity of supply, number of microgrids and the variability of the sizes of microgrids in an area. It should also investigate policies that may affect trade; such as a day-night price plan or demand management. It should then also be able to simulate the effects of factors that will inhibit trade, such as mismatched power factors, equipment failure or renewable intermittence.

The results produced by the simulator should allow the user to gain insight into the economic effectiveness of trading as well as evaluate the energy savings both for the national grid and for energy wastage from the microgrid pool.

To summarise, the objectives of this project are.

- To develop a software model of a microgrid energy trading environment.

- To investigate what factors affect energy trading positively and negatively, and to what extent?

- To make conclusions about the viability of microgrid energy trading and the circumstances under which it could be implemented.

1.5 Method

The method for this project is based on computational modelling. Whilst researching microgrid energy trading one can find source code available for download on the University of Strathclyde's ESRU website. The code is for a microgrid energy trading software package called MGET-SIM and was originally developed by Sheik Muhammed Ali in 2009 in conjunction with his paper on microgrid energy trading (Ali, 2009). The capabilities of the software and its operation are described in chapter 2. MGET-SIM software is written in C and the source code will be adapted and added to in order to feed in more user options and assess the potential effects of factors in microgrid trading. The program simulates trading over 24 hours based on user data inputs and exports relevant data to a text file for analysis.

The success or failure of the simulations will be judged on the technical and economic performance of each virtual trading set up. Successful trading will use as much of the energy contributed to the pool. Therefore a minimum of energy wasted is the ideal circumstances. Trading will also be deemed successful if the national grid is relieved of load. In the current framework 100% of energy transactions will involve grid import, if trading reduces this percentage it will be a large benefit for the national energy market. From the perspective of the individual microgrids, subscription to a trading scheme will be worthwhile if their energy bill is less than it would have been originally. Approaches to measuring these metrics are discussed later in this report.

1.5.1 Scope & Assumptions

There are many issues surrounding microgrid energy trading that will not be investigated during this project. Assumptions made during the creation of the simulation are all within the realms of possibility if not probability.

Firstly, it is assumed that the delivery network for electricity trading is the national grid. The creation of a new set of power networks around the country would be not only expensive but also needless when the national grid could be adapted with various controls and protections. The grid was not created to accept multi directional power flow however but there is already a large body of research and real-world examples of adaptations being made. Most of the problems with bi-directional flow are based in the substation where the energy is stepped-up to a higher network. An advantage of trade is that it occurs over a single low voltage network, avoiding these issues. Using the national grid will ensure security of supply when a microgrid pool cannot satisfy demand and makes exporting surplus energy easier.

It is assumed that a smart network can be established at device level, to microgrid level and to central control level. This is not a significant assumption as developments in smart metering, cloud computing and Internet of Things suggest that such a control network could be easily implemented.

Despite concerns about privacy explained in the literature review, it is assumed that a centralised control system will be used, instead of peer to peer. If the logistics of such a system can be ironed out, it has been proven in comparative studies to produce optimal technical results (Matamoros, Gregoratti, & Dohler, 2012). The objective of this project is to further the work that confirms the viability of microgrid energy trading on a technical and economic standpoint, privacy concerns are therefore not within the scope. The centralised control will have the ability to synchronously timestamp all microgrid devices and data within the pool contributors. This is the only way to guarantee fair trading among the microgrids at any given time. Again, timestamp synchronisation is an established practice by energy providers and could technically be easy to implement across multiple independent networks so long as privacy concerns are put to one side.

Some of the factors that will affect the results such as losses due to distance are difficult to simulate accurately. One could undertake an entire project creating a simulator for wire loses during microgrid trading due to distance. This is outside of the scope of this project. The code written to represent some of the factors being tested in this project capture the essence of the effects that these factors will have on the viability of microgrid energy trading.

Finally, it is assumed that the economic indicators of levelised cost and grid parity are guaranteed as satisfactory (see (Luo, Satoko, Shin, & Davis, 2014)). In other words, the cost of microgrid energy trading must be less than that of importing from the national grid. It is assumed within the MGTrader software that the energy trade prices, both at microgrid and national grid level, are constant for at least 24 hours. There is a night and day price plan that can change this per hour, which will be discussed later. Regardless of this option, the economic side of the simulation is not dynamic as in Ilic et al's work in that energy price does not adapt to demand. There is advantage in this simplification, namely if bidding were possible among the pool contributors the larger microgrids would be able to exploit the system, buying electricity when cheap and storing it before re-releasing energy when demand is high. In this circumstance smaller microgrids would be at the economic mercy of the larger microgrids which decreases is desirability and therefore its viability. The process of bidding and counter-bidding also wastes time and therefore energy; although an intelligent system of software and rules could in theory reduce this wastage it is not within the scope of this project to create this framework. The MGTrader software instead chooses a single random microgrid at a time and assesses if trade is possible with the pool to meet any deficit that microgrid has, this process is repeated until the pool is exhausted or all demands are met for that time step.

2 Chapter Two: Software Development

Chapter one looked introduced the subject area and objectives of this project. It identified the need for the development of software. This chapter explains the development process, introducing the open source MGET-SIM software and explaining the changes made to it for this project in order to create MGTrader.

2.1 MGET-SIM Introduction

MGET-SIM was first developed in 2009. Its purpose is to simulate microgrid energy trading so that the user can make conclusions about the viability of such a system in the real world. The software is designed to be able to simulate both electrical and heat trading (Ali, 2009), one simply needs to consider the relevant factors and remove those that are not relevant. For example, power factor is not relevant in heat trade so the user need only state that power factor should not be considered in a simulation.

The source code for MGET-SIM is available for download at esru.strath.ac.uk/ along with a readme file. The software when downloaded already allowed the investigation of the following factors (Ali, 2009):

- Effect of the number of microgrids in a system (up to 1000)
- Effects of variability in microgrid sizes (capacities and demands)
- Effect of equipment failure being possible
- Effect of renewable energy intermittence
- Effect of separate price plans for peak/off-peak timings

The code and readme are available in Appendix 2 of this document. The basic operation of the program is as follows: The user is asked to provide a text file called mg1.txt, this file contains 48 tab-separated numbers, with each pair of values representing the generation and demand data for a microgrid, for a given hour. MGET-SIM then asks the user to input each variable one by one, how many microgrids are to be simulated? Should intermittence be considered? etc.

Once the software has all the information it needs from the user, it generates N "dummy microgrids" based on the seed data provided by mg1.txt and factors in the chances of failure, intermittence etc. depending on the programme inputs. The simulation then begins with any surplus energy added to the pool and any deficits are recorded as such. Once all the microgrid surpluses/deficits have been analysed trading begins.

A microgrid in deficit is selected randomly for trade. This random selection process is the best way to ensure fairness during trading compared to a bidding process or having a set order, as discussed earlier in this report. If the deficit can be met by the energy in the pool, the microgrid is able to match its demand using the pool by paying the defined pool trade price. If the deficit of the microgrid cannot be met, it must be met by importing from the national grid at the defined import price. It is not possible for a grid to use the pool to meet the majority of its deficit and “top up” using the grid, this is once again due to fairness.

Once all the deficits are rectified, the pool is reset to 0 kWh and the process is repeated for the next time step. Once the 24 time steps are complete a summary of trading is exported to a results text file in the program folder for analysis.

For further information on the original MGET-SIM program and its development, please refer yourself to Sheikh Muhammed Ali’s paper on this topic. Please find details of this paper listed in the references of this paper.

MGET-SIM does a good job at simulating the basics of microgrid energy trading and offers the user some freedom to add or negate factors during the simulation. However, there is room for improvement in MGTrader, by making some superficial changes to the source code in order to make the softer easier to use. Once this is complete, more factors can be added to the simulation for consideration. The new Software, MGTrader will encapsulate these changes.

2.2 Development Process

2.2.1 Changes to how the original MGET-SIM works

To streamline the simulation process, changes are made to the options input. Rather than have the program ask you a series of questions to answer one at a time. The program is changed so that the user is required to state the name of an options file at the outset. MGTrader will then read the file and extract the user’s options, summarise them on screen before carrying out the simulation. The results for the simulation are then exported to a results file called ‘out*optionsfilename*.txt’ instead of a file called results.txt. The advantage of this system is that it means the user can carry out multiple back-to-back simulations in less time without overwriting previous results.

To make the process of analysing the results data from simulations faster, a second results file is created to store just the information relevant to calculating the metrics for success listed in section 1.4.

2.2.2 Diversity of Supply

When running MGET-SIM multiple times one realises that the results of the simulations are greatly influenced by the nature of the input data in mg1.txt. If the seed microgrid had mostly a surplus of energy each hour then, in general, most of the dummy grids will also have surplus and trading is economically viable, if wasteful. If the seed data has mostly deficits each hour then, in general, most of the dummy microgrids will be in deficit and trading was economically less viable and very few deficits are met by what little was in the pool. The results are sensitive to changes in the seed data that a need to improve the programme was identified for MGTrader. To minimise this effect, demand data is taken from a database of valid demand and generation data within the program MERIT (a programme developed by the University of Strathclyde and used in industry and academia as a reliable source). Using this data increases the reliability of the input data and therefore the results become more likely.

Secondly, MGTrader's code allows for three input files to be used instead of one. This has multiple advantages; namely that the user can input three unique grid profiles to represent different technologies, e.g. wind powered office, solar powered university, CHP powered block of flats. This can be used to illustrate the importance of diversity of supply (and demand) in a local area for microgrid trading to be successful.

To integrate this change, the way in which dummy microgrids are created has been adjusted. Originally, MGET-SIM created random data sets by multiplying the numbers in the seed file by numbers dependant on the variability selected by the user. In order to investigate the effect of diversity of supply and demand profiles, the shape of each demand and supply curve in the seed files must be maintained within MGTrader. Therefore, for each microgrid created, 24 generation values and 24 demand values are created within the same scale by multiplying the seed data by a single number. Then, variability is incorporated by adding or subtracting a percentage of that value. For example, microgrid x is 6 times larger than seed microgrid 1. However at hour h microgrid x has 25% more demand than 6 times the value for seed microgrid 1 and 10% less supply. Within the program for this project, seed file 2 is assigned as a microgrid with constant output (e.g. CHP), so any dummy microgrid's supply profiles based on seed file 2 are simply scalars of that data.

2.2.3 Storage

One of MGET-SIM's shortcomings was its lack of storage considerations. Storage is a hugely important part of any microgrid system and would be just as important in a trading scenario and therefore is included in MGTrader. There are two approaches to storage in microgrid trading, collective storage and individual microgrid storage. In collective storage, the centralised system would have access to and control over energy storage for the pool that is paid for and maintained by the contributors to it. This storage could be housed in a neutral location or within the premises of one or more of the microgrid pool's contributors. This could greatly reduce energy wasted at the end of each time step as it can be carried over to the next using the storage.

The second approach to storage is that each contributor to the pool has independent control over their own storage. This would mean that microgrids could keep a private reserve for when they are in deficit, this would lead to less contributions to the pool but also less requirement to access it. This approach could be used by microgrids with larger capacities of storage to exploit the market. If the pool is near empty and demand for energy from it is high, a contributor with a large amount of stored energy (that it may never have intended to use) could release this energy into the pool and make a profit out of the other contributors. Although this is perhaps not in the idealised spirit of microgrid energy trading it would be an acceptable and savvy business move if the storage capacity could be bought at a reasonable rate.

This project looks at centralised storage only. This is because individual storage is unlikely to affect the end results of trading, perhaps only the scale of the results. All the program needs to know is whether a grid is a pool contributor or a pool dependant during each given time step. Whether or not each microgrid has or does not have a private storage facility does not have a bearing on the trading process from the simulators point of view.

By using centralised storage the simulator needs to know from the user what the capacity of the shared storage is and how much energy is stored at hour zero. Therefore the user is asked for a storage capacity in kWh (which can be zero) file and then the desired initial stored energy at hour zero. Both these inputs are to be stated in the options file.

The effect this has is that rather than the energy pool being reset to zero at the end of each time step, some energy can be carried forward to the next. This should reduce the amount of energy wasted, one of the key metrics for microgrid energy trading success. It should also increase the likelihood of trade being possible because as was explained earlier, trade does not take place if the pool cannot meet a grid's entire deficit. Storage will create a larger pool to improve the chance of trade being possible.

2.2.4 Demand Management

One of the major problems with demand-supply matching with renewable resources is the non-dispatchable nature of technologies such as wind or solar power. Traditionally, if demand is high then reserve gas turbines are activated or the output of fossil fuel power stations are increased until supply matches this demand (MacKay, 2009). In renewable energy, there is little that can be done if demand exceeds supply other than import from a foreign source, tap into storage reserves or build a large extra capacity of generators. The framework for all these options are expensive to set up and the results are likely inferior to dispatchable fossil fuel generation.

One novel solution that smart grid technology offers is the ability to manage the demand side of the energy equation. Using grid data, non-vital systems can be switched off remotely in order to reduce the demand and relieve stress of the grid. This already starting to become a growing industry with companies such as Kiwi Power offering demand management services to large organisations in London (Kiwi Power, 2015).

The user of MGTrader is given the option to simulate the effects of demand management in a system. If this option is selected then there is a small chance that the demand of a microgrid will be reduced by 25% and a smaller chance of a 75% reduction. This mechanism could be used by the national grid if it wants to reduce the chance of pool members requesting and import of energy by increasing the size of the pool. The addition of demand management to MGTrader will add another element of smart grid systems and could show the advantage of microgrid energy trading not just locally but nationally also.

2.2.5 Distance

Distance between microgrids does have an effect on the success of energy trading. In heating terms the reason behind this phenomenon is clear, pumping heat as hot water along pipes will result in losses during transmission through conduction in the pipe walls. In electricity this is also true, microgrid energy trading pools are likely to comprise of microgrids within the same low voltage network as trading electricity in different networks creates a high degree of complexity on the part of the national grid. In electronic transmission, higher voltages reduce losses. If two microgrids within the same low voltage network traded over a long distance, the resistance in the wire over that distance would cause high $P = I^2R$ losses in the line.

There is an entire science to power losses in cables and/or heat losses in pipes. It is outside the scope of this investigation into microgrid trading to create an accurate model of such effects. To capture the effect of distance related issues, MGTrader categorises energy transactions into three groups. The first group can trade as normal as the transaction is completed over a short distance. The second group is deemed close enough to trade but at a loss of 50% energy. This is a large loss, but is particularly believable in heat trade. If a user of the MGTrader does not believe this is realistic they can make a simply make an edit to the source code to reduce or increase the losses incurred by trading over this distance. The final group is deemed too far for transaction and therefor exchange cannot occur and grid import is undertaken instead. This is illustrated in Figure 3 below.

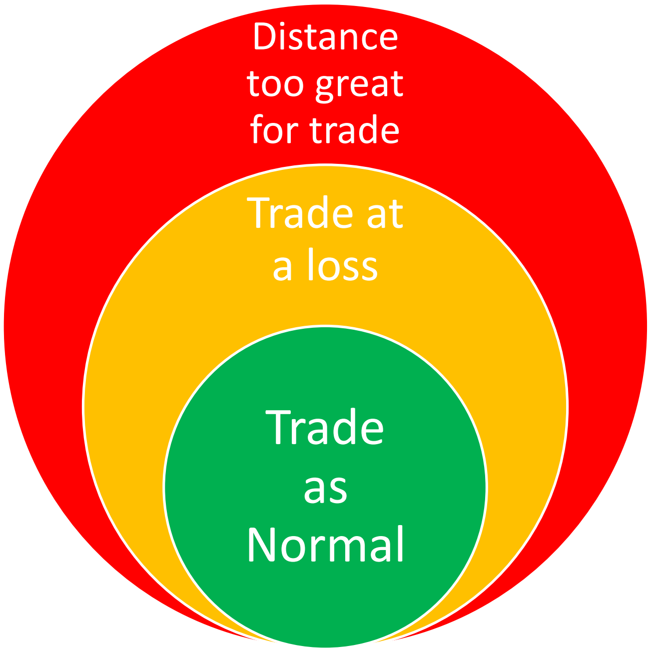


Figure 3 - Graphic representation of MGET-SIM's distance categorisation

Distance considerations may affect the results of each simulation negatively but it will increase the reliability of the end results. If microgrid energy trading remains viable despite this hindrance the case for its establishment in the real world becomes all the stronger.

2.2.6 <u>Power Factor</u>

One hindrance to the viability of multiple microgrids trading electricity is the fact they are all likely to have different power factors. Power factor relates to the size of capacitor bank within a premises and is the ratio of real and apparent power in a circuit. Consumers with power factors less than 1.0 require a higher draw for power from the grid than is actually needed in order to meet demand. This leads to losses in the circuit (de Kock & Strauss, 2004). Domestic appliances now have strict regulations about power factor. For example, new computers are directed by 'Energy Star' criteria to run at a power factor of at least 0.9 during operation (Energy Star, 2015). Some commercial properties do not run at a 1.0 power factor or less and are charged extra by the national grid for doing so.

The MGTrader software simulates power factor considerations in a similar way to distance, by categorising transactions into groups, as illustrated in figure 4. Group 1 assumes that power factors are running at an acceptable level (i.e. ~1.0) and therefore trade can go ahead as normal. This case is the most common outcome. Group 2 assumes that the power factor for the microgrid requesting energy from the pool is less than satisfactory and therefore 25% loses in electricity are recorded during the transaction. No values is attached to this categorisation but for descriptive purposes it could mean a power factor of 0.8 for example. Finally a small selection of transactions are categorised as involving a microgrid with an unacceptable power factor (0.7 say), this transaction is therefore blocked and the grid in question must import from the grid.

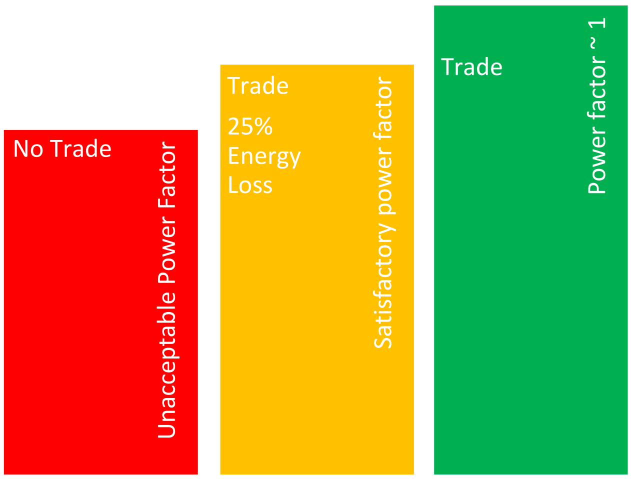


Figure 4 - Graphic Representation of power factor categorisation in MGET-SIM

Like Distance, there is an entire scientific field dedicated to calculating losses due to power factor. Representing this in MGTrader is not within the scope of this project, which aims to capture the essence of power factor losses for trading simulation.

2.3 How MGTrader Works

MGTrader has a number of changes to the way it operates compared to the description in section 2.1. Like before, the user is required to supply data for a seed generation and demand data. However, three such files are now required: mg1.txt, mg2.txt & mg3.txt. Figure 5 shows an example of one such file.

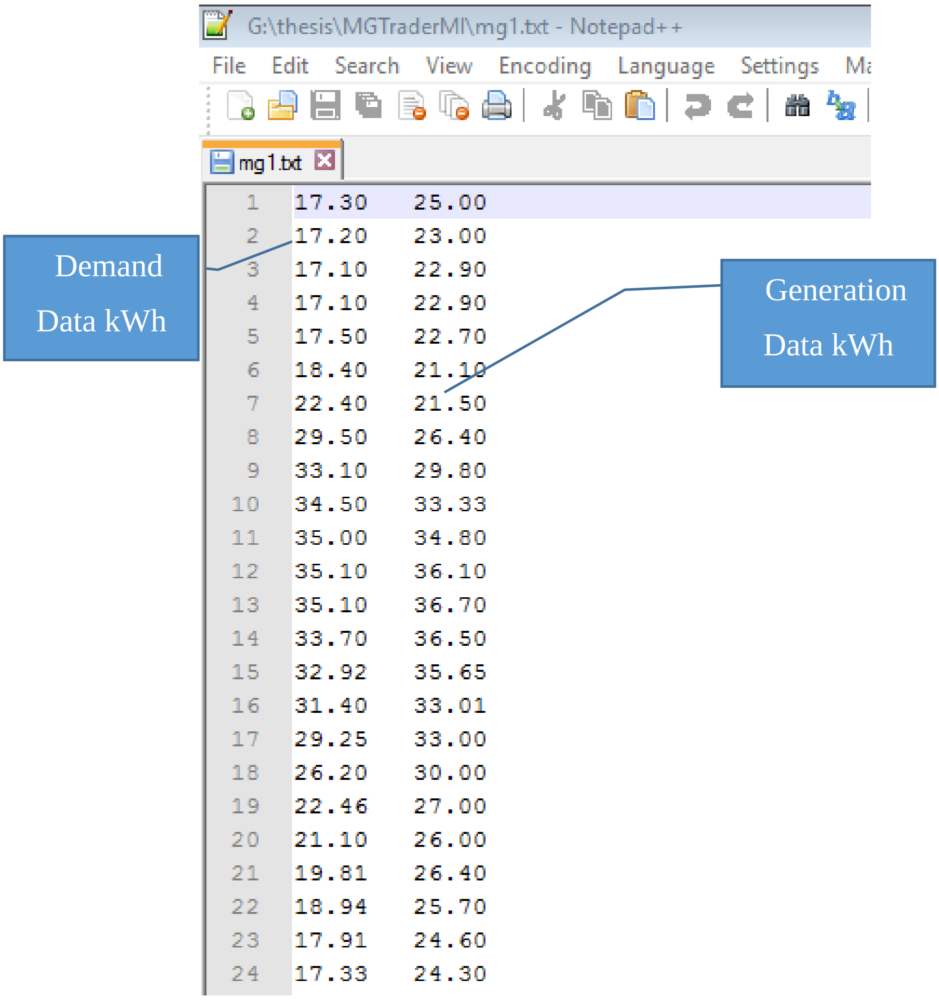


Figure 5 - Example of seed data

One of the other significant changes to the basic operation from MGET-SIM is the way in which options are inputted into MGtrader. Whereas previously MGET-SIM requested information from the user and read the keyboard input, MGTrader allows the user can record all their options in a file which the program will read, speeding up the process of setting up simulations greatly.

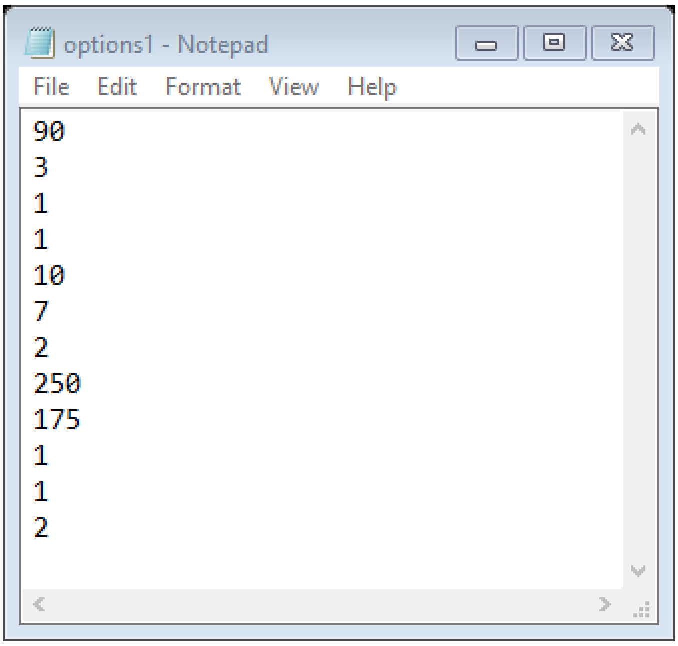


Figure 6 - Example of an options file

For example, figure 6 above tells MGTrader to create 90 microgrids (NB: three of which are already been defined by the user) with high variability in sizes. Equipment failure and renewable intermittence are both considered. The price of national grid energy is 10pence/kWh and the price of microgrid pool energy is 7pence/kWh. There is no peak/off peak price plan. The pool has 250kWh of energy storage, 175kWh is filled at the start of simulation. Demand management and distance are considered while power factor is not. A readme of the MGTrader's new operation is available in appendix 1.

The operation of MGTrader is explained in the flow diagram on the next two pages in figures 7 and 8. The main program decision procedure is represented in blue. Green boxes represent user inputs. Yellow represents the random number generation process and purple represents an outcome.

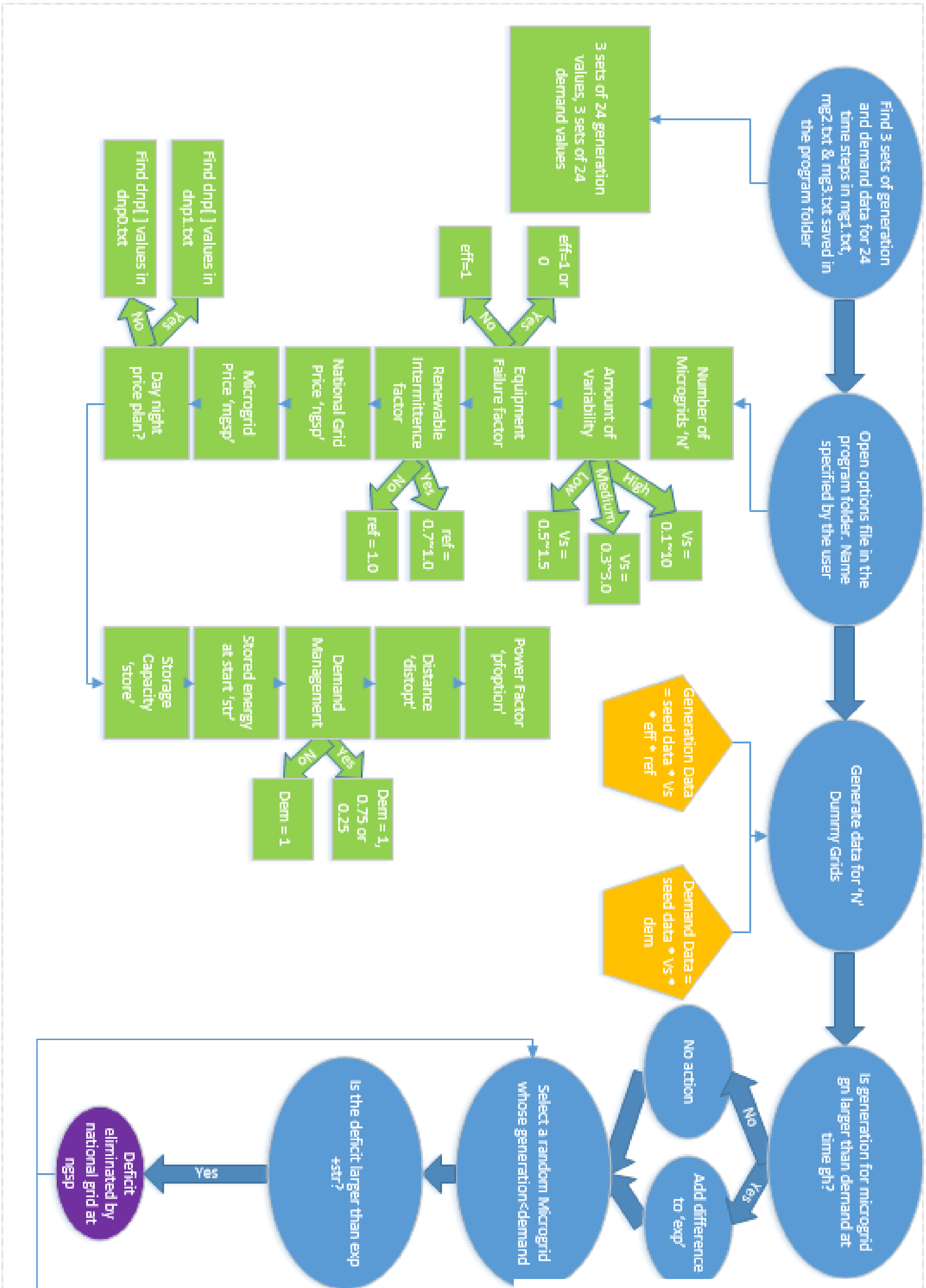


Figure 7 – MGTraderProcess diagram

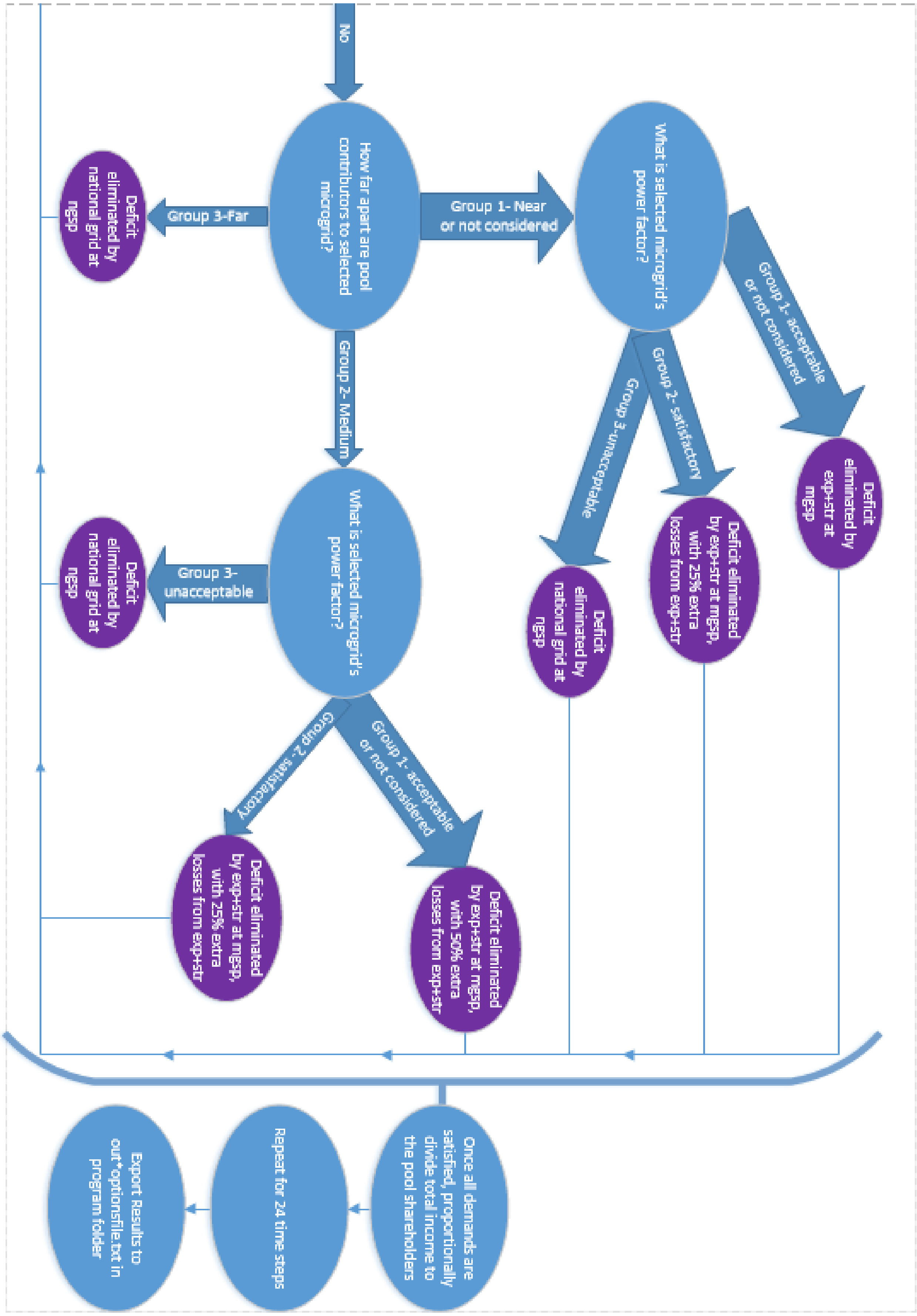
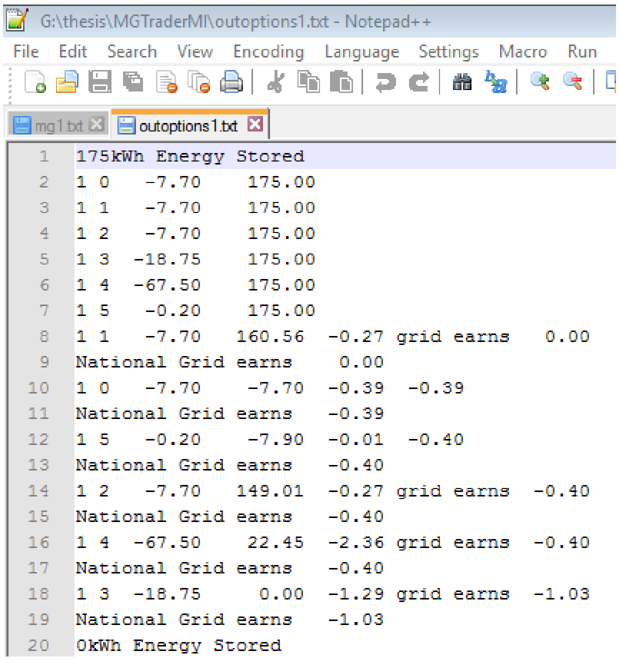


Figure 8 - MGTrader Process diagram cont.

The results file is now no longer a generic results.txt file, MGTrader creates a results file specific to the options file used. The results file, pictured in figure 9, lists information regarding:

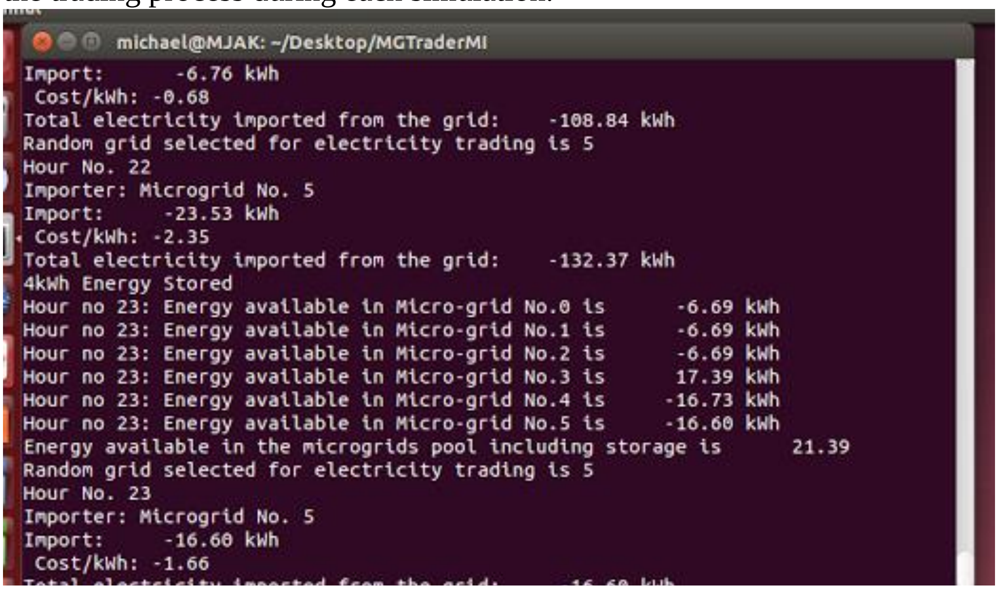
- The amount of energy trading carried out per hour
- The amount of energy left over in the pool at the end of trading
- The number of demands satisfied by the pool and the costs attached




```
175kWh Energy Stored
1 0   -7.70    175.00
1 1   -7.70    175.00
1 2   -7.70    175.00
1 3  -18.75    175.00
1 4  -67.50    175.00
1 5   -0.20    175.00
1 1   -7.70   160.56  -0.27 grid earns   0.00
National Grid earns    0.00
1 0   -7.70    -7.70  -0.39  -0.39
National Grid earns   -0.39
1 5   -0.20    -7.90  -0.01  -0.40
National Grid earns   -0.40
1 2   -7.70   149.01  -0.27 grid earns  -0.40
National Grid earns   -0.40
1 4  -67.50    22.45  -2.36 grid earns  -0.40
National Grid earns   -0.40
1 3  -18.75     0.00  -1.29 grid earns  -1.03
National Grid earns   -1.03
0kWh Energy Stored
```

Figure 9 - Example of a Results File

There is also information available in programme (figure 10) that can add extra insight into the trading process during each simulation.




```
Import:       -6.76 kWh
 Cost/kWh: -0.68
Total electricity imported from the grid:    -108.84 kWh
Random grid selected for electricity trading is 5
Hour No. 22
Importer: Microgrid No. 5
Import:      -23.53 kWh
 Cost/kWh: -2.35
Total electricity imported from the grid:    -132.37 kWh
4kWh Energy Stored
Hour no 23: Energy available in Micro-grid No.0 is      -6.69 kWh
Hour no 23: Energy available in Micro-grid No.1 is      -6.69 kWh
Hour no 23: Energy available in Micro-grid No.2 is      -6.69 kWh
Hour no 23: Energy available in Micro-grid No.3 is      17.39 kWh
Hour no 23: Energy available in Micro-grid No.4 is     -16.73 kWh
Hour no 23: Energy available in Micro-grid No.5 is     -16.60 kWh
Energy available in the micrograds pool including storage is      21.39
Random grid selected for electricity trading is 5
Hour No. 23
Importer: Microgrid No. 5
Import:      -16.60 kWh
 Cost/kWh: -1.66
```

Figure 10 - In program information on Trade Process

2.4 Measures for Success

As discussed in chapter one, success must be judged on a technical energy and economic basis. Using MGTrader’s output, the following calculations are used to measure the success of each microgrid energy trading simulation.

2.4.1 Energy wasted

$$\begin{matrix} Energy\ wasted \\ in\ the\ pool\ (\%) \end{matrix} = \left(\frac{Energy\ not\ used\ in\ the\ pool}{Energy\ added\ to\ the\ pool}\right) \times 100$$

This is a simple equation to measure what factors increase the amount of energy consumed by a group of microgrids. The less energy is wasted the better as it means more income for all the parties involved. Microgrids running on non-renewable energy forms do not want to waste energy as it also wastes an expensive and environmentally unfriendly resource. Even biofuel wastage is undesirable as it wastes an expensive resource that takes time to regrow.

2.4.2 Total import from the grid

$$\begin{matrix} Energy\ import\ from \\ the\ national\ grid\ (\%) \end{matrix} = \left(\frac{Total\ import\ from\ national\ grid}{Total\ Energy\ Consumed}\right) \times 100$$

As Energy demand grows, the national grid is under increasing strain to meet the demands of the public and industry. The microgrid concept is fundamentally a solution to this problem that does not involve huge engineering projects to build power stations to replace the current generation, whether they be in remote areas with renewable resources or not. Therefore, it is importable that the viability of a microgrid trading system be measured in how much demand on the national grid is relieved by the presence of the system.

2.4.3 Microgrid 0’s costs

$$\begin{matrix} Seed\ Grid \\ Costs(\%) \end{matrix} = \left(1 - \frac{expenditure\ (No\ Trade) - expenditure(With\ Trade)}{expenidture(No\ Trade)}\right) \times 100$$

This metric assesses the seed microgrid’s economic performance. It compares the expenditure on energy that the microgrid had to make before a trading framework was established as compared to after trading has begun. A negative number is possible in a circumstance where the microgrid makes a profit from its generation. For example, if the seed microgrid paid £20 for its energy before trading was established but only had to pay £8 on the same day in a world where trading was available; this would mean that the seed grid's costs would go from -100% to -40%, if the grid made £2 from trading this would give a result of +10%.

2.5 Software Validation

The re-worked and developed MGTrader must be validated. There are challenges in doing so. Many of the factors within the simulation are calculated randomly or with elements of randomness within their formulation. Also, with there being no other known like-for-like software in the world available to compare results with, not to mention the lack of real world microgrids or small scale energy trading mechanisms, it is impossible the verify the results of MGTrader in a way one would hope to be able to during software development. However, three methods will be adopted to prove as far as possible that the software is a valid tool for microgrid energy trading simulation.

2.5.1 Simple simulation validation

The most basic form of validation is to set the model for energy trading at its most simple in order to compare the simulation results with results calculated with pen and paper. With the adaptation to MGTrader to provide 3 seed files, the programme is simply asked to not create any dummy grids. Power factor and distance are not considered as their random nature within MGTrader cannot be repeated like for like manually. The three demand profiles used are; mg1- an office demand profile with a mix of generation types, mg2- a hotel demand profile powered by CHP and mg3- a domestic dwelling profile with a wind powered generation profile. These profiles and their sources are discussed in more detail in chapter 3. This information is irrelevant for the purposes of software validation. The cost of microgrid energy trade is 7p/kWh, and the cost of national grid energy is 10p/kWh with no day-night price plan. Storage is not considered.

See below a summary of the hour by hour state of trade in table 2.

Time	mg1 dem	mg1 sup	mg1 diff	mg2 dem	mg2 sup	mg2 diff	mg3 dem	mg3 sup	mg3 diff
Hour	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*
1	17.3	25	7.7	84.94	70	- 14.94	13.05	10	- 3.05
2	17.2	23	5.8	59.25	70	10.75	9.13	11.5	2.37

3	17.1	22.9	5.8	51.33	70	18.67	7.83	13.6	5.77
4	17.1	22.9	5.8	59.22	70	10.78	7.39	12.61	5.22
5	17.5	22.7	5.2	58.64	70	11.36	7.39	12.36	4.97
6	18.4	21.1	2.7	49.11	70	20.89	7.83	11.5	3.67
7	22.4	21.5	-0.9	52.48	70	17.52	10.88	14.23	3.35
8	29.5	26.4	-3.1	70.05	70	-0.05	21.32	16.58	-4.74
9	29.8	29.8	0	56	70	14	24.37	17.62	-6.75
10	34.5	33.33	-1.17	61.47	70	8.53	20.45	18.26	-2.19
11	35	34.8	-0.2	63.32	70	6.68	19.58	19.5	-0.08
12	35.1	36.1	1	58.25	70	11.75	18.71	20.96	2.25
13	35.1	36.7	1.6	58.96	70	11.04	20.45	22.13	1.68
14	33.7	36.5	2.8	32.87	70	37.13	19.14	22.01	2.87
15	32.92	35.65	2.73	87.64	70	-17.64	17.84	21.78	3.94
16	31.4	33.01	1.61	39.99	70	30.01	19.54	21.68	2.14
17	29.25	33	3.75	34.52	70	35.48	26.98	24.84	-2.14
18	26.2	30	3.8	54.2	70	15.8	36.55	31.53	-5.02
19	22.46	27	4.54	77.46	70	-7.46	39.16	32.26	-6.9
20	21.1	26	4.9	82.94	70	-12.94	37.42	33.68	-3.74
21	19.81	26.4	6.59	70.81	70	-0.81	33.94	29.59	-4.35
22	18.94	25.7	6.76	89.94	70	-19.94	32.64	28.3	-4.34
23	17.91	24.6	6.69	92.91	70	-22.91	28.28	27.09	-1.19
24	17.33	24.3	6.97	79.33	70	-9.33	20.88	24.6	3.72

Table 2 - Simple validation hourly generation/demand values

The first mechanism to check is to compare the hour by hour pool size as compared to the above values, as shown below in table 3.

Time	**Pool Size**	**MGTrader Pool Size**	**no. deficits**
Hour	*kWh*	*kWh*	
1	7.7	7.7	2
2	18.92	18.92	0
3	30.24	30.24	0
4	21.8	21.8	0
5	21.53	21.53	0
6	27.26	27.26	0
7	20.87	20.87	1
8	0	0	3

9	14	14	1
10	8.53	8.53	2
11	6.68	6.68	2
12	15	15	0
13	14.32	14.32	0
14	42.8	42.8	0
15	6.67	6.67	1
16	33.76	33.76	0
17	39.23	39.23	1
18	19.6	19.6	1
19	4.54	4.54	2
20	4.9	4.9	2
21	6.59	6.59	2
22	6.76	6.76	2
23	6.69	6.69	2
24	10.69	10.69	1

Table 3 - Comparison of MGET SIM pool size values vs manual calculation

All the results match which proves that the simple function of calculating pool size each hour works correctly. Next the various deficits will be met by the software. For the purposes of validation, this process will be checked in detail at hours 1, 8 and 18. MGTrader selects microgrids randomly for trading. The validation process will accept the software's grid selection and check the results of the trade.

At hour 1, 0 kWh are stored. Microgrid 1 adds 7.7kWh to the pool, microgrid 2 has a -14.95kWh deficit and microgrid 3 has a 3.05kWh deficit. The first grid selected for trading is microgrid 3. The 3.05kWh deficit is satisfied by the 7.7 kWh pool, leaving 4.65 kWh leftover in the pool. The cost of this trade is:

$$7p/kWh \times 3.05kWh = 21.35p \approx 21p.$$

The next grid selected for trading is microgrid 2. Its 14.95kWh deficit cannot be met by remaining energy in the pool so a national grid import will be necessary. Import costs are calculated as:

$$14.95kWh \times 10p/kWh = 1.495 \approx £1.49.$$

The national grid earns all of this amount. Now that trading is complete, it is known that 3.05kWh is used and 100% of this is provided by microgrid 1, therefore microgrid 1 earns:

$$100\% \times 3.05kWh \times \frac{7p}{kWh} = 21p$$

As can be seen from the screenshot of the MGTrader output file below in figure 11, the simulator has calculated this outcome correctly also. Note: the numbering of the microgrids is 0, 1, 2 rather than 1, 2, 3.

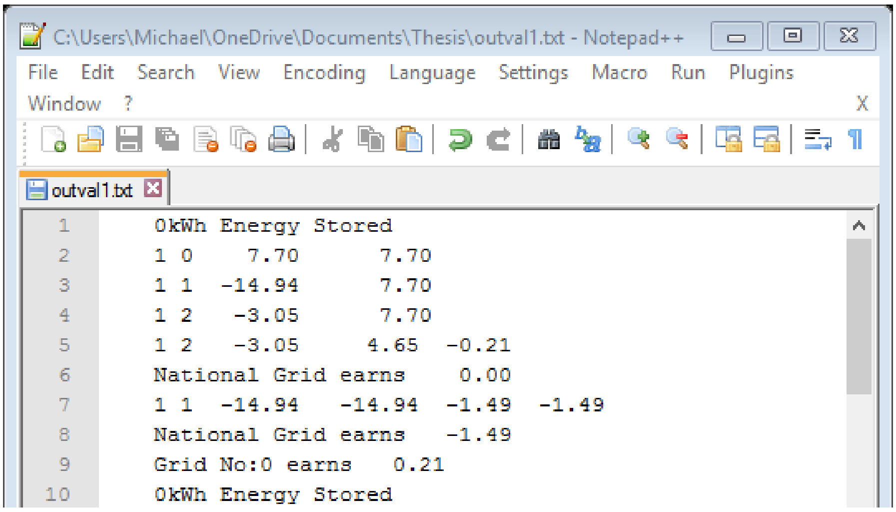


Figure 11 - Hour 1 of validation run results file

No storage is available in this setup and it can be seen that none of the remaining 4.65kWh of energy is carried over to hour 2.

Hour 8 has all 3 of the grids in deficit and therefore no energy available in the pool. The trades should look as follows:

Grid no.	Import Cost	Cumulative import	Cumulative National Grid Earnings
Microgrid 2	$0.05kWh \times 10p = £0.005 \approx £0.01$	0.05kWh	1p
Microgrid 1	$3.10kWh \times 10p = £0.31$	3.15kWh	32p
Microgrid 3	$4.74kWh \times 10p = £0.474 \approx £0.47$	7.89kWh	79p

Table 4 - calculated national grid earnings for hour 8 of simple validation

Once again these results are matched in the results file as illustrated below in figure 12.

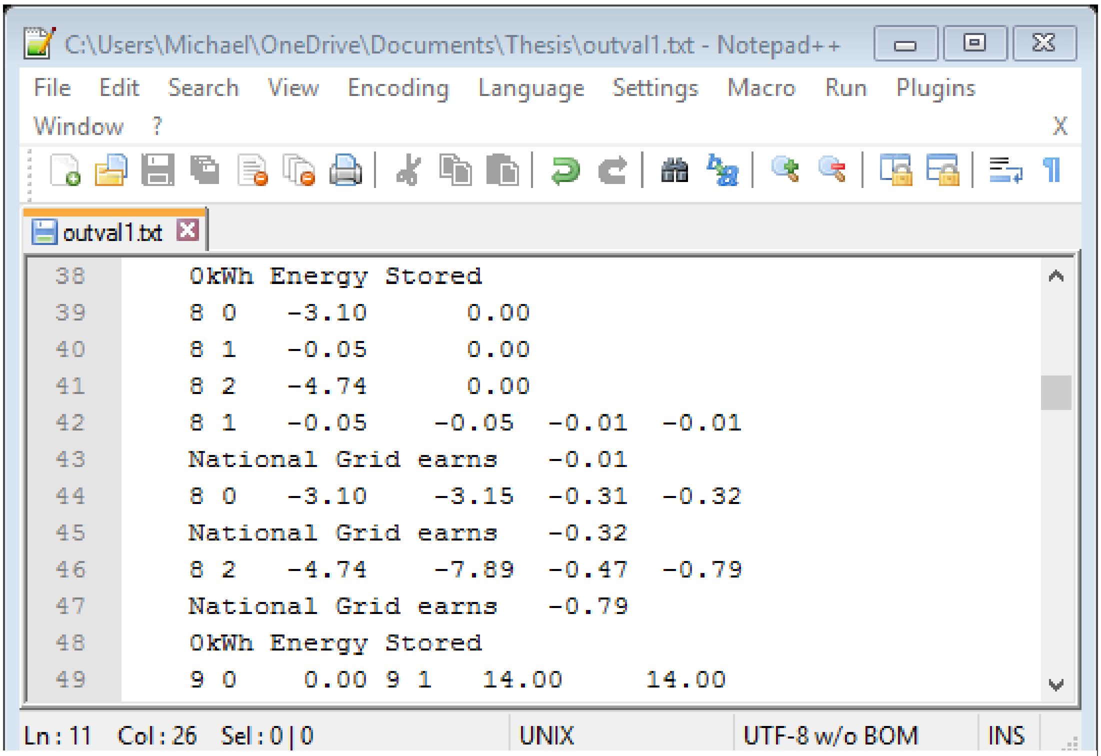


Figure 12 - Hour 8 of validation run results file

During hour 18, microgrids 1 and 2 add 3.8kWh and 15.8kWh respectively to the 19.6kWh pool with microgrid 3 requiring 5.02kWh to meet its demand. Trade is completed correctly as illustrated in the above examples. Once this demand is satisfied the share of the profits are calculated as follows in table 5:

Microgrid 1	$\frac{3.8kWh}{19.6kWh} \times 5.02kWh \times \frac{7p}{kWh} = £0.068 \approx £0.07$
Microgrid 2	$\frac{15.8kWh}{19.6kWh} \times 5.02kWh \times \frac{7p}{kWh} = £0.28$

Table 5 - Microgrid earnings calculations

Once again, the screenshot in figure 13 proves the software calculates these earnings correctly.

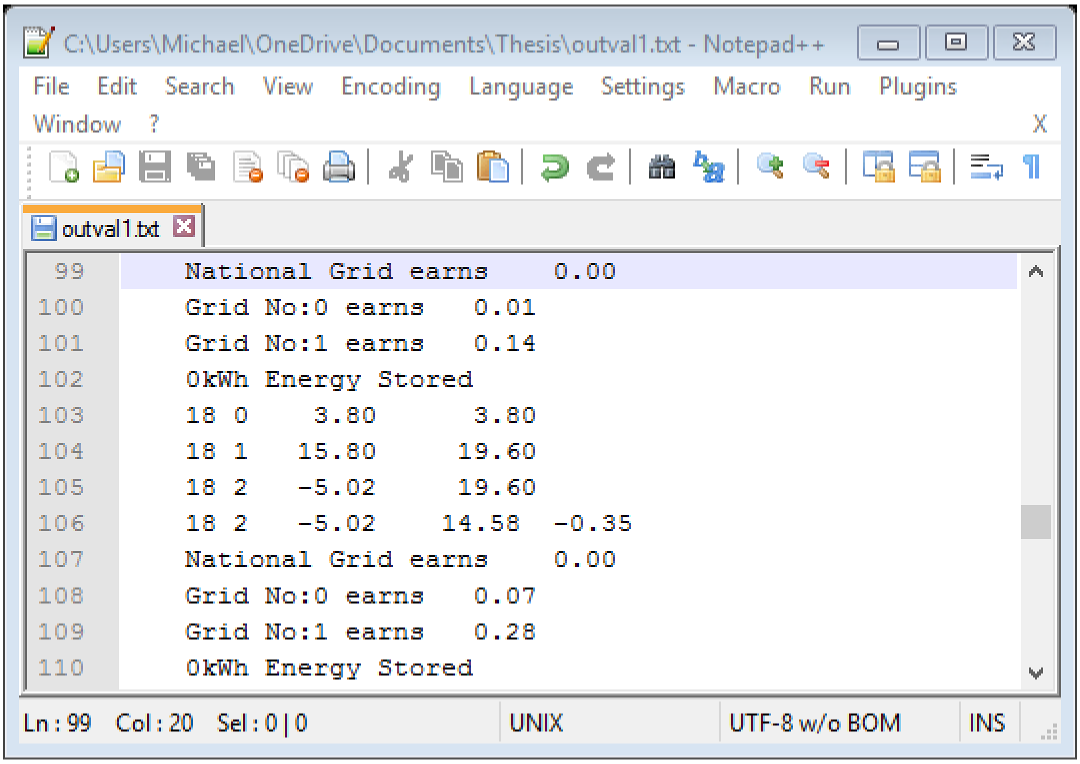


Figure 13 - Hour 18 of validation run results file

These step by step validations for hours 1, 8 and 18, as well as a detailed read of the other results for any obvious errors, satisfies the criteria for verifying the basic mechanisms of MGTrader are working correctly.

2.5.2 Extreme Case Validation

A second way to validate the functionality of MGTrader is to set up scenarios in which the outcome is known. These cases are invariably with extreme inputs. This validation will investigate the following…

1) When most microgrids are in deficit, when trade would be expected to be unviable with a large amount of national grid imports.

2) When most microgrids are in surplus, when trade is viable, national grid imports are minimal but with a considerable amount of wasted energy at the end of each time step.

Firstly in case 1; the seed files are set with mg1.txt the same as was in section 2.4.1 and mg2.txt and mg3.txt always in deficit. The chance of mg1.txt being used as a seed for dummy grids is reduced to 1 in 4 instead of 1 in 3 to decrease the number of microgrids in surplus further. Twenty microgrids with medium variability will be set up to trade, with no storage. Distance and power factor will be considered to reduce the chance of trade. Renewable intermittence and equipment failure are considered and demand management and day-night price plans are not. The prices of 10 pence/kWh for national grid energy and 7 pence/kWh for microgrid pool energy remain.

Hour	**Energy Pool size**	**National Grid Import**
H	*kWh*	*kWh*
1	24.09	427.26
2	21.6	192.07
3	28.82	195.39
4	21.84	185.66
5	33.2	20.43
6	24.62	175.06
7	1.44	242.44
8	7	44.55
9	0	44.66
10	17.32	325.59
11	43.88	374.3
12	42.7	279.32
13	46.1	279.74
14	14.66	120.99
15	42.2	236.42
16	5.41	199
17	7.35	289.92
18	43.72	339.67
19	36.7	54.86
20	55.15	359.69
21	6.59	552.25
22	31.91	585.06
23	33.09	425.73
24	6.97	422.71

Table 6 - Extreme Case 1 Pool size vs Grid Import

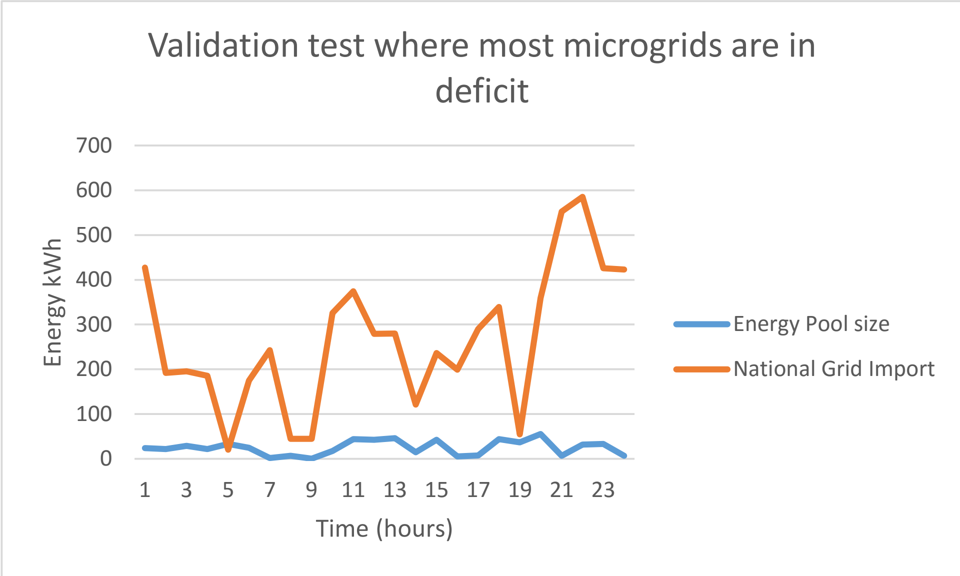


Figure 14 - pool size vs energy imported in extreme validation case 1

The results, displayed in Table 6 and visualised in Figure 14, show that the simulation behaves as one would expect it to when given the inputs it has been given. The fact that on one in three seed grids had a chance of being in surplus, with only a one in four chance of a dummy grid being created using that data, means that the pool size is always small relative to the amount of energy required. However, there is evidence that the random number generator can still create surpluses as pool sizes do vary. As one would expect, when the pool is larger then, in general, the national grid import is less. Although overall demand has a big influence also.

For case 2 the second and third seed files are switched so that they are always in surplus. Demand management is activated along with a large 1000kWh store which is full at the start of the simulation. Power factor, distance, peak/off-peak price plans, intermittence and equipment failure are all not considered.

Hour	**Energy Pool size**	**National Grid Import**	**Storage**	**Energy wasted**
H	*kWh*	*kWh*	*kWh*	*kWh*
1	169	0	1000	148
2	528.4	0	1000	526
3	507.13	0	1000	507.13
4	405.29	0	1000	401.64
5	312.35	0	1000	312.35
6	493.98	0	1000	482.9
7	403.93	0	1000	393.43
8	281	0	1000	269.13
9	343.22	0	1000	287.03

10	290.13	0	1000	256.1
11	365.04	0	1000	350.78
12	395.97	0	1000	378.41
13	385.44	0	1000	382.85
14	747.53	0	1000	740.69
15	258.93	0	1000	222.96
16	640.32	0	1000	632.68
17	670.31	0	1000	635.6
18	610.28	0	1000	585.63
19	333.09	0	1000	256.48
20	348.71	0	1000	308.67
21	320.26	0	1000	311.45
22	251.99	0	1000	190.01
23	364.66	0	1000	242.53
24	400.16	0	1000	398.36

Table 7 - Extreme Case 2 Pool size vs Grid Import

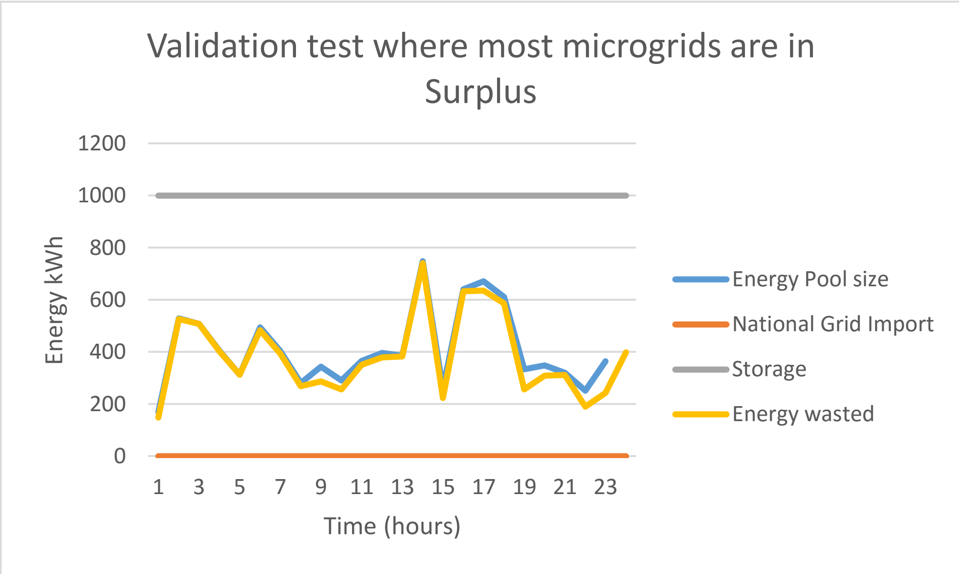


Figure 15 - Extreme Case 2 Pool size, grid import, storage and energy wasted

Once again, the validity of MGTrader's core functions are confirmed by the results in Table 7 and Figure 15. With so much surplus energy being produced by the 20 microgrids, the national grid is never drawn from and much of the pool's energy is wasted with the stored energy never tapped.

2.5.3 Comparison of results between MGET-SIM and MGTrader

The final method for data validation is to compare the results of the new MGTrader with that of the original MGET-SIM currently available for download online. Sheik Muhammed Ali created the program and in his thesis created a 'final case' which he put forward as the ideal circumstance for microgrid trading based on his earlier findings during his project. This segment will recreate the 'final case' scenario and investigate any discrepancies between the results.

Muhammed Ali's Final case is summarised in Table 8:

Input	**Case**
Total Microgrids	101
Variability	High
Failure	Yes
Intermittence	Yes
Peak/Off Peak Rates	No
National Grid Import Price	10
Microgrid Trade Price	7

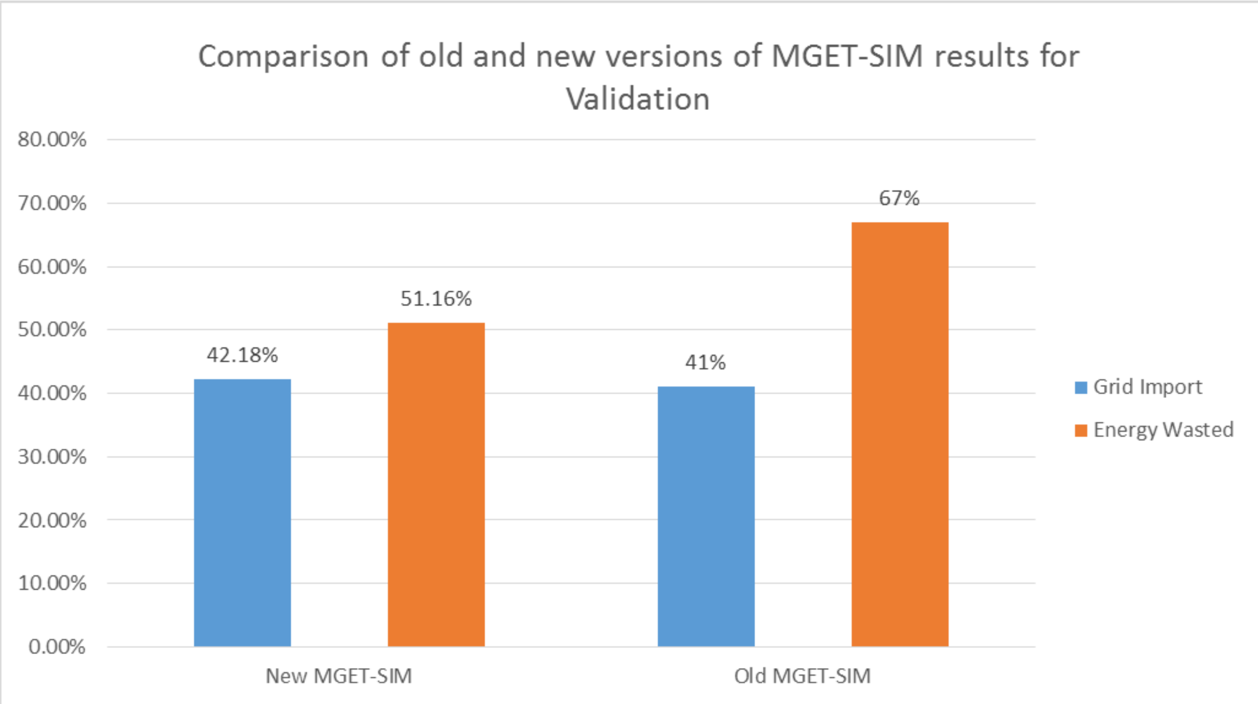
Table 8 – 'Final Case' from (Ali, 2009) for comparison

The data in mg1.txt is the same as in the previous sections. Since MGET-SIM did not use multiple inputs during his simulations the MGTrader is adjusted to only use mg1.txt for seed data for the purpose of this validation.

	MGTrader	**MGET-SIM**
National Grid Import	42.18%	41%
Energy Wasted	51.16%	67%
Microgrid 0's costs	-387.04%	3%

Table 9 - Comparison of Results for Validation of MGTrader

It can be seen that none of the results in table 9 match exactly. In the case of national grid import, the results are within a margin of error that comes inherently through the random number generation within the two programme's code. As for the other results, the discrepancy can perhaps be put down to the seed data. As mentioned in section 2.2.2, the amount of influence on the results excerpted by the seed data is huge. It is one of the principle reasons multiple input files have been integrated into MGTrader for this project. Since the MGET-SIM seed data is unavailable online with the software package or in his report on his findings, it is therefore impossible to make a fair attempt to replicate his results. When this is added to effects of random number generation mentioned earlier it is clear that the results could never have been mimicked exactly in the first place, this was never the purpose of this section.



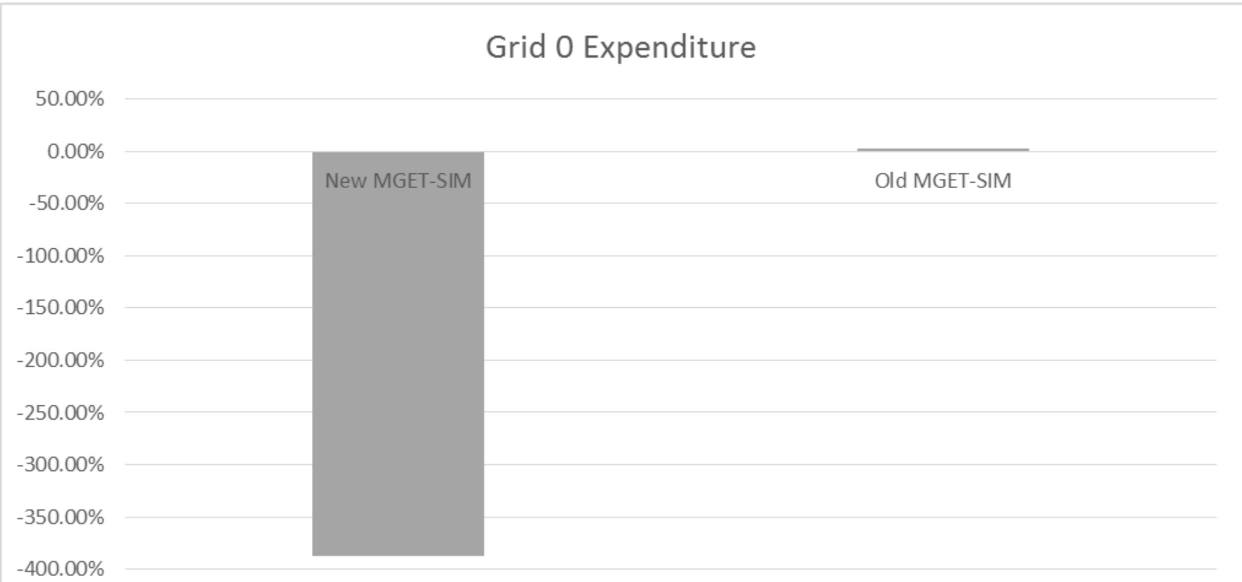


Figure 16- Comparisons for Validation of MGTrader

What can be confirmed from these results in figure 16 is that the MGTrader still produces results that are believable compared to the old results. The energy costs incurred for microgrid 0 is the only case where the results are significantly different.

The seed data used in this project has microgrid 0 spending 54p on its energy over the course of the 24 hours. With trading in place in the scenario set out by Muhammed Ali in his paper, microgrid 0 earns £2.09. This does suggest that the generation data taken from MERIT for the seed data has a large over-capacity compared to what MGET-SIM's seed grid was equipped with.

Despite the differences in the results from MGET-SIM, the validity of the new MGTrader software can be confirmed. The reasons for these differences can be identified as either unfixable due to unavailable seed data, or due to changes in the code that actually improve the way in which MGET-SIM worked; such as the way in which dummy grids are created.

The significant changes to functionality when creating dummy grids and additional features mean that the findings previous research using MGET-SIM can no longer be taken as canon. This project will investigate the effects of all the factors available to the user implement during simulations, not just the new ones, using MGTrader.

3 Chapter Three: Microgrid Energy Trade Investigation

Having explored the field of microgrid energy trading and defined the objectives of the project in chapter one and developed the new MGTrader software in chapter two, this third chapter discusses the simulations run during the project.

Results are discussed simulation-by-simulation. However, overall conclusions of the project will be made in chapter four.

For these simulations, a national grid electricity price is set at 15p/kWh, which is around the price of electricity one would expect in the UK according to the DECC report in March 2015 (DECC, 2015). The microgrid energy price for these simulation is more difficult to justify as there is no real world microgrid energy trading. The price must be lower than the national grid import price but greater than the feed in tariff to the national grid; this can depend on the generation technology. For this project, the microgrid energy price is set at 11p/kWh.

MGTrader has fifteen different variables that can be inputted into the programme. Energy prices, the profiles for the three input files, day-night pricing, storage capacity and energy stored at the start can set to anything the user likes. These inputs are then run through the other variables that have 384,000 combinations. Of course, this report cannot investigate each of these combinations, the majority of which will have only marginal differences to one another. For Example, a simulation with 500 microgrids is unlikely to produce different results to a simulation with 501 microgrids. Therefore, this report investigates the effects of a number of the 15 variables independently. There is no reason to believe that the cumulative impacts of each of the factors in this simulation are not additive. That is to say that one would not expect the impact of demand management to be positive in isolation but then negative or extra positive in combination with distance, for example. Once each factor's effect is investigated, a simulation that creates the most realistic case with the optional factors adjusted in order to encourage trading will be run and the findings presented.

As MGTrader uses random number generation it is likely that if two simulations are run with the same set-up that the results will be different. In order to address the effects of random number generation each set of results is an average of 3 simulations.

3.1 Diversity of Supply

Diversity of supply is an important element of making microgrid energy trading successful. If all microgrids within a low voltage network are solar powered domestic properties then trade is unlikely to occur as all properties have similar demand and supply profiles that effectively cancel each other out. Within MGTrader, the use of a single file means that a user can manipulate the simulation to provide his preconceived conclusions using the seed data. Multiple seed files makes this more difficult and therefor increases the scientific validity of the software to a degree.

To test the effect of diversity of supply, a copy of MGTrader software is created where only one input file is used. The supply-demand profile of this seed microgrid is illustrated in figure 17.

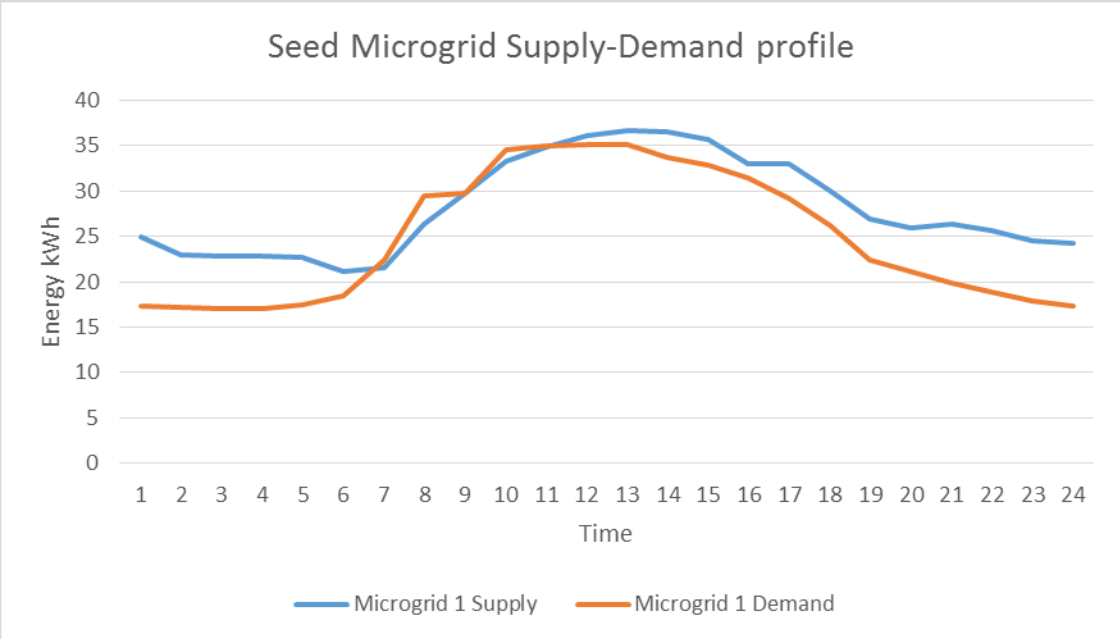


Figure 17 - Seed Microgrid data (Grid 0)

This demand profile's shape is similar to that of an office building. With low demand at night and peak demand during business hours. The supply profile is made up of photovoltaics and small-scale wind power. The solar panels peak their output in the middle of the day and the wind power provides power at times of low sunlight.

Using the full version of MGTrader, a second simulation is run using the above seed data as well as the following two sets of seed data.

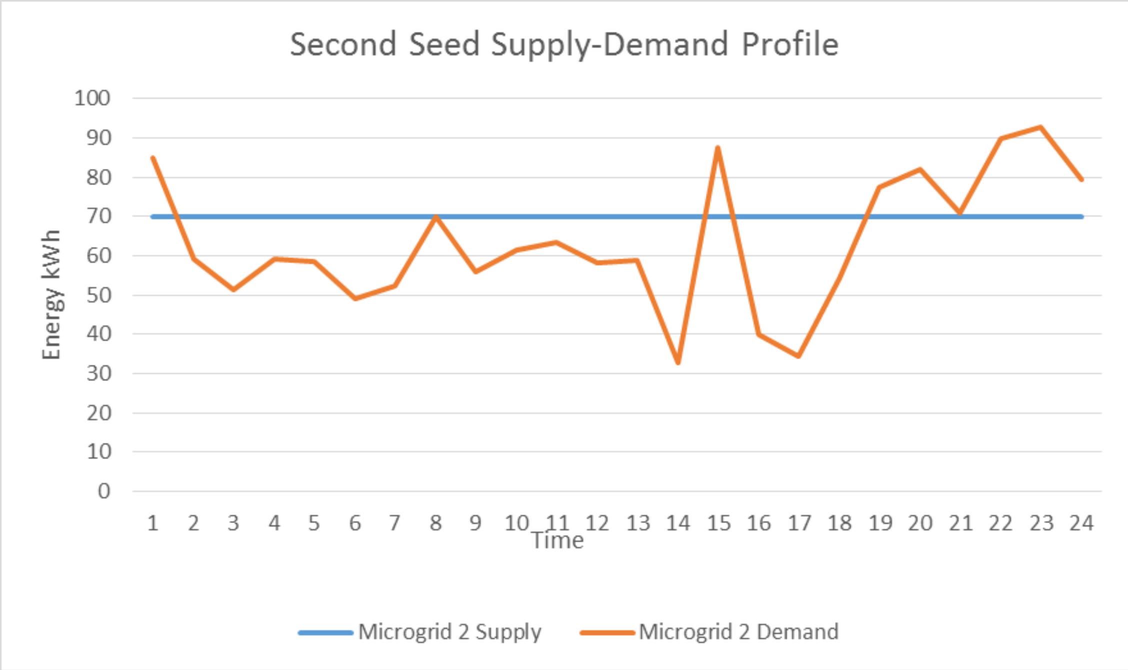


Figure 18 - 2nd Seed Microgrid Data

Figure 18 shows demand profile shape is typical of a large hotel, with supply coming from a CHP unit with a constant output of 70kWh.

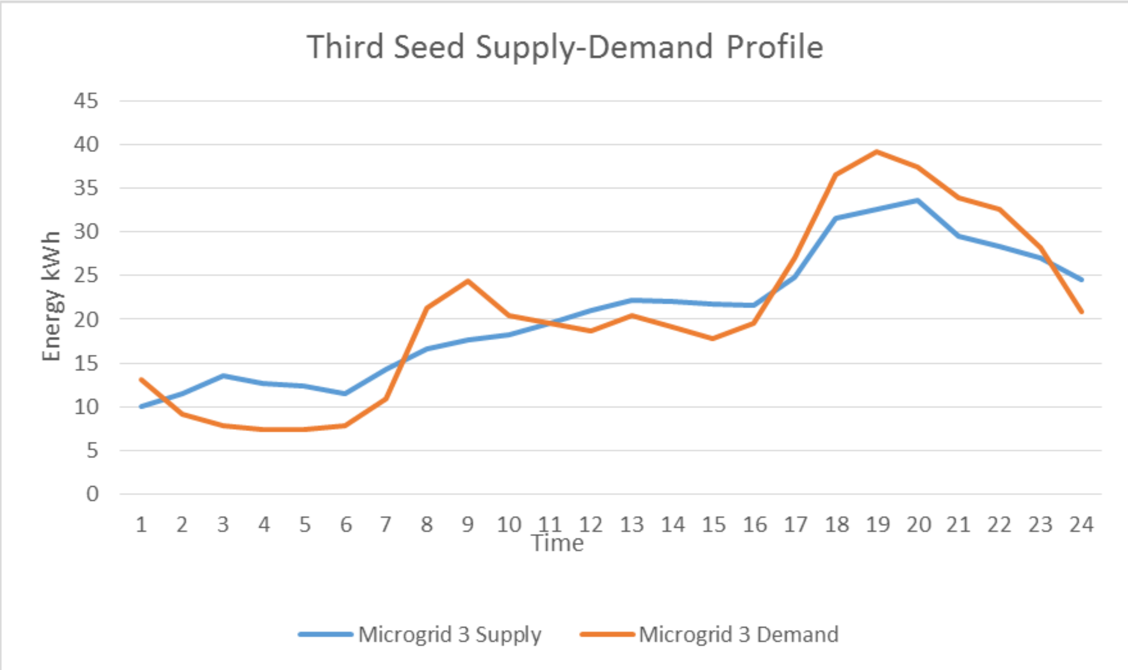


Figure 19 - 3rd Seed Microgrid Data

Figure 19 shows a demand profile that mimics a typical domestic profile. With low demand at night, a peak in the morning as people typically get ready for work/school and another peak in the evening when people return home, artificial lighting is needed and other electronic appliances are typically used. The supply profile shape is derived from the output of a small scale wind turbine on a winter's day in Glasgow.

Variable	Case 1	Case 2
Number of input files	1	3
Number of Microgrids	10	10
Variability	Medium	Medium
Failure	No	No
Renewable Intermittence	No	No
Peak/Off-Peak Price Plan	No	No
Storage	No	No
Demand Management	No	No
Distance	No	No
Power Factor	No	No

Table 10 - MGTrader set up to investigate Diversity

The results of these simulations can be seen below.

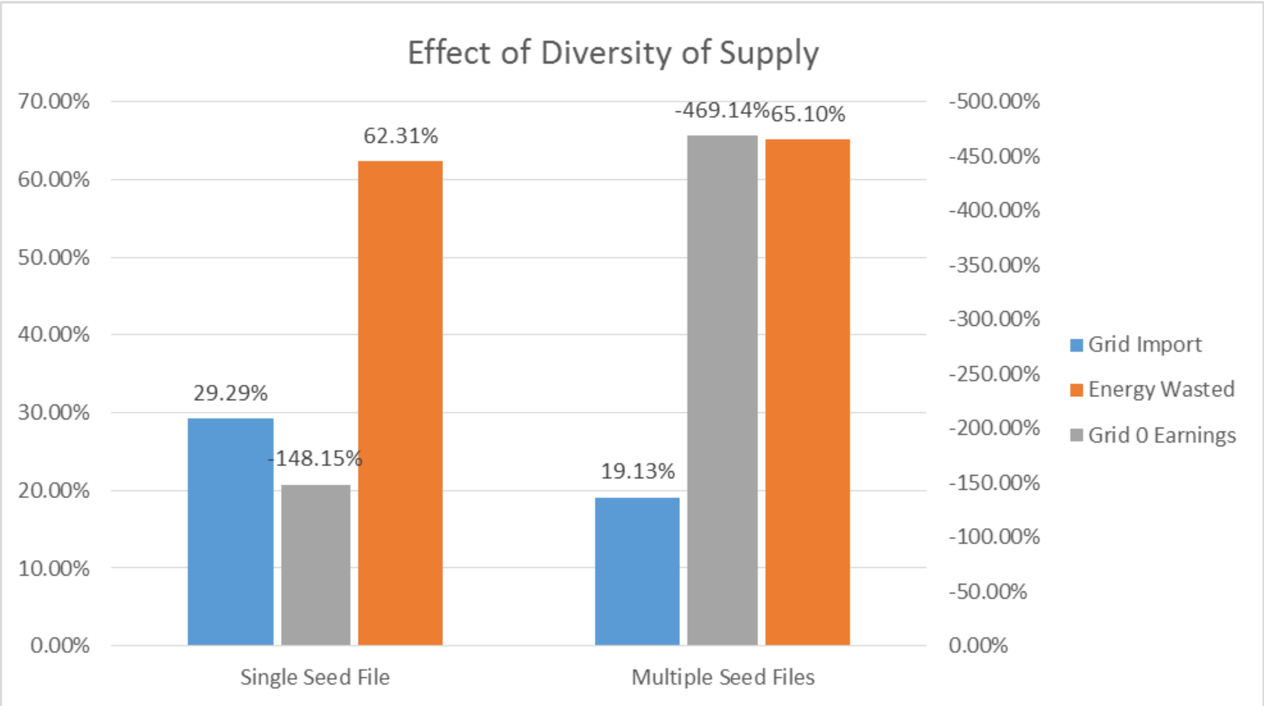


Figure 20 - Effect of Diverse Supply types among members of Energy pool

The benefits of diversity of supply are clear to see in figure 20. The amount of energy wasted rises 2.79% although this can be attributed to the random number generator. National grid import is reduced by a third because the pool size is more likely to be stable. When the first seed file is in deficit there is a higher likelihood that another grid with a different profile will have a surplus to meet that deficit. On the hand, when the first seed file is in surplus it is more likely another microgrid with a different supply profile will want to buy that energy. This can be seen in the results for 'Grid 0 Earnings' (which is on the secondary axis), the earnings with multiple input files are triple that of with a single input file because it effectively mimics a diverse supply across the low voltage network.

The remaining simulations shall use multiple input files as standard.

3.2 Number of Microgrids

The effect of number of microgrids will have a large effect on the viability of microgrid energy trading. If trading is viable with just a few microgrids available then it could be rolled out in the near future and would have the potential to act as a driving force in the roll out of distributed and embedded generation. However, if trade is only viable with many microgrids then it can only be seen as a hypothetical for the future after the steady increase in microgeneration reaches a certain point.

Variable	Case 1	Case 2	Case 3
Number of Microgrids	10	50	100
Variability	Medium	Medium	Medium
Failure	No	No	No
Renewable Intermittence	No	No	No
Peak/Off-Peak Price Plan	No	No	No
Storage	No	No	No
Demand Management	No	No	No
Distance	No	No	No
Power Factor	No	No	No

Table 11 -MGTrader set up to investigate the effect of Number of Microgrids

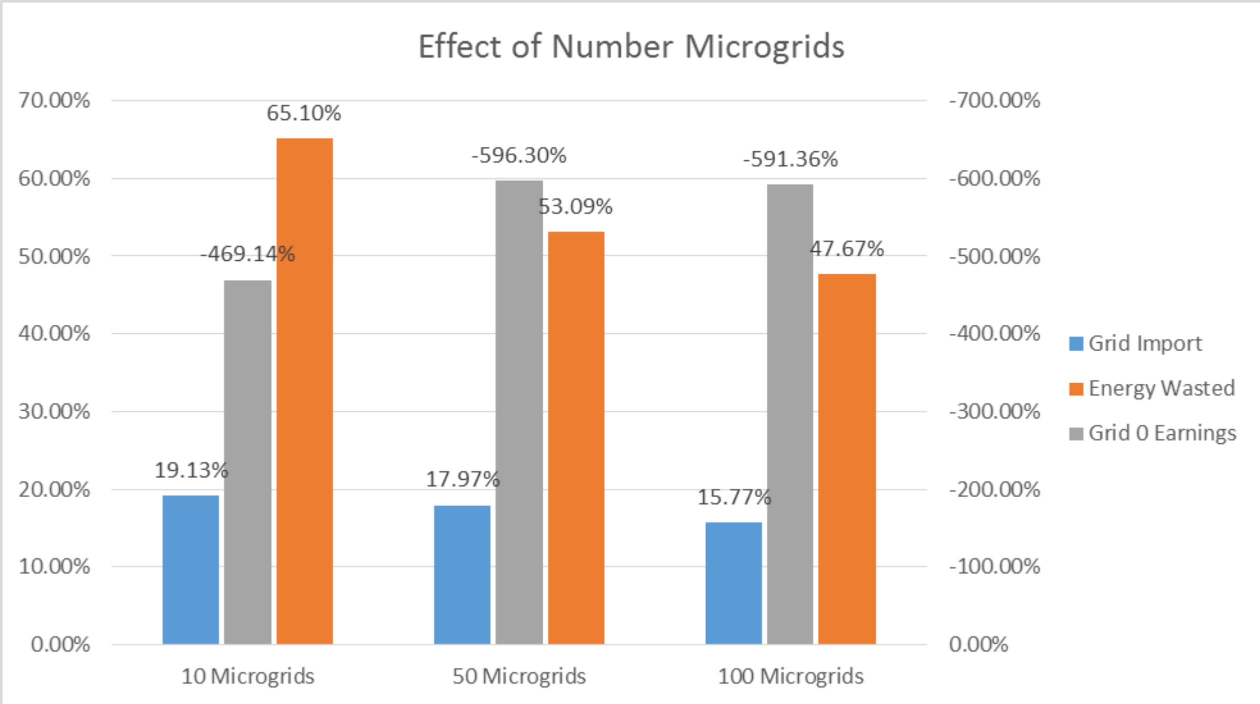


Figure 21 - Effect of Number of Microgrids Trading

As can be seen in figure 21, trading conditions do improve with more microgrids. The load on the national grid is reduced with more microgrids providing energy to the pool. As there are also more microgrids in need of energy, less energy is wasted at the end of each time step with more microgrids, with a considerable 17.43% drop between 10 and 100 microgrids. Interestingly, microgrids are likely to make a profit with more microgrids to trade with however, this has a peak value. The best set up from a microgrid's economic point of view is to have enough local microgrids to trade with but not so many that its share of the energy pool (and therefore the spoils) is too diluted. Illustrated in figure 21, microgrid zero benefits by £1.11 by having 50 local microgrids as opposed to 10. However as this increases to 100 microgrids in the third case, profits reduce slightly by 4p as compared to 50 microgrids. Microgrid energy trading among just 10 microgrids has an instant improvement in all the measures of viability which implies that trading schemes could start in the near future.

3.3 Variability

Just as diversity of supply types is important, the variability of size will also have an impact.

Variable	Case 1	Case 2	Case 3
Number of Microgrids	10	10	10
Variability	Low	Medium	High
Failure	No	No	No
Renewable Intermittence	No	No	No
Peak/Off-Peak Price Plan	No	No	No
Storage	No	No	No
Demand Management	No	No	No
Distance	No	No	No
Power Factor	No	No	No

Table 12 - MGTrader set up to investigate Variability

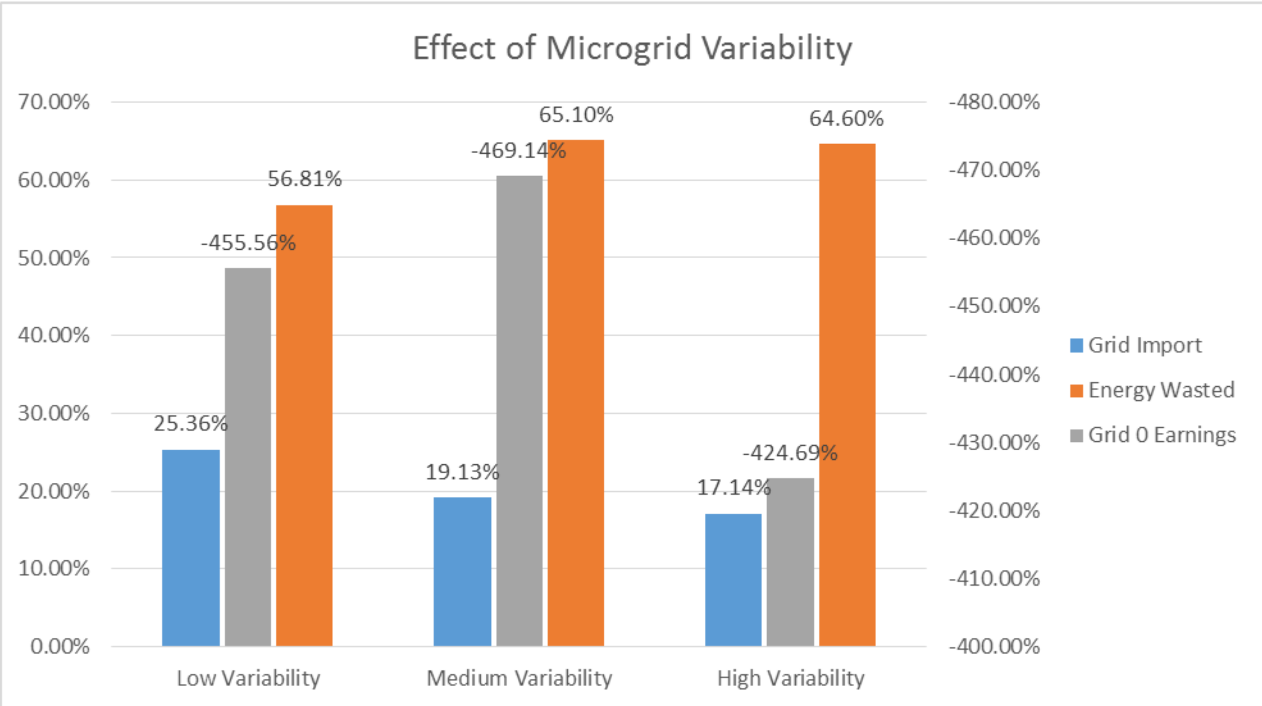


Figure 22 - Effect of Variability of Microgrid sizes within a low voltage network

The results of the simulation (figure 22) show that with greater variation of sizes of microgrids, the smaller the load on the national grid, with and 8% drop across the simulation cases. This is the arguably the primary objective of the modern microgrid/embedded generation concept (Galvin & Yeager, 2009). However, with larger grids present in a trading scenario, larger surpluses are fed into the pool and therefore 7.8% more energy is wasted than with low variability. In economic terms, microgrid 0 does 39p less well with high variability, than the prime medium variability, because there are much larger microgrids present for trade. The larger the microgrid, the more likely it is that it will have a large share of the pool. Therefore, any given microgrid will benefit more economically if it has a large capacity relative to the other microgrids available for trading.

3.4 Equipment Failure

Equipment failure or maintenance time will increase demand on the pool and/or national grid. The effects of this demand are investigated here.

Variable	**Case 1**	**Case 2**
Number of Microgrids	10	10
Variability	Medium	Medium
Failure	No	Yes
Renewable Intermittence	No	No
Peak/Off-Peak Price Plan	No	No
Storage	No	No
Demand Management	No	No
Distance	No	No
Power Factor	No	No

Table 13 - MGTrader set up to investigate the effects of equipment failure

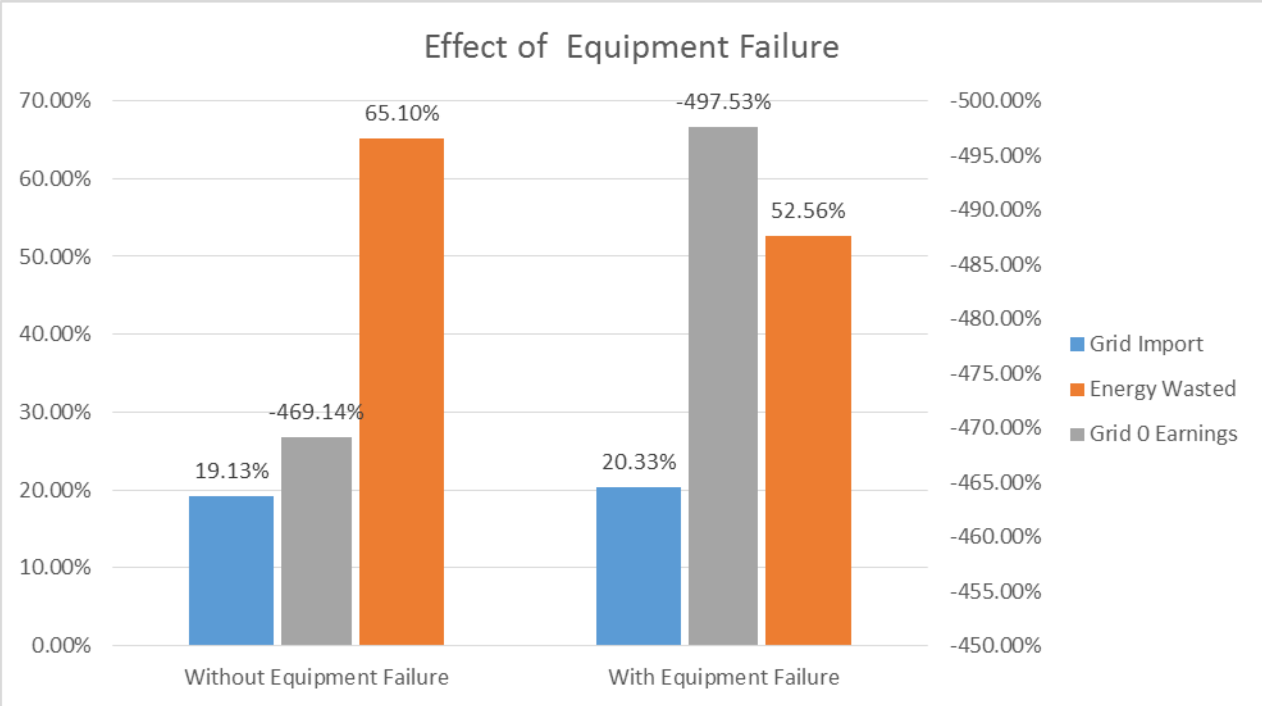


Figure 23 -Effect of Equipment failure considerations

As the microgrids require 100% of their energy be met by the national grid or the pool when their equipment fails or is unavailable during maintenance, the demand on the pool goes up, as expected, by 12.5%. With more energy used in the pool and less wasted at the end of each time step, the national grid import actually remains fairly constant, meaning that trading provides an affordable safety net from equipment failure and maintenance for microgrid owners, a problem identified in chapter 1. Microgrid 0 does not have any failure during its 24 time steps and therefore earns more money while providing for its peers when they are not generating.

3.5 Renewable Intermittence

This simulation investigates the effects of renewable unreliability during generation.

Variable	Case 1	Case 2
Number of Microgrids	10	10
Variability	Medium	Medium
Failure	No	No
Renewable Intermittence	No	Yes
Peak/Off-Peak Price Plan	No	No
Storage	No	No
Demand Management	No	No
Distance	No	No
Power Factor	No	No

Table 14 - MGTrader set up to investigate the effects of Renewable Intermittence

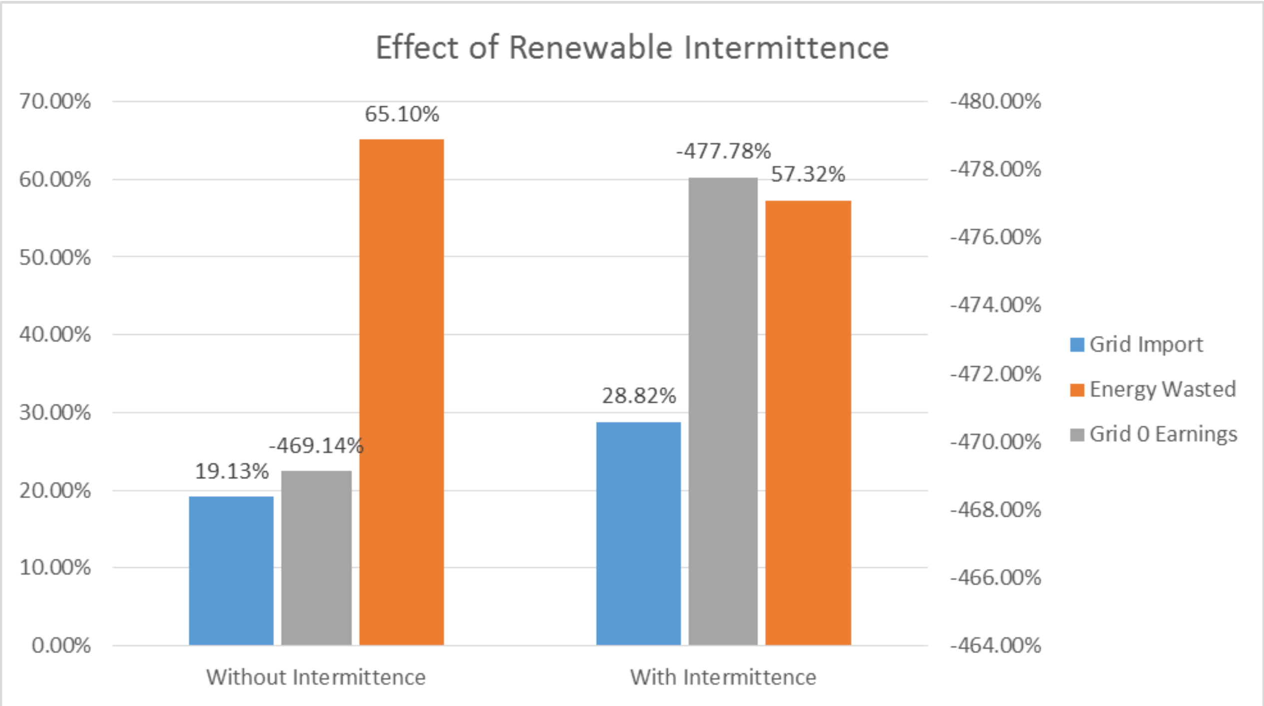


Figure 24 - Effect of Renewable Intermittence

It can be seen that demand on the pool and national grid increases greatly as a result of this consideration. As can be seen in figure 24, the amount of the energy wasted is falls by 11% compared to that where intermittence is not considered. The effect of renewable intermittence is much like equipment failure. However, the impact is perhaps greater. Although renewable intermittence only reduces generation by 30% rather than 100% in the case of failure, the likelihood and frequency of this happening is much higher than failure and therefore impacts the results over 24 time steps to a more noticeable extent. A 50% increase in national grid import is the most noticeable change in the results when considering Renewable intermittence factor. This is because the pool has less energy being contributed to it across the board and therefore is less equipped to meet the demands of the microgrids in deficit. The increased number of deficits does mean that less energy is wasted from the pool. Microgrid 0 benefits from the intermittence of its peer's renewable resources in a similar way to in the case of equipment failure.

3.6 Peak/Off-Peak Price Plans

Peak/off-peak price plans such as economy 7 in the UK allow for cheaper electricity in the early hours of the morning when demand nationally is low. The effect of such a scheme on microgrid energy trading could be significant. The price plan consists of a 50% price reduction per kWh from the hours of 12am until 6am.

Variable	Case 1	Case 2
Number of Microgrids	10	10
Variability	Medium	Medium
Failure	No	No
Renewable Intermittence	No	No
Peak/Off-Peak Price Plan	No	Yes
Storage	No	No
Demand Management	No	No
Distance	No	No
Power Factor	No	No

Table 15 - MGTrader set up to investigate the effects of price plans

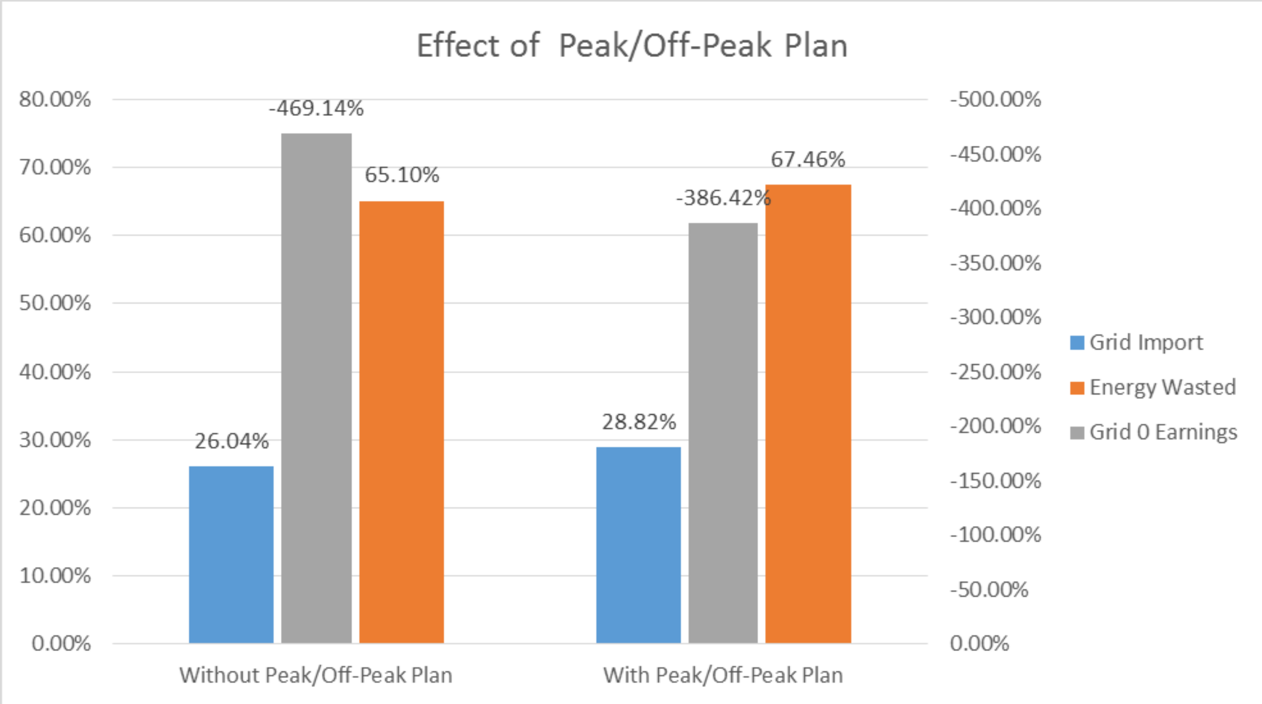


Figure 25 - Effect of Peak/Off-Peak price plan

The difference in the grid import and energy wasted results can be attributed to differences in the random number generator results as the price plan has no effect on these metrics. Figure 25 shows that the introduction of the day night price plan reduces the earnings for microgrid 0 by 73p. However, having this day night price plan will make microgeneration seem more affordable as pool member with their own storage will be able to buy cheap electricity during the price plan times and avoid charges at times of peak demand.

3.7 Storage

Several simulations were conducted to investigate the effects of different capacities of storage. Finally, a simulation was run where the storage had 125kWh available at the start of trading to illustrate the effect of this option for the user of MGTrader.

Variable	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
Number of Microgrids	10	10	10	10	10	10
Variability	Medium	Medium	Medium	Medium	Medium	Medium
Failure	No	No	No	No	No	No
Renewable Intermittence	No	No	No	No	No	No
Peak/Off-Peak Price Plan	No	No	No	No	No	No
Storage (Available at start)	None	25kWh	100kWh	500kWh	1000kWh	500kWh (125kWh)
Demand Management	No	No	No	No	No	No
Distance	No	No	No	No	No	No
Power Factor	No	No	No	No	No	No

Table 16 - MGTrader set up to investigate Storage

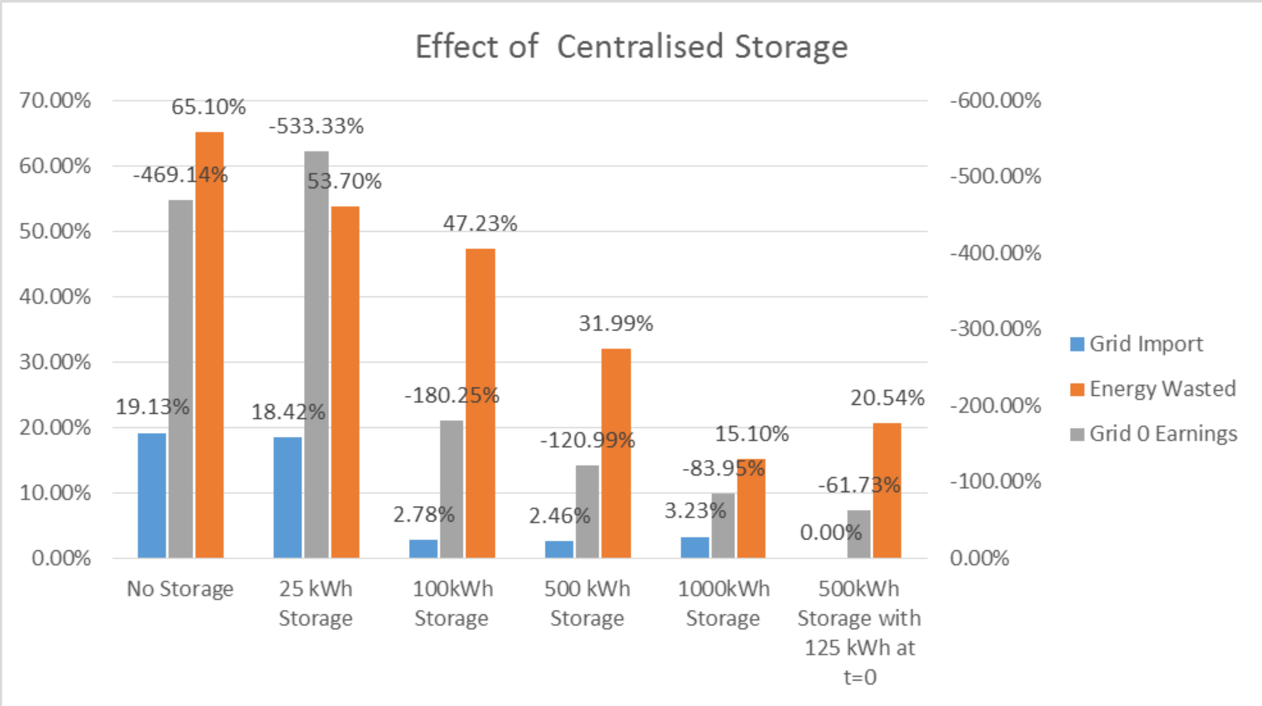


Figure 26 - Investigation into the effect of Centralised Storage on Trade

The results in figure 26 show that, in general, the more centralised storage the better. Energy wasted is reduced significantly from 65% with no storage to 15% with 1000kWh storage. As excess energy at the end of each time step is used to fill the storage, there is less energy leftover at the end of each time step. In the early time steps of each simulation, barely any electricity is wasted where the capacity is 100kWh+. More significantly, the reduction on demand on the national grid is considerable which is positive. Indeed, if the storage had some energy available at the start of trading then the import could eliminate the need for national grid import. However, there is a need for a sanity check when looking at the results. The capital costs of installing storage are not considered here and a large energy store for a pool of just 10 microgrids is likely to be just too expensive to realise. This is especially true when the economic earnings for microgrid 0 are examined. As there are so many contributors to the energy store over time, microgrid 0's share of the energy pool is reduced and therefore makes less money when profits of trade are distributed. Therefore, when it comes to centralised storage, the pool manager must strike a balance between the savings in energy wastage from the pool and reduction in national grid import with the capital cost of installation and the economic appeal for the pool contributors.

3.8 Demand Management

Demand management is likely to become part of the smart grid revolution so it is important to investigate the effect this might have on another possible result of the smart grid transition; microgrid energy trading.

Variable	Case 1	Case 2
Number of Microgrids	10	10
Variability	Medium	Medium
Failure	No	No
Renewable Intermittence	No	No
Peak/Off-Peak Price Plan	No	No
Storage	No	No
Demand Management	No	Yes
Distance	No	No
Power Factor	No	No

Table 17 - MGTrader set up to investigate the effects of Demand Management

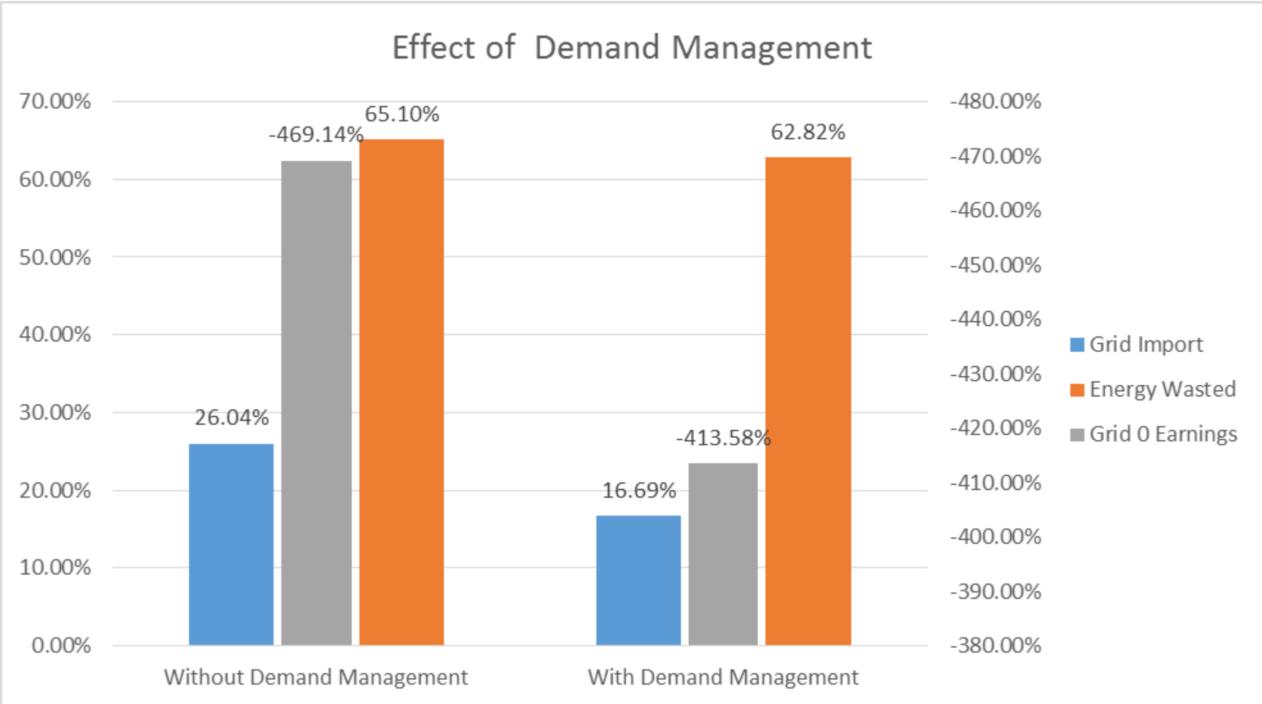


Figure 27 - Effect of Demand Management on Trade

It can be seen in figure 27 that demand management reduces the load on the national grid by 36% as there are less deficits to be met. Energy wasted remains fairly constant because although there are less deficits to address there are greater contributions to the pool from the grids impacted by demand management. Grid 0 makes less money because there are less buyers of the energy in the pool as the demand is being managed for some of the other microgrids. It has already been seen that microgrid energy trading reduces the load on the national grid significantly. Therefore the need for demand management is reduced which is preferable to the microgrids both economically and functionally. A microgrid owner does not want to have services shut down by the grid to reduce demand unless absolutely necessary. This simulation suggests that microgrid energy trading could reduce likelihood of demand management procedures being carried out. By implementing microgrid energy trading demand management could well appear more appealing to businesses and therefore more widespread and successful when absolutely needed.

3.9 Distance

Distance considerations add another element of the real world into the trading simulator. Although it was found earlier that more microgrids makes trading more viable, this must be balanced by how many microgrids can you have close enough to one another to trade without incurring significant losses. 100 microgrids in the same rural low voltage network will be less viable than 100 microgrids in a denser urban low voltage network. Figure 28 explores the effect of this phenomenon.

Variable	Case 1	Case 2
Number of Microgrids	10	10
Variability	Medium	Medium
Failure	No	No
Renewable Intermittence	No	No
Peak/Off-Peak Price Plan	No	No
Storage	No	No
Demand Management	No	No
Distance	No	Yes
Power Factor	No	No

Table 18 - MGTrader set up to investigate Distance Considerations

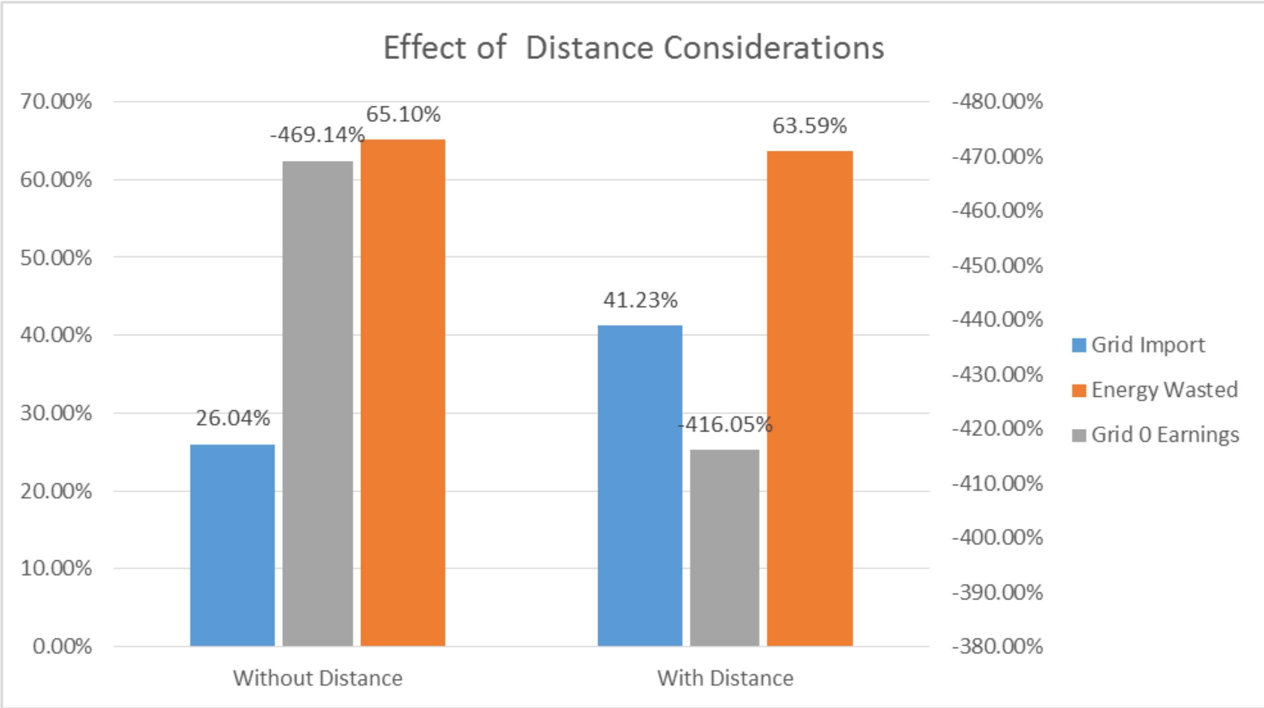


Figure 28 - Effect of Considering Issues related to Distance on Trade

The simulations show that because some microgrids are simply too far apart, more energy is needed from the national grid, 41% of transactions use the national grid as opposed to 26% of transactions is distance is not considered. The energy wasted at the end of each time step remains relatively constant because although less trade occurs, more energy is drawn from the pool for trade between grids an intermediate distance apart. Grid 0 makes less money because is sometimes has to pay for up to 50% more energy than it needs to meet its deficits, if not the national grid rate, due to the distance between the trading parties.

3.10 Power Factor

Similarly to distance, power factor considerations add an extra dimension of realism to electricity trading between microgrids. The effects are illustrated in figure 29.

Variable	Case 1	Case 2
Number of Microgrids	10	10
Variability	Medium	Medium
Failure	No	No
Renewable Intermittence	No	No
Peak/Off-Peak Price Plan	No	No
Storage	No	No
Demand Management	No	No
Distance	No	No
Power Factor	No	Yes

Table 19 - MGTrader set up to investigate Power Factor Considerations

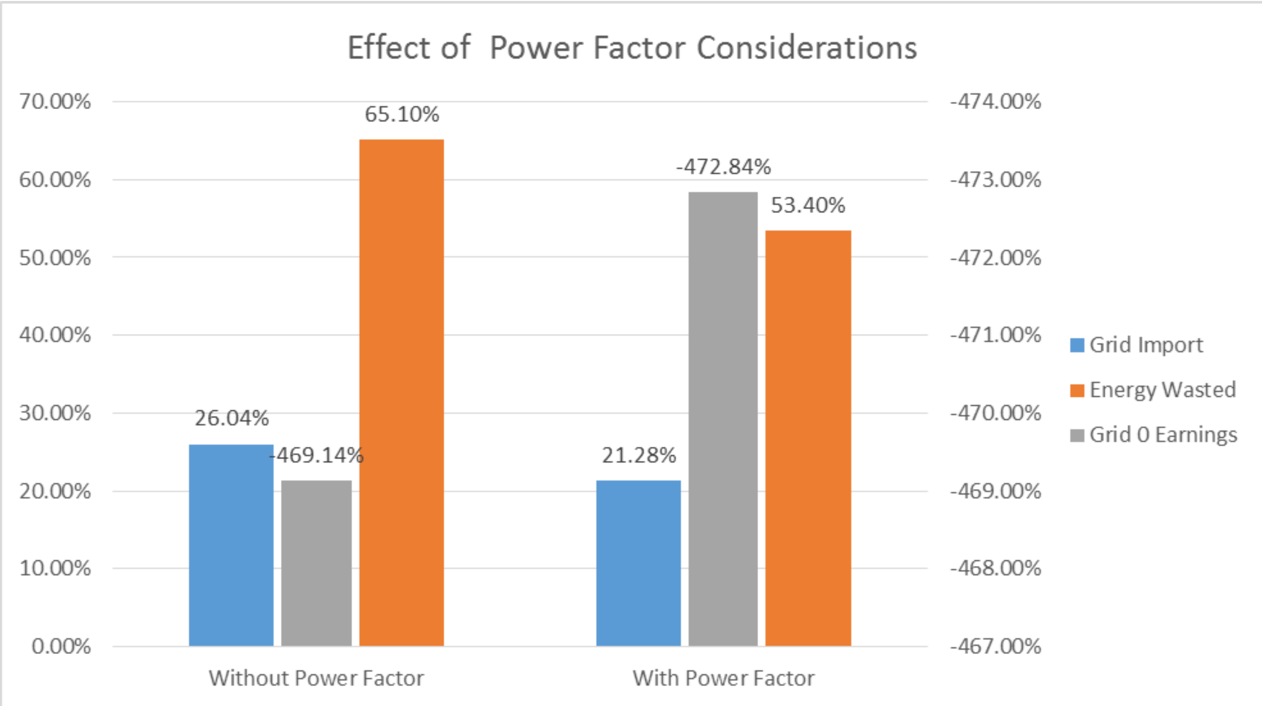


Figure 29 - Effect of Considering Issues related to Power Factor on Trade

One would expect power factor to have the same effect as distance on the simulations. Especially since they are written in the same way for the source code of MGTrader, however it can be seen that this is not the case. Grid 0’s expenditure remains the same (within a margin that can be attributed to random number generation). 12% less energy is wasted at the end of each time step due to the extra energy needed for some of the transactions. However, surprisingly the grid is used less when power factor is considered. There is only a small chance of the power factor being improper for any trade to occur but one would still expect this chance to increase the demand on the grid. However, the contrary is true. Even when considering the effects of random number generation there is still probably a decrease in demand on the national grid. As no explanation for this phenomena can be found it shall be considered an anomaly.

3.11 Final Case

Having examined the effect of each of the factors individually. One can begin to understand the effects of various factors and create a case which is both realistic and complimentary to trade. The later of these two criteria for the final case is difficult to judge as some factors are good for trade in some aspects and not in others. For example, the more storage and variability among the pool decreases the load on the national grid and energy wasted but also makes trading less profitable for the members of the pool. Therefore, two cases will be examined, one that prioritises national grid import (which often correlates with energy wasted from the pool) and a second that prioritises the economic benefits for microgrids. The cases are as follows:

Variable	**Case 1**	**Case 2-Energy**	**Case 3-Economic**
Number of Microgrids	10	100	50
Variability	Medium	High	Medium
Failure	No	Yes	Yes
Renewable Intermittence	No	Yes	Yes
Peak/Off-Peak Price Plan	No	Yes	No
Storage	None	500kWh	None
Demand Management	No	Yes	No

Distance	No	Yes	Yes
Power Factor	No	Yes	Yes

Table 20 - MGTrader set up for the Final Cases

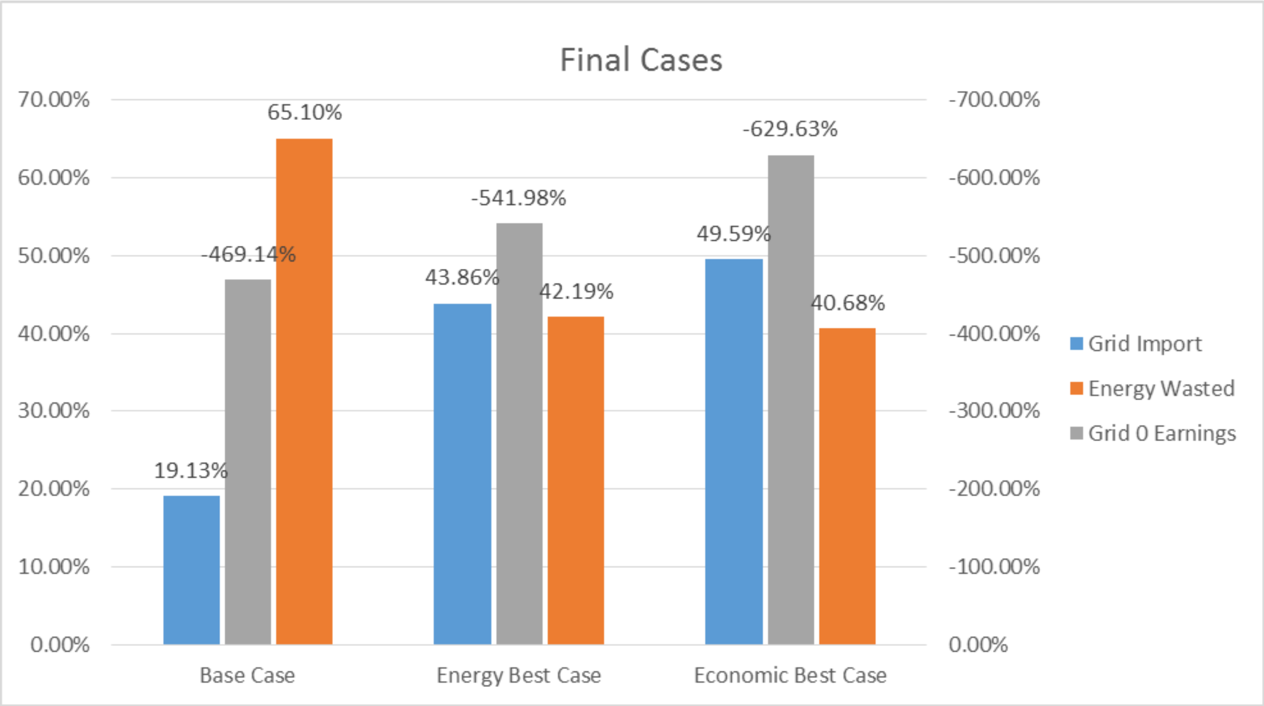


Figure 30 - Chart presenting two alternative cases in which trade is most viable

It can be seen in figure 30 that the consideration of failure, intermittence, power factor and distance results in a large increase of national grid imports as a percentage of transactions compared to the base case. Both scenarios waste a similar amount of energy from the pool. In order to decide which of the two scenarios is preferable, one must evaluate the amount of grid import vs the economic benefit for grid 0. The better scenario economically has a near 50% grid import which is not ideal. However, the gain economically between the two scenarios is greater than the increase in national grid import. A pool manager would have to weigh up this compromise before offering the terms of trading to his customers. As mentioned in section 3.6, the peak/off-peak price plan offers opportunity for microgrids to buy cheap electricity and avoid costs at times of peak demand or even sell on the energy for a profit. Since this cannot be investigated within MGTrader one cannot say for certain that this would make the first scenario better economically for the pool members but it is reasonable to hypothesise it.

The next chapter will take the information discussed in chapter three and link them back to the original objectives of the project laid out in chapter one to make the overall conclusions of this report.

4 Chapter Four: Conclusions and Future Work

The findings derived from the results of simulations using MGTrader have given great insight into the potential of microgrid energy trading. There are caveats to making trade work effectively according to the results but there is no reason to believe trading will not be possible in future. This chapter summarises the project, addressing whether or not the original objectives stated in chapter one have been achieved and defining potential future work to be done.

4.1 Is energy trading viable among microgrids?

This project has done nothing to disprove the viability of microgrid energy trading. Over the course of this project, MGtrader was run hundreds of times with different variables and seed data and there was never a result that suggested the national grid would be used more, or that constituent microgrids would lose money, compared to current circumstances. The simulations also did nothing to disprove that the trade of heat energy would be impossible either. The further developments to MGTrader have resulted in the benefits of microgrid energy trading being less significant that suggested by Sheik Muhammed Ali in 2009. However, trade between microgrids would still undoubtedly be of benefit to the national grid and the energy industry as a whole by encouraging independent energy generation, particularly through small scale renewables.

4.2 What are the caveats to making microgrid energy trading work?

There are a number of promotors and inhibitors for microgrid energy trading. Smart metering has allowed for mechanisms such as special energy price plans and demand management. The results of this project suggest that such plans have the potential to compliment microgrid energy trading. Trade is made more lucrative and successful by having a wide variety of sizes, demands and supply types within a low voltage network. However, distance is an inhibitor to trade. Therefore, the ideal microgrid energy trading environment would be in an urban setting with a diverse mix of universities, hospitals, hotels, businesses and domestic properties of various different sizes. Rural low voltage networks often span huge areas and trade would be inefficient as there would be many loses over the wires or, in the case of heat, pipes. Power factor considerations are an inhibitor to trade and should be regulated by the pool manager to ensure efficient power transaction.

Trade could be set up immediately in theory but with the current lack of microgrids, other than on a small scale, it would be unlikely to be lucrative. The more microgrids contributing and withdrawing from an energy pool the more successful trade is. From a microgrid's point of view, there is a point where greater numbers dilutes the potential profits to be had from trading but this effect is minor. Trading can offer opportunity for microgrids such as to use individual storage to buy energy cheap during night time rates and sell during peak times. Ultimately, microgrid energy trading is a force for good in terms of both energy and economics.

Centralised storage was proven to promote successful trade and reduce load on the national grid. However, sizing storage appropriately is important or the cost of installation and maintenance will be too high and the individual microgrid's potential profits from export become less appealing. Microgrid energy trading offers microgrid owners a more affordable safety net (than the national grid) when their equipment is failing, down for maintenance, or subject to renewable intermittence. If care is taken to create the right environment, trade can become a tool with huge potential to relieve the national grid and reward for microgrid owners.

4.3 Summary

In chapter one, the following project objectives were defined:

- To develop a software model of a microgrid energy trading environment.
- To investigate what factors affect energy trading positively and negatively, and to what extent?
- To make conclusions about the viability of microgrid energy trading and the circumstances under which it could be implemented.

The software was developed using the open source MGET-SIM software available on the University of Strathclyde's ESRU website, changing and developing it into MGTrader. Additions were made to the software to create an improved, realistic computer model and to investigate more factors that could be involved with microgrid energy trading. Alongside the additions, improvements were made to the operation of the programme, in particular the way in which variability influences the random number generator. These changes meant that, once the software was validated, an investigation of all the options available in MGTrader was merited, not just for the new additions. The development of the new MGTrader software successfully created a microgrid energy trading model environment.

At thorough, factor by factor investigation was carried out looking at the promotors and inhibitors to microgrid energy trading. It was found that;

- Diversity of supply types encourages trade.
- The more microgrids trading, the better in terms of energy. However, there some minor nuances to this economically.
- The greater the variety of microgrid size among energy pool contributors, trade is more successful.
- The negative effects equipment failure and renewable intermittence on a microgrid are mitigated by trade.
- Centralised storage, if sized correctly, would encourage trade.
- Demand management, another smart grid concept, works well with trade rather than conflicting with it.
- Distance and Power Factor both inhibit trade success but can be managed with rules of trade such as a maximum distance between trading grids.
- Peak/Off-Peak price plans neither inhibit nor contribute to trade. Economically it reduced the earnings of microgrids but with a more sophisticated strategy than what is currently available for MGTrader; it is hypothesised that price plans could be used as a tool for economic benefit.

The final conclusion of this work is that microgrid energy trading is not only viable but also has the potential to be hugely successful. There are caveats to the success of trade. However, trading does reduce the load on the national grid and provides an equal if not better alternative to feed-in-tariffs currently available. Further investigation is needed in this new fledgling field of the energy industry but microgrid energy trading potential for national grid load reduction, renewable installation and financial prosperity for microgrids is encouraging.

4.4 Future Work

During the course of this short three month project, many opportunities for further work were identified but were passed over because of the time restraints or because they were deemed outside the scope of the project. This section discusses some of these opportunities.

In terms of additions to MGTrader. There is an opportunity to add individual storage for each microgrid in addition to the centralised store. There are complications with this as one would have to write intelligent algorithm informing the microgrids when to buy electricity and when to use its own storage. Also storage assigned to each dummy microgrid would have to be proportional to the capacity of the microgrid in order to be realistic, which could be difficult to model in the current MGTrader set-up. Without this consideration, individual storage would have little effect on the overall results or would result in microgrids spending more than necessary on their energy.

One potential source of income for the energy pool would be to seek the excess energy at the end of each time step to local demand-only customers, this could be done fairly simply in MGTrader by setting one of the seed files to have no supply, so long as the code was adapted to prioritise microgrids. An experiment into how this would influence trading success would offer some interesting insight into a potential business avenue for the pool. With are round 40% of pool energy wasted in the final case simulation there is a considerable resource to be commoditised.

With much of the research in microgrid energy trading investigating trade models, integrating a more sophisticated trade platform into MGTrader could make the software more useful.

Much of the code for MGTrader captures the essence of factors such as distance or power factor rather than creating detailed models that represent the effects. Distance, for example, could be better represented by having each microgrid assigned with a coordinate (x,y). The losses incurred from trade between two microgrids could be proportional to the difference between those coordinates. The impact of distance is much greater on heat trade than it is on electricity so perhaps it is time heat trade within MGTrader be turned into a separate entity. These improvements in the quality of MGTrader would be of benefit to the credibility of the software going forward.

Adding 3 seed files greatly improved MGTrader. However, the user should be able to add more or less seed data without editing the source code.

Ultimately, many of the changes to MGtrader that could be made would increase the precision of the software which, although beneficial, is necessarily the best use of resources in this field going forward. Aside from a real world experimental set-up, which is a long way from coming into fruition. The next step arguably should be to create brand new software that takes a new approach to the same objective, simulating microgrid energy trading. This new software could define microgrids as individual entities with supply data, demand data, power factor, location, storage, maintenance schedule, demand management plan etc associated within them. The MGTrader relies on random number generation in a way that does not lend itself to achieving this association easily and therefore the code is often written to capture the effect of the factors simulated rather than developing a detailed model. By creating new software one could validate or dismiss the findings of MGTrader more emphatically. The new software could investigate peer-to-peer trading which many academics see as the way forward when microgrid privacy is considered. In a field of research that is as small and new as microgrid energy trading, new software would be of huge benefit as the concept starts to grow in the energy industry's consciousness.

References

Ali, S. M. (2009). *Electricity Trading Among Microgrids.* Glasgow: Universtiy of Strathclyde.

Consumer-Led Network Revolution. (2012, September 5). Customer Led Network Revolution (CLNR) | Fully Charged. Durham, Northumberland, UK.

Cui, T., Wang, Y., Nazarian, S., & Pedram, M. (2014). An Electricity Trade Model for Microgrid Communities in Smart Grid. *IEEE Power & Energy Society INnovative Smart Grid Technologies Conference.*

de Kock, J., & Strauss, K. (2004). *Practical Power Distribution for Industry.* Elsevier.

DECC. (2015). *Average variable unit costs and fixed costs of electricity for UK regions.*

Department of Energy & Climate Change. (2014). *UK Energy Statistics.*

Energy Star. (2015). *Energy Star Program Requirements for Computers Version 5.0.* Retrieved from Energy Star: http://www.energystar.gov/ia/partners/prod_development/revisions/downloads/computer/Version5.0_Computer_Spec.pdf

Fast Company. (2011, August 9). *Microgrid.* Retrieved from visual.ly: http://visual.ly/microgrid

Galvin & Yeager. (2009). *Perfect Power- How the Microgrid Revolution will Unleash Cleaner, Greener and more Abundant Energy.* New York: McGraw-Hill.

Gregoratti, D., & Matamous, J. (2015). Distributed Energy Trading: The Multiple Microgrid Case. *IEEE Transactions on Industrial Electronics, vol 62, no. 4*, 2551-2559.

Ilic, D., Da Silva, P., Karnouskos, S., & Griersemer, M. (2012). An Energy market for trading electricity in smart grid neighbouhoods. *6th IEEE Interational Conference on Digital Ecosystems Technologies (DEST).*

Kiwi Power. (2015). *About us*. Retrieved from Kiwi Power: http://www.kiwipowered.com/about

Luo, Y., Satoko, I., Shin, N., & Davis, P. (2014). Autonomous Cooperative Energy Trading Systems Between Prosumers for Microgrid Systems. *3rd IEEE International Workshop on Global Trends in Smart Cities* (pp. 693-696). Edmonton: goSMART 2014.

MacKay, D. J. (2009). *Sustainable Energy -- Without the hot air.* Cambridge: UIT.

Matamoros, J., Gregoratti, D., & Dohler, M. (2012). Microgrids Energy Trading in Islanding Mode. *IEEE SmartGridComm 2012 Symposium Conference Proceedings* (pp. 49-54). Tainan City: IEEE.

Open Energy Information. (n.d.). *Definition: Microgrids*. Retrieved from Open EI: http://en.openei.org/wiki/Definition:Microgrids

Pengelly, M. (2013, February 4). *Super Bowl delayed as power outage hits Superdome in New Orleans*. Retrieved from The Guardian: http://www.theguardian.com/sport/2013/feb/04/super-bowl-power-outage-superdome?guni=Article:in%20body%20link

Privat, G. (2012). How Information and Communication Technologies will Shape Smart Grids. In N. H. al, *Smart Grids* (pp. 263-280). London: John Wiley & Sons, Inc.

Sean Farrell, T. G. (2014, October 28). *National Grid: no risk of winter blackouts after fires and plant closures*. Retrieved from The Guardian: http://www.theguardian.com/business/2014/oct/28/national-grid-no-winter-blackout

Tao, C. (2014). The Microgrids Concept. In N. Hatziagyriou, Microgrids: Archetectures and Control (pp. 1-24). John Wiley & Sons Ltd. In *The Microgrids Concept* (pp. 1-24). John Wiley & Sons Ltd.

Tazoe, T., Matsumoto, J., Ishi, D., Okamoto, S., & Yamanaka, N. (2012). Novel Scheduling Method to Reduce Energy Cost by Cooperative Control of Smart Houses. *IEEE Int. Conference on Power System Technology (POWERCON)*, (pp. 1-6).

USwitch. (2014). *Smart Meters explained*. Retrieved from USwitch: http://www.uswitch.com/gas-electricity/guides/smart-meters-explained/#step1

YouGen. (2014). *Combined Heat & Power*. Retrieved from YouGen: http://www.yougen.co.uk/renewable-energy/Combined+Heat+'26+Power/#howmuchdoesitcost

Appendix 1

Code for MGTrader

```
#include <stdio.h>
#include <stdlib.h>
#include <time.h>
#include <string.h>

void init_mm();
int number_range(int from, int to);
int number_mm(void);
static int rgiState[2 + 55]; // for random number

int main(int argc, char *argv[])
{
        FILE *impfile;
        FILE *resultsfile;
        FILE *supdemdataone;
        FILE *supdemdatatwo;
        FILE *supdemdatathree;
        FILE *options;
        FILE *daynightprice;
    int c, i, j, x, z, N, abc, vsz, effz, refz, dnpz, xyz, lmn, mno, opq, pqr, qrs, gsk, gh,
gn, traderand, y, store, str, demz, demy, rnda, rndb, rndc, distchance, pfchance, seedfile,
ffc, pno, vcr;
    float mg[1000][48], vs, ngsp, mgsp, eff, ref, dnp[24], trade[1000][24], exp, grid,
cost, costg, ghi, jkl, mnop, inc[1000][24], demx, dem, pn, vc;
    int dnlp, distopt, pfoption;
        char infilename[100];
        char outfilename[120];
        char important[120];

    if ((supdemdataone = fopen("mg1.txt", "r")) == NULL)
```

```
    {
        printf("Cannot open file mg1.txt.\n");
        exit(1);
    }
        for (i = 0; i < 48; i++)
    {
                if (fscanf(supdemdataone, "%f", &mg[0][i]) != 1)
                {
                        break;
                }
    }
    fclose(supdemdataone);
    x = i;
    printf("Supply & Demand data in first text file is found for %d hours\n", (x/2));
    for (i = 0; i < x; i++)
    {
                printf("mg[0][%d] = %6.2f\n", i, mg[0][i]);
        }
//new
 if ((supdemdatatwo = fopen("mg2.txt", "r")) == NULL)
    {
        printf("Cannot open file mg2.txt.\n");
        exit(2);
    }
        for (i = 0; i < 48; i++)
    {
                if (fscanf(supdemdatatwo, "%f", &mg[1][i]) != 1)
                {
                        break;
                }
    }
    fclose(supdemdatatwo);
    x = i;
    printf("Supply & Demand data in second text file is found for %d hours\n", (x/2));
```

```
    for (i = 0; i < x; i++)
    {
                  printf("mg[1][%d] = %6.2f\n", i, mg[1][i]);
          }
//two
if ((supdemdatathree = fopen("mg3.txt", "r")) == NULL)
    {
        printf("Cannot open file mg3.txt.\n");
        exit(3);
    }
          for (i = 0; i < 48; i++)
    {
                  if (fscanf(supdemdatathree, "%f", &mg[2][i]) != 1)
                  {
                              break;
                  }
    }
    fclose(supdemdatathree);
    x = i;
    printf("Supply & Demand data in text third file is found for %d hours\n", (x/2));
    for (i = 0; i < x; i++)
    {
                  printf("mg[2][%d] = %6.2f\n", i, mg[2][i]);
          }
//end
          if (argc < 2)
                  {
                     printf("please define options file: main <option-file-name>\n");
                     exit(2);
                  }
                  strcpy(infilename, argv[1]);
                  options = fopen(infilename, "r");
                  if (options == NULL)
                  {
```

```
			printf("unable to open file %s\n", infilename);
			exit(3);
		}



	// How many dummy grids are required?
	fscanf (options, "%d", &N);
	printf ("%d microgrids created\n", N);

	// How much variability in size is required
	fscanf (options,"%d", &vsz);
	if (vsz== 1)
	{
		printf("low variability selected.\n");
	}
	if (vsz== 2)
	{
		printf("medium variability selected.\n");
	}
	if (vsz== 3)
	{
		printf("high variability selected.\n");
	}
	while (vsz < 1 || vsz > 3)
	{
		printf ("Error: Please Enter a value in the given range. \n"
		      " Enter 1 for low, 2 for medium and 3 for high.\n");
		exit(4);
	}

	// Is equipment failure possibility to be considered?
	fscanf (options, "%d", &effz);
	if (effz==1)
```

```
{
	printf("Equipment Failure is considered .\n");
}
if (effz==2)
{
	printf("Equipment Failure is not considered.\n");
}
while (effz < 1 || effz > 2)
{
	printf ("Error: Please Enter a value in the given range. \n "
		"Enter 1 for Yes, 2 for    No.\n");
	exit(5);
}

// Is intermittence of renewable energy sources to be considered
fscanf (options,"%d", &refz);
if (refz== 1)
{
	printf("Intermittence Considered.\n");
}
if (refz== 2)
{
	printf("Intermittence Not Considered.\n");
}
while (refz < 1 || refz > 2)
{
	printf ("Error: Please Enter a value in the given range. \n");
	exit(6);
}

// National grid electricity price
fscanf (options, "%f", &ngsp);
printf("National Grid Electricity Price %.1fpence/kWh\n", ngsp);
while (ngsp < 0.001)
```

```
	{
		printf ("Error: Invalid Price entered \n Please enter the national grid electricity	price in pence/kWh\n");
		exit(7);
	}
	// Microgrid electricity price
	fscanf (options, "%f", &mgsp);
	printf("Microgrid Electricity Price %.1fpence/kWh\n", mgsp);
	while (mgsp >= ngsp)
	{
		printf ("Error: Invalid Price entered \n Price must be less than national grid electricity price\n "
			"Please enter the micro-grid electricity price in pence/kWh\n");
		exit(8);
	}
	// night money saver plan
	fscanf (options,"%d", &dnpz);
	if(dnpz== 1)
	{
		printf("Day-Night saver plan selected\n");
	}
	if(dnpz== 2)
	{
		printf("No Day-Night saver plan selected\n");
	}
	while (dnpz < 1 || dnpz > 2)
	{
		printf ("Error: Please Enter a value in the given range. \n Do you want to consider different electricity rates in day & night?\n "
			"Enter 1 for Yes, 2 for No.\n");
		exit(9);
	}

	//Storage ask for capacity
```

```
fscanf(options, "%d", &store);
printf("Storage capacity set at %dkWh\n", store);

//Energy stored at start.
fscanf(options, "%d", &str);
printf("Energy available in store at start of simulation %dkWh\n", str);
while (str > store)
{
	printf("Error: Invalid stored energy amount \n amount stored must be less than or equal to storage capacity\n");
	exit(10);
}
//Demand Management
fscanf (options,"%d", &demz);
if (demz== 1)
{
	printf("Demand Management Considered.\n");
}
if (demz== 2)
{
	printf("Demand Management Not Considered.\n");
}
while (demz < 1 || demz > 2)
{
	printf ("Error: Please Enter a value in the given range. \n");
	exit(11);
}
//Distance
fscanf(options, "%d", &distopt);
if(distopt == 1)
{
	printf("Distance considered\n");
}
if(distopt == 2)
```

```
	{
		printf("Distance not considered\n");
	}
	while (distopt< 1 || distopt > 2)
	{
		printf ("Error: Please Enter a value in the given range. \n Do you want to consider power factor?\n "
			"Enter 1 for Yes, 2 for No.\n");
		exit(12);
	}
	//power factor
	fscanf(options, "%d", &pfoption);
	if(pfoption == 1)
	{
		printf("powerfactor considered\n");
	}
	if(pfoption == 2)
	{
		printf("powerfactor not considered\n");
	}
	while (pfoption< 1 || pfoption > 2)
	{
		printf ("Error: Please Enter a value in the given range. \n Do you want to consider power factor?\n "
			"Enter 1 for Yes, 2 for No.\n");
		exit(13);
	}
	fclose(options);

	//assess options
	printf("Press y then Enter to continue to results\n");
	scanf("%d", &y);

	init_mm(); //seed the number generator
```

```
for (j = 3; j <= N; j++)
{
	seedfile = number_range(1, 3);
	if (vsz == 1)
	{
		abc = number_range( 0, 10 );
		vs = (0.1*(5.0+abc));
	}
	if (vsz == 2)
	{
		ffc = number_range(1,2);
		if(ffc==1)
		{
			abc = number_range( 0, 7 );
		}
		if(ffc==2)
		{
			abc = number_range( 8, 27 );
		}
		vs = (0.1*(3.0+abc));
	}
	if (vsz == 3)
	{
		ffc = number_range(1,2);
		if(ffc==1)
		{
			abc = number_range( 0, 9 );
		}
		if(ffc==2)
		{
			abc = number_range( 10, 99 );
		}
		vs = (0.1*(1+abc));
	}
```

```
for (i=0; i<48; i++)
{
    if (vsz == 1)
    {
        vcr = number_range( 1, 15 );
    }
    if (vsz == 2)
    {
        vcr = number_range( 1, 30 );
    }
    if (vsz == 3)
    {
        abc = number_range( 1, 45 );
    }
    pno = number_range (1 , 2);
    if(pno == 1)
    {
        pn=1;
    }
    if(pno == 2)
    {
        pn = -1;
    }
    vc = pn * 0.01 * vcr;
    if (effz == 1)
    {
        lmn = number_range( 0, 1 );
        mno = number_range( 0, 1 );
        opq = number_range( 0, 1 );
        pqr = number_range( 0, 1 );
        qrs = number_range( 0, 1 );
        eff =
(lmn+mno+opq+pqr+qrs)/(lmn+mno+opq+pqr+qrs+0.000001);
    }
```

```
if (effz == 2)
{
	eff = 1.0;
}
if(demz == 1)
{
	rnda = number_range( 0, 1 );
	rndb = number_range( 0, 1 );
	rndc = number_range( 0, 1 );
	demx = (rnda+rndb+rndc)/(rnda+rndb+rndc+0.000001);
	if (demx == 0)
	{
		demy = number_range(1, 6);
		if (demy == 1)
		{
			dem = 0.25;
		}
		if (demy > 1)
		{
			dem = 0.75;
		}
	}
	else
	{
		dem = 1.0;
	}
}
if(demz == 2)
{
	dem =1.0;
}
if (refz == 1 && seedfile != 2)
{
	xyz = number_range( 7, 10 );
```

```
		ref = (0.1*(xyz));
	}
	if (refz == 2 || seedfile == 2)
	{
		ref = 1.0;
	}
	if (dnpz == 1)
	{
		if ((daynightprice=fopen("dnp1.txt", "r"))==NULL)
		{
			printf("Cannot open the night package file.\n");
			exit(14);
		}
		for (dnlp = 1; dnlp <= 24; dnlp++)
		{
			if (fscanf(daynightprice, "%f", &dnp[dnlp]) != 1)
			{
				break;
			}
		}
		fclose(daynightprice);
	}
	if (dnpz == 2)
	{
		if ((daynightprice=fopen("dnp0.txt", "r"))==NULL)
		{
			printf("Cannot open the price package file.\n");
			exit(15);
		}
		for (dnlp = 1; dnlp <= 24; dnlp++)
		{
			if (fscanf(daynightprice, "%f", &dnp[dnlp]) != 1)
			{
				break;
```

```
            }
        }
        fclose(daynightprice);
    }
    {
        if(seedfile == 1)
        {
            // Pick out odd numbered ones i.e. demand
            if (i % 2 != 0)
            {// Odd numbered elements are demand
                mg[j][i]= (mg[0][i] * vs * dem +
(vc*vs*mg[0][i]));
            }
            else
            {// Even ones are supply
                mg[j][i]= (mg[0][i] * vs * eff * ref +
(eff*vc*vs*mg[0][i]));
            }
        }
        if(seedfile == 2)
        {
            // Pick out odd numbered ones i.e. demand
            if (i % 2 != 0)
            {// Odd numbered elements are demand
                mg[j][i]= (mg[1][i] * vs * dem +
(vc*vs*mg[1][i]));
            }
            else
            {// Even ones are supply
                mg[j][i]= (mg[1][i] * vs * eff * ref);
            }
        }
        if(seedfile == 3 )
        {
```

```
                                        // Pick out odd numbered ones i.e. demand
                                        if (i % 2 != 0)
                                        {// numbers 1, 3, 5 etc numbered elements are
demand
                                                mg[j][i]= (mg[2][i] * vs * dem +
(vc*vs*mg[2][i]));
                                        }
                                        else
                                        {// Even ones are supply
                                                mg[j][i]= (mg[2][i] * vs * eff * ref +
(eff*vc*vs*mg[2][i]));
                                        }
                                }
                                printf ("mg[%d][%d] is %10.2f\n", j, i, mg[j][i]);
                        }
                }
        }
        strcpy(outfilename, "out");
        strcat(outfilename, infilename);
        resultsfile = fopen(outfilename, "w");
        strcpy(important, "imp");
        strcat(important, infilename);
        impfile = fopen(important, "w");
        if (important == NULL)
        {
                printf("\nError opening important results file\n");
                exit(16);
        }
        if (resultsfile == NULL)
        {
                printf("\nError opening results file\n");
                exit(17);
        }
        for (gh = 1; gh <= 24; gh++)
```

```
{
    exp = str;
    grid = 0;
    mnop = 0;
    printf("%dkWh Energy Stored\n", str);
    fprintf(resultsfile, "%dkWh Energy Stored\n", str);
    for (gn = 0; gn <= N; gn++)
    {
        trade [gn][gh]= (mg[gn][(gh*2)-2])-(mg[gn][(gh*2)-1]);
        printf ("Hour no %d: Energy available in Micro-grid No.%d
is %10.2f kWh\n", gh, gn, trade[gn][gh]);
        fprintf(resultsfile, "%d %d %7.2f ", gh, gn, trade[gn][gh]);
        if ((trade[gn][gh])>0)
        {
            exp = exp + (trade[gn][gh]);
            ghi = exp;
            fprintf(resultsfile, "%9.2f\n", exp);
        }
        if ((trade[gn][gh])<0)
        {
            fprintf(resultsfile, "%9.2f\n", exp);
        }
        if (gn == N)
        {
            printf ("Energy available in the microgrids pool
including storage is %10.2f\n", exp);
            for (gsk=0; gsk<(10*N); gsk++)
            {
                traderand = number_range( 0, gn );
                if ((trade[traderand][gh])<0)
                {
                    printf ("Random grid selected for
electricity trading is %d\n", traderand);
                    if(distopt == 1)
```

```
{
    distchance = number_range(1,12);
}
if(distopt == 2)
{
    distchance = 1;
}
if(pfoption == 1)
{
    pfchance = number_range(1,20);
}
if(pfoption == 2)
{
    pfchance = 1;
}
if (((trade[traderand][gh])+exp)>0 && distchance<=5)
{
    if(pfchance <= 15)
    {
        cost = (trade[traderand][gh])*dnp[gh]*mgsp*0.01;
        printf ("Hour No. %d\nImporter: Microgrid No. %d\nImport: %10.2f kWh\n Cost: £%3.2f\n",

    gh,traderand,(trade[traderand][gh]),cost);
        fprintf (resultsfile, "%d %d %7.2f", gh,traderand,(trade[traderand][gh]));
        exp = exp + (trade[traderand][gh]);
        printf ("Energy still available: %10.2f kWh\n",exp);
        fprintf(resultsfile, "%9.2f %6.2f\n", exp,cost);
```

```
(trade[traderand][gh])= 0;
if(traderand==0)
{
fprintf(impfile,
"Hour %d Grid 0 spends %5.2f and %5.2f\n", gh, cost, costg);
}
cost = 0;
costg = 0;
}
if(pfchance>15 &&
pfchance<=19)
{
cost =
(trade[traderand][gh])*dnp[gh]*mgsp*0.01;
printf ("Hour
No. %d\nImporter: Microgrid No. %d\nImport: %10.2f kWh\n Cost: £%3.2f\n",

gh,traderand,(trade[traderand][gh]),cost);
fprintf (resultsfile,
"%d %d %7.2f", gh,traderand,(trade[traderand][gh]));
exp = exp +
(1.25*(trade[traderand][gh]));
if(exp<0)
{
costg =
(exp*dnp[gh]*ngsp*0.01);
mnop=mnop +
(exp*dnp[gh]*ngsp*0.01);
exp = 0;
}
printf ("Energy still
available: %10.2f kWh\n",exp);
fprintf(resultsfile,
"%9.2f %6.2f grid earns %6.2f\n", exp,cost, mnop);
```

```
(trade[traderand][gh])= 0;
if(traderand==0)
{
    fprintf(impfile,
"Hour %d Grid 0 spends %5.2f and %5.2f\n", gh, cost, costg);
}
cost = 0;
costg = 0;
}
if(pfchance > 19)
{
costg =
(trade[traderand][gh])*dnp[gh]*ngsp*0.01;
printf ("Hour
No. %d\nImporter: Microgrid No. %d\nImport: %10.2f kWh\n Cost/kWh: %3.2f\n",

gh,traderand,(trade[traderand][gh]),costg);
fprintf (resultsfile,
"%d %d %7.2f", gh,traderand,(trade[traderand][gh]));
grid = grid +
(trade[traderand][gh]);
fprintf(resultsfile,
"%9.2f %6.2f", grid,costg);
printf ("Total electricity
imported from the grid: %10.2f kWh\n",grid);
(trade[traderand][gh])= 0;
mnop=mnop+costg;
fprintf(resultsfile,
"%7.2f\n", mnop);
if(traderand==0)
{
    fprintf(impfile,
"Hour %d Grid 0 spends %5.2f and %5.2f\n", gh, cost, costg);
}
```

```
cost = 0;
costg = 0;
}
}
if ((((trade[traderand][gh]))+exp)>0 &&
distchance>5 && distchance<=8)
{
if(pfchance <= 15)
{
cost =
(trade[traderand][gh])*dnp[gh]*mgsp*0.01;
printf ("Hour
No. %d\nImporter: Microgrid No. %d\nImport: %10.2f kWh\n Cost: £%3.2f\n",

gh,traderand,(trade[traderand][gh]),cost);
fprintf (resultsfile,
"%d %d %7.2f", gh,traderand,(trade[traderand][gh]));
exp = exp +
(1.5*(trade[traderand][gh]));
if(exp<0)
{
costg =
(exp*dnp[gh]*ngsp*0.01);
mnop=mnop +
(exp*dnp[gh]*ngsp*0.01);
exp = 0;
}
printf ("Energy still
available: %10.2f kWh\n",exp);
fprintf(resultsfile,
"%9.2f %6.2f grid earns %6.2f\n", exp,cost, mnop);
(trade[traderand][gh])= 0;
if(traderand==0)
{
```

```
fprintf(impfile, "Hour %d Grid 0 spends %5.2f and %5.2f\n", gh, cost, costg);
}
cost = 0;
costg = 0;
}
if(pfchance>15 && pfchance<=19)
{
cost = (trade[traderand][gh])*dnp[gh]*mgsp*0.01;
printf ("Hour No. %d\nImporter: Microgrid No. %d\nImport: %10.2f kWh\n Cost: £%3.2f\n",
gh,traderand,(trade[traderand][gh]),cost);
fprintf (resultsfile, "%d %d %7.2f", gh,traderand,(trade[traderand][gh]));
exp = exp + (1.875*(trade[traderand][gh]));
if(exp<0)
{
costg = (exp*dnp[gh]*ngsp*0.01);
mnop=mnop + (exp*dnp[gh]*ngsp*0.01);
exp = 0;
}
printf ("Energy still available: %10.2f kWh\n",exp);
fprintf(resultsfile, "%9.2f %6.2f grid earns %6.2f\n", exp,cost, mnop);
(trade[traderand][gh])= 0;
if(traderand==0)
{
```

```
fprintf(impfile,
"Hour %d Grid 0 spends %5.2f and %5.2f\n", gh, cost, costg);
}
cost = 0;
costg = 0;
}
if(pfchance > 19)
{
costg =
(trade[traderand][gh])*dnp[gh]*ngsp*0.01;
printf ("Hour
No. %d\nImporter: Microgrid No. %d\nImport: %10.2f kWh\n Cost/kWh: %3.2f\n",

gh,traderand,(trade[traderand][gh]),costg);
fprintf (resultsfile,
"%d %d %7.2f", gh,traderand,(trade[traderand][gh]));
grid = grid +
(trade[traderand][gh]);
fprintf(resultsfile,
"%9.2f %6.2f", grid,costg);
printf ("Total electricity
imported from the grid: %10.2f kWh\n",grid);
(trade[traderand][gh])= 0;
mnop=mnop+costg;
fprintf(resultsfile,
"%7.2f\n", mnop);
if(traderand==0)
{
fprintf(impfile,
"Hour %d Grid 0 spends %5.2f and %5.2f\n", gh, cost, costg);
}
cost = 0;
costg = 0;
}
```

```
}
if (((trade[traderand][gh])+exp)<0 ||
distchance>8)
{
costg =
(trade[traderand][gh])*dnp[gh]*ngsp*0.01;
printf ("Hour No. %d\nImporter:
Microgrid No. %d\nImport: %10.2f kWh\n Cost/kWh: %3.2f\n",

gh,traderand,(trade[traderand][gh]),costg);
fprintf (resultsfile,
"%d %d %7.2f", gh,traderand,(trade[traderand][gh]));
grid = grid +
(trade[traderand][gh]);
fprintf(resultsfile, "%9.2f %6.2f",
grid,costg);
printf ("Total electricity imported
from the grid: %10.2f kWh\n",grid);
(trade[traderand][gh])= 0;
mnop=mnop+costg;
fprintf(resultsfile, "%7.2f\n",
mnop);
if(traderand==0)
{
fprintf(impfile,
"Hour %d Grid 0 spends %5.2f and %5.2f\n", gh, cost, costg);
}
cost = 0;
costg = 0;
}
fprintf(resultsfile, "National Grid
earns %7.2f\n", mnop);
}
}
```

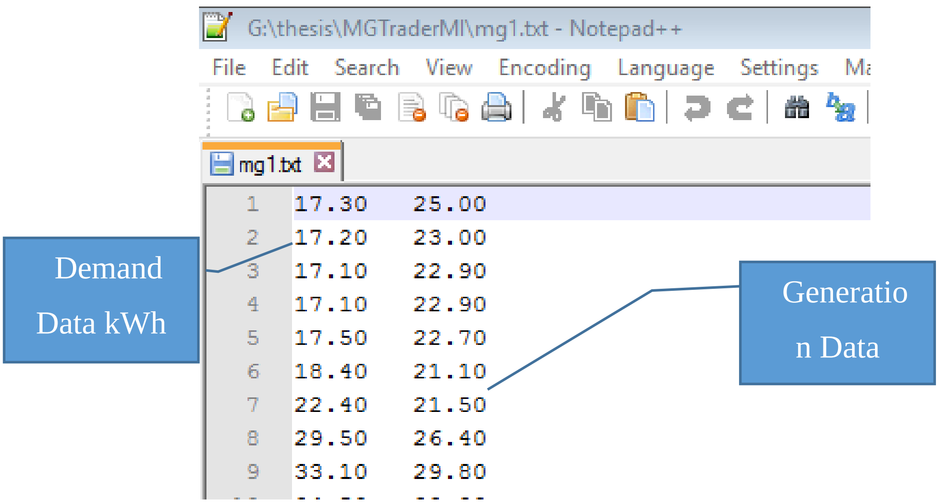
```
                jkl=ghi-exp;
                fprintf(impfile, "Hour %d grid import is %5.2f
percent\n", gh, 100*(abs(grid)/(abs(grid)+jkl)));
            }
            inc[i][gh]=0;
            for (i=0;i<=N;i++)
            {
                if ((trade[i][gh])>0)
                {

    inc[i][gh]=((trade[i][gh])*dnp[gh]*mgsp*0.01*jkl)/ghi;
                    if (inc[i][gh]>0)
                    {
                        fprintf(resultsfile, "Grid No:%d
earns %6.2f\n", i,inc[i][gh]);
                        if(i==0)
                        {
                            fprintf(impfile, "Hour %d Grid 0
earns %5.2f\n", gh, inc[i][gh]);
                        }
                        inc[i][gh]=0;
                    }
                }
            }
            jkl=0;
        }
        if(exp >= store)
        {
            fprintf(impfile, "Hour %d Energy Wasted is %5.2f percent\n\n",
gh, (100*((exp-store)/(ghi-str))));
            str = store;
        }
        if(exp < store)
        {
```

```
                fprintf(impfile, "Hour %d No Energy wasted\n\n", gh);
                str = exp;
            }
    };
    fclose(impfile);
    fclose(resultsfile);
    printf ("See the %s file in the program folder for simulation results, highlighted
data found in %s\n", outfilename, important);
    return 0;
}
int number_mm( void ) //for random number generator (ref.16) //
{
    int *piState;
    int iState1;
    int iState2;
    int iRand;
    piState = &rgiState[2];
    iState1 = piState[-2];
    iState2 = piState[-1];
    iRand = ( piState[iState1] + piState[iState2] )        & ( ( 1 << 30 ) - 1 );
    piState[iState1] = iRand;
    if ( ++iState1 == 55 )
    iState1 = 0;
    if ( ++iState2 == 55 )
    iState2 = 0;
    piState[-2] = iState1;
    piState[-1] = iState2;
    return iRand >> 6;
}
/*
* Generate a random number.
*/
int number_range( int from, int to ) //for random number generator
{
```

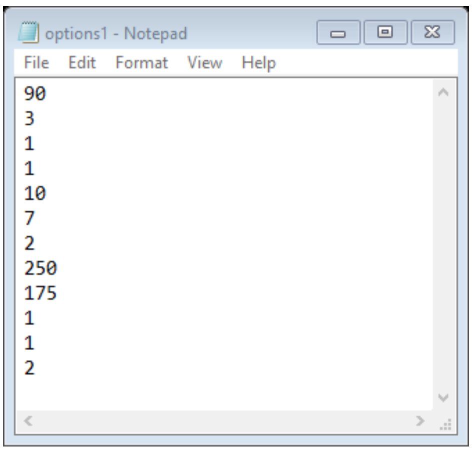
```
    int power;
    int number;
    if ( ( to = to - from + 1 ) <= 1 )
    return from;
    for ( power = 2; power < to; power <<= 1 )
    ;
    while ( ( number = number_mm( ) & ( power - 1 ) ) >= to )
    ;
    return from + number;
}
/*
* This is the Mitchell-Moore algorithm from Knuth Volume II.
*/
void init_mm( ) //for random number generator
{
    int *piState;
    int iState;
    piState = &rgiState[2];
    piState[-2] = 55 - 55;
    piState[-1] = 55 - 24;
    piState[0] = ( (int) time( NULL ) ) & ( ( 1 << 30 ) - 1 );
    piState[1] = 1;
    for ( iState = 2; iState < 55; iState++ )
    {
        piState[iState] = ( piState[iState-1] + piState[iState-2] )
        & ( ( 1 << 30 ) - 1 );
    }
    return ; //end of code for random number generator
}
```

MGTrader Readme file

1) Before the simulation process can begin. Three seed files must be entered into the program folder named mg1.txt, mg2.txt and mg3.txt. Within each of there should be 48 numbers, the first value should be a demand and the second value should be a supply and so on until there is supply and demand data in kWh for 24 time steps. It is recommended that the user inputs seed data with relatively high supply and demand values as the software will generate some microgrids that are much smaller than the seed data.



2) Secondly and options text file needs to be created in the program folder. The file should look like this:



For example, the file screenshotted above tells MGTrader to create 90 microgrids (NB: three of which are already been defined by the user) with high variability in sizes (1 being low, 2 being medium). Equipment failure and renewable intermittence are both considered (2 would represent ignoring these factors). The price of national grid energy is 10pence/kWh and the price of microgrid pool energy is 7pence/kWh. There is no peak/off peak price plan. The pool has 250kWh of energy storage, 175kWh is filled at the start of simulation. Demand management and distance are considered while power factor is not.

3) Open a command prompt and navigate to the directory where the program is stored. Run the program, quoting the name of the options file that you have created. The program will pause to allow you to review the seed data and the summary of the simulation that is about to take place. Press y and enter to continue.

4) The programme will create two files at the end of the simulation. One file called imp*optionsfilename*.txt will provide a summary of the important information hour by hour used for calculating the grid import, energy wasted and grid 0 energy expenditure over the 24 timesteps. The second file out*optionsfilename*.txt will provide a full and in depth breakdown of the simulation's trade results.

Appendix 2

Please find the source material used to start this project. Thanks to Sheikh Muhammed Ali and the University of Strathclyde ESRU team.

Original code for MGET-SIM

```
#include <stdio.h>
#include <stdlib.h>
#include <iostream.h>
#include <time.h>

void init_mm( );
int number_range( int from, int to );
int number_mm( void );
static int rgiState[2+55]; // for random number
int main(void)
{
FILE *fp; /* file pointer */
int c,i,j,x,z,N,abc,vsz,effz,refz,dnpz,xyz,lmn,mno,opq,pqr,qrs,gsk,gh,gn,traderand;
float
mg[1000][48],vs,ngsp,mgsp,eff,ref,dnp[24],trade[1000][24],exp,grid,cost,costg,ghi,j
k
l,mnop,inc[1000][24];
if ((fp=fopen("mg1.txt", "r"))==NULL)
{
printf("Cannot open file.\n");
71
}
for (i = 0; i < 48; i++)
{
if (fscanf(fp, "%f", &mg[0][i]) != 1)
{
break;
}
```

```
}
fclose(fp);
x = i;
printf("Supply & Demand data in text file is found for %d hours\n", (x/2));
for (i = 0; i < x; i++)
{
printf("mg[0][%d] = %6.2f\n", i, mg[0][i]);
}
// ask user how many dummy grids are required
printf ("what are the number of dummy micro-grids do you want to simulate
electricity trading with?\n");
scanf ("%d", &N);
// ask user how much variability in size is required
printf ("what should be the variability in size of dummy micro-grids from the given
micro-grid?\n Enter 1 for low, 2 for medium and 3 for high.\n");
scanf ("%d", &vsz);
while (vsz < 1)
72
{
printf ("Error: Please Enter a value in the given range. \n what should be the
variability in size of dummy micro-grids from the given micro-grid?\n Enter 1 for
low, 2 for medium and 3 for high.\n");
scanf ("%d", &vsz);
}
while (vsz > 3)
{
printf ("Error: Please Enter a value in the given range. \n what should be the
variability in size of dummy micro-grids from the given micro-grid?\n Enter 1 for
low, 2 for medium and 3 for high.\n");
scanf ("%d", &vsz);
}
// ask user if equipment failure possibility is to be considered
printf ("Do you want to consider the possibility of equipment failure in microgrids?\
n Enter 1 for Yes, 2 for No.\n");
```

```
scanf ("%d", &effz);
while (effz < 1)
{
printf ("Error: Please Enter a value in the given range. \n Do you want to
consider the possibility of equipment failure in micro-grids?\n Enter 1 for Yes, 2 for
No.\n");
scanf ("%d", &effz);
}
73
while (effz > 2)
{
printf ("Error: Please Enter a value in the given range. \n Do you want to
consider the possibility of equipment failure in micro-grids?\n Enter 1 for Yes, 2 for
No.\n");
scanf ("%d", &effz);
}
// ask user if intermittence of renewable energy sources is to be considered
printf ("Do you want to consider the intermittence of renewable energy supplies in
micro-grids?\n Enter 1 for Yes, 2 for No.\n");
scanf ("%d", &refz);
while (refz < 1)
{
printf ("Error: Please Enter a value in the given range. \n Do you want to
consider the intermittence of renewable energy supplies in micro-grids?\n Enter 1 for
Yes, 2 for No.\n");
scanf ("%d", &refz);
}
while (refz > 2)
{
printf ("Error: Please Enter a value in the given range. \n Do you want to
consider the intermittence of renewable energy supplies in micro-grids?\n Enter 1 for
Yes, 2 for No.\n");
scanf ("%d", &refz);
74
```

```
}
// ask user the national grid electricity price
printf ("Please enter the national grid electricity price in pence/kWh\n");
scanf ("%f", &ngsp);
while (ngsp < 0.001)
{
printf ("Error: Invalid Price entered \n Please enter the national grid electricity
price in pence/kWh\n");
scanf ("%f", &ngsp);
}
// ask user the microgrid electricity price
printf ("Please enter the micro-grid electricity price in pence/kWh\n");
scanf ("%f", &mgsp);
while (mgsp >= ngsp)
{
printf ("Error: Invalid Price entered \n Price must be less than national grid
electricity price\n Please enter the micro-grid electricity price in pence/kWh\n");
scanf ("%f", &mgsp);
}
// ask user ask user if the night money saver plan is to be considered for electricity
price
printf ("Do you want to consider different electricity rates in day & night?\n Enter 1
for Yes, 2 for No.\n");
scanf ("%d", &dnpz);
75
while (dnpz < 1)
{
printf ("Error: Please Enter a value in the given range. \n Do you want to
consider different electricity rates in day & night?\n Enter 1 for Yes, 2 for No.\n");
scanf ("%d", &dnpz);
}
while (dnpz > 2)
{
printf ("Error: Please Enter a value in the given range. \n Do you want to
```

```
consider different electricity rates in day & night?\n Enter 1 for Yes, 2 for No.\n");
scanf ("%d", &dnpz);
}
init_mm(); //seed the number generator
for (j=1; j<=N; j++)
for (i=0; i<48; i++)
{
if (vsz == 1)
{
abc = number_range( 0, 10 );
vs = (0.1*(5.0+abc));
}
if (vsz == 2)
76
{
abc = number_range( 0, 27 );
vs = (0.1*(3.0+abc));
}
if (vsz == 3)
{
abc = number_range( 0, 100 );
vs = (0.1*abc);
}
if (effz == 1)
{
lmn = number_range( 0, 1 );
mno = number_range( 0, 1 );
opq = number_range( 0, 1 );
pqr = number_range( 0, 1 );
qrs = number_range( 0, 1 );
eff = (lmn+mno+opq+pqr+qrs)/(lmn+mno+opq+pqr+qrs+0.000001);
}
if (effz == 2)
{
```

```
eff = 1.0;
}
if (refz == 1)
{
77
xyz = number_range( 7, 10 );
ref = (0.1*(xyz));
}
if (refz == 2)
{
ref = 1.0;
}
if (dnpz == 1)
{
if ((fp=fopen("dnp1.txt", "r"))==NULL)
{
printf("Cannot open the night package file.\n");
}
for (int dnlp = 1; dnlp <= 24; dnlp++)
{
if (fscanf(fp, "%f", &dnp[dnlp]) != 1)
{
break;
}
}
fclose(fp);
}
if (dnpz == 2)
{
78
if ((fp=fopen("dnp0.txt", "r"))==NULL)
{
printf("Cannot open the price package file.\n");
}
```

```
for (int dnlp = 1; dnlp <= 24; dnlp++)
{
if (fscanf(fp, "%f", &dnp[dnlp]) != 1)
{
break;
}
}
fclose(fp);
}
{
if (i%2!=0)
{
mg[j][i]= (mg[0][i]*vs);
}
else mg[j][i]= (mg[0][i]*vs*eff*ref);
printf ("mg[%d][%d] is %10.2f\n", j, i, mg[j][i]);
}
};
fp = fopen("results.txt", "w");
if (fp == NULL)
79
{
printf("\nError opening write.txt\n");
exit(1);
}
else;
for (gh=1; gh<=24; gh++)
{
exp = 0;
grid = 0;
mnop=0;
for (gn=0; gn<=N; gn++)
{
trade [gn][gh]= (mg[gn][(gh*2)-2])-(mg[gn][(gh*2)-1]);
```

```
printf ("Hour no %d: Energy available in Micro-grid No.%d is %10.2f
kWh\n", gh, gn, trade[gn][gh]);
fprintf(fp, "%d %d %7.2f ", gh, gn, trade[gn][gh]);
if ((trade[gn][gh])>0)
{
exp = exp + (trade[gn][gh]);
ghi = exp;
fprintf(fp, "%9.2f\n", exp);
}
if (gn == N)
{
80
printf ("Energy available in the microgrids pool is %10.2f\n", exp);
for (gsk=0; gsk<(10*N); gsk++)
{
traderand = number_range( 0, gn );
if ((trade[traderand][gh])<0)
{
printf ("Random grid selected for electricity trading is %d\n",
traderand);
if (((trade[traderand][gh])+exp)>0)
{
cost = (trade[traderand][gh])*dnp[gh]*mgsp*0.01;
printf ("Hour No. %d\nImporter: Microgrid No. %d\nImport:
%10.2f kWh\n Cost/kWh: %3.2f\n", gh,traderand,(trade[traderand][gh]),cost);
fprintf (fp, "%d %d %7.2f", gh,traderand,(trade[traderand][gh]));
exp = exp + (trade[traderand][gh]);
printf ("Energy still available: %10.2f kWh\n",exp);
fprintf(fp, "%9.2f %6.2f\n", exp,cost);
(trade[traderand][gh])= 0;
}
if (((trade[traderand][gh])+exp)<0)
{
costg = (trade[traderand][gh])*dnp[gh]*ngsp*0.01;
```

```
printf ("Hour No. %d\nImporter: Microgrid No. %d\nImport:
%10.2f kWh\n Cost/kWh: %3.2f\n", gh,traderand,(trade[traderand][gh]),costg);
81
fprintf (fp, "%d %d %7.2f", gh,traderand,(trade[traderand][gh]));
grid = grid + (trade[traderand][gh]);
fprintf(fp, "%9.2f %6.2f", grid,costg);
printf ("Total electricity imported from the grid: %10.2f
kWh\n",grid);
(trade[traderand][gh])= 0;
mnop=mnop+costg;
fprintf(fp, "%7.2f\n", mnop);
}
fprintf(fp, "National Grid earns %7.2f\n", mnop);
}
}
jkl=ghi-exp;
}
inc[i][gh]=0;
for (i=0;i<=N;i++)
{
if ((trade[i][gh])>0)
{
inc[i][gh]=((trade[i][gh])*dnp[gh]*mgsp*0.01*jkl)/ghi;
if (inc[i][gh]>0)
{
fprintf(fp, "Grid No:%d earns %6.2f\n", i,inc[i][gh]);
inc[i][gh]=0;
82
}
}
}
jkl=0;
}
};
```

```
fclose(fp);
printf ("See the results.txt file in the program folder for simulation results\n Press C
then Enter to close the program");
scanf ("%d",&c);
return 0;
}
int number_mm( void ) //for random number generator (ref.16) //
{
int *piState;
int iState1;
int iState2;
int iRand;
piState = &rgiState[2];
iState1 = piState[-2];
iState2 = piState[-1];
iRand = ( piState[iState1] + piState[iState2] )
& ( ( 1 << 30 ) - 1 );
piState[iState1] = iRand;
83
if ( ++iState1 == 55 )
iState1 = 0;
if ( ++iState2 == 55 )
iState2 = 0;
piState[-2] = iState1;
piState[-1] = iState2;
return iRand >> 6;
}
/*
* Generate a random number.
*/
int number_range( int from, int to ) //for random number generator
{
int power;
int number;
```

```
if ( ( to = to - from + 1 ) <= 1 )
return from;
for ( power = 2; power < to; power <<= 1 )
;
while ( ( number = number_mm( ) & ( power - 1 ) ) >= to )
;
return from + number;
}
/*
84
* This is the Mitchell-Moore algorithm from Knuth Volume II.
*/
void init_mm( ) //for random number generator
{
int *piState;
int iState;
piState = &rgiState[2];
piState[-2] = 55 - 55;
piState[-1] = 55 - 24;
piState[0] = ( (int) time( NULL ) ) & ( ( 1 << 30 ) - 1 );
piState[1] = 1;
for ( iState = 2; iState < 55; iState++ )
{
piState[iState] = ( piState[iState-1] + piState[iState-2] )
& ( ( 1 << 30 ) - 1 );
}
return ; //end of code for random number generator
}
```

Readme

1. First the user has to copy a text file (should be named as mg1.txt) in the program folder. This text file contains the hourly generation/demand data of a microgrid (tab

separated values) for one day (i.e. 24 time-steps). Units are assumed as kWh. The data should be in a format like:

80.00 23.00 82.00 22.00 80.00 23.00 81.00 24.00

As an alternate option, the user can simply edit the already available mg1.txt file in the program folder with its own microgrid data.

2. The data is stored in an array ‘mg[0] [48]’.

3. The user is asked for required number of dummy microgrids, say N. on the basis of user input, the program generates N number of array from mg[1] [48], mg[2] [48],… mg[N] [48]. At this moment, program is designed so it could generate up to 1000 microgrids. With little modification in the program, it could generate more.

4. The user is prompted for variability in size of dummy microgrids from the given microgrid: (1-low, 2-medium, 3-high)

- If ‘low’: the program generates a random number Vs. (Vs = 0.5~1.5)
- If ‘medium’: the program generates a random number Vs (Vs = 0.3~3.0)
- If ‘high’: the program generates a random number Vs (Vs = 0.1~10.0)

5. The user is asked if the impact of equipment failure is to be considered: (yes/no)

- If ‘yes’: the program generates a number ‘eff’ i.e. either ‘0’ or ‘1’. (eff = 0.0 or eff = 1.0).. The Code has been modified in a way so it does not generate ‘0’ very often.
- If ‘no’: the program always takes (eff = 1.0)

6. The user is asked if the intermittence of renewable energy sources is to be considered: (yes/no)

- If ‘yes’: the program generates a random number ‘ref’. (ref = 0.7~1.0)
- If ‘no’: the program always takes (ref = 1.0)

7. The user is asked for the national grid electricity price in pence/kWh. It is given the name ‘ngsp’.

86

8. The user is asked for the microgrid electricity price in pence/kWh. It is given the name ‘mgsp’.

9. The user is asked if the day/night price plan is to be considered (yes/no). The program folder contains two more files, dnp0.txt and dnp1.txt. These correspond to day/night price plans.

- If ‘yes’: the program makes an array ‘dnp[24]’ taking input from dnp1.txt.
- If ‘no’: the program makes an array ‘dnp[24]’ taking input from dnp0.txt.

10. Once the program has taken the required data from the user, it will generate values for each dummy microgrid in the mg[N][48] array in the following manner:

mg[N][0]=mg[0][0] x vs x eff x ref

mg[N][2]=mg[0][2] x vs x eff x ref

mg[N][46]=mg[0][46] x vs x eff x ref

Supply data of dummy grids

mg[N][1]=mg[0][1] x vs

mg[N][3]=mg[0][3] x vs

Mg[N][47]=mgone[47] x vs

Demand data of dummy grids

11. Now after all dummy microgrid arrays have been generated, a two dimensional array is generated which is trade[gn][gh], where gn corresponds to grid number and gh corresponds to hour of the day. It is calculated by taking the difference of demand and supply in each hour in a grid.

trade [gn][gh] = (mg[gn][(gh*2)-2])-(mg[gn][(gh*2)-1])

12. If ‘trade [gn][gh]>0’, its value is added in the available electricity pool (exp) whose initial value is ‘0.0’ in every hour.

13. A random number ‘traderand’ is generated and if (trade[traderand][gh])<0), then the randomly selected grid’s demand shall be met from the pool. If the pool can not satisfy its demand, then its demand will be met from the national grid.