Department of Mechanical and Aerospace Engineering

Optimising the future utilisation of renewable energy resources through smart grid control of electric vehicle charging loads

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Copyright Declaration

Abstract

The current rate of anthropogenic global carbon emissions is perceived by many to be inflicting irreversible damage to Earth's atmospheric composition. We therefore require innovative solutions to curb the increasing fossil fuel dependency of modern life, and provide a sustainable relationship with natural resources for generations to come. The transportation sector constitutes one of the largest contributories to anthropogenic global carbon emissions. A transition from the popular internal combustion vehicle to a cleaner alternative therefore presents an alluring possibility for significant change.

The primary objective of this thesis is to investigate how a forecasted scenario of high electric vehicle market penetration may be optimally controlled within a futuristic smart grid environment. Smart control of electric vehicle recharging profiles vehicles may be implemented to maximise utilisation of distributed renewable energy sources, and ease stress on outdated grid architecture to facilitate significant increase in overall electrical demand through electrification of the transport sector.

In this thesis, extensive literature reviews are presented alongside critical opinion to provide a conceptual insight into how electric vehicle recharging profiles present the most viable opportunity for a futuristic smart grid environment where demand follows supply, rather than supply following demand. In the initial development phase, such methods may be refined within aggregated public electric vehicle recharging facilities which present a microgrid representation of power flows on a national grid scale.

To assess the potential of smart electric vehicle recharging, existing commercial tools are reviewed. Of these, none provide opportunity for dynamic, unconstrained modelling of electric vehicle recharging profiles. Thus, a new model is developed and intensely calibrated. With intention of supporting effective model use, an analysis methodology is designed to investigate opportunities for the smart charging enhanced utilisation of distributed renewable energy sources, and deliver qualitative outputs for further use.

Seasonal simulations of buildings with varying occupancy demand for electric vehicle recharging facilities and varying renewable electricity supply, quantitatively prove that progression from an uncontrolled electric vehicle recharging strategy to smart one is a viable solution to enhancing the utilisation of distributed renewable energy sources, and the core operating principles may be feasibly scaled to more expansive grid networks.

Acknowledgments

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Finally, and perhaps most importantly, I take this opportunity to acknowledge friends and family who assisted immensely in the successful completion of this thesis. To my friends, a constant source of encouragement, for understanding my limited capacity to engage socially these past few months, and providing assistance in whatever way they could. To my family, for providing constant moral support, but also financial support and access to resources, without which I would not have been able to complete this thesis, nor other components for the fulfilment of this degree to the best of my ability.

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) (2014) publishes with high confidence that recent anthropogenic greenhouse gas (GHG) emissions are the highest they have been in history. Increased anthropogenic GHG emissions in recent decades have been driven largely by economic and global population growth. The atmospheric concentration of GHGs are the highest they have been in history (UC San Diego, 2015). This establishes an almost unequivocal link of causation from human activity to climate warming, which from the melting of polar ice caps to the accelerated desertification of land, is exerting widespread impacts on both natural and human systems.

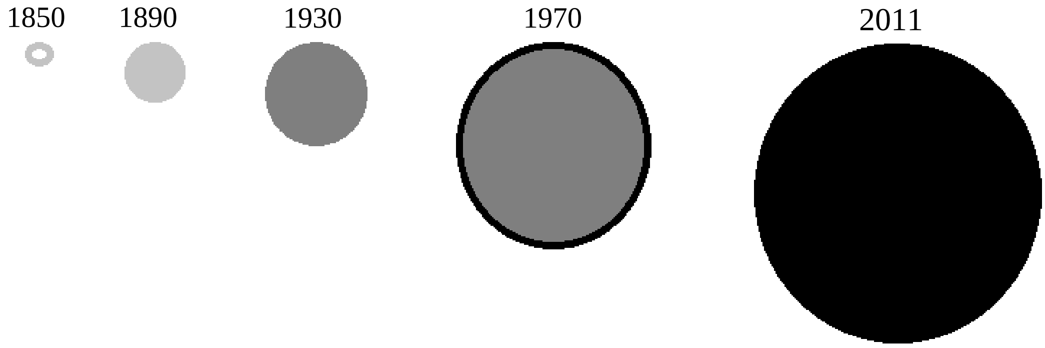

Figure 1. Scaled representation of historical global carbon dioxide emissions (Friedrich and Damassa, 2014).

To combat global climate change, the Kyoto Protocol (UN, 1997) was implemented in February 2005. The Kyoto Protocol is an agreement which commits member bodies to internationally binding GHG emission reduction targets. As developed countries like the United Kingdom (UK) are predominantly responsible for the currently high atmospheric concentrations of GHGs stemming from decades of industrial expansion, the Protocol places greater responsibility on developed nations to modify established practices, while affording developing nations wiggle room to exploit the previously under exploited economic and societal prosperity offered by fossil fuel exploration.

Under its responsibility to combat domestic contributions to global climate change, the United Kingdom enacted with the Climate Change Act of 2008 that "it is the duty of the Secretary of State to ensure that the net UK carbon account for the year 2050 is at least 80% lower than the 1990 baseline" (The National Archives, 2008). The Climate Change (Scotland) Act passed in 2009 committed Scotland to a 42% reduction in emissions by 2020 (Scottish Government, 2009). Although there has been a reduction of 34.3% in GHG emissions from Scotland since 1990 (BBC, 2015), it is currently failing annual climate change targets. We must therefore readdress efforts to date, and seek to identify new sectors for potential improvement.

The consumption of UK energy is divided into four primary sectors – domestic, industrial, transport and services. According to statistics published by the Department of Energy Climate Change (DECC) (2015a), consumption from the domestic sector represents 27% of overall UK consumption in 2014, the industrial sector 17%, the transport sector 38%, the services sector 13%, and the remaining 5% was used for non-energy purposes (the consumption of energy products that do not directly provide energy, and may include use in chemical feedstock, road making material etc.).

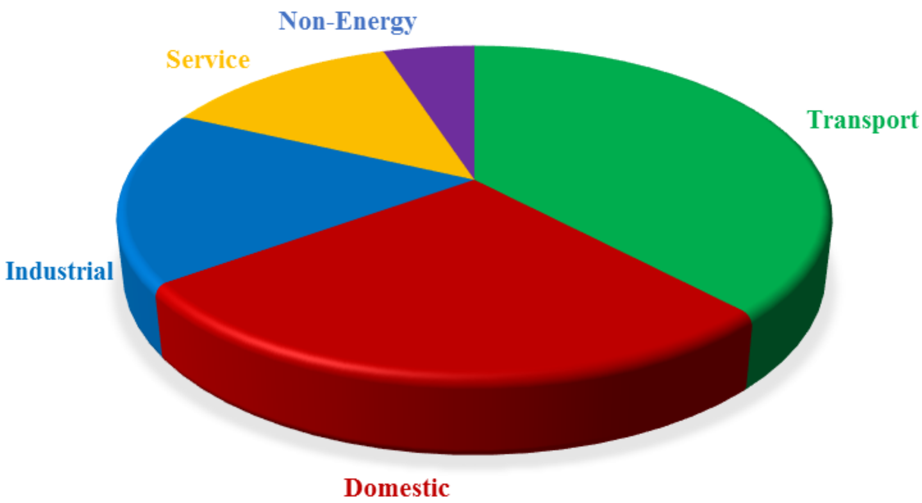

Figure 2. UK energy consumption by sector for 2014.

The transport sector is therefore the largest individual contributor of UK energy consumption currently. This transport energy consumption can be further diversified into four types of transport; air, rail, road and water. According to statistics published by the Department of Energy Climate Change (DECC) (2015b), consumption from air transport represents 23% of UK transport consumption in 2014, rail transport 1.9%, road transport 74%, and water transport just 1.4%.

Road transport represents the most significant opportunity to reduce GHG emissions in the UK. Political measures encouraging consumer usage of cleaner transport methods and technological advancements in internal combustion engine (ICE) vehicle efficiency will, to an extent, achieve this. However, a complete transition from the current fossil fuel dependency of road vehicles and associated infrastructure, to an electric solution, represents the most prominent opportunity for revolutionary change.

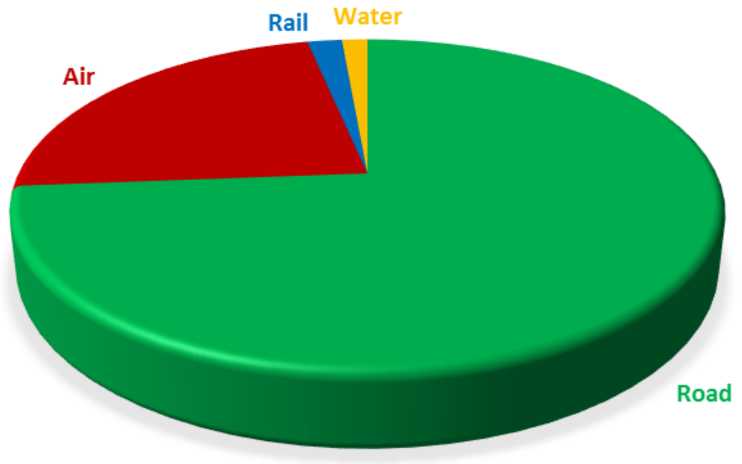

Figure 3. UK transport energy consumption by transport type for 2014.

Although the first electric vehicle (EV) models were invented nearly two centuries ago, a practical model affordable to the common consumer is yet to present itself in the UK. Their share of new car registrations is however increasing, now representing approximately 1% of the total new car market in the UK (Lane, 2015a). This growth has been accelerated by; greater consumer education of both the benefits of owning an electric vehicle and the need for greater sustainability in general practices of everyday human life; continued research advancing relevant technological systems, reducing manufacturing costs and consequently the consumer purchase price; and endogenous incentives (Perdiguero and Jimenez, 2012) such as unrestricted access to bus lanes in congested urban areas and free parking facilities (Transport for London, 2015) (Gitlin, 2015), designed to further encourage the perceived practicality of EVs.

Various governmental and scientific bodies are now beginning to ponder what future may be painted for an energy sector forecasted in the not so distant future to feature a prominent integration of EVs. Although current forecasts of when the EV boom will strike are somewhat tentative due to difficulty in predicting a number of intrinsically linked variable factors, it is postulated by many to be a question of when, not if. The provisions for such an event therefore need to be considered as of today.

On the utility side there is one particular question which dominates; are current grid electricity distribution network assets capable of satisfying a future scenario of greatly increased peak electrical demand, while minimalising the associated GHG emissions?

The answer is probably not, at least not within the current UK grid infrastructure. It is likely that more financially and carbon intensive methods of despatchable electricity generation will bear the brunt, and the EV transition will not be so clean after all.

To facilitate the clean integration of EVs, smarter grid technologies are required. The smart grid is a developing concept, the focus of ongoing research and demonstration projects, which will enable two-directional grid communication between the utility company and its consumers. In theory, this will allow utility companies control over consumers domestic appliances suitable for flexible intervention. As EVs are typically parked in excess of 90% of the time, and do not intuitively require the maximum quantity of electricity which may be delivered in this time, they present an extremely flexible source of demand side management (DMS).

If EV recharging schedules can be autonomously controlled without impacting on the consumer's range of mobility, they present a hugely dynamic source of demand side flexibility which may be altered on a second by second basis to particularly correlate with the available quantity of renewable electricity supply at that timestep. In a future where high levels of EV market penetration conjoin with the development of a smart grid, we may envision an idealised scenario where national grid supply profiles are no longer ramped up at great expense to follow demand, but instead demand is managed to follow supply. Managing this network across theoretically millions of system nodes distributed across the breadth of the UK is a daunting infrastructural, particularly ICT challenge, but not dissimilar to those comparably overcome by previous generations.

On the consumer side there is one particular question which dominates; will sufficient facilities for opportunistic EV recharging be provided within targeted areas of public infrastructure, similar to the current positioning of gasoline refilling stations, to enable EVs to be used more conveniently over typical driving patterns? Refilling strategies for ICEs and EVs are uniquely different in that ICEs may be refilled in designated areas of regulated safety at high speed, whereas EVs may be refilled anywhere with compatible sockets yet at comparatively slow speed.

However, with the proportion of time that EVs are parked, should suitable recharging facilities be positioned within areas of most probable use; particularly workplace and communal car parks; the EV refilling strategy is, in many ways, more convenient for the driver in that it does not require any diversion from points of travel. This will require the obvious provision of more robust EV recharging facilities from relevant bodies. It will also require greater awareness in the consumer's attitude to vehicle refilling, diverting away from the ICE born concept of emergency refilling, to a more considered EV concept of topping up whenever and wherever possible. A suitable public infrastructure for recharging EVs is requisite to this accomplishment.

This thesis investigates how aggregated areas of EV recharging such as workplaces present the opportunity to trial run ideas and technologies of the relatively unknown smart grid, and adjacently develop a preliminary quantity of EV recharging facilities within areas of public infrastructure. Particular focus is on demonstrating how smart control over EV recharging schedules may be implemented to optimise the utilisation of distributed renewable electricity sources and thus improve the overall evaluation of public infrastructure suitability for EV recharging facilities with onsite generation.

2. Literature review

2.1 A brief history of the electric vehicle

Despite what may be perceived as a technically immature innovation, the EV is not a recent development. Although it is difficult to accurately determine the initial inventor of the EV given a lack of global communication networks in historic times, the first crude electric-powered carriage is proposed to have been invented sometime between 1832 and 1839 in Scotland by Robert Anderson (Bellis, 2015). However, it was not until the second half of the 19th century that French and English inventors began to build practical road EVs using newly invented electric batteries (Matulka, 2014).

Interest in road EVs increased greatly at the turn of the 20th century, particularly in the United States, as the mass population was enticed by possibilities of greater freedom in their mobility and a simple operation road vehicle to replace steam engines (INL, n.d.). Indeed, in 1897 the first commercial application was established with a fleet of New York City taxis. Somewhat ironically, given their modern day reputation as gas guzzling sports cars, one of the first developers of a road EV intended for the mass consumer market, was Ferdinand Porsche. Designed when Porsche was 22 years old, the P1 was powered by a rear-mounted electric drive unit and could briefly reach a top speed of 21 mph, with a reported range of 49 miles (Edelstein, 2014).

Porsche was not alone in his pursuit of the EV. Many innovators acknowledged the desire for suitable EVs, and explored ways to improve its technology. Thomas Edison was one of them, and partnered briefly with Henry Ford in 1914 to explore options for a low cost EV, with Ford doubting the long-term viability of the gasoline-powered Model T that he had introduced just a few years earlier (Strohl, 2010). However, the consumer demand for the Model T was too strong. Coupled with the invention of the electric starter by Charles Kettering in 1915, simplifying and increasing the safety of the ignition process from previous iron hand cranks, the pursuit of a mass market EV was put on the back-burner as the power of gasoline shifted into focus (History, 2015).

EVs all but disappeared for the next fifty years. The United States, a revolutionary champion of the EV concept up to this point, abandoned research and development as gasoline-powered vehicles became ever more popular among consumers. The reasons behind its popularity were two pronged; firstly, the US by the 1920s had a better road network connecting cities which demanded long range vehicles; secondly, discovery of

Texas crude oil considerably reduced the price of gasoline, increasing affordability for the common consumer (Handy, 2014). It was not until 1973, that a combination of internal and external events resparked particularly manufacturer interest in the EV.

Technological advancements in oil exploration and refinery methods in the US were struggling to maintain pace with consumer demand, and the US became increasingly dependent on foreign imported oil (US Department of State, 2013). This relationship was critically exacerbated in 1973, when Arab members imposed an embargo against exporting petroleum to the US amongst other nations in retaliation for their supplying of arms to the Israeli military (Macalister, 2011). Strain inflicted on the US economy by this embargo dawned a realisation that greater fuel independence was required, and this could not be sustainably achieved within the current gasoline relationship. It was time for the EV concept to be dusted off and return to consideration.

However, gasoline power had just passes through an undistracted fifty year period of unremitting development, acquiring levels of technological innovation which the EV could not accelerate to catch up with. The range and recharging opportunities of these EVs presented a significant step back in freedom of mobility that the mass consumer market was understandably not willing to accept, particularly not at greater expense. The refining of alternative fuel sources in the US leading to a reduction in oil prices, coupled with the high manufacturing cost of EVs, leaned favourably towards gasoline powered vehicles in a comparative economic evaluation.

EVs were once again ignored until 1990, when, in growing recognition of a need to combat global climate change but at a localised level alleviate problems with poor air quality in dense urban environments, California passed the Zero Emissions Vehicle (ZEV) act requiring 2% of vehicles to have zero tailpipe emissions by 1998, and 10% by 2003 (Shahan, 2015a). This served as the benchmark for further US states to design their own similar measures. In efforts to comply, General Motors allocated substantial funding towards the research and development of EVs and in 1996 released the EV1 (Anderson and Anderson, 2009). Despite initial optimism, EV1 production ceased not long after its launch amidst conspiracy theories suggesting the interference of big oil.

Toyota’s unveiling of the Prius in 1998, the world’s first commercially mass produced hybrid car, utilising a new battery chemistry, heralded the beginning of a new era for the EV. Although a promising start, the Prius did not present a conclusive solution to the EV, employing revolutionised hybrid technology that retained an albeit minimised dependency on gasoline power to achieve similar performance levels to an ICE. But the Prius's introduction may be interpreted to have provided the necessary impetus for development of a modern EV industry. Something of a rat race commenced at the turn of the 21st century, with large manufacturers recognising whoever invented a viable EV for the mass consumer first, would be able to consume a significant proportion of the automobile market in the absence of direct competition.

2.2 State of the art electric vehicle

Leading up to the present day situation, and EV popularity is growing with state of the art developments in the requisite technology and a consumer market more educated of the need to adjust sustainability practices. Tesla in particular have received industry wide praise over the past decade for bringing EVs more in line with the performance of ICEs, with their open patent policy providing a platform for other manufacturers to join the collective effort of developing a viable mass market EV. Despite popularity growth, EVs still only constitute a tiny percentage of the UK road vehicle market. Although it is difficult to obtain accurate figures, the Society of Motor Manufacturers and Traders (SMMT) (Nichols, 2014) EVs 2014 market share constituted less than 2%. There must exist fundamental obstructions to market growth. Let us therefore take this opportunity to discuss state of the arts in EV functionality; providing discussion where relevant on various economic, social and of course technological obstructions which contribute to a ceiling on EV market growth.

2.2.1 Propulsion mechanism

The basic mechanism of EV propulsion has not changed significantly since its initial conception, with an understanding of theoretical electromagnetism pre-dating interest in EV design. All EVs contain three primary components; (1) an energy (i.e. power) storage unit; (2) a central control unit; and (3) a propulsion unit. To propel an EV, power is first extracted from the power storage unit through the central control unit, or Power Management System (PMS). The PMS is the brains of the EV, performing key functions of power modulation and power conversion, but most importantly it decides how much power is transferred from the power storage unit to the propulsion unit, an electric motor (CarNewsCafé, 2013).

How does the PMS know how much power to transfer? The accelerator pedal within the EV is connected to a pair of potentiometers. Potentiometers, to refresh high school physics, are adjustable voltage dividers which act as variable resistors. These send a signal to the PMS on how much power is to be transferred, ranging from zero power when the car is stationary, to full power when the driver floors the accelerator pedal. For any setting in-between, the PMS chops the maximum deliverable power thousands of times per second to create an equivalent average quantity (Brain, 2015). The correct quantity of power culminates in the propulsion unit, an electric motor, which simply makes the wheels move with the conversion of electrochemical to kinetic energy.

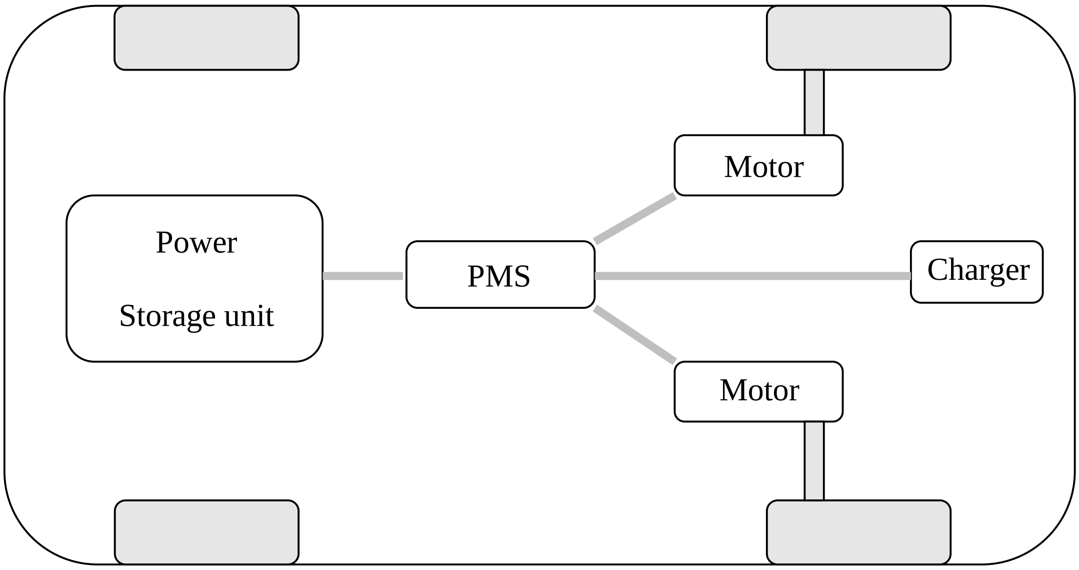

Figure 4. Basic EV powertrain with key components.

A simple description of EV propulsion is complete. To enhance their efficiency, most EVs further deploy a relatively new innovation of regenerative braking. Conventional braking wastes energy, although this may not be physically obvious. To envision this, think about riding a bicycle. To gain speed, the cyclist must pedal fast and exert kinetic energy. Yet if the cyclist brakes to a halt, this same kinetic energy has to be re-exerted to regain lost momentum when the cyclist sets off again. Where did this kinetic energy go? From energy conservation laws, this energy cannot have been destroyed, but must have assumed another form. The friction of metal brakes on rubber wheels converts this kinetic energy to useless heat. A more efficient braking system would find a better way of storing this kinetic energy in some alternative form which may be re-used at a later time (Woodford, 2014).

Regenerative brakes are a method of returning kinetic energy to the power storage unit as electrochemical energy. As described above, conventionally electrochemical energy is transferred through the electric motor to the wheels for kinetic energy and movement. However, any permanent magnet motor can be run backwards as a generator rather than a consumer of electrochemical power. So when an EV driver presses the brake pedal, electronic circuits reverse direction and power flows from the motor/generator back to the power storage unit. Rather than expelling excess kinetic energy as waste heat, it has been stored as electrochemical energy for later use. This process of regenerative braking is not one hundred per cent efficient as conventional brakes are required in conjunction to increase the rate of deceleration in fast response situations, but it is a considerable improvement from zero (Gable, 2015).

2.2.2 Power storage unit

The central core of the EV is that it must have some way to store electrochemical power. There are different EV variations of how this power is stored, which may be segregated into three distinct categories; (1) battery EVs (BEVs); (2) plug-in hybrid EVs (PHEVs); and (3) fuel cell EVs (FCEVs). BEVs are the most easily understood of the three. They use similar battery technology to that used in laptops, mobile phones and other electrical appliances to store electrochemical power. Batteries, stacked in connected modules of foundational battery cells, adhere to the same fundamental operational principles, albeit with more advanced thermal management systems. These batteries are recharged using power from anything from a domestic wall socket, right up to super charged innovations which can deliver equivalent quantities of power at twenty-five times the speed or more.

PHEVs are similar to BEVs, but they possess an additional ICE which may extend the restricted driving range of a similar BEV. The PHEV utilises an energy management strategy (EMS); simple control logic that decides what proportion of power is delivered at any timestep from the electric motor or secondary ICE. The most prevalent PHEV operational modes are: (1) pure electric mode; (2) charge depleting mode – similar to pure electric mode, but ICE provides power shortfall when demanded tractive power exceeds electric motor capacity; (3) charge sustaining mode – maintains a fixed state of charge (SOC) within the power storage unit through intelligent engine and motor management (Geller, Quinn, and Bradley, 2010).

PHEVs are distinguished from conventional hybrid vehicles in that, as the name would suggest, rather than just being charged on the move via regenerative braking, they may be plugged into a power source to ensure full electric capacity. It is important to stress that conventional hybrid vehicles which cannot be plugged in are not considered EVs, as they rely exclusively on gasoline to generate electricity. This definition is somewhat ambiguous given all electricity for BEVs and PHEVs is generated somewhere, and could conceivably have been generated from coal combustion in a worst case scenario. However, it remains as a distinguisher between propulsion mechanisms (UCS, 2015).

Lead-acid, lithium ion (li ion) and nickel-metal hydride (Ni-MH) have traditionally been the three leading battery chemistries for use in BEVs and PHEVs, due to their comparatively strong performance across key battery specifications including; energy density, power density, battery lifetime, safety, and cost. Lead-acid is the most mature of these battery chemistries and has therefore been used extensively within BEVs and PHEVs to date (Zhou et al, 2011). However, current research and development has shifted focus to the li ion battery. The li ion battery has the highest energy density (energy per unit area) of all rechargeable battery chemistries suitable for vehicular application. This intuitively makes them lighter, reducing the power required for propulsion and making them logistically simpler for future scenarios where BEVs and PHEVs are forecasted to constitute a significant proportion of the road vehicle market (Azadfar, Sreeram, and Harries, 2015).

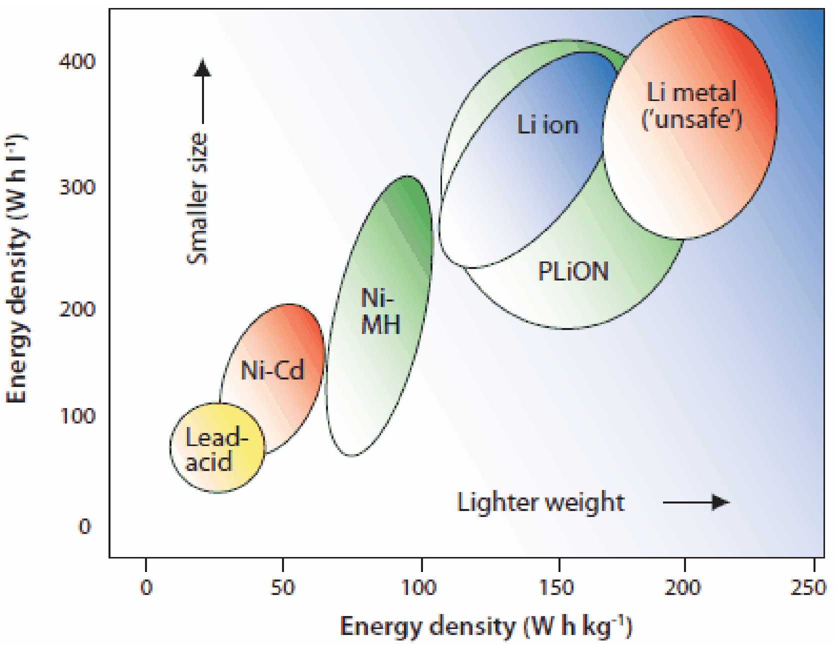

Figure 5. Energy density of battery chemistries, both volumetric and mass.

Li ion may be sub-categorised into a group of uniquely doped chemistries which all possess a lithium metal oxide anode, but use a variety of different compounds. Some of the more important li ion chemistries include; lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminium (NCA), and lithium titanate oxide (LTO). It is well recognised that which battery chemistry to use is the most important design consideration in a BEV or PHEV, and although there is a general consensus that li ion is the most viable, there are design trade-offs to consider in which of these sub-chemistries is most suitable for vehicular use (Dhand and Pullen, 2013).

Research of a next generation li ion battery will continue to develop new materials and explore chemistries which may create the idealised scenario of increased durability and energy density, coupled with reduced battery size or weight. This research shares a common interest across not just the transport sector, but also the commercial production of popular consumer products such as laptops and mobile phones. A collation of useful research on such an industrialised scale presents obvious promise. Much of the initial focus will be on increasing energy density. Element Energy (2012a) describes various channels of potential development which may increases the energy density of batteries currently suitable for vehicular application, by a factor as high as three.

Increased energy density has the potential to lower manufacturing expenses; due to less material being required per kWh capacity; and additionally reduced demand on systems which manage the battery performance over an optimal thermal operating range, who now have less cells to monitor. With modern energy densities, the battery must be very large, in particularly BEVs, to provide the consumer with an all-electric driving range that is compatible with typical driving patterns. Despite the range anxiety phenomenon which persists in a common consumer's interpretation of EV viability, advancements in energy density have enabled the manufacture of a market of suitable vehicles which may satisfy typical driving patterns. Figure 6 shows the electric range of some popular EVs available on the UK market, using manufacturer data validated by various sources on the World Wide Web, far in exceedance of the average distance travelled per day in England (dashed line); manipulating survey data provided by Department for Transport (2014a) determined this to be eighteen miles.

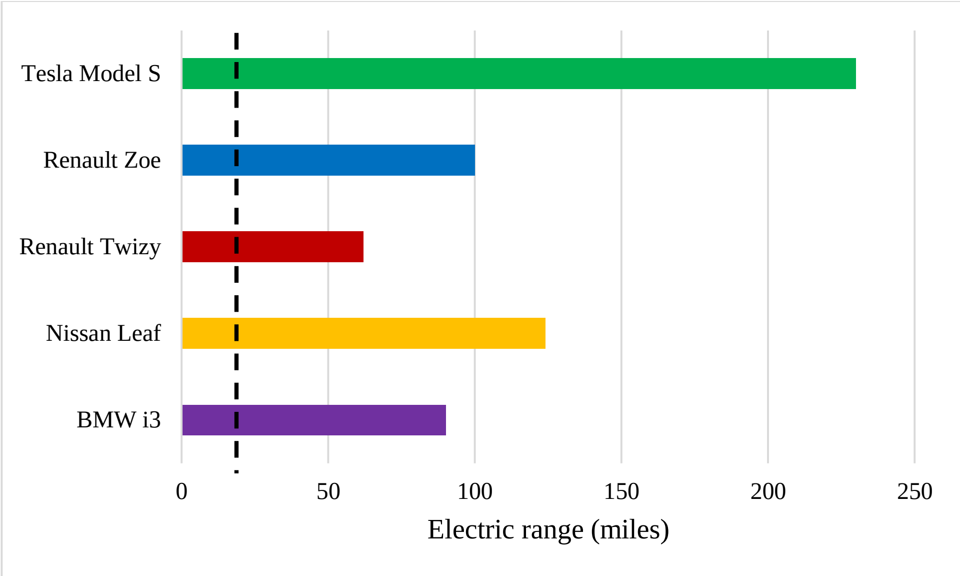

Figure 6. Electric range of some popular EVs dispel range anxiety.

The problem with current battery technology is that to achieve such all electric driving ranges presented in Figure 6, batteries have to be very large to compensate for deficient energy density. As batteries are large, material purchase and construction is expensive to the manufacturer. This cost of BEVs and PHEVs is therefore inherently transferred to the consumer, compromising their economic viability for mass market penetration. Although battery manufacturing costs may generally reduce in the near future as other obstructions to EV market growth are alleviated, demand increases and by economy of scale the operating efficiency of plants may increase, energy density remains key.

There are some conspiracy theorists who believe a solution for energy density and the EV in general has been stagnated not by a lack of technological capacity or innovation, but by interference from multinational organisations whose profits would diminish with the introduction of a viable EV into the road vehicle market. In the popular film, "Who Killed the Electric Car?", documentary film maker Chris Payne alleged General Motors purposely scrapped the previously mentioned EV1 despite high consumer demand. This appeared counter-intuitive. Being the company that forces the EV into a golden age of growth would create huge revenues in absence of direct competition. Many conspiracy theorists believe the explanation lies with big oil. Economically dependent on gasoline powered vehicles, these companies have combined forces with auto manufacturers, to an extent economically impaired by the reduced maintenance requirements of an EV, to purchase patents for effective EV designs and store them away in dark corners hidden from a common consumer's knowledge (HowStuffWorks, 2010). Although interesting to point out, and more grounded than the proclamation of unidentified flying objects, the remainder of this thesis will persist with indisputable truths!

The third distinct EV category, fuel cell EVs (FCEVs) may provide direct competition to the future development of battery based EVs. FCEV propulsion mechanisms are just the same as those described above for BEVs and PHEVs. However, instead of drawing electricity from a power storage unit, FCEVs continually generate electricity utilising energy stored within a fuel cell. Hydrogen is the primary fuel of focus in current study.

Hydrogen is injected as a fuel by pumps similar to those used in conventional gasoline pumps today, and combines directly with oxygen in air within an electrochemical cell (Stickland, 2015). At the cell anode, hydrogen catalytically disassociates i.e. it splits up into a proton and an electron. The proton passes through a proton exchange membrane (PEM) to the cathode. The electron cannot pass through and is conducted by an electric circuit to the electric motor, where it generates electricity to turn the FCEV's wheels. Electrons expelled from the external circuit reunite with protons in the cathode. Oxygen and hydrogen therefore combine to form water vapour, the sole emission product from FCEV propulsion (Lane, 2015b).

There are a great number of further potential advantages to the FCEV. Thomas (2009) demonstrated that in direct comparison with battery powered EVs, for any vehicle range greater than one hundred miles, fuel cells are superior to batteries across a broad range of key performance factors including mass, volume, GHG reductions and well-to-wheel operating efficiency when using natural gas or biomass for life cycle analysis. However, the current development of FCEVs considerably lags that of battery counterparts. Only one prototype vehicle exists on the UK market today (Thomas, 2015), with large scale commercialisation not expected for a few years yet (Veziroglu and Macario, 2010).

As a relatively immature research field without real-life demonstration results to justify its potential, the FCEV concept has so far failed to grasp the attention of the media nor, more relevantly, the R&D budgets of large automobile manufacturers. There are major questions concerning the size of on-board hydrogen storage required, and the safety of this highly flammable gas on-board. Most pertinently, governments have in recent years provided subsidiary assistance to development of cleaner transport methods. However, replacing current oil-based infrastructure with hydrogen would cost such astronomical sums of money, that government enthusiasm is sparse (Conserve Energy Future, 2015).

A battery powered EV presents a more viable solution for a clean transportation future, with the supporting infrastructure effectively already in place with a national electricity network that, after centuries of use and refinement, is comfortably understood. (From this point forward in the literature review, in the interest of simplicity, the term EV will therefore only refer to BEVs and PHEVs as the sole discussion of this thesis.)

2.2.3 Recharge mechanism

EV Battery packs must be rechargeable. A description of the EV recharging mechanism is therefore required. Power is delivered conventionally via a compatible cable, albeit wireless demonstration pilots are in place (Osborne, 2015), from a suitable source such as a domestic wall socket. This power enters through an EV inlet to a charging control system (CCS). The CCS transforms this alternating current (AC) power to direct current (DC) power which can then be used to charge the battery (Azadfar, 2015).

Battery charging typically consists of two distinct phases; a main charging phase where the bulk of requested power is delivered into the battery, and a final charge phase where the battery is conditioned and balanced. Opportunity charging refers to topping up the battery in awareness that a full charge is not possible within the forecasted duration for which the EV will be stationary. This typically involves only the main charging phase (Van den Bossche, 2010). Such recharging behaviour is not recommended. To sustain high levels of battery performance, a periodic full charge is advisable. Opportunity day time charging complemented by conditional night time charging may present a solution.

Zhou (2011) experimentally determined an equation to relate the life cycle of a li ion battery to the depth of discharge (DoD). Life cycle is the number of recharge cycles a battery can facilitate prior to its maximum capacity falling below 80% of the original capacity. DoD is the SOC within the battery at the commence of a specific recharge cycle. Using this equation, Figure 7 displays the number of cycles yielded by most li ion chemistries increases exponentially with decreasing DoD. In a continued discussion of battery performance from above, it is relevant to assume that the vast majority of EV owners would not frequently risk DoD approaching zero in fear of deficient freedom of mobility in particularly unforeseen circumstances. Although advancements in material and technological design are of course critical to an overall performance evaluation of EV batteries, the human influence over recharge behaviour is a significant factor which merits identification.

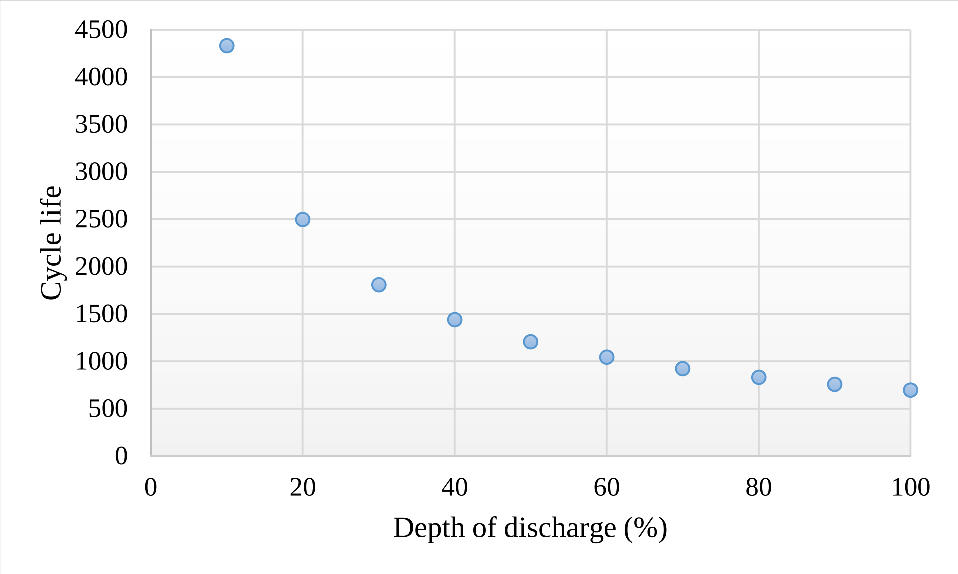

Figure 7. Li ion cycle life as a function of depth of discharge (Zhou 2011).

The state of the art study of EV recharging concerns speed. EV recharging speeds may be segregated into three predominant categories; slow, fast and rapid. Slow charging in most cases involves a standard single-phase 13A three-pin plug, no different from any other electrical appliance, connected to the AC supply network. This corresponds to a deliverable power of approximately 2.3kW. Studies show consumer preference for the home as the location of EV recharging (Next Green Car, 2015). The ease of domestic installation ensures slow charging remains the most common method for recharging EVs. The speed of power delivery is sufficient to restore the majority of EV batteries in a single overnight charge (Wirgman, 2015). However, to extend EV driving ranges, there exists unequivocal consumer demand for faster recharging mechanisms.

Fast charging may reduce recharging times to less than half the time of slow charging, delivering a maximum single-phase current of 32A. This corresponds to a deliverable power of approximately 7kW. While less commonly used in larger applications such as electric buses, fast three-phase charging is technically possible. In a single-phase power supply system, a single conductor carries a current of 32A. In a three-phase system, two further conductors carry a current of 32A. Three times as much power can therefore be delivered. This corresponds to deliverable power of approximately 22kW.

Rapid charging significantly reduces recharging times. From a three-phase AC supply, a current of 63A is delivered. This corresponds to a deliverable power of approximately 43kW in rapid AC chargers. However, rapid AC is a relatively new development. The

EV CCS must be capable of converting a higher quantity of charge from AC to DC for battery storage. Of the top fifteen most registered EVs in the UK, only the Renault Zoe is compatible (EVSE, 2015). Rapid DC chargers are more common. Rapid DC chargers are typically rated at a maximum current of 125A, corresponding to a deliverable power of approximately 50kW. They possess power electronics that communicate from the EV to the charging station the correct level of current to be converted from AC to DC, thus removing any dependency on the EV's on-board CCS conversion capacity.

Figure 8 illustrates the all electric range from a thirty minute charge at the progressively faster recharging speeds described above, using manufacturer data validated by various sources on the World Wide Web for the Nissan Leaf, BMW i3 and Renault Zoe.

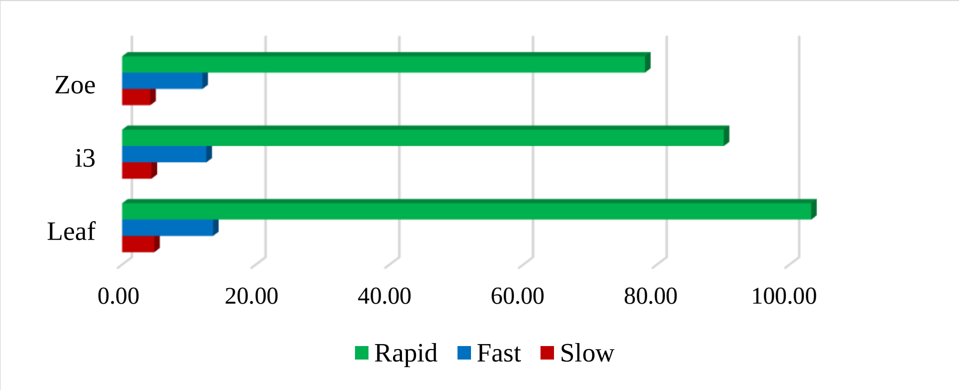

Figure 8. Electric range achieved in thirty minute charge at different recharge speeds.

The potential opportunities offered by these faster recharging mechanisms have created discussion amongst relevant policymakers about the creation of a public infrastructure for EV recharging, which, although not necessary to the same extent, would provide a level of opportunistic charging similar to that provided for gasoline powered vehicles in the jungle of refilling stations we live amongst today. A public infrastructure for EV recharging would not represent a charge point on every street corner, but be targeted to convenient and safe locations in response to consumer preferences (Department for Transport, 2011b). Need for public EV recharging infrastructure may appear redundant if educational schemes are implemented to dispel misconceptions giving rise to range anxiety amongst consumers. But there exists a particular demand to; provide suitable facilities for those living in apartment buildings, or otherwise, that do not have access to home charging facilities; provide consumer reassurance; and most pertinently extend the range of EVs to satisfy, albeit infrequent, long distance journeys.

Surveys (Next Green Car, 2015) indicate that with over 50% of UK cars commuting, the workplace is the second preferred recharging location for EV owners. With regards to other places of extended stay within public infrastructure, a survey of EV owners carried out on behalf of the South and West London Transport Conference outlined that less than 5% would prefer recharging facilities within park and ride stations, a prevalent recommendation given the close proximity of a high voltage electricity supply (City of Westminster, 2009). Despite possible perception as an unnecesary expense, recharging facilities within workplaces would be engaged by most within the commercial sector as an opportunity to present a starkly visual commitment to sustainability causes that differentiates from competitors.

A public infrastructure requiring only slow recharge speeds within workplaces given the typical duration of time spent stationary, supplemented by a targeted positioning of currently expensive rapid charging stations across the UK motorway network, would appear to present a reasonable, viable quantity of EV recharging facilities within public infrastructure. Despite endogenous encouragement for the installation of such facilities via the UK's Plugged in Places programme (Department for Transport, 2013c), uptake from both the commercial and public sector has so far been tentative, and featured only small demonstration pilots (Glasgow City Council, 2015).

This reluctance is coined as a "chicken and egg" problem (Galizia and Hochster, 2015). Should policymakers invest in infrastructure while the requisite consumer base, albeit forecasted, does not presently exist, or do they incentivize EV purchases to first create the demand? It is proposed by City of Albany (2012) that while EV owners are trained to the impositions of electric driving, the common consumer is not sufficiently educated and for psychological purposes will require evidence of recharging opportunities within public infrastructure to consider a switch from ICEs. Although the initial development of this infrastructure will most likely be funded by the public sector in the introductory phase, support from the commercial sector will be required. The commercial sector may therefore have to accept an initial, necessary underutilisation of facilities to stimulate a sizable consumer base through changed public perception.

There are more than just economic and simple logistical barriers to the growth of public EV recharging infrastructure, but additional technological barriers. One current barrier which intertwines all three is the development of an overall accounting system, similar to the use of mobile phone SIM cards, which would enable the charge point supplier to charge the consumer on a rate of use basis (Smokers et al, 2010). Although segregated metering for EV charging does not exist within current grid infrastructure, places of public EV recharging infrastructure with no secondary electricity use should not present obstruction to the development of a fair market for both supplier and consumer. Further barriers would include a standardisation of EV charging leads to replace the broad array of model compatibilities within the current UK market, and a number of particularly logistical factors which would require unique consideration on a case by case basis.

2.2.4 Environmental impact

The proposition of public EV recharging infrastructure assumes a hypothetical future scenario where EVs constitute a significant proportion of the road vehicle market. The global pursuit of EVs is predominantly motivated by an awareness of the need to reduce anthropogenic GHG emissions, of which road transport is a significant contributory. Although projections for a future EV landscape vary considerably due its dependency on a number of variable factors (IEA, 2013), there is justifiable concern over how clean a transition from oil to electricity based vehicle propulsion really is.

As EVs do not have any tailpipe emissions, it would appear simplistic to state that they are healthier for the physical environment by direct comparison with ICEs. However, we have to consider whether the displacement of emissions from immensely distributed ICEs to centralised national grid power generation assets, constitutes positive change for the physical environment. In a localised consideration, EVs displace emissions from dense urban areas. With increases in population density stimulated by the opportunity of employment and greater prosperity, unsustainable levels of industrialisation within cities has degraded air quality to the impact of population health (Lucas, 2011). High EV market penetration offers the opportunity to alleviate this problem, and additionally reduce noise levels. But what about in an overall consideration?

A complete comparative assessment of EVs versus ICEs must analyse all aspects of the vehicle’s life, from manufacturing right through to end-of-life recycling. Unfortunately, little is known about the environmental impacts of manufacturing, use and recycling of li ion batteries used within EV application. This makes it difficult to perform a reliable comparative assessment. Nordelof et al (2014) investigates the usefulness of life cycle assessments in EV studies and concludes from a review of current literature a deficient methodology that, amongst other failings, does not adapt a future time perspective to model advances in material processing, manufacturing processes, and changes in the grid composition of electricity generation. However, Notter et al (2010) do state that the "environmental burdens of mobility are dominated by the operation phase", with recent advancements in battery technology, especially related to life cycle, significantly reducing environmental impacts of the manufacturing phase (Zackrisson, Avellan, and Orlenius, 2010). The environmental impact of EVs therefore depends substantially on the source of electricity during operation (Granovskii, Dincer, and Rosen, 2006).

Meaningful reductions in GHG emissions within hypothetical future scenarios of high EV market penetration is conditional on the utilisation of low carbon electricity sources (Samaras and Meisterling, 2008). However, there are industry wide concerns that as transport systems in parallel with heating systems increasingly electrify in the UK over the coming years, the increase in peak demand may lead to a significant degradation of electricity generation infrastructure (Nathan, 2012). Despite a concerted UK effort, and particularly within Scotland, to increase our low carbon electricity supply capacity, the intrinsic intermittency of the most popularly deployed sources will limit their ability to securely satisfy future increases in electrical demand.

Grid scale energy storage has traditionally been the proposed solution for the smoothing of low carbon, or renewable, sources of electricity. However, by comparison with the quantity of electricity generation in the UK, only a miniscule quantity of grid storage is in place (Shahan, 2014b). Energy storage can effectively load follow to precisely match supply with demand on a second by second basis, replacing conventional despatchable power generation plants which may take several minutes or even hours to come online, and at great carbon expense. The most established storage technology is hydroelectric. Hydroelectric storage facilities however require very specific geographical features, the availability of which is restricted by a number of factors including the need to maintain national heritage in areas of typically scenic areas. Other forms of energy storage such as commercial scale batteries and mechanical flywheels may be deployed more rapidly to the point of requirement, but are currently restricted by technological factors which inherently depreciates their economic sense (Poullikkas, 2013).

Development of battery technology may improve through manufacturing economies of scale given cross-sector interest in li ion research. Additionally, sufficiently periodic end-of-life recycling of EV batteries within hypothetical future scenarios may enable a secondary application within grid storage systems, regardless of scale, and enhance the viability of a network distribution system supplied by a combination of instantaneous and artificially delayed low carbon electricity supply. However, it is more probable that increased electrification of the transport sector will be satisfied by more despatchable, high carbon methods of electricity generation which may be more comfortably ramped up and down within an outdated grid architecture.

Anair and Mahmassani (2012), and Acha, Green, and Shah (2011) both concluded that in the worst case future scenario for the UK where the electricity for EV propulsion is generated by coal, the wells to wheels emissions would be slightly higher than the most efficient gasoline propelled equivalent. If this hypothetical future scenario is realised, as proposed by many experts pessimistic about current distribution network capacity, the EV is not so clean after all. After decades of financial commitment, innovation, and research, the EV may present a detrimental contribution to global GHG emissions.

2.3 A smart future for the electric vehicle

Global anthropogenic GHG emissions are, at present rates, not sustainable. Although electrification of the road transport sector presents initial promise for positive change, within the current deficiencies of conventional low carbon electricity solutions a future of high EV penetration levels could actually be the opposite. But rather than abandoning all hope for the EV to provide transition to a clean transport sector, the power industry must now seek to investigate a more intelligent solution with potential to revolutionise the way we interact with electricity.

2.3.1 Smart grid

The current UK grid was, in common with grids in most so called developed countries, designed nearly a century ago when needs were much simpler; power generation was distributed to a localised scale, and the majority of households had a very simple electrical demand for lighting and maybe a radio. Utilities delivered the electricity, and then billed the consumer monthly on a fixed rate of usage. This archaic one-directional interaction is insufficient to facilitate increasingly complex and dynamic demands from expanding consumer bases increasingly reliant on non-essential electrical appliances which enhance the quality of modern life, and equally demanding of ever present, instantaneous grid communication (U.S. Department of Energy, 2013).

In achieving a balance between electrical supply and demand, national grid operators currently modulate the output of despatchable sources of electricity generation, using assumptive forecasting algorithms to follow consumer demand profiles on a per second basis. Figure 9 shows the segregated UK power demand on a typical winter day (National Grid Electricity Transmission, 2014). In the interests of operating efficiency, nuclear operates at a fixed load, while coal and natural gas are ramped up and down to load follow peaks and troughs in population behaviour. These despatchable methods function in an idle mode, always spinning, always burning fuel in preparation of being requested at short notice. And modulating their output is a carbon intensive procedure.

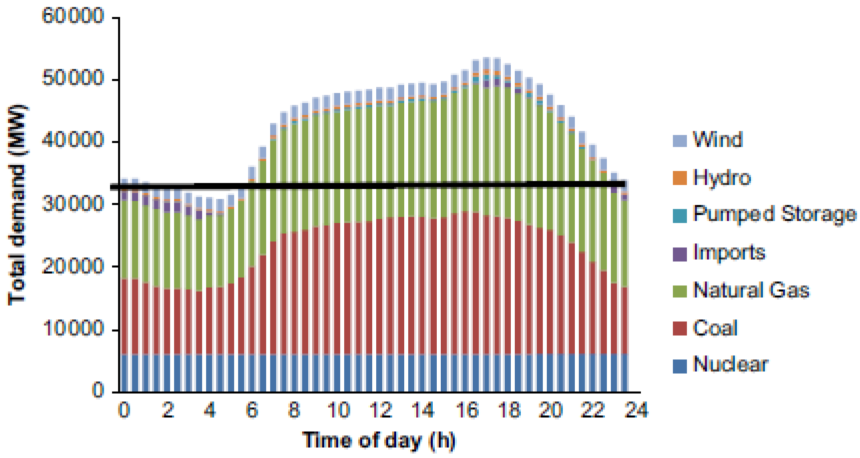

Figure 9. Segregated UK power supply-demand on typical winter day.

An idealised scenario would be to replace the convention of supply follows demand, to a more efficient scenario introducing demand side management (DSM) where demand follows supply. By the dynamic redistribution of suitable loads, we could, to an extent, flatten the supply profile presented in Figure 9 and using fast response mechanisms, enable an easier grid integration of intermittent low carbon resources like wind. Such a scenario would require the introduction of a modernised electrical grid that by a series of retrofit measures, will progressively replace the outdated grid architecture of today.

The smart grid is such a modernised electrical grid. Although currently in a conceptual and small scale demonstration phase, the smart grid introduces functionality for two-directional communication between the utility and consumer. Electricity information is autonomously exchanged on a per second basis. Through utility control and monitoring capabilities, the consumer is either smartly requested or pervasively interrupted in their use of non-essential electrical appliances, DSM, during key periods where normal grid capacity is stretched and would otherwise require the supplement of carbon intensive methods of despatchable generation described previously (Scientific American, 2011).

The level of information exchange requisite to the smart grid will require development of new tools and software in a convergence of communication technology, information technology and power system engineering (Farhangi, 2010). This will provide utilities with greater system visibility, and thus enable unprecedented capability in supply side optimisation, with particular reference to the increased utilisation of highly distributed sources of renewable electricity generation. The development of a suitable smart grid is a daunting infrastructural but particularly ICT challenge, and a venture that will cost the UK purse incomprehensible sums of money. Policymakers have however identified the far reaching social, economic and environmental implications of the smart grid, and resultantly dedicated considerable resources to ensure its integration takes an efficient evolutionary path. Ofgem's £500 million Low Carbon Networks fund provides support for network company innovation projects to test and trial new smart grid technologies (DECC, 2014c) which will ultimately form the basis of a smarter electricity future.

2.3.2 Demand side flexibility

Although smart grid necessity is in part motivated by concern over the future increase in overall electrical demand created by increased electrification of the transport sector, the need to better manage supply chains is a realisation for national grid operators today in the absence of a significant EV market. National grid operators are seeking measures to increase the efficiency of cross-regional power generation and distribution. There is particular focus on optimising utilisation of low carbon electricity generation sources whose current distribution, over a UK consideration, displays an obvious geographical disparity between peak points of supply and demand. If this generation problem can be alleviated by the introduction of a smart grid, far reaching possibilities can be realised, none more significant than reducing current UK dependence on imported electricity.

UK Government (2014) states that; since Q1 2010, the UK has been a net importer of electricity; and total net imports in Q2 2O14 were the highest reported in the quarterly time series, accounting for 6% of total electricity supply. This electricity balance is indicative of failing grid architecture, particularly when the UK possesses mountainous and surrounding water environments ideally tailored for a more significant capacity of low carbon electricity generation than continental neighbours. This line of discussion is intended to convey the unequivocal need for a smart grid, regardless of what extent EVs penetrate the road vehicle market. The question should not therefore concern what a smart grid can do to facilitate EVs, but how EVs can facilitate the smart grid.

The most conclusive advantage of a large number of EVs within a futuristic smart grid environment is a high level of flexible DSM less obtrusive on consumer lifestyle than smart metering of domestic appliances. Utility companies in the UK provide economy tariffs for electricity. These employ varying hourly tariff rates, scaled so as to encourage consumers to use electricity at times more convenient for grid distribution capacity. In an EV context, this static level of DSM is sufficient at current penetration levels, where the segregated demand from EV recharging is negligible in overall grid consideration. However, within a future scenario of high EV penetration levels, more dynamic smart recharging strategies should be deployed.

EVs present expansive demand side flexibility because they are stationary for far longer than their average daily recharge requires. This flexibility could be further extended by the introduction of a public EV recharging infrastructure particularly within long stay workplaces, although this is not essential. EVs do not, particularly in the case of PHEVs which feature a secondary propulsion mechanism, therefore constitute critical loads and may be autonomously redistributed by external agents to prioritise times of low carbon electricity availability, reduced demand from other sectors, or both, provided the EV owner's mobility is not excessively compromised (Robinson et al, 2013).

To what extent EV owners would be willing to cease control of recharging schedules to an external agent during grid participation, remains an important question. Consumer acceptance would inevitably depend on the remuneration received for providing such grid services. Weller and Sioshansi (2015) propose that the EV owner be compensated for the service provided to the equivalent grid operator value that recharge time shifting provides. However, this may be impossible to implement on a per transaction basis due to complexity of determining the actual value provided, and therefore fixed rate pricing would appear the reasonable solution. Sioshanshi and Denholm (2010) propose that if the EV owner is properly remunerated by such pricing schemes, market enthusiasm for EVs would actually increase. As the EVs primary purpose is driving, consumers would invest in them primarily as vehicles. However, the opportunity for secondary use as a grid resource provides further positive contribution to an overall economic assessment of EVs versus ICEs.

EV demand side flexibility would have to be properly managed to maximise consumer satisfaction by sufficient power delivery while also ensuring optimal grid performance. Fazelpour et al (2014) describe a common sense control methodology where intelligent algorithms handle smart charging optimisation within a smart grid environment of two directional communication capability. The algorithms develop a priority based system which identifies load constraints such as; SOC of arriving vehicles, number of vehicles requesting charge, and individual times available for recharging, and then calculates the optimal power distribution that ensures all EVs receive adequate quantity of equivalent driving range within the allocated time.

The demand side flexibility of EVs may appear a simple concept to integrate within a future smart grid environment by the description provided. If realised, there is a natural synergy between renewable energy intermittency and EV flexibility which, if exploited, would enhance overall grid performance. Somewhat counter-intuitively, an increase in overall electricity demand due to high penetration levels may actually reduce the overall GHG emissions from electricity generation. The demand side flexibility of EVs could ease the curtailment of intermittent renewable sources within current grid architecture, and enable greater utilisation of low carbon electricity for other domestic, commercial or industrial loads which present no directly obvious connection to EVs.

Curtailment of solar and particularly wind energy is an increasingly topical subject in the UK as overall capacity increases, but within outdated grid architecture. There exists a geographical disparity particularly within Scotland between points of peak demand, and points of optimal renewable electricity generation. During periods of excess supply, the lack of suitable storage technologies and a deficient grid infrastructure incapable of exporting to more concentrated areas of demand; results in useful clean electricity being dumped. As one pertinent example of this, despite having the world’s first active network management system which controls generation and demand loads to optimise renewables utilisation, the Orkney Isles grid network is heavily curtailed. In response, residents replaced their ICEs with EVs. By smart management of recharging schedules that correlate with periods of previously excess renewable supply, the residents are now effectively refuelling their vehicles for free (Urban Foresight, 2014).

This Orkney Isles example provides a representation of what may be perceived on grid scales to be the primary technological obstacle to an acceleration of renewable energy capacity; their level of underutilisation within an outdated grid architecture. Despite advancements in forecasting accuracy (Met Office, 2014), grid operators must account for instantaneous errors in particularly wind forecasting of approximately 5% (National Grid, 2015). Rather than logically assuming a 95% limit on actual wind generation from forecasting, EVs could provide most of their value to the grid as flexible loads to avoid curtailment of renewable energy.

2.3.3 Vehicle to grid

Current grid networks require a quantity of additional generating capacity that can ramp up power output at short notice in request from grid operators anticipating a shortfall in conventional generating capacity. To provide the necessary fast response times, these despatchable generators must run at low or partial speed during periods of inoperation to be already grid synchronised. Such operating reserves are thus referred to as spinning reserves (Kempton and Tomic, 2005). Spinning reserves constitute one of a package of power markets called ancillary services. In their simplest description, ancillary services are special services and functions that enable grid operators to maintain a secure balance of supply to demand.

Spinning reserves impose an obvious economic cost on grid networks, and a GHG cost on the physical environment, by forcing grid operators to run generators in a partially loaded standby configuration to respond to system contingencies, an unpredictability in renewable supply forecasting, and random variations in demand (Hummon et al, 2013). Alternative sources such as grid scale energy storage and particularly demand response systems, may replace the inefficient configuration of spinning reserves with significant economic and environmental advantages.

One solution would be to store available low carbon electricity when it is not needed, and redistribute to periods when it is. Given current capacity restrictions on grid scale energy storage systems, the optimal solution would be to couple with a form of energy storage that already exists to serve another purpose; EVs (Short and Denholm, 2006). Many researchers have acknowledged the economic and environmental benefits of EVs which may add vehicle to grid (V2G) functionality. In this configuration, EVs may be able to discharge some of their stored electricity back to the grid when grid connected. This would create a more dynamic form of operating reserve, and cleaner. EV recharge and discharge schedules could be controlled within a smart grid environment to act as a buffer for low carbon electricity; recharging during periods of excess supply, and then discharging at times when either grid capacity is stretched or the carbon content of grid electricity is typically high. This artificial form of grid storage would increase overall utilisation of renewable energy by the grid.

If V2G is to be implemented, control over EV recharging schedules would need to be ceased from the consumer to load aggregators. Although individual customers have the financial motivation to save on charging costs, they usually are not able to do so in the most efficient way nor to anywhere near the same extent of autonomy possible within a smart grid (Jin, Tang, and Ghosh, 2013). These load aggregators would form a pooling of EVs, and charge each at the optimal rate according to SOC priority based algorithms. It is therefore necessary to centralise EVs, concentrating the distribution of potentially hundreds of thousands of unique nodes into aggregated sites (Smokers et al, 2010). This creates a simpler management system, replicating to some extent an apparent simplicity in spinning reserves concentrated to a few centralised sources of predictable generation. EVs within a certain postcode, multi-storey car parks or high density workplaces would be automatically collated to form a group.

Although V2G is merely at a conceptual development phase, it is postulated by Lund and Kempton (2008) that for V2G it work, each EV must have three required elements; (1) grid connection; (2) communication with grid operators to allow external control; and (3) auditable on-board metering to ensure consumer is remunerated to the value of their provided grid service. It is essential that the operational control logic which allows the grid operator primary control may be overridden to ensure consumer mobility is not impaired, and that degradation of battery performance is minimalized. The relationship between life cycle and DoD was presented previously in Figure 7. V2G would mandate that EVs always maintain a consistently higher SOC in capacity to perform grid V2G. This would enforce less favourable DoDs and reduce battery performance. Again, the consumer would have to be suitably compensated for this. Furthermore, if this battery degradation equated over time to an overall increase in electrical demand despite V2G operation, the whole process would be non-effective (Benders et al, 2012).

V2G is only effective if the EVs parked at any one time is significant enough to make a difference. The implementation of V2Gs is restricted currently by the storage capacity of EVs, both as individual units and overall in terms of market penetration. It is further restricted by the capacity of electric cables connecting EV and grid. For instance, if six hours are required to charge an EV battery, it takes the same six hours to discharge this power back to the grid. So V2G can respond quickly but not quantitatively to demand, at least not in individual units (Canet et al, 2011). Current forecasts for EV penetration in the coming years would therefore only present a limited potential for V2G to replace spinning reserve capacity. There are further operational limitations of V2G. The Dutch Company SP Innovation (2008) published a report stipulating that depending on battery chemistries and discharge strategies, the bidirectional efficiency of V2G is between 45 and 85%. This bidirectional efficiency is defined as the percentage of power sent back to the grid that was delivered in the first place. According to The World Bank (2015), the UK's current electric power transmission and distribution losses account for 8% of output. Even in a best case scenario, V2G presents a comparatively inefficient process. It would therefore be more valuable within an integrated future of smart grids and EVs to pursue and refine optimal methods of demand side flexibility, rather than V2G.

2.4 Summary

EV popularity is growing through continued battery technology advancement which is alleviating a predominant obstruction of high purchase cost to the consumer. However, EVs still only constitute a tiny market share of the road transport sector. The obstruction to growth has transgressed from an economic consideration, to one of logistics. Without a suitable EV recharging public infrastructure to enable levels of opportunistic refilling and freedom of mobility comparable to current ICEs, consumers are reluctant to change to a transport method which may ultimately impair their quality of life. A level of EV recharging public infrastructure is therefore required with immediate priority to provide psychological reassurance, and consequently accelerate EV uptake.

Grid operators are now contemplating whether a significant future electrification of the transport sector would be achievable within the current architecture of grid distribution assets, while satisfying the motivational objective of reducing overall GHG emissions. Smarter grid technologies are required. Although the smart grid is necessary to facilitate mass market EV penetration, EVs are necessary for maximised smart grid performance, offering unprecedented levels of unobtrusive demand side flexibility. The potential to adjust electrical demand at almost instantaneous timescales presents EVs as the most viable implementing tool to transition power networks from a supply follows demand paradigm, to one of demand following supply. This would facilitate increased capacity of national grids to accommodate renewable energy's inherent intermittency, and create increased utilisation of low carbon electricity across all demand sectors.

3. Objectives and methodology

3.1 Problem definition

Problem definition is requisite to formulating relevant objectives achievable within the scope of this thesis. In order to assess the research process of this thesis, the following two questions must first be answered by identification of key or deficient areas of study within the literature review provided previously:

[1] For who is it a problem, and why?

The imminent introduction of a smart grid is a daunting infrastructural, particularly ICT challenge, that if not implemented correctly may stimulate severe economic depression both through misuse of funds, but also through a continued dependence on outdated grid architecture making climate change targets compliance comparatively inefficient. The smart grid's problem is it requires a more sophisticated deployment of technologies we already know about, but also development of technologies which do not currently exist. It is crucial that public money being invested in smart grid pilots just now is done so effectively. The key lessons learned from these demonstration pilots will enable grid operators and relevant policymakers to successfully implement the smart grid on more expansive regional and national networks, and realise its true transformational value.

To ensure the smart grid's success, mass market penetration of EVs is proposed as being essential due to the afforded level of unobtrusive demand side flexibility. A persisting obstacle to EV market growth is the lack of public EV recharging infrastructure offering almost unbounded freedom of mobility. Workplaces have been presented from surveys to be the preferred public EV recharging destination. However, the commercial sector is reluctant to engage with such development, with the initial underutilisation necessary to encourage EV uptake constituting a bad short term investment. Endogenous support may be received if high density workplaces with a conventional building load, adjoining EV parking facilities, and feasible installation of onsite renewable generation resources (particularly solar photovoltaic panelling); participate in smart grid trials. They would provide an optimal microgrid representation in which grid operators could refine new technologies and establish concepts to optimise future widespread deployment, while developing a preliminary level of public EV recharging infrastructure as a secondary motive.

The key problem to be addressed in this thesis concerns relevant policymakers and grid operators; a number of challenges currently obstruct the spread of smart grid pilots in the UK. These challenges include a struggle to establish business cases in environments where regulatory incentives do not reflect policy agenda, and further challenges of data privacy and cybersecurity. Most pertinently however, smart grid pilots are encountering challenges in consumer engagement; both in effectively communicating the benefit of smart grid technologies to consumers, and then in delivering implementations of high-quality. Consequently, pilots have thus far failed to stimulate accelerated participation (Giles et al, 2010). The development of a revolutionary smart grid, with EV dependency or not, will not be achieved to the desired speed or scale while there exists insufficient encouragement for voluntary trial participation within suitable environments.

[2] Then what should be done about it?

Consumers and local policymakers require greater demonstration, both within real life and simulated environments, of the potential benefits of smart grid technology trials to increase the utilisation of low carbon electricity, which is reflected in an overall energy evaluation. This would enable particularly the commercial sector to differentiate from competitors as industry leaders in embracing ideas of sustainability, but doing so with economic prosperity not frequently associated with cleaner renovation measures. Such statements must be supported by quantitative evidence encompassing dynamic analysis of a range of sensitive, stochastic system variables.

3.2 Objectives

The primary thesis objective is therefore to quantitatively investigate the potential for smart EV recharging strategies which may be feasibly implemented within real life environments, such as demonstration projects, to optimise the utilisation of renewable energy sources. This objective is composed of small, progressive objectives:

(i) develop a functional modelling tool for detailed technical analysis;

(ii) implement a smart EV recharging simulation procedure to defined case studies using this modelling tool;

(iii) evaluate the success of this modelling tool and simulation procedure through comparative analysis of results for a range of future scenarios, and discuss how they address the primary thesis objective;

(iv) and identify areas for future work.

3.3 Methodology

A flow diagram outlining the project architecture is provided in Figure 10.

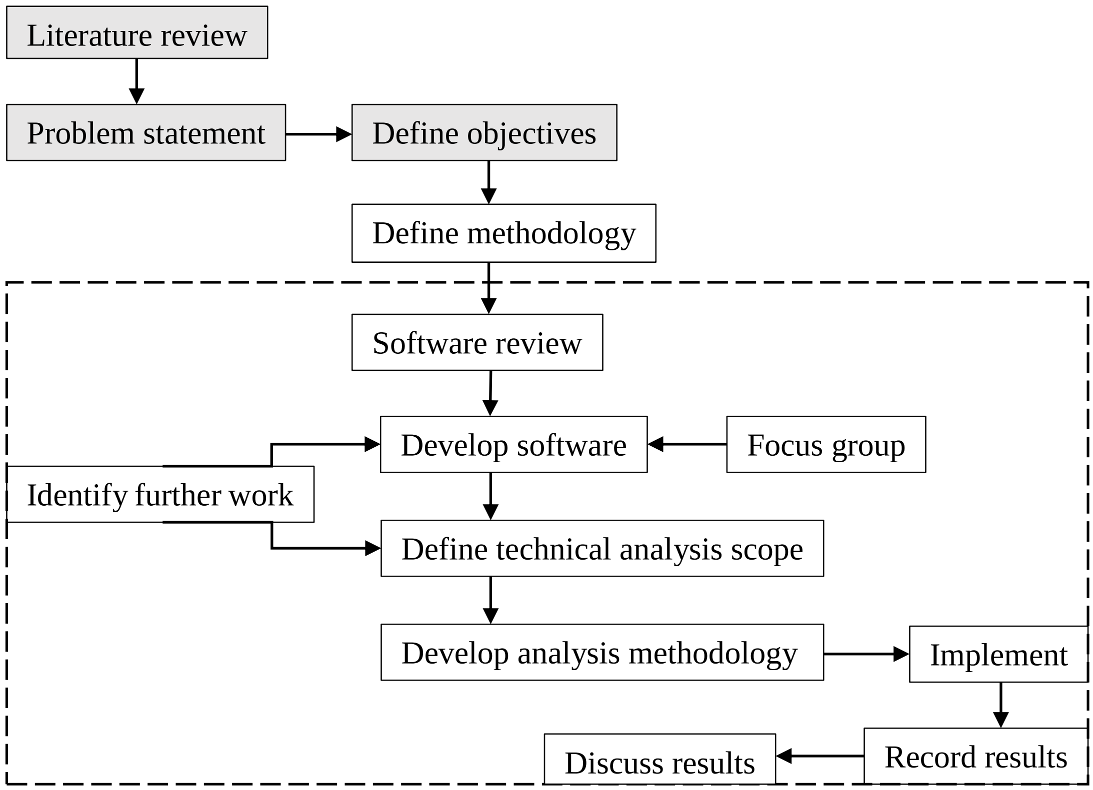

Figure 10. Project architecture.

The first few stages of this architecture which formulate the overarching scope of this thesis has already been presented. An extensive literature review was conducted from the basis of an initial thesis scope to "investigate the extent to which electric vehicles can be charged from renewable sources with an initial focus on adjacent or local PV, but then looking at potential synergies with other local energy systems and potential for larger scale wind and grid interactions." Identification of key or deficient areas in the literature review enabled the formulation of a concise problem statement and from this the definition of thesis objectives, both of which were presented just previously.

To realise thesis objectives, a progressive project methodology is defined. This is also presented schematically inside the dashed line box of Figure 10 above:

- Stage 1: Review the capabilities of existing software to model and analyse the performance of EV recharging strategies within dynamic environments. This is intended to provide motivation for the development of a new modelling tool which combines advantages of existing software to form one complete solution.

- Stage 2: Develop a modelling tool that enables the requisite level of technical analysis of EV recharging strategies. This will have particular functionality to progress from uncontrolled EV charging strategies to smart ones for optimised utilisation of renewable energy sources. This software will be refined constantly with the feedback of an identified focus group consisting of industry experts, relevant policymakers, academic supervisors and colleagues.
- Stage 3: Following development of the new modelling tool the level of technical analysis relevant to the primary thesis objective, and achievable within scope of available time, resources, and the modelling tool's functionality will be defined. Scenarios are suitably defined for simulated case study environments within the modelling tool to enable progressive analysis from a base case of no EV demand to one with integrated smart EV recharging capabilities. These case studies will be defined with logically assumed variations in building occupancy demand for EV recharging facilities and sensitive configurations of renewable supply.
- Stage 4: An analysis methodology is designed. Basic parameters of a consistent simulation methodology are defined, however prominent consideration is given to development of a suitable simulation methodology for smart EV recharging, requiring some functionality outwith the modelling tool. A methodology for the recording of simulation results is also defined to enable efficient generation of results most relevant to the primary thesis objective.
- Stage 5: Prepare and present simulation results to effectively demonstrate the quantitative impact of smart EV recharging strategies, as the thesis objective, in a clear and cohesive manner. Discuss the presented results, both within context of the primary thesis objective, but also how they, and by extension the thesis itself, translate from a condensed example necessary for detailed technical analysis within thesis scope, into the bigger picture.
- Stages 1-5: In parallel to the five project methodology stages described above, scope for further work, both on the part of the author and external contributors, will be identified throughout. To maintain progressive description of what was achievable within scope of this thesis, further work is however presented within one collated section following conclusions.

The remainder of this thesis is organised according to the staged methodology described above, and content predominantly concentrated within Section 4 which follows.

4. Technical analysis

A description of technical analysis provided in this section follows a logical progression towards presentation and discussion of results relevant to the primary thesis objective. The dashed box presented in Figure 10 provides a graphical illustration of progression. To expand on this in writing, the remainder of this section is organised as follows.

A review of existing modelling software is first conducted in Section 4.1. In conclusion, a summary of strengths and weaknesses is collated. This summary provides guidelines for the development of a new modelling tool which is more specifically tailored to the primary thesis objective, while encompassing additional features related to presentation and assumptions of operation which are, to an extent, replicated from existing software.

A description of this modelling tool development is provided in Section 4.2. Requisite data population of this modelling tool is segregated into sub-sections relevant to each stage in its progressive use; from specifying relevant EV or renewable system inputs, through to how this is synthesised by a calculation procedure in Microsoft Excel, and then results autonomously generated for key parameters in an appropriate format.

To utilise the modelling tool's functionality in satisfying the primary thesis objective, progressive scenarios for technical analysis are defined by a consistent and methodical approach in Section 4.3. A base case is first established in absence of any EV demand, requiring the definition of typical building loads, which adjoin EV recharging facilities in optimal workplace environments for smart grid trials, and renewable supply systems. Progressive scenarios are then developed to quantify the impact of implementing smart EV capabilities. The application of modelling assumptions is described throughout.

To simulate progressive scenarios defined in Section 4.3, and generate results relevant to the primary thesis objective, a simulation methodology is required. Description of a simulation methodology is given in Section 4.4. This description includes some basic parameters, such as climate, applied consistently to all scenario simulations, but more prominently describes the methodology devised for simulating smart EV recharging strategies, which requires functionality outwith the scope of the new modelling tool.

Finally, simulation results are presented in Section 4.5. These results are presented in a suitable format to enable the extraction of more detailed qualitative conclusions, both within the context of the primary thesis objective, but also how they fit within a bigger picture. Discussions stimulated from this are therefore provided in Section 4.6.

4.1 Software review

In order to satisfy the thesis objective, software is required that enables unbounded and dynamic analysis of demand profiles from EV recharging which are then matched to a renewable energy supply quantity. The software must be able to either autonomously generate, or enable the user to manually do so in a simple, deductive manner, key results related to parameters of system, environmental and financial performance. A review of existing software is thus conducted in order to assess their suitability.

There are various tools available on the World Wide Web which enable performance analysis during the operational phase of different vehicle types, including EVs:

(1) ADVISOR is a MATLAB/Simulink-based vehicle simulation program. This program enables analysis of vehicle operating performance and fuel economy. A significant advantage of using the MATLAB/Simulink environment is the flexibility and ease of changing the model, with MATLAB further enabling the results to be plotted simply (Wipke and Cuddy, 2015).

(2) IGNITE is a physics-based simulation program. This program enables similar analysis of vehicle operating performance, fuel economy, thermal management and emissions by detailed powertrain integration (Ricardo Software, 2015).

Despite both of these programs possessing advanced modelling capabilities across key areas of overall EV analysis, the analysis is predominantly focussed to simulations of the drive cycle, not the deployed EV recharging strategies and how these may influence the performance of electricity supply networks.

Tools have been developed for use in published papers with a research objective to model the future grid impact of additional demand for electricity due to EV recharging:

(3) Benders et al (2012) developed a Microsoft Excel spreadsheet model for the calculation of the future annual electricity demand originating from EVs. Input parameters included the number of EVs, their efficiency, their typical driving behaviour and various load management variables. A significant advantage of Benders et al’s spreadsheet model is that it can facilitate time progression, thus potentially simulating a future environment with smart grid functionality.

(4) Lacey et al (2013) developed a Microsoft Excel modelling tool to allow analysis of EV recharging on the distribution network, mainly the low voltage feeders,

11/0.4 kV substation and also part of the 11 kV section. A significant advantage of Lacey et al's modelling tool is the presentation of a user-friendly interface.

Although the basic functionality of these Microsoft Excel models may be of some use, the analysis concentrates focus on quantifying the future impact of high EV penetration levels on grid distribution capacity within rigid assumptions of EV recharge behaviour. Neither offer sufficient scope for a dynamic analysis of smart EV recharging strategies. With a similar research objective to these two papers, Kelly, Hand, and Samuel (2014) used an adaption of the ESP-r building simulation tool to model the consequences of both an electrification of heating and transport sectors on the electrical demand of a future, net zero energy dwelling:

(5) ESP-r was developed at The University of Strathclyde by a collaborative effort of the Energy Systems Research Unit (ESRU). In undertaking its assessments, it is equipped to model stochastic variables of air, heat, light, moisture and most relevantly electrical power flows at specified temporal and spatial resolutions. The ESP-r version adapted by Kelly, Hand, and Samuel enables assessment of how different EV recharging strategies may be deployed to minimise the peak electrical demand on dwellings.

Despite sophisticated, extensive capabilities, ESP-r's capacity to integrate with sources of renewable energy and generate an overall EV demand to supply match is restricted. Furthermore, with a lack of template EV recharging profiles accessible via the World Wide Web, the applied analysis methodology would require manual re-definition of demand profiles in external text files for each progressive scenario, which may then be imported into ESP-r with some difficulty. This would incorporate a significant source of random human error into the analysis methodology, not to mention the inefficiency of such a process. An internal functionality to generate EV recharging demand profiles is thus essential. This disadvantage may be further attributed to HOMER Pro:

(6) HOMER Pro is simulation software labelled the global standard for optimising microgrid design across any sector. There are two significant advantages of this software. Firstly, its optimisation functionality, which examines and sorts all possible system configurations to optimise a variable of choice. Secondly, its sensitivity analysis module, which helps to generate a results set with feasible

uncertainty ranges due to the unknown potential impact of variable factors on system performance (HOMER Energy, 2015).

There is a piece of software accessible via the World Wide Web which would appear to provide an optimal platform for demonstrating the primary thesis objective:

(7) The Zero Carbon Energy Model (Zero Carbon Britain, n.d.) shows hour by hour the match of supply to demand. This software possesses specific functionality for modelling EV recharging, and inbuilt algorithms to progress this to a smart strategy optimising the utilisation of renewable energy sources.

Unfortunately, there is no technical documentation available via the World Wide Web to support the accurate calibration of this model. It would unsuitable to use this model while no reliable means exists to prove its validity. A second piece of software accessed via databases at The University of Strathclyde, offers further opportunity:

(8) Merit was again developed at The University of Strathclyde by a collaborative effort of ESRU. Merit is a quantitative evaluation tool designed to specifically allow the user to assess the demand supply match, and maximise the utilisation of various renewable energy systems. Simulated performance of these systems is achieved by algorithms based on design specifications, locational parameters and meteorological data.

Similar to ESP-r, Merit enables the user to generate their own electricity demand from EV recharging, and contains a substantial database of meteorological climate data and building loads defined to international standards, offering scope for unbounded analysis of various scenarios. Unfortunately, Merit’s suitability for analysis falls just short, for two primary reasons. Firstly, there is no inbuilt functionality that would enable scenario progression towards efficient deployment of smart EV recharging strategies. Secondly, there is not a suitable means to quantify results of this were it possible. Although Merit does calculate a percentage match value, this is determined to assist the optimal sizing of renewable supply systems to a fixed demand. Any excess renewable supply is thus calculated as a negative factor. The primary objective of this thesis is to quantitatively demonstrate the impact of smart grid technologies at optimising utilisation of renewable electricity for EV recharging. Whether using microgrid representations of a workplace, previously identified as the optimal environment for trialling such technologies, or more expansive regional and national grid networks, both would possess some capacity to export excess generation to an external grid network, and potentially with economic prosperity. It is therefore not suitable for excess renewable energy to be calculated as a negative factor in the all-important demand supply match result. It is possible to export simulation results from Merit into Microsoft Excel and post-process for the required outputs, but doing so is somewhat clumsy and inefficient.

Finally, an undergraduate student project (Maloney, 2015) conducted at The University of Strathclyde attempted to develop suitable software:

(9) The RESERV (Renewable Energy Supply Electric Road Vehicles) calculator tool enables a user to determine the EV recharging demand match to a quantity of renewable energy supply. A significant advantage of this tool is that the user interface is specifically designed for EV use. This will appeal to consumers and localised policymakers who do not wish to navigate to tabs of a more expansive, sophisticated program tailored to those with pre-existing technical knowledge.

This calculator tool provides introduction to core principles that should be integrated into any software intended for modelling various EV recharging strategies. However, as might be expected within the restricted scope of an undergraduate student project, it does incorporate a significant number of deficiencies. These deficiencies spread across; usability; the variability of potential modelling scenarios with regards to rigid definition of the type and quantity of renewable electricity supply; methods used to simulate these scenarios; and the accuracy of formulas used to generate meaningful results.

4.1.1 Summary

In order to satisfy the thesis objective, software is required that enables unbounded and dynamic analysis of demand profiles from EV recharging which are then matched to a renewable energy supply quantity. Following an extensive review of available software, it is concluded that none currently exists of sufficient modelling capacity. That software is commercially limited in analysis of EV recharging may be indicative of insubstantial demand from researchers, relevant policymakers and grid operators, at least while the level of EV penetration into the road transport sector remains negligibly low. However, if targeted areas of public infrastructure, such as workplaces, are to provide a suitable environment for trialling smart grid technologies fundamental to a revolutionised power industry, modelling capability within a simulated environment is necessary to quantify the impact of smart EV recharging strategies, and encourage real life trial participation.

4.2 Modelling tool development

In response to the software review, it was decided that a new modelling tool is necessary to simulate smart EV recharging strategies and analyse how they enhance the utilisation of renewable electricity generation. The development of this modelling tool constitutes a key deliverable of this thesis. Although tailored with relevance to the primary thesis objective, this modelling tool was intended to plug gaps in existing software. Therefore, its development was with intention of providing general applicability for use in future, related research. The modelling tool was developed using Microsoft Excel.

The first stage of development was to create a demonstration version with all the basic functionality which may be expanded for detailed analysis. This demonstration version was, however, uniquely designed as an educational tool to provide introduction to some core concepts of EV recharging. This demonstration version can only model a single recharge event for the maximum specification of two vehicles within a domestic setting. To replicate the most likely domestic scenario of overnight EV recharging, this single recharge event was not confined to a rigid 24 hour time period, and could traverse from one day into the next.

For the demonstration tool and further use in analysis, it was important from the outset to define basic operation. The modelling tool would enable the user to; (1) specify any EV model popularly available on the UK market; (2) select a model compatible charge point type/recharge speed; (3) specify a time period for the recharge event; (4) and then design a distributed renewable energy system consisting any combination of solar PV panelling, with optional battery storage, and wind power. The power output from these distributed renewable energy sources would be specific to the specified calendar month, and to meteorological conditions at defined locations within close proximity. The tool would then autonomously simulate this event and generate clear results for key system, environmental and financial performance parameters.

According to the four stage operation described, the demonstration tool was segregated into two distinct input sections for; [1] an EV recharge event, corresponding to stages (1)–(3) above; and [2] the renewable energy supply system, corresponding to stage (4). Appropriate population of these input sections is now described in Section 4.2.1 for the EV recharge event, and in Section 4.2.2 for the renewable energy supply system. Key formulas outlining the applied calculation procedure are provided throughout.

4.2.1 Electric vehicle inputs

The objective of the modelling tool's electric vehicle inputs is to generate an exit state of charge (SOC), or all electric driving range, according to four specified inputs; (1) the EV model; (2) the entry SOC; (3) the charge point type, or recharge speed; and (4) the duration of recharge event. The necessary energy delivered to achieve this exit SOC, is that which will be ideally be supplied by a renewable energy system to be defined.

4.2.1.1 *EV model.* The most popular EV models in the UK were populated according to new car registration statistics published by the Department for Transport (2015d). As necessary, it was assumed that all registrations remain road-worthy and in use. In any case, any discounting factor for would be applied equally across all EV models and not impact qualitatively EV market share. 21 EVs were extracted from the Department for Transport spreadsheet. 10 of these used in analysis are presented in Table 1 with market share of the overall defined EV set, alongside some key performance specifications.

EV model	Market share (%)	Battery capacity (kWh)	Electric range (miles)	Dashboard display
Mitsubishi Outlander	33.848	12.0	32.5	16 Bars
Nissan Leaf	28.094	24.0	124.0	12 Bars
BMW i3	7.877	18.8	90.0	Range
Renault Zoe	5.528	22.0	100.0	Range
Toyota Prius PHEV	4.820	4.4	15.5	Range
Vauxhall Ampera	4.313	16.0	16.0	Range
Tesla Model S	3.197	60.0	60.0	Range
BMW i8	2.068	7.0	23.0	Range
Renault Twizy	1.681	6.1	62.0	10 Bars
Renault Kangoo	1.369	22.0	106.0	4 Bars

Table 1. Modelling tool – EV specifications.

EV specifications populating Table 1 were obtained from reliable sources on the World Wide Web. All EV batteries are li ion. The electric range refers to the maximum driving range of BEVs, and the maximum all electric range without ICE assistance in PHEVs. This will vary according to the age of the vehicle and the associated battery degradation, the driving behaviour per cycle, use of e.g. air conditioning, and ambient temperature. Average values adhering to industry standards, are however sufficient for analysis.

4.2.1.2 *Charge point type.* EV compatibility with select charge point types, each with a maximum deliverable power rating, varies according to the EV inlet type and on-board PMS conversion capacity. It was therefore important that charge point compatibility was enforced, particularly within the demonstration tool, to avoid a potential to define misleading higher recharge speeds than compatible with EV models. The charge point compatibility corresponding to Table 1 is presented in Appendix A.

4.2.1.3 *Exit State of Charge calculation*.

As described, there are four components to the exit SOC calculation. The vast majority of pre-existing tools generate an entry SOC from the user specifying a distance driven from previous recharge. This assumes the EV battery is full after every recharge event, and every recharge event occurs in one location. Thesis problem definition identified a need for public EV recharging infrastructure that enables opportunity recharging to supplement primarily home based recharging. It would therefore be contradictory to assume recharge events only occurred in one location, and with regards to opportunity charging, that the duration of every recharge event is sufficient to restore a full charge.

A new equation was dependent on the connected charge point possessing functionality to manually read the entry SOC. Electropaedia (2015) describe the procedure of SOC estimation within a practical environment. In a static state with no directional charge, only sensors are required to provide a measurement of the current battery status. These provide equivalent analogue inputs for ambient temperature, cell voltages and currents to a DC converter. The DC output is then synthesised by a microprocessor to generate an accurate SOC estimate. Given apparent simplicity to manual SOC reading, at least whilst static (as at point of entry), it was reasonable to assume this SOC measurement technique would be more suitable than one based on historic driving behaviour within a practical environment, and thus more relevant to model within a simulated one.

Estimating the SOC during a recharge event is more complex procedure which must integrate over a number of non-linear, stochastic variables. In a sophisticated practical environment, look up tables would be used; the performance characteristics of a sample battery cell are recorded once within a controlled laboratory environment, and used as a reference template for the rest of the population. Unfortunately, the complexity of this could not be facilitated within the developed modelling tool, both due to a lack of the necessary resources and the restricted scope of this thesis. In compensation, the ongoing SOC is measured as a function of the entry SOC, duration of recharging and deliverable charge point power, with application of an empirically averaged linear efficiency factor. The equation devised for exit SOC is thus:

$$\left(\frac{d_r}{d_m} + \left\{\frac{P * \eta * [t_e - t_s]}{b_c}\right\}\right) * 100\ (\%) \qquad (1)$$

Where: d_r is the remaining range / battery bars on the dashboard display;

d_m is the maximum range / battery bars on the dashboard display;

d_r / d_m is the entry SOC;

P is the maximum deliverable power of the charge point type (kW);

η is the recharging efficiency = 0.8;

t_e is the end time for recharging event;

t_s is the start time for recharging event;

b_c is the battery capacity (kWh).

4.2.1.4 *Exit all electric driving range calculation.*

By implementing the basic principles of EV recharging within the modelling tool, using necessary application of underpinning assumptions, the key output from the EV inputs section is the all electric driving range. From the exit SOC calculated above, it is simple to deduce the exit all electric driving range is this multiplied by the EV battery capacity. The relevance of this output will become more evident in scenario definition to follow. However, in introduction, it allows the autonomous calculation of the time required to restore charge sufficient to satisfy typical driving behaviours in modelled scenarios.

Definition of an EV recharging event within the modelling tool is presented to be user friendly, see Figure 11. By specification of five simple inputs described in the preceding text, the all electric driving range achievable is the primary output. Two examples given in Figure 11 ask a user to define dr as either remaining battery bars, or remaining range. This depends on the selected EV model, and will change automatically. The correct unit of measurement is presented in the column entitled Dashboard Display, see Table 1.

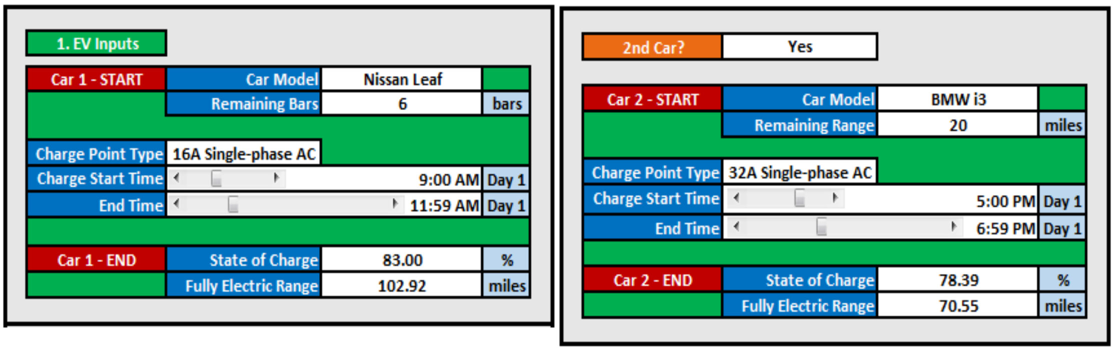

Figure 11. Modelling tool - EV inputs user interface.

4.2.2 Renewable energy system inputs

Description of EV inputs population is complete. The modelling tool, as the fourth stage in operation, will then enable design of distributed renewable energy systems consisting any combination of solar PV panelling, optional battery storage, and wind power. This will quantify the EV demand which may be satisfied by onsite renewable electricity or otherwise, subtracting for integrated building loads, and autonomously generate results for key parameters of system performance. Sub-sections that follow deliver description of how inputs such as location and month populated the modelling tool. Equations for calculating temporally available renewable power from first wind and then solar PV are provided, to show these inputs translate into the overall energy supply.

4.2.2.1 *Location and Month.* Average meteorological conditions from each month were required across a geographic spread of the UK. Annual data was obtained at a temporal resolution of one hour from the ESP-r climate database for 13 locations. Furthermore, for analysis local to the point of thesis compilation, archive climate data for Glasgow 2006-2011 was obtained from the Met Office following an academic data request. This location quantity offers scope for diverse climatic analysis, with substantial variation of meteorological conditions in different latitudes, urban densities, coastal proximities, and more. All annual data was synthesised for average values at a temporal resolution one hour for each calendar month, forming 12 average days per climate location. This was sufficient for the demonstration version of the tool where only one recharge event can be defined over a period of 48 hours, although later expanded for detailed analysis.

4.2.2.2 *Wind.* Although distributed wind power is not overly relevant within a domestic environment, the demonstration tool purpose was to develop full functionality for later analysis in a more expansive environment of public infrastructure. Wind was therefore included in the demonstration tool. Electricity generation from wind power may be calculated by the following equation (Clarke and Kelly, 2015a):

$$P = 0.5 * C_P * \rho * A * V^3 \ (W) \tag{2}$$

Where: C_p is the wind power coefficient, the ratio of actual to real power;
ρ is the air density = 1.225 kgm^{-3}
A is the rotor blade swept out area;
V is the wind speed.

The only complication in applying (2) was generating usable C_p's for all wind speeds within the ESP-r/Met Office climate database. The following procedure was applied. Wind curves were obtained from HOMER Pro for nine different wind turbines. These provided deliverable power in wind speed increments of 0.5 or 1ms^{-1}, depending on the turbine, according to (2). To extract applied C_p factors and, as an approximate measure, apply to any ESP-r/Met Office wind speed within 50% of the respective turbine's wind speed increment (i.e. if wind speed = 12.3ms^{-1} for increment 0.5ms^{-1}, use 12.5ms^{-1} C_p; for increment 1ms^{-1}, use 12ms^{-1} C_p), deliverable powers were divided by 0.5*ρ*A*V^3. Now that usable C_p's had been obtained, the average wind speeds synthesised for each climate location could then be translated to deliverable wind power for any of the nine HOMER Pro wind turbines used. These C_p's are provided in Appendix B.

4.2.2.3 *Solar PV.* Electricity generation from solar PV power may be calculated by the following equation (Clarke and Kelly, 2015b):

$$P = \eta * I_T \ (W/m^2) \tag{3}$$

Where: η is the panel efficiency = 0.15 (Mackay, 2009);

I_T is the total solar radiation incident on a PV panel. This is a sum of the anisotropic sky diffuse component of the radiation incident on the PV panel ($I_{s\beta}$), direct beam intensity ($I_{d\beta}$), and the ground reflected radiation intensity ($I_{r\beta}$):

$$I_T = I_{s\beta} + I_{d\beta} + I_{r\beta} \tag{4}$$

And:

$$I_{s\beta} = I_{fh} * \left\{\frac{1 + \cos(90 - \beta_f)}{2}\right\} * \left\{1 + \left(1 - \left[\frac{I_{fh}}{I_{Th}}\right]^2\right) * sin^3\left(\frac{\beta_f}{2}\right)\right\} * \left\{1 + \left(1 - \left[\frac{I_{fh}}{I_{Th}}\right]^2\right) * cos^2(i_\beta) * sin^3(90 - \beta_s)\right\} \tag{5}$$

And:

$$I_{d\beta} = I_{dh} * \frac{cos_{i\beta}}{sin_{\beta s}} \tag{6}$$

And:

$$I_{r\beta} = \frac{1}{2}\{1 - \cos(90 - \beta_f)\} * I_{Th} * r_g \tag{7}$$

Where: I_{fh} is the diffuse horizontal solar radiation;

β_f is the surface inclination;

$I_{Th} = I_{fh} + I_{dh}$, where I_{dh} is the direct horizontal solar radiation;

$i_\beta = \cos^{-1} \{ \sin \beta_s * \cos (90 - \beta_f) + \cos \beta_s * \cos \omega * \sin (90 - \beta_f) \}$, where;

ω = solar azimuth - surface azimuth, and surface azimuth is the degrees from north a solar PV panel is facing;

β_s is the solar altitude;

r_g is the ground reflectivity = 0.25 (Intelligence, n.d.).

I_{fh}, I_{dh}, and thus I_{Th} were obtained from ESP-r / Met Office and synthesised for average values. β_f and surface azimuth are user defined parameters. Only two variables therefore required definition; solar azimuth and solar altitude, specific to each climate location. These were obtained from The United States Naval Observatory (2015). Values at temporal resolution one hour were obtained for an arbitrary but consistent day in each month, and from the corresponding year. (ESP-r's climate database provides one year of weather data, which due to variation across the database, was assumed to have been chosen as representative of average conditions to that climate location.) This required only definition of specific coordinates of latitude and longitude to each climate location.

4.2.2.4 *Solar PV Battery Storage.* The option to specify any quantity of solar PV battery storage was included, with a user defined linear efficiency factor. This efficiency factor will vary according to battery chemistry. Grid based storage systems have traditionally favoured lead acid batteries. Despite widespread usage, lead acid energy density, both mass and volumetric, remains one of the lowest in battery design. Li ion batteries, as discussed in this thesis, present a more efficient solution for large scale manufacturing. Relevant to grid based storage systems, they have a very low rate of self-discharge. In proposing the long term viability of li ion favourably over lead acid batteries, a default efficiency $\eta = 0.85$ was therefore assumed, according to Ali and Ali-Oettinger (2012).

4.2.2.5 *Building Load.* Matching EV recharge schedules to renewable energy supply is not sufficient to determine the smart time for recharging. Electricity demand from other sectors should be considered as well. If the modelling tool was to simulate a microgrid environment of a more expansive network, the three primary components of; (1) a fixed load, from building use; (2) a flexible EV load; and (3) renewable supply; all had to be recreated to an appropriate scale, and integrated into the modelling tool's functionality.

Building loads were obtained from the ESP-r database. Annual demand profiles were originally generated by Born (2001) through a rigorously calibrated procedure. Demand profiles span the commercial, domestic, industrial and recreational environments. They therefore presented optimal opportunity for varied analysis of EV recharging schedules. To integrate into the modelling tool, annual demand profiles were synthesised from text files at half hour temporal resolution, to average profiles at one hour temporal resolution to correlate with meteorological conditions. For the demonstrative tool's domestic use, only domestic building loads may therefore be specified for one to three bedrooms with optional electric heating. The system inputs user interface is presented in Figure 12.

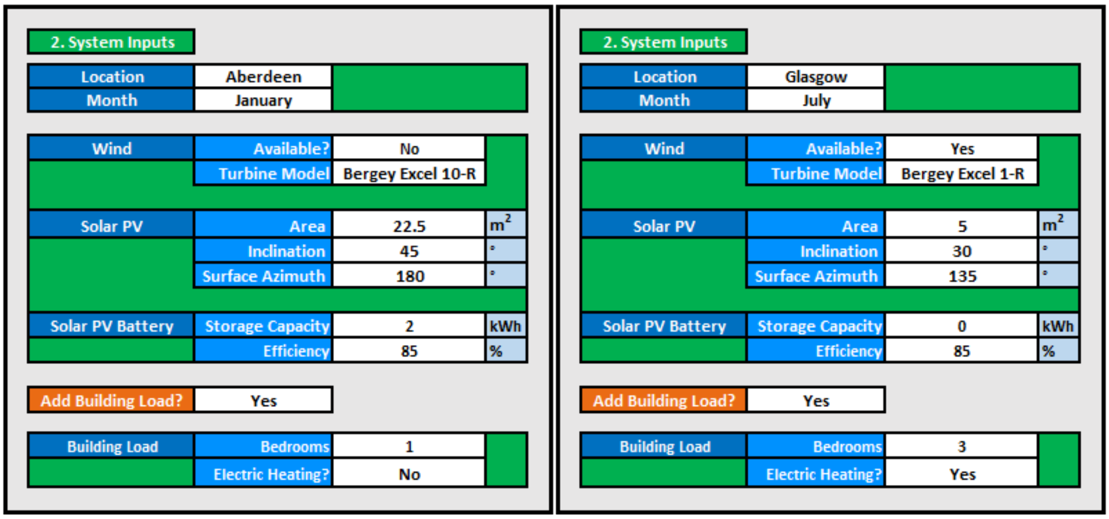

Figure 12. Modelling tool – System inputs user interface.

4.2.3 Calculation procedure

Now the modelling tool was populated with requisite data for both EV inputs and those governing renewable electricity generation, functionality was developed for an accurate simulation using chosen Microsoft Excel software. The tool's calculation procedure is designed to generate the EV demand and renewable supply, with optional building load, at each timestep from the user's definition of specific inputs to relevant equations given previously, and enable generation of overall results for key performance parameters. Given the complexities of modelling the EV-renewable energy-building system within limited software, a simplified staged procedure was designed to execute the necessary calculations from specified inputs. Please note a blow by blow description of formulas used in the modelling tool to create this calculation procedure are not provided in this thesis. However, the modelling tools and further materials crucial to the compilation of this thesis, are openly available for download and detailed scrutiny in Hercus (2015).

	Demand (kWh)	Supply (kWh)		Battery Level (kWh)	Grid Exchange (kWh)	% Supply			
		Wind	Solar PV			Wind	Solar PV	Battery	Grid
Day 1	0.139	0.000	0.000	0.000	-0.139	0.000	0.000	0.000	100.000
8:00 AM	0.216	0.000	0.000	0.000	-0.216	0.000	0.000	0.000	100.000
9:00 AM	3.534	0.000	0.092	0.000	-3.443	0.000	2.591	0.000	97.409
10:00 AM	3.525	0.000	0.410	0.000	-3.115	0.000	11.630	0.000	88.370
11:00 AM	3.532	0.000	0.715	0.000	-2.817	0.000	20.249	0.000	79.751
12:00 PM	0.247	0.000	0.852	0.514		0.000	100.000	0.000	0.000
1:00 PM	0.263	0.000	0.902	1.057		0.000	100.000	0.000	0.000
2:00 PM	0.230	0.000	0.892	1.619		0.000	100.000	0.000	0.000
3:00 PM	0.216	0.000	0.787	2.000	0.124	0.000	100.000	0.000	0.000
4:00 PM	0.238	0.000	0.472	2.000	0.235	0.000	100.000	0.000	0.000
5:00 PM	6.917	0.000	0.000	0.000	-4.917	0.000	0.000	28.915	71.085
6:00 PM	6.993	0.000	0.000	0.000	-6.993	0.000	0.000	0.000	100.000

Figure 13. Modelling tool – Calculation procedure.

The staged calculation procedure is now described with assistance from Figure 13. This image is a condensed illustration (corresponding to EV inputs defined in Figure 11, and renewable supply system inputs defined on the LHS of Figure 12) of outputs from the modelling tool's calculation procedure. This provides introduction to a logical flow of description as to how they were generated, in the text that follows.

- Stage 1: Calculate the energy demand from a user defined EV recharge event. Through use of necessary underpinning assumptions, EV energy demand is not dependent on what may be described as external recharging factors such as the time of year, location or meteorological conditions only on EV inputs and consequential outputs specified previously.

- Stage 2: Calculate the energy demand from an integrated building. To provide brief explanation of formulas used within the modelling tool; to allow extensive analysis over a number of scenarios, the energy demand here from an integrated building and, in particular, the temporally available supply of renewable energy, would require inbuilt functionality to assume any possible value determined by inter-dependent variables. To achieve this, the Microsoft Excel Index function was used extensively, and supplemented by the If function for instances of a reduced number of inter-dependent variables. At this stage, the energy demand from an integrated building is indexed from an external spreadsheet, according to definition of relevant inputs for the time of year and building type.

- Stage 3: Calculate the maximum available energy supply at each timestep from both wind and solar PV. Available energy from wind, relevant to each turbine, climate location and calendar month is provided at one hour temporal resolution within an external spreadsheet, and indexed according to specification of inputs. Similarly, available energy from solar PV, relevant to each climate location and calendar month is provided at one hour temporal resolution within a different external spreadsheet, and indexed according to specification of inputs.
- Stage 4: Determine the segregated supply of energy at each timestep from the four sources of supply; (1) wind; (2) solar PV; (3) solar PV battery storage, if specified; and (4) the grid. Although not fully demonstrated by the example of Figure 13 provided, the supply of energy follows a preferential hierarchy where; instantaneous wind power is first used to supply demand, where possible, due to possessing no storage capacity; followed by instantaneous solar PV power; then battery stored solar PV power (this solar PV order reduces power storage bi-directional efficiency losses); finally, any deficit is satisfied by grid import. This preferential hierarchy was designed to maximise utilisation of energy from renewable sources.

The primary difficulty in implementing this calculation procedure within the limitations of available software was to integrate solar PV battery storage that prioritised "creating" solar PV supply excess over wind supply excess, could then accept this solar PV excess, but then, most pertinently, fluctuate only between a battery level of zero (empty) and the maximum defined storage capacity by consideration of dynamic grid exchanges (in Figure 13, note additional functionality to export to the grid in periods of supply beyond demand and solar PV storage capacity from 3-5p.m. in this example, under assumption that capacity for grid export is unconstrained).

To use Figure 13 as an example, particular difficulty was encountered in modelling the solar PV battery to drain from the maximum storage capacity (2kWh) at 5p.m., despite excess solar PV supply in the timestep previous (i.e. not drain from 2.235kWh). This could not be achieved with a novice application of Minimum and Maximum functions. In overcoming this, communications were established with suitable technical contacts through relevant help forums available on the World Wide Web. The solution was then rigorously tested to ensure reliability over all possible variations in relevant inputs.

4.2.4 Results generation

All inputs described in Sections 4.2.1 and 4.2.2, are autonomously synthesised by the calculation procedure just described to generate key performance results related to; (1) the environmental impact of the system in measured CO_2 emissions; (2) the financial performance, defined by quantities of grid import and renewable generation eligible for the UK Government's Feed-in Tariffs (FITs) scheme; (3) overall demand supply match results; and (4) the system's correlation coefficient. The accuracy to which these results could be generated within a simulated environment was impaired due to the necessary, processional use of "accurate as far as possible" assumptions, as to be expected within a simulated environment. However, the results hold validity, particularly for use in a comparative analysis where it may be reasonably postulated that slight inaccuracies in experimental procedure are applied with equal weight throughout. It should be stated that environmental and financial results consider only the operation phase of the system, with exception of auxiliary running costs due to maintenance for example. Results over an entire life cycle, from manufacturing to decommissioning, cannot be realistically simulated due to their dependency on a range of unpredictably variable factors.

4.2.4.1 *Environmental: CO_2 emissions.* Wind and solar PV power were defined to have zero CO_2 emissions. These CO_2 emissions therefore depend on the quantity, and carbon content, of temporal grid imported electricity. Robinson et al (2013) obtained typical UK electricity generation data at half hourly intervals from the National Grid, based on summed total output from predominant generation sources. To convert to equivalent CO_2 emissions, average carbon emission factors for generation and transmission were obtained from DECC. For each half hourly interval, Robinson et al then calculated the seasonal carbon content of grid electricity, and presented within relevant graphs.

As the raw data which populated these graphs could not be obtained from the sources referenced within the paper, nor could any updated data be obtained in a suitable format from the World Wide Web, the seasonal carbon content of grid electricity was extracted from presented graphs by imprinting vertical gridlines at hourly intervals and reading across to the corresponding carbon content. Although an approximate procedure, given the vertical axis's concentrated scale, the uncertainty incurred due to human error would not realistically exceed more than 1 or 2%, and was therefore reliable for use. CO_2 emissions in the modelling tool are then simply calculated as the sum of the quantity of grid imported electricity at each timestep multiplied by the indexed carbon content.

4.2.4.2 *Financial.* The financial net balance due to operation is a simple calculation of only one expenditure source, grid imported electricity, and one source of income, FITs payments, albeit with two sub-segregated channels of generation and grid export. Fixed tariff rates were applied for the quantity of grid imported electricity. Despite the popular growth of economy based tariffs, reliable quotes could not be obtained from the World Wide Web during tool development with necessary regional differentiation for each climate location. Therefore, fixed tariff rates were taken from British Gas, the UK's largest domestic energy supplier, and supplemented by Power NI and Jersey Electricity for climate locations outwith British Gas boundaries. These unit costs were calculated using a necessary, consistent assumption on annual electricity consumption.

For financial income, the FIT scheme is a government programme designed to promote uptake of small scale renewable technologies. Consumers are paid fixed rates for every unit of electricity they generate, and a different rate for every unit exported to the main grid. The rate for grid export was 4.85p/kWh for both wind and solar PV at the time of tool development. The rate for generation varies according to technology and capacity. For use in the modelling tool, applying a relevant tariff for wind generation was simple. All selectable wind turbines, with the exception of Vergnet GEV MP-R, have a capacity of 100kW or less and thus receive a generation tariff 14.45p/kWh. Vergnet GEV MP-R receives 12.05p/kWh (valid 1.4.2015 - 31.1.2016) (Feed-In Tariffs Ltd, 2015).

Developing relevant tariffs for solar PV generation was not as simple as FITs rates for solar PV are scaled according to capacity in units of kW, whereas the quantity of solar PV generation was specified according to m^2, as necessitated by (3). Various sources on the World Wide Web (Regen SW, n.d.) state solar PV panels require average surface area 7-8m^2 for every kW of installed capacity. As an approximate measure, an average conversion factor of 7.5m^2 was therefore applied to default tariffs published in kW capacity, to convert to m^2 capacity. The results of this are provided in Table 2. Area converted tariffs were thus applied to the tool (valid 1.7 - 1.10.2015).

Solar PV Capacity (kW)	**Solar PV Capacity (m^2)**	**Tariff (p/kWh)**
$kW \leq 4$	$m^2 \leq 30$	13.39
$4 < kW \leq 10$	$30 < m^2 \leq 75$	12.13
$10 < kW$	$75 < m^2 \leq 375$	11.71
$50 < kW \leq 150$	$375 < m^2 \leq 1125$	9.98
$150 < kW \leq 250$	$1125 < m^2 \leq 1875$	9.54
$kW > 250$	$m^2 > 1875$	6.16

Table 2. Solar PV FITs generation tariffs in m^2 (Energy Saving Trust, 2014).

4.2.4.2 *Demand Supply Match.* The demand supply match is the critical result. It, to an extent, determines a performance evaluation of environmental and financial parameters defined just previously. It was described in the software review that Merit uses a match equation where excess renewable supply is integrated as a negative contributing factor. In the context of Merit's intended application, the optimal sizing of renewable energy systems to a fixed quantity of demand, it is correct to do so, as any excess may not be feasibly exported. This, therefore, constitutes an oversized supply system, with the cost of installation including a proportional value of waste. However, in the sole interest of maximising renewable energy utilisation, and the added capacity for grid export as an inbuilt assumption, excess supply should not exert any influence on the demand supply match result. To correct for this, the simple equation below was constructed and applied to the modelling tool:

$$Match = \left\{1 - \left(\frac{\sum_{t=0}^{n} S_{tG}}{\sum_{t=0}^{n} D_t}\right)\right\} * 100\ (\%) \tag{8}$$

Where: S_{tG} is the grid imported electricity supply at any timestep t;
D_t is the electricity demand at any timestep t.

4.2.4.4 *Correlation Coefficient.* The correlation coefficient (CC) quantifies any existing trend between electricity demand and supply profiles. It does not consider the relative magnitudes of the demand and supply profiles. So, for example, if solar PV capacity in a supply system doubled in size, there would be no change in the CC. And in reverse of this, if the demand and supply profile were in perfect phase with each other, but of very different magnitude, this would result in perfect correlation (CC=0), but obviously not a perfect match. Born (2011) defines an equation for determining the CC:

$$CC = \frac{\sum_{t=0}^{n}(D_t - d) * (S_t - s)}{\sqrt{\sum_{t=0}^{n}(D_t - d)^2 * \sum_{t=0}^{n}(S_t - s)^2}} \tag{9}$$

Where: D_t is the electricity demand at any timestep t;
d is the mean electricity demand over time period n;
S_t is the electricity supply at any timestep t;
s is the mean electricity supply over time period n.

This CC result may be thought of as defining natural synergy between a demand profile and a renewable supply profile. Although this may not assist in system sizing, it does provide preliminary introduction as to what may be the most suitable type of renewable supply technology for a demand profile. From this base, changes may be implemented to relevant capacities through energy efficiency measures or system resizing, in order to provide an optimal demand supply match result.

Definition of a CC result forms the final action in development of a demonstration EV recharging modelling tool. Figure 14 displays the results section's user interface for the corresponding system defined by Figure 13. On the LHS is a graph of the segregated breakdown of electricity supply at each time step. On the RHS a graph of demand versus supply. Outputs for key performance results are autonomously calculated, according to all procedures previously described, and presented below.

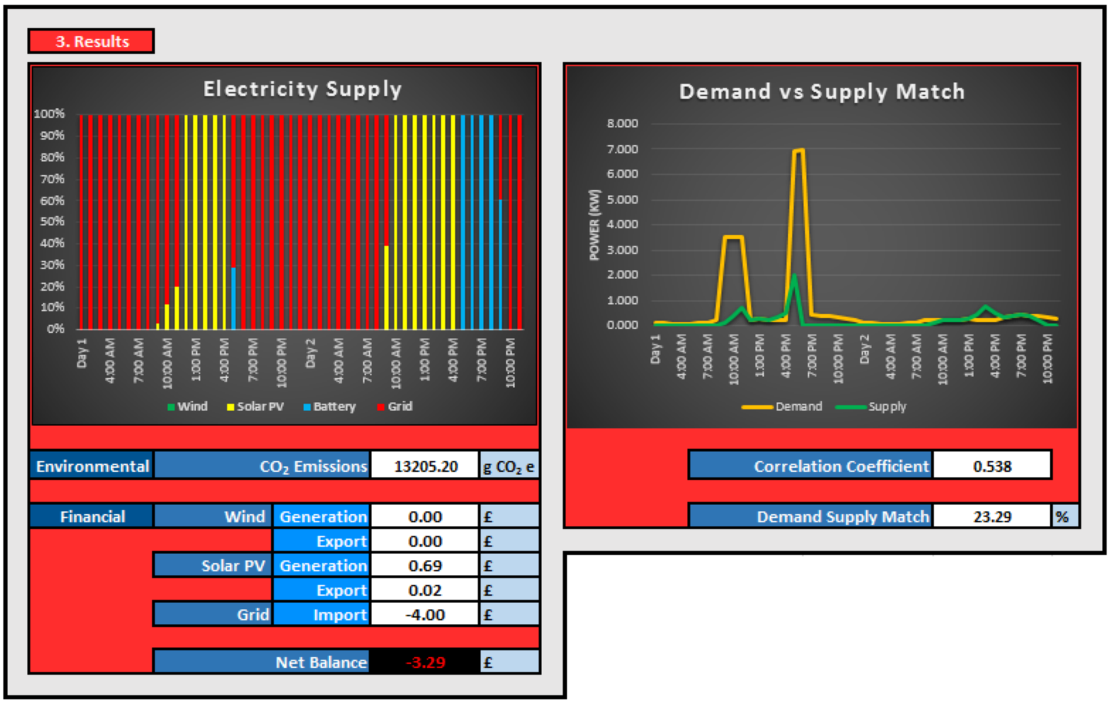

Figure 14. Modelling tool – Results user interface.

The EV recharging modelling tool described in preceding discussion is a demonstration version of general applicability. It possesses all basic functionality for detailed analysis of smart EV recharging strategies, and thus the capacity for generating results relevant to the primary thesis objective. However, the functionality is restricted to only a single recharging event over 48 hours and the maximum specification of two EVs, while the available renewable supply is only calculated for average meterological values over a 24 hour period. This was modified to enable more extensive, realistic analysis of the progressive scenarios defined below, with modifications described where relevant.

4.3 Definition of EV recharging scenarios for simulation

As a reminder, the primary thesis objective is to quantitatively demonstrate the potential for smart EV recharging strategies to optimise utilisation of renewable energy sources through particular analysis of workplace orientated microgrids, which were identified as a suitable trial environment for the development of smart grid technologies, with the secondary motive of developing preliminary public EV recharging infrastructure. In the intention of achieving this, the modelling tool was developed to integrate three primary components of a suitable workplace; (1) a fixed building load; (2) a flexible EV load; and (3) a quantity of renewable energy supply. To realise the modelling tool's potential in demonstrating the primary thesis objective, progressive scenarios need to be defined for simulation within the developed modelling tool in a consistent, methodical manner.

4.3.1 Scenario 1 – Base case with no EV recharging demand

We start by establishing the base case in absence of EV demand, requiring the definition of fixed building loads which adjoin EV recharging facilities, and from this the logically assumptive deduction of renewable supply capacities for both wind and solar PV. These definitions of building loads and renewable supply capacities are applied consistently throughout progressive scenarios for analysis defined in following sub-sections, where again a logically assumptive quantity of EV recharging demand is integrated. Scenario consistent definition of building loads and renewable supply quantities enables isolation of the EV recharging demand, the parameter of primary investigative analysis, and thus fair comparison of the base case versus the introduction of an uncontrolled EV demand, through to the base case versus a smart controlled EV demand, or any stage inbetween.

4.3.1.1 *Building demand.* Fixed building loads were obtained from the Merit database, whose generation was described previously for the demonstration modelling tool. The modelling tool was extended for eleven building types across commercial and industrial sectors, which may feasibly constitute a place of work. To represent a reasonable spread of intended building use, six building loads were selected for analysis; Offices A, Offices B, Light Industry, Research and Development, General Industry A, and Sports and Recreation.

These selected building loads demonstrated hour to hour variation, but insignificant day to day variation. It was therefore appropriate to continue to use average daily values for each calendar month at one hour temporal resolution. The demonstration modelling tool had to be modified to simulate commercial and industrial building loads, rather than residential ones. For potential future use, all eleven were defined. The average daily demand of the six buildings chosen for analysis is presented in Appendix C for seasonal simulations; winter (January), spring (April), summer (July), and autumn (October).

4.3.1.2 *Renewable supply*. Equivalent renewable supply systems features two channels of analysis; solar PV, and wind power; with two quantities of each to be defined. This will enable comparative performance evaluation on the impact of smart EV recharging strategies in the two most prominently distributed renewable energy technologies, and quantify how impact varies with system size. Solar PV was defined without battery storage in proposition that smart grid technologies which control EV recharging schedules present a more viable solution in the long term for optimising a system's demand supply match, particularly given the technological immaturity, associated purchase cost, and land space requirement within the simulated areas of high building and population density. Wind power, which is not suitable for onsite or adjoining installation in the vast majority of workplaces due to the disruptive impact of typically high density building environments on natural air flows, may however be provided from a local wind farm through, for example, some form of green community partnership. Wind power analysis is thus feasible for analysis.

For each of the six buildings, two quantities of solar PV were deduced from the floor area provided by Born (2001). With no indication as to whether the floor area published was for the overall building or just one level, nor the number of levels per building type, published floor area was reasonably assumed to be one level. This therefore constitutes the maximum available roof space for the installation of solar PV panelling, applying a basic assumption that panels cannot be integrated vertically onto facades, the roof does not overhang the building in any way, and furthermore that space above parking areas is not suitable for use within a typically high density urban environment, due to solar shading at low levels both from the adjoining and surrounding buildings.

It should be stated that location variable meteorological values which provide the inputs to renewable electricity generation equations were expanded from average daily values at one hour temporal resolution in the demonstration modelling tool, to average weekly values at one hour temporal resolution for the purpose of analysis. This enables more realistic analysis incorporating day to day natural weather fluctuations. Furthermore, the number of recharge events which can be defined was extended from one to five as you would expect, and six in the case of Sports & Rec. to assume one day weekend use.

Accounting for a reduction in available roof space due to ventilation ducts, access for maintenance and similar uses, the first quantity of solar PV was chosen to be 75% of the building floor area, and consistent angles for inclination and surface azimuth were defined. The second quantity of solar PV panelling was chosen arbitrarily to be 25% of the building floor area, in order to demonstrate any significant variation in smart EV recharging performance due to system sizing.

To provide a fair technological comparison of solar PV versus wind, the annual supply of energy from solar PV defined for the two scenarios above had to be matched as close as possible to the annual supply of energy from wind. This was achieved by; calculating annual supply of energy for solar PV in each building; dividing by the annual supply of energy from all 9 HOMER Pro wind turbines; returns number of turbines required to a nonsensical decimal place; number of turbines was thus rounded to the nearest figure; percentage change due to rounding was determined; and, finally, turbine with the lowest percentage change from rounding was chosen as most accurate, and respective number of turbines required provided final definition of wind power supplies approximately equivalent to 25 and 75% solar PV. The results of this procedure are presented in Table 3, and provide an indication of the capacity of renewable supply systems modelled.

Building	**Floor area**	**Solar PV 25%**	**Solar PV 75%**	**Wind 25%**	**Wind 75%**
	(m^2)	(m^2)	(m^2)	(Bergey Excel 10-R)	(NPS 100C-24)
Offices A	3000	750	2250	27	5
Offices B	1700	425	1275	15	3
Light Industry	675	164.25	492.75	6	1
R & D	3000	750	2250	27	5
General Industry	2750	687.5	2062.5	25	5
Sports & Rec.	500	125	375	5	1

Table 3. Base case – System sizing.

4.3.2 Scenario 2 – Uncontrolled EV recharging demand

The next step in development of a suitable technical analysis procedure was to quantify a workplace occupancy demand for EV recharging facilities. As mentioned previously, the uncontrolled controlled charging scenario, and all further scenarios, are designed in a consistent approach to the base case, albeit with variations in EV recharging demand. Defining a level of occupancy EV recharging demand within an uncontrolled charging scenario, will provide the platform from which to introduce logical steps of progression towards a final smart charging scenario, and enable step by step comparison if desired. This platform describes a logical quantity of demand within a hypothetical future, using the provided floor area of modelled Merit buildings as the starting point from which a series of logical assumptions are applied, as detailed within the text that follows.

4.3.2.1 *EV demand.* The uncontrolled charging scenario assumes an EV recharges from the moment of charge point entry till the point of exit, or till full charge is restored, whichever comes first. Although uncontrolled, this scenario was modified to have SOC zero on day one entry with scope for full recharge if possible, but all following days the entry SOC was the previous exit SOC minus an average driving range accounting for the commute distance home, typical evening recreational use, and then the commuted distance back to work. Sustrans (2014) gives the average commute length in Scotland to be 9 miles. Figures for average evening recreational use could not be obtained, and so a reasonable distance of 7 miles was used for roundness to 25 miles round cycle use. Therefore, if a full charge was provided on day one, only an equivalent charge of 25 miles would need to be provided daily for the week's remainder, avoiding nonsensical scenarios where an EV is simulated to have driven e.g. more than 100 miles every day.

In order to quantify demand for EV recharging facilities, the floor area for each building type presented in Table 3 was converted to building occupancy, by applying the mean density of one workplace per 10.9m^2 net internal area (BCO, 2013). This mean density varies according to building usage, region and other factors, but was sufficient for use. The proportion of demand for EV recharging facilities within this occupancy was then calculated for a short term future scenario with more substantial EV market penetration, where the impact of smart EV recharging strategies could be demonstrated with greater prominence. EV penetration forecasts could not be obtained. A statement from the Committee on Climate Change (Element Energy, 2015b) which "foresees the market for EVs and plug in hybrids will have to reach 16% by 2020 in order to achieve the UK's targets" was therefore used, intuitively discounting to 15% for FCVs exclusion. This was then modified for a probable proportion of the EV market that do not work, the retired community. Assuming retirement age to be 65, data from Department for Transport (2010e) and ONS (2012) was manipulated to deduce the proportion of the

UK driving population (aged 17 and over with a driving license) who will own an EV, but not drive it to work, was 16%. This discounts the workplace EV share to 12.6%.

Table 4 presents the occupancy, and within this the demand for EV recharging facilities, for the six buildings selected for analysis, using the procedure described. The demand for EV recharging facilities could have been further discounted in consideration of the typical breakdown of commuting mode. However, it is conventional to model the worst case scenario in analysis which, in this instance, refers to all 12.6% of occupancy who own an EV using it in favour of public transport or an alternative means of commute.

Building	Floor area (m^2)	Occupancy level	EV charge points
Offices A	3000	275	35
Offices B	1700	156	20
Light Industry	675	62	8
R & D	3000	275	35
General Industry	2750	252	32
Sports & Rec.	500	46	6

Table 4. Building occupancy level and EV charge point demand.

As the EV power demand is dependent on the connected model i.e. its range, the EV market shares given in Table 1 were applied to the number of EV charge points given in Table 4 to create a realistic model distribution. This distribution was further specified according to typical work patterns. The average time of a working day, and thus the time available for EV recharging at a workplace, may be assumed as 9-5. However, the emergence of flexi-time contracts have demonstrated workforce preference for earlier starts. In consideration of this, it was arbitrarily assumed that 40% of the workforce work 8-4, 50% 9-5, and 10% 10-6. Tables 5 -7 present results of the applied procedure.

	Offices A	Offices B	Light Industry	R & D	General Industry	Sports & Rec.
Outlander	5	3	1	5	4	1
Leaf	4	2	1	4	4	1
i3	1	1	0	1	1	0
Zoe	1	0	1	1	1	1
Prius	1	1	0	1	1	0
Ampera	1	0	0	1	1	0
Model S	0	1	0	0	0	0
i8	1	0	0	1	1	0
Twizy	0	0	0	0	0	0
Kangoo	1	0	0	1	0	0

Table 5. EV model distribution per building: 8-4.

	Offices A	Offices B	Light Industry	R & D	General Industry	Sports & Rec.
Outlander	6	3	2	6	6	1
Leaf	5	3	1	5	4	1
i3	2	1	1	2	2	1
Zoe	1	1	0	1	1	0
Prius	1	0	1	1	1	0
Ampera	1	1	0	1	1	0
Model S	1	0	0	1	1	0
i8	0	1	0	0	0	0
Twizy	1	0	0	1	1	0

Table 6. EV model distribution per building: 9-5.

	Offices A	Offices B	Light Industry	R & D	General Industry	Sports & Rec.
Outlander	1	1	0	1	1	0
Leaf	1	1	0	1	1	0

Table 7. EV model distribution per building: 10-4.

Finally, the temporal EV power demand is of course dependent on the connected charge point type. A single phase AC charge point was selected as the common denominator from Appendix A charge point compatibilities with maximum current draw 32A. Those EV models only compatible with drawing 16A current would be able to connect to such higher capacity charge points, but only draw to their safe limit as described by the IEC 62196 standard. The installation of charge points with optional current draw is not only possible but actively encouraged as a fundamental design aim of modern EV recharging facilities within public infrastructure, to enable participation of EVs with both slow and fast recharging speed capacity. Therefore, EVs populating the previous tables that are compatible with 32A single phase AC charging draw the full 32A (6.6kW) in analysis, while those only compatible with 16A single phase AC charging, draw 16A (3.3kW).

As the number of charge points calculated for EV occupancy demand in Table 4 would suggest, the demonstration modelling tool had to be significantly expanded to allow the maximum specification of thirty-five potential EVs during analysis, and for the unique specification of EV recharging events over a simulated period up to a maximum of six days. The expanded version of the demonstration modelling tool follows the exact same principles described in relevant preceding text. For this reason, the demonstration tool was sufficient for presentation within this thesis, and simpler to do so with illustrations given its comparatively condensed size. The version of the modelling tool expanded for technical analysis is, however, openly available for download from Hercus (2015).

4.3.3 Scenario 3 – Controlled EV recharging demand

The uncontrolled EV recharging scenario described in preceding text quantified a level of occupancy demand for EV recharging facilities, using Merit floor areas as a template from which to implement a series of logical assumptions. The controlled EV recharging scenario is identical to uncontrolled, but with one fundamental difference, alluded to in preceding text, which establishes a closer conformity between simulated environments necessary for technical analysis in this thesis, and real life ones. The maximum power delivered daily from the charge point to the EV is not uncontrolled, but controlled to an equivalent maximum all electric driving range, taken in this instance to be 25 miles, or the maximum EV model range, whichever is less. Using assumptions described, this is sufficient to allow travel home from a workplace, recreational evening use, and finally travel to work the following day. The following paragraph identifies the need for this scenario with particular consideration of practical applications in a hypothetical future.

To restrict the exit driving range may appear contradictory given previous statements regarding the role of a public EV recharging infrastructure to alleviate consumer range anxiety. However, in a theoretical consideration, despite the demand side flexibility of EVs it is still favourable to minimalise the electrical demand from the transport sector during the day when there is pre-existing peak demand from other, more rigid sectors. Of course, it may be that following a sustained period of excess supply and subtracting for its re-distribution by integrated V2G functionality, the delivered charge exceeds this 25 miles limit. This would make perfect sense as, intuitively, and assuming it does not encourage profligate consumer behaviour, the EV's demand the following day would be reduced by an equivalent amount. Furthermore, for distributed EV charging stations operated by a workplace or other commercial body, there exists the need to maintain a viable economic model by both limiting the quantity of electricity which is imported from the grid, and assuming the continuation of FITs payments or similar endogenous support, exporting low carbon electricity to the grid as often as possible. Although this may appear to displace the consumer's interest, maintaining a viable economic model would inevitably reduce the cost of charge point usage, and thus satisfy all parties.

Unfortunately the temporal resolution of the modelling tool is restricted to one hour. This therefore means that, for an example where 20 miles of equivalent charge can be transferred per hour, the EV would require 2 hours of charge with a SOC equivalent to 40 miles at exit. To minimalise the cumulative impact of this in analysis, the entry SOC the following day was therefore taken to be 40-25=15 miles, and so only one hour of charge is required. It can be deduced that the same argument applies for the following two days as well. However, this cannot be compensated for EV models which can gain more than the equivalent of 25 miles in a single hour of recharging, due to the modelling tool's restricted temporal resolution. This is not a source of experimental error though, it just means the scenario definition is not resolute. Because the deficiency is applied consistently to smart charging that follows, comparative analysis is still perfectly valid.

4.3.4 Scenario 4 – Smart EV recharging to optimise utilisation of renewable energy

The scenario definition of smart charging is exactly the same as controlled but with one key difference, which defines the smart concept; the time for 25 miles equivalent charge is controlled to optimise utilisation of renewable energy sources, through consideration of both a fixed building load, and the flexible demand of all other EVs. The controlled EV recharging demand was modelled as a "dumb" scenario, where all EVs charge from their respective time of arrival at a workplace, to an exit time (or end of charging time to be more precise), equivalent to the duration of a recharge required to restore 25 miles all electric driving range. Smart EV recharging deploys strategies which schedule this equivalent power demand to specific timeslots which optimise the utilisation of energy from designed renewable energy supply systems, with consideration of the temporally available supply, fixed building demand, and crucially flexible demand from other EVs. To add further weight to the preceding discussion on why an upper exit range limit was imposed from a smart charging modelling consideration, it compressed the duration of EV recharging to a smaller proportion of the working day, and therefore offers greater scope for quantitatively demonstrating the impact of smart EV recharging strategies.

Smart charging could not be integrated into modelling tool development due to, in the simplest description, Excel's incapacity to dynamically react to the definition of smart time for e.g. EV #7 charging following smart re-distribution of demand for EV #1-6 i.e. what may have been the smart time for charging in the default structure, may no longer be following the Excel recommended smart re-distribution of the 6 demands previous. A suitable simulation methodology was therefore required to model smart EV charging utilising the modelling tool's original functionality and results, but where the optimal schedules for EV recharging are determined by an external, more accurate means. This is now described following the definition of some basic parameters applied consistently across simulations of all four defined scenarios.

4.4 Simulation methodology

There were some basic parameters which were applied consistently across simulations of defined scenarios. Climate location would not impact qualitatively on hypothesised results, however Glasgow was chosen specifically in the thought that the results would be more meaningful in the vicinity of the predominant audience's location. To generate quantitative results within the analysis timeframe, it was decided that month to month analysis would not be suitable. Seasonal simulations, commonly used in energy systems analysis, would be more relevant and easier to interpret from a presentation of results. In light of this, January was therefore chosen to be seasonally representative of winter, April spring, July summer, and October of autumn. Solar PV and wind turbine power generation (of those defined in scenario definition) corresponding to the meteorological conditions in Glasgow are presented for these seasonal simulations in Appendix D.

Although the level of complexity in implementing seasonal simulations varied across each scenario definition, all results were generated and recorded by consistent methods. As the maximum time for workplace EV recharging was only modelled for 10 hours of the day (although these 10 hours given the proportionally much higher demand would significantly influence measurement of overall system performance) the modelling tool results section was expanded to show results in both an overall consideration, but also only over EV hours of 8-6. This would ensure in the comparative analysis of smart EV recharging strategies versus controlled ones of equal overall demand, that the impact of smart EV recharging was not quantitatively diluted by idle time not abundantly relevant to the primary thesis objective. For each seasonal simulation, two results were therefore recorded for the four key performance parameters of; (1) environmental CO_2 emissions; (2) financial net balance; (3) demand supply match; and (4) correlation coefficient.

The first three scenarios preceding smart charging were straightforward to simulate and only required the correct definition of system inputs and, with the exception of the base case, EV inputs from a rigid start time to an exit time fixed by a simple SOC of defined electric driving range equivalent. All necessary inputs had been determined in scenario definition and so the simulation procedure was a simple one of loading correct system variables and plugging in numbers, albeit over an extensive number of EV inputs. In a further simplification of the simulation procedure, scenario definitions do not vary from season to season. Therefore, following initial definition of EV inputs in the modelling tool, only the month input required alteration to generate results over all simulations.

As mentioned previously, the analysis methodology for smart charging could not be as simple and would require external capabilities outwith the modelling tool to optimise EV recharging schedules. These smart schedules would then be plugged back into the modelling tool to generate consistent results in comparative analysis. The methodology devised for optimising EV recharging schedules was not by any means a sophisticated, nor time efficient one. However, it was identified as the only available approach which would generate complete results emphasising the quantitative impact of smart charging.

The first stage was to create template EV recharging schedules for all six buildings, as defined by the controlled charging scenario, within a Microsoft Excel spreadsheet. The allocation of any EV to a timeslot was assigned a numerical demand value of 3.3 or 6.6, corresponding to their maximum compatible power draw (kW) from a single phase AC charge point. Allocation of EVs to a start timeslot was defined according to Tables 5-7, and their exit timeslots the recharge period for an exit SOC equivalent to a minimum of 25 miles. This may vary daily according to the remaining excess charge, as described previously due to the limited one hour temporal resolution of the modelling tool.

Light

Day 1	Outl'r	Leaf	Zoe	Outl'r	Outl'r	Leaf	i3	Prius	EV Demand	Supply	Balance	Score
8:00 AM	3.3	6.6	6.6						16.5	4.957	-11.543	-43.72
9:00 AM	3.3		6.6	3.3	3.3	6.6	6.6	3.3	33	5.827	-27.173	
10:00 AM	3.3			3.3	3.3			3.3	13.2	10.099	-3.1013	
11:00 AM	3.3			3.3	3.3				9.9	7.997	-1.9027	
12:00 PM				3.3	3.3				6.6	8.722	2.1215	
1:00 PM									0	9.894	9.8936	
2:00 PM									0	9.896	9.8956	
3:00 PM									0	10.945	10.945	
4:00 PM									0	11.519	11.519	
5:00 PM									0	8.613	8.6135	
Day 2	Outl'r	Leaf	Zoe	Outl'r	Outl'r	Leaf	i3	Prius	EV Demand	Supply	Balance	Score
8:00 AM	3.3	6.6	6.6						16.5	3.583	-12.917	-40.408
9:00 AM	3.3			3.3	3.3	6.6	6.6	3.3	26.4	6.068	-20.332	
10:00 AM	3.3			3.3	3.3			3.3	13.2	6.041	-7.1589	
11:00 AM				3.3	3.3				6.6	7.210	0.6103	
12:00 PM									0	8.037	8.0375	
1:00 PM									0	8.933	8.9335	
2:00 PM									0	9.466	9.4657	
3:00 PM									0	8.452	8.4516	
4:00 PM									0	10.341	10.341	
5:00 PM									0	13.187	13.187	

Figure 15. Simulation methodology - Template EV recharging schedule.

Figure 15 provides a condensed example of template EV recharging schedules created for two days in the light industry building. EV Demand is simply the summed EV power draw per timeslot. Supply is extracted from the modelling tool's calculation procedure, and is specifically the supply of renewable electricity available for EV demands having first subtracted for relevant building loads per timeslot. Supply is therefore a fixed quantity. Balance is simply the Supply minus the EV Demand per timeslot.

The Score presented in Figure 15 is the sum of all negative Balance values i.e. timeslots where demand is in excess of supply, and thus quantifies the amount of electricity which will have to be imported from the grid within the template EV recharging schedule. The manual method of EV recharging schedule smart optimisation was to move EV demand boxes along vertical planes within yellow boundaries (defined according to calculated work patterns) to utilise positive supply balances in green, and thus minimalise negative supply balances in red. Although after repeating the procedure for 6 buildings over 4 seasons of 5 days with 4 different renewable systems, a degree of familiarity had been developed in intuitively shifting demands according to Balance per timeslot, the Score provided an autonomous calculation as to how smart the EV recharging schedule was, with the aim to be as close to zero as possible.

Light

Day 1	Outl'r	Leaf	Zoe	Outl'r	Outl'r	Leaf	i3	Prius	EV Demand	Supply	Balance	Score
8:00 AM			6.6						6.6	4.957	-1.6428	-10.837
9:00 AM			6.6						6.6	5.827	-0.773	
10:00 AM	3.3			3.3					6.6	10.099	3.4987	
11:00 AM	3.3			3.3					6.6	7.997	1.3973	
12:00 PM	3.3			3.3	3.3				9.9	8.722	-1.1785	
1:00 PM	3.3			3.3	3.3				9.9	9.894	-0.0064	
2:00 PM					3.3				3.3	9.896	6.5956	
3:00 PM		6.6			3.3			3.3	13.2	10.945	-2.2553	
4:00 PM						6.6	6.6	3.3	16.5	11.519	-4.9809	
5:00 PM									0	8.613	8.6135	

Day 2	Outl'r	Leaf	Zoe	Outl'r	Outl'r	Leaf	i3	Prius	EV Demand	Supply	Balance	Score
8:00 AM									0	3.583	3.5829	-5.2438
9:00 AM		6.6							6.6	6.068	-0.532	
10:00 AM									0	6.041	6.0411	
11:00 AM			6.6						6.6	7.210	0.6103	
12:00 PM	3.3			3.3	3.3				9.9	8.037	-1.8625	
1:00 PM	3.3			3.3	3.3				9.9	8.933	-0.9665	
2:00 PM	3.3			3.3	3.3				9.9	9.466	-0.4343	
3:00 PM						6.6		3.3	9.9	8.452	-1.4484	
4:00 PM							6.6	3.3	9.9	10.341	0.4409	
5:00 PM									0	13.187	13.187	

Figure 16. Simulation methodology - Smart EV recharging schedule.

Figure 16 shows the smart optimised EV recharging schedule corresponding to Figure 15, where red areas indicate the controlled template. The Score indicates a reduction in grid imported electricity by greater than a factor of four in day one, and nearly a factor of eight in day two for this condensed example of the light industry building. Note that smart optimised EV recharging schedules for all building types and renewable supply configurations over all seasonal simulations, are openly available to download and view from Hercus (2015).

It should be stated that the Score was only the sum of grid imported electricity. It was contemplated that this should be modified for CO_2 emissions by integrating temporal carbon contents synthesised for the modelling tool, in the thought that it may actually be favourable, from an environmental consideration anyway, to import more electricity from the grid at timeslots of reduced carbon content. However, such modelling would incorporate unnecessary complexity for the generation of results hypothesised to exert negligible quantitative difference. Furthermore, relevant to workplaces which typically maintain preference for economically sound environmental measures, such modelling would place excessive emphasis on environmental performance and to the detriment of overall system match and thus, crucially, financial results.

It is important to note two key deficiencies of the modelling tool's capacity to simulate smart charging. To use the Renault Zoe as an example from Figure 16, it would be more favourable to slow the rate of power draw to 3.3kW in Day 1, as is possible in practical applications, and spread the same quantity of demand over a greater period to further enhance the utilisation of renewable energy. So in this example draw 3.3kW from 8-11 and from 2-3, rather than drawing the maximum 6.6kW from 8-10. Unfortunately, EV demand scaled over defined power limits could not be developed within the modelling tool's functionality. This particular example introduces a second key deficiency of the modelling tool to simulate smart charging. Recharge events can only be defined in time blocks of continuous recharging from rigidly defined start to end times. The equivalent duration cannot be split up by specification of a time for available for recharging, within which recharging comes on and offline when appropriate to align with optimal supplies of renewable energy i.e. it is not possible to draw 3.3kW from 8-11 and then from 2-3.

However neither of these modelling tool deficiencies, with regards to implementing EV recharging strategies as smartly as possible, would impact significantly on quantitative results. Indeed the small light industry building example provided is the most prominent example, and demonstrates negligible scope for improvement. This scope only reduces further in larger buildings where EV demand is concentrated into proportionally smaller blocks of demand which may be more flexibly aligned to maximise renewable energy utilisation. Although the modelling tool is presented as deficient in modelling smart EV recharging strategies, the extent of this is minimal. Developing corrective functionality would not be necessary, nor probably possible, within the scope of this thesis, and the applied simulation methodology is more than suitable for comparative analysis.

Manual optimisation of smart EV charging schedules was conducted for all 6 buildings over the 4 defined seasons for 4 different renewable supply scenarios. Once optimised, the start and end times for each EV model were transferred from external spreadsheets similar to the condensed example provided above, into corresponding input sections of the modelling tool. Using the modelling tool's calculation procedure, results could then by generated by a method consistent across all four scenarios defined. In the results and discussion that follows, this will enable fair comparative analysis between the logically designed progressive scenarios, but with particular concentration on the controlled to smart EV recharging progression, and a leaped progression from base case to smart EV recharging, as most relevant to the primary thesis objective.

4.5 Results

Of the six buildings defined to support investigation of the quantitative impact of smart EV recharging strategies on the utilisation of renewable energy sources, only Offices A is presented in results to enable further discussion. Detailed analysis of the other five buildings would not contribute qualitatively to any conclusions drawn, however, results of conducted simulations are provided for reference in tabular form, see Appendix E.

Results presented are all comparative of one defined scenario versus another. Therefore, the second result is indexed to the first in order to specifically demonstrate performance change from one defined scenario to the next. Results for environmental performance, CO_2 emissions, are expressed conveniently as percentage changes from the first defined scenario to the second, where positive change constitutes a reduction in CO_2 emissions. Results for system performance, demand supply match, are calculated as percentages conventionally. The indexed results are therefore not expressed as a percentage change from the first defined scenario to the second, but as the scalar change in match expressed with units percent (i.e. 25% in scenario one to 50% in scenario two is expressed as an indexed change of 25%, not 100%). Results for financial performance, net balance, are, for reasons to be discussed, only presented briefly in tabular form to enable comparison from a first defined scenario to the second. To index the results in this instance would be fairly meaningless with no knowledge of the original value. Furthermore, they could not be expressed conveniently as a percentage change due to frequent transitions from positive to negative (or vice versa) net balance from a first scenario to the second.

Results are first presented to allow comparison of the Offices A base case performance, in absence of EV demand, with performance following the implementation of a smart, controlled EV recharging strategy for all four variations of the renewable supply system defined. Results are then presented to enable analysis only of the specific progression from a controlled EV recharging strategy, to a smart controlled EV recharging strategy. These are intended to develop greater understanding of any variation in performance change across the different types and capacities of renewable supply systems defined, following the implementation of smart EV recharging. To enable comparative analysis of these two distinct system variables, the same data is, on occasion, presented in more than one graph for ease of interpretation. Results are presented over both the overall seasonal simulations described, and the seasonal simulations condensed to periods for defined EV recharging in the workplace (8-6), to demonstrate any proportional impact.

4.5.1 Base case vs. smart EV recharging

The comparative presentation of results for the base case scenario versus the smart EV recharging scenario is only presented over EV hours for seasonal simulations of all four renewable supply system configurations. As the smart EV recharging scenario reverts to the base case outwith EV hours, this will enable more accurate comparative analysis in discussion, where the impact during EV hours is not diluted by presentation of overall weekly simulations in which EV hours constitute only a small proportion (10/24).

	Winter		Spring		Summer		Autumn	
	Base	Smart	Base	Smart	Base	Smart	Base	Smart
Solar PV 25%	245.4	968.6	0.00	74.5	0.00	82.7	57.3	365.5
Wind 25%	289.2	1047.2	22.4	214.0	236.6	928.1	275.2	896.7
Solar PV 75%	182.8	183.5	0.00	0.00	0.00	0.17	57.3	57.3
Wind 75%	156.7	500.7	0.00	0.00	103.6	307.8	211.0	506.8

Table 8. Base case vs. smart EV recharging - CO_2 emissions (kg CO2 e).

	Winter		Spring		Summer		Autumn	
	Base	Smart	Base	Smart	Base	Smart	Base	Smart
Solar PV 25%	41	-173	367	277	359	267	240	104
Wind 25%	56	-164	458	345	85	-132	99	-99
Solar PV 75%	234	159	892	817	872	797	622	548
Wind 75%	433	292	1511	1437	513	396	546	413

Table 9. Base case vs. smart EV recharging – Net balance (£).

	Winter		Spring		Summer		Autumn	
	Base	Smart	Base	Smart	Base	Smart	Base	Smart
Solar PV 25%	63.12	35.99	100.00	94.98	100.00	94.15	91.46	75.33
Wind 25%	56.83	30.78	96.59	85.51	62.45	34.79	58.50	39.52
Solar PV 75%	72.50	87.87	100.00	100.00	100.00	99.99	91.46	96.20
Wind 75%	76.58	66.92	100.00	100.00	83.41	78.29	68.13	65.81

Table 10. Base case vs. smart EV recharging – Demand supply match (%).

4.5.2 Controlled charging vs. smart EV recharging

4.5.2.1 *Technological comparison: Solar PV vs. wind (25%).*

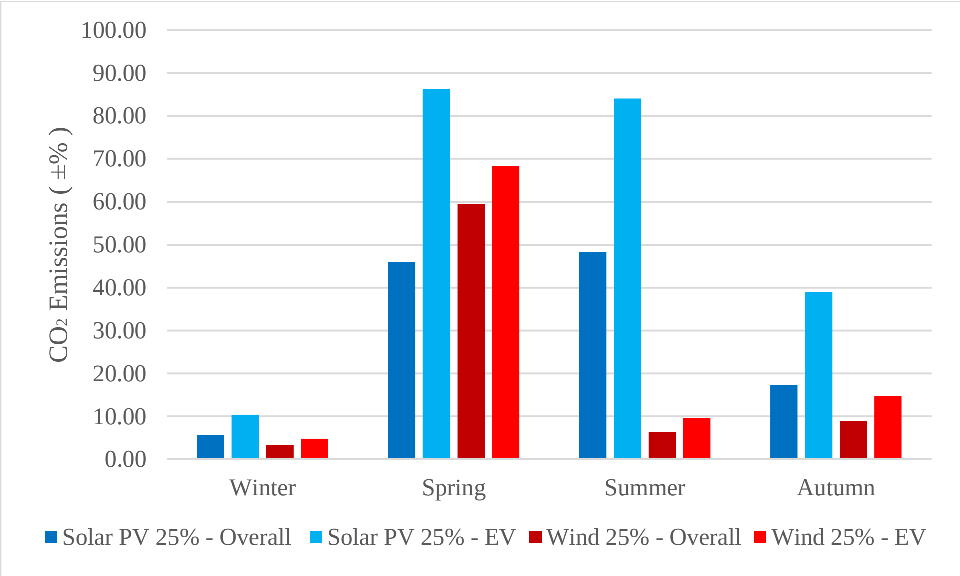

Figure 17. Controlled charging vs. smart EV recharging:
Solar PV vs. wind (25%) – CO_2 emissions percentage change.

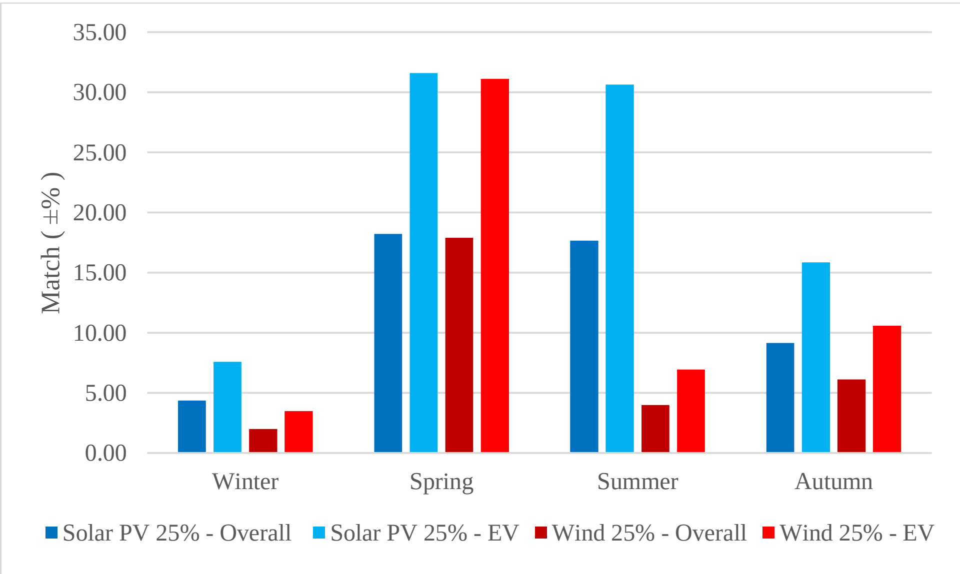

Figure 18. Controlled charging vs. smart EV recharging:
Solar PV vs. wind (25%) – Demand supply match change.

4.5.2.2 *Technological comparison: Solar PV vs. wind (75%).*

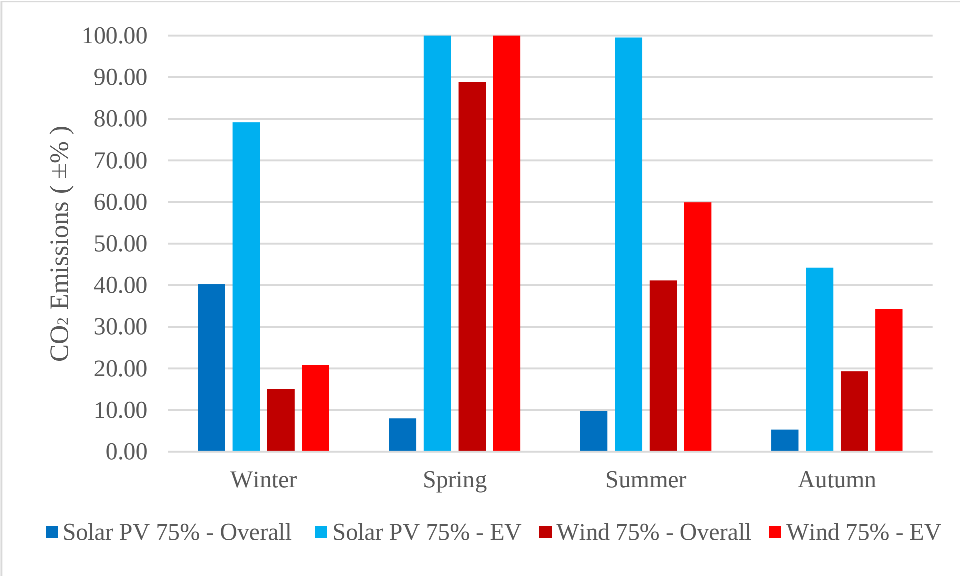

Figure 19. Controlled charging vs. smart EV recharging:
Solar PV vs. wind (75%) – CO_2 emissions percentage change.

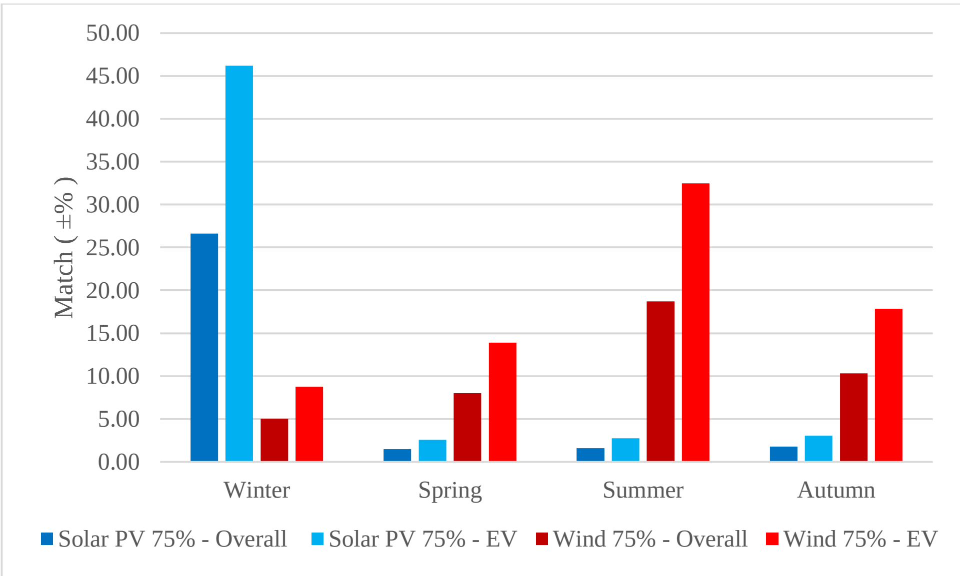

Figure 20. Controlled charging vs. smart EV recharging:
Solar PV vs. wind (75%) – Demand supply match change.

4.5.2.3 *Capacity comparison: Solar PV (25%) vs. solar PV (75%).*

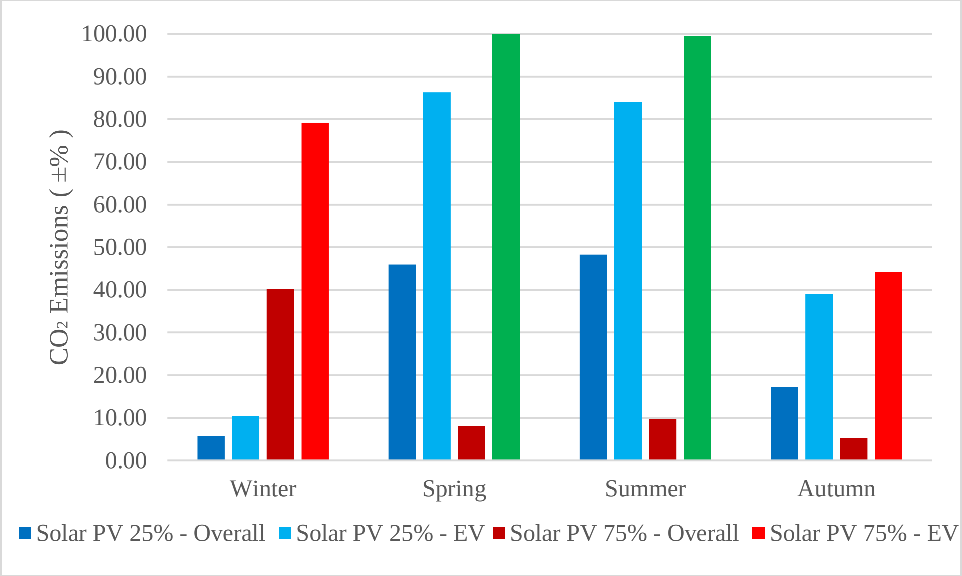

Figure 21. Controlled charging vs. smart EV recharging:
Solar PV (25%) vs. solar PV (75%) – CO_2 emissions percentage change.

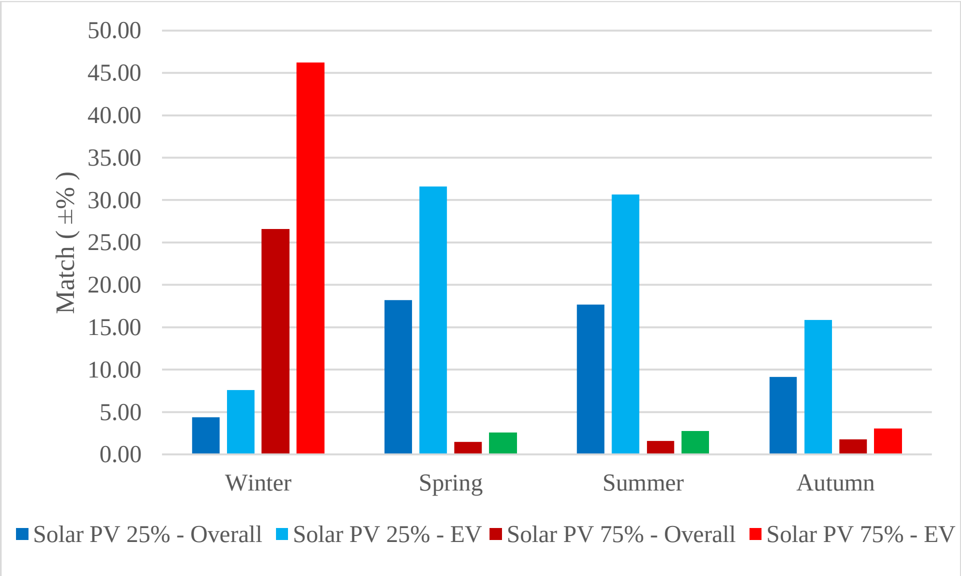

Figure 22. Controlled charging vs. smart EV recharging:
Solar PV (25%) vs. solar PV (75%) – Demand supply match change.

4.5.2.4 *Capacity comparison: Wind (25%) vs. wind (75%).*

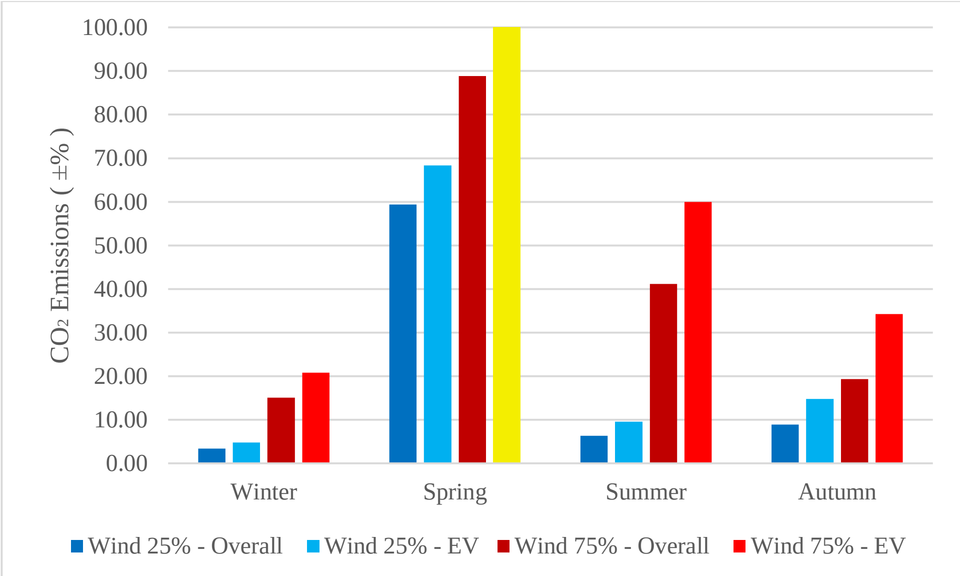

Figure 23. Controlled charging vs. smart EV recharging:
Wind (25%) vs. wind (75%) – CO_2 emissions percentage change.

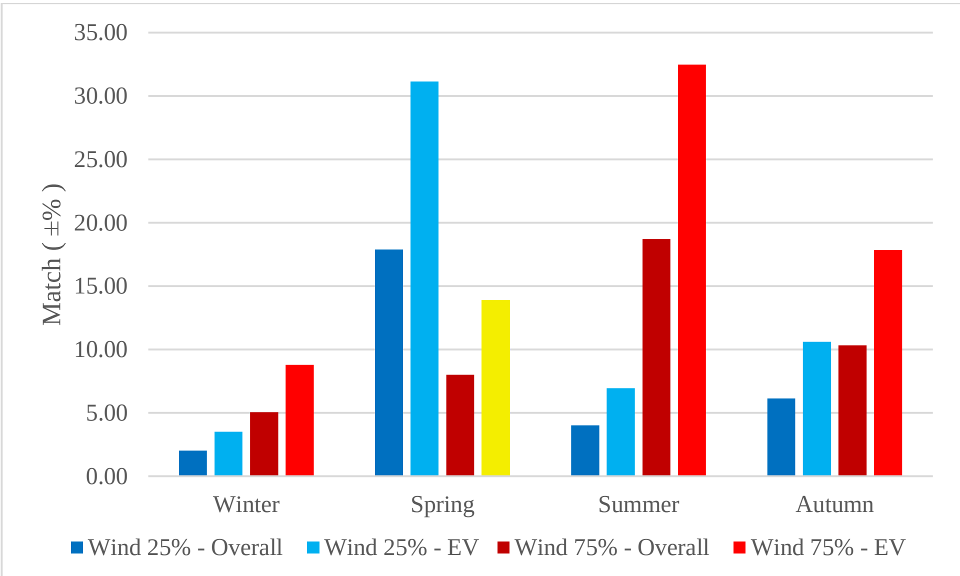

Figure 24. Controlled charging vs. smart EV recharging:
Wind (25%) vs. wind (75%) – Demand supply match change.

4.6 Discussion

It was identified from an extensive literature review that, in order to facilitate the mass market penetration of EVs in the UK projected for the not so distant future, smart grid technologies would have to develop in parallel to prevent the degradation of electricity network assets due to increased electrification of the transport sector. EVs present an unobtrusive source of flexible demand side flexibility which integrated in the smart grid would be able to adjust temporal demand to particularly supply from renewable energy sources. This would optimise the utilisation of renewable energy not just with regards to EV electrical demand, but also the demand across other sectors such as commercial, domestic and industry through both an increased capacity of grid networks to facilitate intermittent renewable energy, and unique V2G functionalities which may enable EVs to perform secondary grid functions comparable to grid energy storage.

It was presented that the growth of the EV market is currently restricted by a number of factors; prominently the lack of suitable public EV recharging infrastructure to allow a level of opportunistic range extension comparable to the current ICE infrastructure, and alleviate the consumer-bred concept of range anxiety. Meanwhile, the development of smart grid technologies is restricted by a lack of scalable trialling opportunities to refine functionality for more expansive network use. Places of work were identified in this thesis as providing an opportunity to coalesce these two problems into one suitable solution. EV recharging facilities within the workplace would introduce a preliminary level of public EV recharging infrastructure at a convenient location of long term use, while workplaces would also provide an optimal environment for the trialling of smart grid technologies, where with the reasonable assumption of a fixed adjoining building load, a quantity of distributed renewable energy supply and a substantial, flexible EV demand; workplaces would give a micro-representation of large scale grid interactions.

Relevant decision makers are however reluctant to engage with, and participate in smart grid trials as the operational benefits of such technology have not been communicated effectively, but there more pertinently lacks quantitative evidence to support conceptual discussions and postulations, from both real life and realistic simulation environments. This problem formulated the primary thesis objective; to quantitatively demonstrate the potential for smart EV recharging strategies to optimise utilisation of renewable energy sources, by using suitable simulation software whose key operating principles may be feasibly replicated in a practical application such as identified workplaces.

An extensive review of pre-existing software was therefore conducted to assess their suitability in effectively demonstrating results, relevant to the primary thesis objective. It was concluded that no such software existed in its default format. A new modelling tool was therefore developed using Microsoft Excel, universally accepted commercial software. This modelling tool, although requiring necessary rudimentary assumptions to model EV recharging, and restricted in scope by intrinsic factors, of which temporal resolution is most prominent; provides well calibrated modelling capacity relevant to the thesis objective, and plugs a hole in pre-existing software.

To apply this modelling tool in demonstrating the thesis objective, various progressive scenarios for technical analysis were defined and a simulation methodology developed. These scenarios, although again based on some necessary assumptions to provide both a base case template for comparative analysis of smart EV recharging strategies, and to model future, hypothetical scenarios of high EV road market penetration, were reliably defined. Any sources of perceived error/uncertainty were therefore applied consistently throughout the analysis procedure, and for the purpose of predominantly comparative analysis, the new modelling tool was more than suitable for use.

Prior to analysing optimal deployment of smart charging capacity via defined scenarios, the first result to communicate is why relevant decision makers in places of high public use, such as workplaces, want to invest in EV recharging facilities, and furthermore what benefit may be exploited by the use of smart grid technologies, whether on a trial basis or not. Tables 8-10 present key environmental, financial and system performance results from the progression of a base case in the absence of EV demand, to the scenario of EV demand with integrated smart recharging, specifically for hours of EV recharging activity (8-6).

The environmental results in Table 8 cannot be used for fair comparison. The simulated seasonal CO_2 emissions do not vary to scale with the proportional increase in overall electrical demand during EV hours (compare the proportional increase of 2.3 with the yellow annotated result). This is because EV introduction acts as a stimulating event in some timeslots to push the existing building load for Offices A over a zero emissions threshold from renewable electricity generation, and the modelling tool does not have functionality to then re-assess what emissions are from the building load, and what emissions are specifically due to the EVs.

The match results in Table 10 cannot be used also. It would be unfair to evaluate a false scenario where an increased match result is due to increased overall electrical demand, and depending on the temporal distribution of this, could assume any value between the worst case scenario (reduced by a proportional factor of 2.3) and the best case scenario (increased by a factor of 2.3). The financial (net balance results) are therefore presented from Table 9 to analyse performance change from the base case scenario to the scenario of EVs with smart recharging capacity. In any case, economics are, particularly within the commercial sector, the predominant result of consideration.

The results for Table 9, ignoring those in red, indicate that progression from the base case to smart EV recharging constitutes an average reduction in financial performance of 23.3% across all seasonal simulations and renewable supply configurations. This is not a reduction proportional to the increased electricity demand from EVs, and therefore the reduced renewable export quantity and assumed increased grid import quantity. The explanation for this result lies in an imbalanced economy for power exchange favouring utility providers. As an assumption, every kWh of energy added by EVs is either a kWh which is imported from the grid, or a kWh which cannot be exported to the grid, at an average cost of 8.5p/kWh. However, the smart EV recharging strategy has preference to optimise the utilisation of renewable energy sources. The distribution of lost income is therefore predominantly from grid export, in terms of the electricity quantity anyway. Because grid export tariff rates are small by comparison with the equivalent cost of grid import, the average cost of every EV kWh is not 8.5p as calculated to be proportional, but considerably less. In this regard, grid export does not constitute value for money. It is preferential for operators of distributed renewable energy sources to maximise the utilisation of electricity onsite by introducing a flexible source of demand, EVs.

These results provide encouragement for areas of public infrastructure, like workplaces, to install EV recharging facilities and through participation in smart grid trials, to use the example provided, increase their overall electricity demand by 230%, but with only a 23% reduction in income from grid interaction; a reduction in income which could be feasibly recuperated and expanded beyond by the simple installation of pay per use EV recharging facilities using sim card functionality similar to mobile phones. Although in this instance financial results can be modelled as representative of system performance for comparative analysis, other factors such as the installation of suitable technologies and ongoing maintenance costs must be incorporated into a complete analysis. For this reason, financial results are not presented in the remainder of discussion. Any change in net balance results can, to an extent, be intuitively deduced from environmental and match results in any case, and would not therefore add any more weight to qualitative conclusions drawn from technical analysis.

The results discussed above indicate that EVs with smart recharging functionality can be introduced with substantially less proportional detriment to the overall performance of distributed grid systems than the increase in electrical demand may appear to suggest. That smart grid functionality can develop the natural synergy between the intermittency of renewable electricity generation, and the demand side flexibility of EV recharging, requires little vindication beyond the concept from quantitative simulation results. All results presented in Figures 17-24 above, and externally in Appendix E, unequivocally demonstrate the significant quantitative impact of smart EV recharging functionality to optimise the utilisation of renewable energy sources in demand satisfaction. However, to develop a more complete understanding of the finer details in smart EV recharging strategies, particularly within a distributed setting, discussion is provided below on the comparative performance of smart charging versus its dumb charging equivalent for the two most commonly distributed sources of renewable electricity generation, and what influence variations in their relative capacity exerts.

The results discussed here are only to demonstrate, relevant to the thesis objective, the improvements in system performance brought by use of smart grid technologies. In this context, only the indexed results are therefore analysed, not how this fits into an overall consideration. To start with a technological comparison of solar PV versus wind, results in Figures 17 and 18 demonstrate that the introduction of smart EV recharging strategies for a solar PV supply system consistently outperforms any performance improvement due to introduction in a wind supply system, across all seasonal simulations at 25%. In a distributed setting where the proportion of demand is significantly greater during EV hours, with only a low quantity of building load outwith, it is not overly surprising that smart solar PV outperforms smart wind. The vast majority of supply from solar PV is concentrated within the period of EV demand side flexibility, and therefore allows more extensive scope for smart grid optimisation of EV recharging schedules.

It may be postulated that the procedure used to ensure equivalent sizing of solar PV and wind incorporated bias, in that apparent equality was modelled over a complete annual simulation, and not just hours of EV activity. In the worst case scenario where all solar

PV electricity generation is assumed to be concentrated to the 10 hours of EV activity, and wind is evenly distributed across all 24 hours of the day, it is clear that this would not provide a fair base case from which to measure performance improvements due to smart EV functionality's implementation. There is in fact 2.4 times more electricity, for use of a better phrase, to play about with in the solar PV scenario, than there is for wind. However, this was necessary to maintain translation to a real life, practical application where a renewable supply system would have to be sized for optimal performance in an overall consideration, not just for 10 hours of the day to suit disproportional demand. To size wind power capacity to be equivalent to solar PV over only EV hours, would incorporate significant quantities of excess electricity during the low demand hours of modelled workplace environments, with no guarantee of grid export capability. In any case, grid export is presented as part of an unfair energy economy, and would not enable sufficient scope to recuperate the installation cost of additional capacity.

A technological comparison of solar PV versus wind at 75% renewable supply capacity, presented in Figures 19 and 20, would appear to contravene the postulated synergy of solar PV electricity generation and EV demand side flexibility within a smart grid. Only in the winter seasonal simulation is performance improvement due to smart recharging capability more significant in solar PV than wind. These results have got nothing to do with variation in supply profiles, as the proportion of supply over the day still exhibits the same temporal distribution, there is just three times more of it at each timestep. And, in an overall evaluation not presented within the indexed results, solar PV consistently outperforms wind following the implementation of smart recharging capability, yet the percentage change is comparatively small. This result is quite simply indicative of the curtailment of smart grid functionality by a template dumb controlled charging scenario where the quantity of available supply is excessive to the demand. In other words, the default supply system is oversized, and all capacity for smart grid functionality to inflict positive change through control of demand side flexibility, is restricted.

The impact of supply oversizing in restricting smart EV recharging functionality is best illustrated by correlation of the green annotated columns in Figures 21 and 22, and to a lesser extent for wind by correlation of the yellow annotated columns in Figures 23 and 24. With regards to the green annotated columns, an almost 100% reduction in CO_2 emissions for both spring and summer simulations during EV hours would apparently indicate that smart EV recharging has exerted significant, positive change. However, if you then correlate with the increased demand supply match, which is almost negligible, it may be intuitively deduced that the template recharging strategy restricted smart EV recharging capacity. That such a substantial percentage reduction in CO_2 emissions is correlate by a negligible increase in demand supply match, is indicative of the template having supply consistently in excess of demand, with very little CO_2 emissions, which are simple to eradicate by the re-distribution of only a small fraction of EV loads, but only constitutes a tiny change in system performance.

The fundamental principle of smart EV recharging has been described as optimising the utilisation of renewable energy sources in satisfying, within this context, electrical demand for EVs. But to co-adjacently optimise the performance of smart EV recharging strategies, the renewable supply system has to be correctly sized to allow the smart grid to stretch its operation to maximum capacity. This is particularly relevant to the defined situation where places of high public use, such as workplaces, are used as environments for trialling smart grid technologies. There is demand from the participating consumer to, if not correctly size distributed renewable energy sources, not oversize. Deliberate undersizing with smart EV recharging implementation would, from a purely economic sense, constitute value for money, and such a strategy may be actively communicated to encourage trial participation. Although reducing quantities of low carbon electricity for use either onsite or externally through grid export may not present, in the short term, an environmentally sound model, it would enable relevant policymakers to trial smart grid technologies in an extremely demanding environment, and refine techniques which may be scaled to more expansive grid networks which will revolutionise energy use.

The results discussed satisfy the primary thesis objective in that they demonstrate the capacity of smart grid functionalities to ease future facilitation of a substantial increase in electrical demand due to high levels of EV penetration into the road vehicle market. The primary thesis objective may centre around a short term problem, but it possesses long term implications. The development of a preliminary level of public EV recharging infrastructure and smart grid technology within suitable trial environments is necessary to accelerate the growth of both markets. To encourage growth through demonstrative simulation results, this thesis has presented a concentrated example of how smart grid control of EV recharging schedules may optimise utilisation of distributed renewable energy sources and significantly improve system performance. However, how the smart grid and EVs interact within more expansive grid networks in long term projections of more prominent use, may enter levels of sophistication beyond what may be deduced from this thesis.

To provide a concluding line of discussion mindful of the bigger picture, it may be that the demand side flexibility of EVs is not used to just ensure the utilisation of low carbon electricity for EV recharging and avoid degradation of electricity network assets due to electrification of the transport sector, but to increase the reliability of renewable energy for use in other sectors. This is not because the integrated EV demand may be scaled at infinitesimal temporal resolution comparable to the intermittency of renewable energy and maintain security for more critical loads, but the role large penetration of EVs may fulfil as an active, dynamic grid resource. V2G functionality has the potential to solve the holy grail of grid scale energy storage by the use of EVs.

The participation of EVs connecting bi-directionally with the grid allows re-distribution of excess renewable energy by a conceptually simple and cost effective means. Energy storage is a pertinent technological, economical and perhaps even logistical modern day problem for grid operators which presents no obvious, conventional solution. With EV V2G functionality, consumers would purchase their vehicle for the primary function of driving, but may fulfil secondary functions in grid services, with suitable remuneration for the impact of high cycle use on battery life and any restriction in transport mobility.

The areas of high use public infrastructure relevant to this thesis would present optimal aggregated sites for V2G application, as the concentrated demand reduces strain on grid monitoring systems, while they also encourage EV grid connection during the hours of peak demand, thus ensuring maximum V2G capacity when it is most needed. Although it has been modelled in objective relevant technical analysis that EV recharging should be encouraged during the day within areas of public infrastructure, in an idealised future scenario, daytime EV grid connection would be for a sole purpose of V2G application. Particularly within forecasted levels of EV penetration, it is desirable to concentrate the bulk of recharging activity to night-time, continuing to use smart grid functionality to modulate rates of EV demand to intermittent renewable supply, and to an extent flatten grid supply profiles. In this idealised vision, EVs would present an unobtrusive source of demand side flexibility for the majority of the day, and enable consistent facilitation of intermittent renewable energy. But it is an idealised scenario. Whether the smart grid can exploit EV-RE synergy to the proposed extent, and realise a feasible opportunity to revolutionise modern day power networks, is a question that remains to be answered.

5. Conclusions

The market growth of EVs is currently restricted by a number of factors, pertinently the lack of suitable opportunity for EV recharging within areas of public infrastructure that will enable almost unlimited range extension comparable to ICEs. Such areas of public infrastructure would, under certain conditions, provide the optimal environment to trial new technologies of the conceptual smart grid. In an idealised future scenario, the smart grid may utilise the unobtrusive demand side flexibility of high EV market penetration and secondary capacity for grid storage functions to revolutionise power networks from a supply follows demand paradigm to one where demand follows supply, encompassing significant and far reaching ramifications within the overall sustainability concept.

To encourage smart grid trial participation, this thesis implemented a technical analysis methodology to quantitatively demonstrate the significant impact of relevant smart grid technologies to ease EV integration within a simulated environment. The effectiveness of these technologies is under communicated by current literature, and any postulations within not robustly vindicated by extensive experimental testing in both the simulated environments modelled, and real life ones.

Commercial and academic modelling tools available for use cannot model the specific demand of EV recharging, at least not with sufficient scope for varied analysis relevant to the primary thesis objective. A rudimentary modelling tool was therefore developed in Microsoft Excel for this purpose. This modelling tool, although deficient in achieving the complexity and sophistication of pre-existing ones, enabled consistent analysis for demonstrating the quantitative impact of smart EV recharging strategies.

This thesis has demonstrated the capacity for smart grid functionalities to optimise EV recharging schedules for utilisation of renewable energy sources in distributed contexts. Simulation results from the developed modelling tool indicate that the smart grid may be used to facilitate the secure introduction of EVs, exerting disproportional impact on systems performance in consideration of the overall increase in electrical demand. More detailed analysis derived two key qualitative results; that the performance of smart grid functionalities is significantly influenced within modelled grid distributed scenarios, by both the type and capacity of renewable energy source. For optimal overall performance it is therefore important to establish accurate sizing methods for all system components, and evaluate on a case by case basis the most suitable system configuration.

6. Future work

The vast majority of project work which compiled this thesis concerned development of a new modelling tool for EV recharging. Although the amount of time and resources dedicated to tool development hindered the extent of technical analysis conducted and qualitative conclusions, the modelling tool is a key deliverable which, from discussions with an identified focus group, exhibits potential for more extensive commercial use. This will require further work to add the requisite level of sophistication, particularly with regards to temporal resolution, and integrate system complexities compensated for in modelling by rudimentary assumptions such as linear efficiency factors, which would in a practical application vary dynamically according to relevant parameters such as the age of a system and the ambient temperature. The modelling tool should also allow for time progression; the enhancement of efficiencies relevant to system performance from future innovation and research.

In addition, more advanced modelling functionality should be developed to enable V2G analysis. Despite being conceptually discussed as a fundamental component of synergy between EVs and renewable energy, no analysis was presented within this thesis due to the complexity of modelling, but also a lack of relevant literature on which to base this. All relevant technologies are in a certain state of development. To make more reliable statements with quantitative vindication, regarding the possibility of combining electric mobility with renewable energy through the smart grid, more research is required both in whatever way the thesis author can contribute, but also from energy industry experts. Finally, the modelling tool could either be presented via a website, or less likely a smart mobile phone application to enable access and use for interested parties.

With regards to technical analysis conducted, this could be extended to different system variations of renewable electricity generation, such as micro-CHP units, and, within the distributed environments modelled, analysis of smart grid performance with night time EV recharging from particularly fleet vehicles. The analysis could also be extended to complete annual simulations, and to further climates not necessarily outwith the UK, but encompassing a broader span of meteorological conditions due to coastal proximity, urban density and similar environment variables. Finally, although sensitivity exercises would not provide any new outputs, they would enable more reliable results analysis over a feasible range of best to worst case scenarios.

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Appendix A – Modelling tool – EV charge point type compatibility

	13A single phase AC	16A single phase AC	32A single phase AC	16A 3-phase AC	32A 3-phase AC	64A 3-phase Rapid AC	125A Rapid DC	Tesla Supercharger
Power (kW)	2.3	3.3	6.6	11	22	43	50	120
Outlander								
Leaf								
i3								
Zoe								
Prius PHEV								
Ampera								
Model S								
i8								
Twizy								
Kangoo								
iOn								
Panamera E								
i MiEV								
fortwo ED								
C-Zero								
V60 PHEV								
Volt								
e-up!								
Roadster								
Fluence								
E-NV 200								

Appendix B – Modelling tool – Wind turbine power coefficients

Wind speed (ms^{-1})	Bergey Excel 1-R	Windera S	Bergey Excel 6-R	Bergey Excel 10-R	NPS 100C-21	XANT M-21	Norvento nED 100	NPS 100C-24	Vergnet GEV MP-R
2	0.083								
3	0.271	0.036	0.269	0.160	0.090	0.349	0.127	0.155	
3.5		0.160							
4	0.312	0.230	0.312	0.265	0.311	0.413	0.329	0.393	0.095
4.5		0.291							0.223
5	0.333	0.315	0.306	0.288	0.408	0.415	0.395	0.405	0.292
5.5		0.343							0.330
6	0.354	0.350	0.298	0.297	0.427	0.415	0.418	0.399	0.339
6.5		0.365							0.348
7	0.364	0.373	0.287	0.297	0.416	0.414	0.428	0.386	0.343
7.5		0.370							0.376
8	0.344	0.365	0.274	0.299	0.389	0.415	0.435	0.401	0.389
8.5		0.352							0.394
9	0.320	0.333	0.264	0.295	0.362	0.405	0.436	0.358	0.393
9.5		0.312							0.389
10	0.293	0.286	0.247	0.291	0.324	0.392	0.430	0.297	0.384
10.5		0.259							0.377
11	0.268	0.231	0.225	0.283	0.283	0.354	0.323	0.237	0.371
11.5		0.204							0.350
12	0.231	0.178	0.191	0.267	0.243	0.273	0.249	0.191	0.320
12.5		0.156							0.286
13	0.186	0.134	0.154	0.218	0.205	0.215	0.196	0.152	0.254
13.5		0.116							

Appendix C – Scenario definition – Building loads

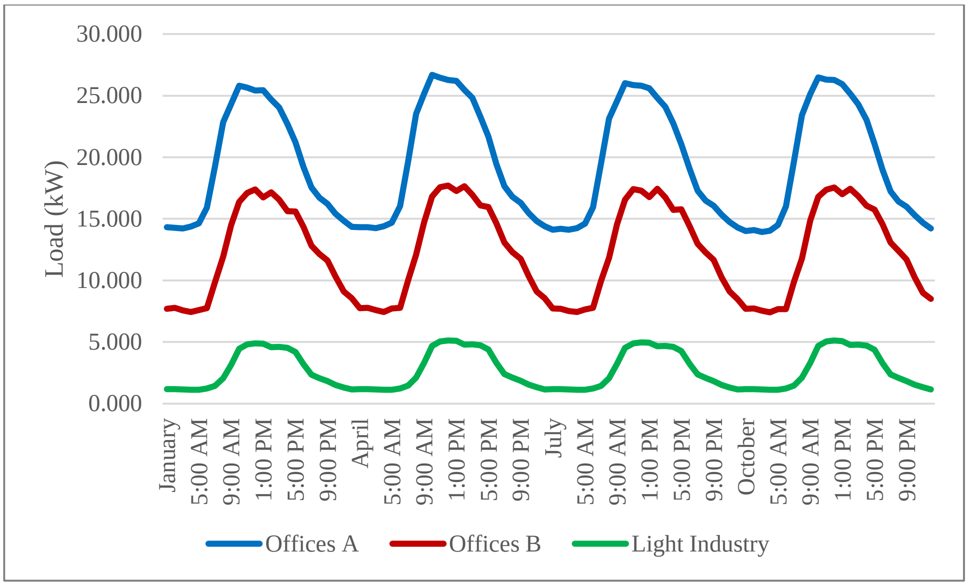

Figure C1. Offices A, Offices B, and Light Industry.

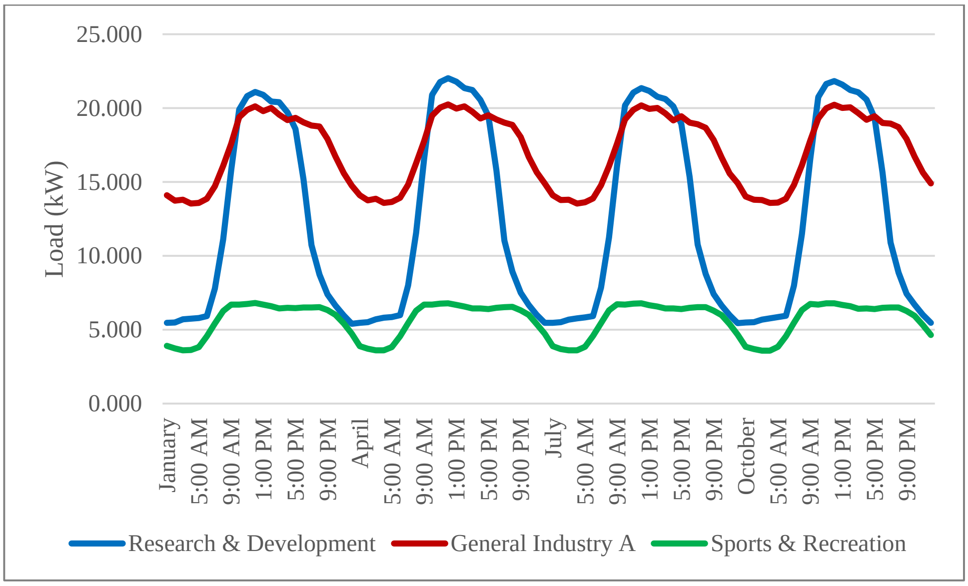

Figure C2. Research & Development, General Industry, and Sports & Recreation.

Appendix D – Simulation methodology – Renewable power for Glasgow

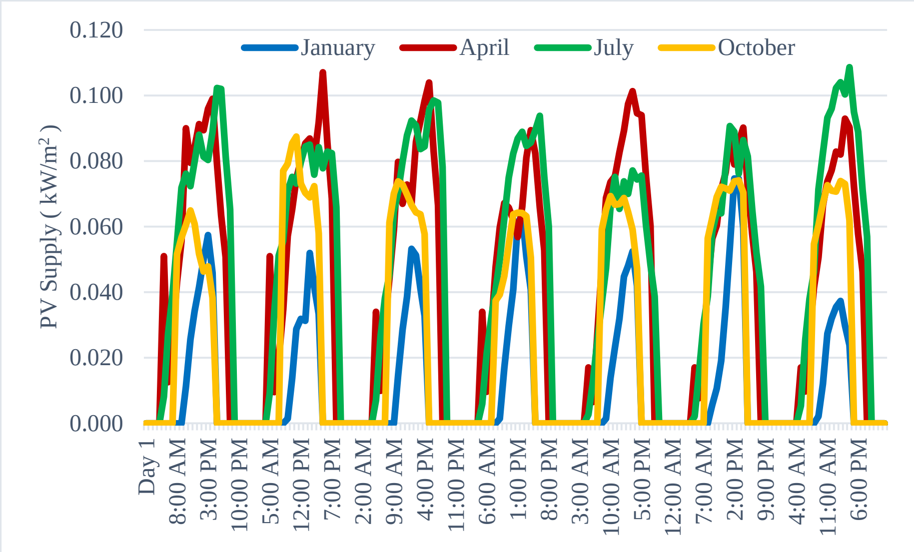

Figure D1. Glasgow PV supply (kW/m^2).

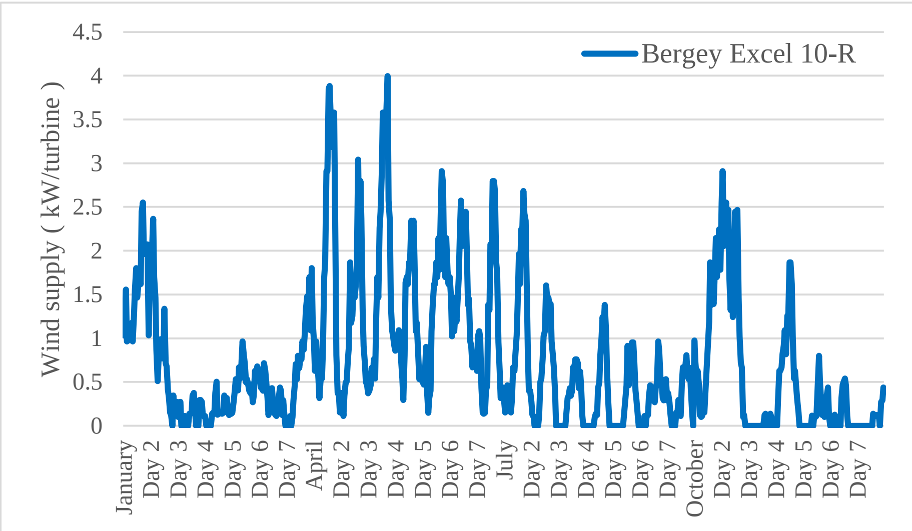

Figure D2. Glasgow wind supply (kW/turbine) – Bergey Excel 10-R.

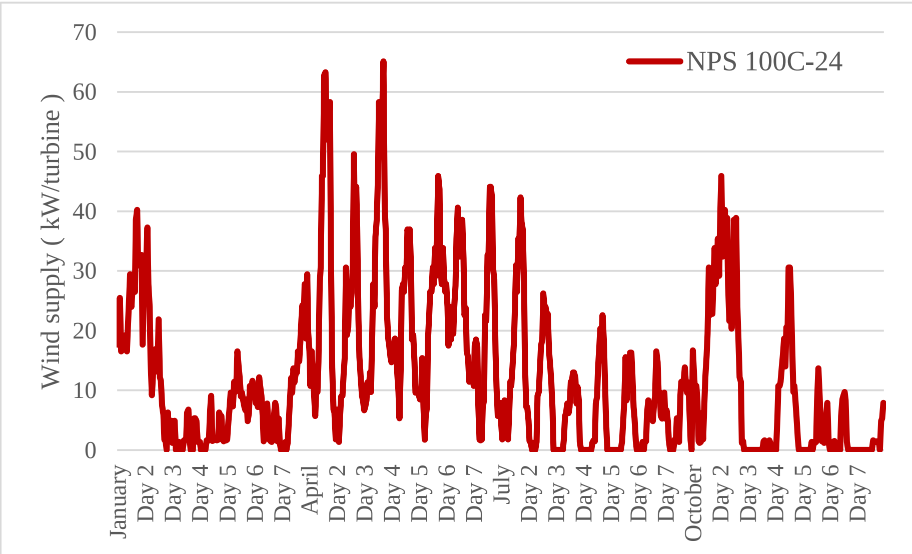

Figure D3. Glasgow wind supply (kW/turbine) – NPS 100C-24.

Appendix E – Extra tabular results

	Winter			Spring			Summer			Autumn		
	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)
Offices B	-38.66	77.64	25.05	-5.23	3.00	0.95	-9.11	4.41	1.41	-4.38	4.69	1.49
Light Industry	-57.91	29.45	35.26	-14.12	1.36	1.58	-17.17	1.33	1.57	-9.95	2.00	2.33
R & D	-55.87	128.87	34.25	-6.06	2.42	0.63	-14.99	5.20	1.37	-6.98	6.30	1.64
General Industry	-38.89	118.85	26.25	-2.99	2.82	0.62	-5.78	4.65	1.03	-3.52	5.84	1.29
Sports & Rec.	-29.16	27.49	20.35	-20.17	7.50	5.63	-21.85	6.79	5.10	-8.05	4.55	3.42

Table E1. Solar PV 75% - Overall.

	Winter			Spring			Summer			Autumn		
	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)
Offices B	-77.43	77.64	43.54	-100.00	3.00	1.66	-100.00	4.41	2.45	-35.59	4.69	2.60
Light Industry	-85.96	29.45	50.04	-100.00	1.36	2.25	-100.00	1.33	2.24	-46.00	2.00	3.32
R & D	-84.47	128.87	49.24	-89.28	2.42	0.91	-100.00	5.20	1.97	-37.73	6.30	2.36
General Industry	-81.39	118.85	47.47	-100.00	2.82	1.12	-94.18	4.65	1.86	-35.83	5.84	2.33
Sports & Rec.	-63.89	27.49	36.74	-100.00	7.50	10.12	-100.00	6.79	9.16	-51.93	4.55	6.14

Table E2. Solar PV 75% - EV hours.

	Winter			Spring			Summer			Autumn		
	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)
Offices B	-13.47	13.71	4.39	-90.21	20.95	6.63	-40.28	53.03	16.92	-16.90	27.85	8.85
Light Industry	-20.45	6.10	7.24	-99.59	9.24	10.76	-49.94	19.60	23.12	-24.42	11.10	12.94
R & D	-21.73	27.11	7.02	-97.64	31.45	8.37	-56.01	94.38	24.89	-24.70	48.47	12.62
General Industry	-17.38	24.29	5.36	-88.84	28.15	6.19	-47.38	92.02	20.31	-18.29	42.82	9.44
Sports & Rec.	-11.91	5.92	4.44	-63.02	7.54	5.66	-27.49	16.14	12.12	-13.41	10.02	7.53

Table E3. Wind 75% - Overall.

	Winter			Spring			Summer			Autumn		
	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)
Offices B	-18.87	13.71	7.65	-100.00	20.95	11.56	-57.83	53.03	29.49	-30.93	27.85	15.43
Light Industry	-23.55	6.10	10.30	-100.00	9.24	15.33	-58.50	19.60	32.89	-34.52	11.10	18.43
R & D	-25.37	27.11	10.10	-98.52	31.45	12.08	-66.86	94.38	35.84	-35.55	48.47	18.20
General Industry	-25.20	24.29	9.70	-100.00	28.15	11.21	-70.39	92.02	36.73	-34.36	42.82	17.07
Sports & Rec.	-16.80	5.92	7.98	-74.45	7.54	10.18	-43.48	16.14	21.76	-25.42	10.02	13.51

Table E4. Wind 75% - EV hours.

	Winter			Spring			Summer			Autumn		
	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)
Offices B	-2.93	6.93	2.22	-39.85	48.64	15.39	-40.69	45.23	14.43	-10.99	18.47	5.87
Light Industry	-10.82	6.64	7.88	-56.56	16.71	19.45	-60.13	16.63	19.61	-26.73	10.59	12.35
R & D	-11.03	29.64	8.05	-69.07	89.35	23.26	-67.05	81.47	21.43	-29.17	51.24	13.34
General Industry	-7.48	25.84	5.71	-46.50	85.94	18.90	-47.53	79.91	17.64	-18.96	47.14	10.39
Sports & Rec.	-0.93	1.03	0.78	-17.64	11.14	8.36	-19.21	10.95	8.22	-4.92	4.05	3.05

Table E5. Solar PV 25% - Overall.

	Winter			Spring			Summer			Autumn		
	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)
Offices B	-5.40	6.93	3.87	-74.84	48.64	26.84	-70.13	45.23	25.15	-25.05	18.47	10.23
Light Industry	-15.29	6.64	11.21	-78.72	16.71	27.71	-79.12	16.63	27.91	-44.60	10.59	17.59
R & D	-15.88	29.64	11.57	-97.23	89.35	33.55	-89.53	81.47	30.86	-50.28	51.24	19.24
General Industry	-14.29	25.84	10.32	-97.42	85.94	34.21	-91.13	79.91	31.90	-47.87	47.14	18.79
Sports & Rec.	-1.85	1.03	1.39	-38.13	11.14	15.03	-37.28	10.95	14.77	-12.01	4.05	5.47

Table E6. Solar PV 25% - EV hours.

	Winter			Spring			Summer			Autumn		
	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)
Offices B	-2.25	4.38	1.40	-53.30	49.47	15.65	-4.04	8.06	2.57	-5.76	12.65	4.02
Light Industry	-5.01	2.50	2.97	-72.22	19.85	23.10	-9.15	4.82	5.69	-11.99	7.03	8.21
R & D	-5.62	12.38	3.28	-76.82	92.88	24.10	-10.89	25.22	6.63	-13.59	35.33	9.20
General Industry	-4.21	11.02	2.43	-67.44	87.13	19.16	-8.13	22.41	4.95	-10.88	33.50	7.33
Sports & Rec.	-0.75	0.67	0.50	-34.75	15.24	11.43	-1.53	1.40	1.05	-3.23	3.15	2.37

Table E7. Wind 25% - Overall.

	Winter			Spring			Summer			Autumn		
	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)	CO_2 (±%)	Balance (£)	Match (±%)
Offices B	-3.26	4.38	2.44	-60.95	49.47	27.30	-6.18	8.06	4.48	-9.83	12.65	7.01
Light Industry	-5.88	2.50	4.22	-73.86	19.85	32.91	-11.15	4.82	8.09	-16.48	7.03	11.69
R & D	-6.64	12.38	4.72	-79.05	92.88	34.79	-13.42	25.22	9.55	-18.88	35.33	13.26
General Industry	-6.14	11.02	4.40	-78.29	87.13	34.69	-12.58	22.41	8.95	-18.87	33.50	13.25
Sports & Rec.	-1.14	0.67	0.90	-49.63	15.24	20.56	-2.53	1.40	1.88	-5.66	3.15	4.24

Table E8. Wind 25% - EV hours.