Electric Vehicle Charge Management System

Sarah Conway
B.A.I. Engineering
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Supervisor: Dr. Donal O’Mahony

School of Computer Science and Statistics
O’Reilly Institute, Trinity College, Dublin 2, Ireland
DECLARATION

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

_________________________________________  ________________________
Name                                           Date
Acknowledgements

Firstly I would like to thank my supervisor Dr. Donal O’Mahony for the advice, input and guidance that he has given me throughout this project.

I would also like to thank my parents for all the support and encouragement they have given me not only this year but in everything I have done.

Finally, I would like to thank Robert for his unwavering encouragement, for believing in me and for keeping me somewhat sane over the last few years.
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<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>AIMD</td>
<td>Additive Increase Multiplicative Decrease</td>
</tr>
<tr>
<td>API</td>
<td>Application Programming Interface</td>
</tr>
<tr>
<td>AWT</td>
<td>Advanced Window Builder</td>
</tr>
<tr>
<td>BEV</td>
<td>Battery Electric Vehicle</td>
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<tr>
<td>CER</td>
<td>Commission for Energy Regulation</td>
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<tr>
<td>CPP</td>
<td>Critical Peak Pricing</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
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<tr>
<td>DOD</td>
<td>Depth of Discharge</td>
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<td>DR</td>
<td>Demand Response</td>
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<td>DSM</td>
<td>Demand Side Management</td>
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<tr>
<td>DSM</td>
<td>Demand Side Management</td>
</tr>
<tr>
<td>DSO</td>
<td>Distribution System Operator</td>
</tr>
<tr>
<td>EDF</td>
<td>Électricité de France</td>
</tr>
<tr>
<td>ER-EV</td>
<td>Extended-Range Electric Vehicle</td>
</tr>
<tr>
<td>ESB</td>
<td>Electricity Supply Board</td>
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<tr>
<td>EV</td>
<td>Electric Vehicle</td>
</tr>
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<td>EVSE</td>
<td>Electric Vehicle Supply Equipment</td>
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<td>GHG</td>
<td>Greenhouse Gas</td>
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<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
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<tr>
<td>GWT</td>
<td>Google Web Toolkit</td>
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<tr>
<td>HEV</td>
<td>Hybrid Electric Vehicle</td>
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<tr>
<td>ICE</td>
<td>Internal Combustion Engine</td>
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<tr>
<td>IDE</td>
<td>Integrated Development Environment</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electrotechnical Commission</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>JDBC</td>
<td>Java Database Connectivity</td>
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<td>JFC</td>
<td>Java Foundation Classes</td>
</tr>
<tr>
<td>JSOM</td>
<td>Java OpenStreetMap Editor</td>
</tr>
<tr>
<td>JSON</td>
<td>JavaScript Object Notation</td>
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<tr>
<td>LDV</td>
<td>Light Duty Vehicle</td>
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<tr>
<td>Li-ion</td>
<td>Lithium-ion</td>
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<tr>
<td>Li-poly</td>
<td>Lithium-polymer</td>
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<tr>
<td>MO</td>
<td>Market Operator</td>
</tr>
<tr>
<td>NiCd</td>
<td>Nickel Cadmium</td>
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<tr>
<td>NiMH</td>
<td>Nickel-Metal Hydride</td>
</tr>
<tr>
<td>OSM</td>
<td>OpenStreetMap</td>
</tr>
<tr>
<td>PEV</td>
<td>Plug-In Electric Vehicle</td>
</tr>
<tr>
<td>PNNL</td>
<td>Pacific Northwest National Laboratory</td>
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<tr>
<td>RCD</td>
<td>Residual-Current Device</td>
</tr>
<tr>
<td>RDBMS</td>
<td>Relational Database Management System</td>
</tr>
<tr>
<td>REST</td>
<td>Relational State Transfer</td>
</tr>
<tr>
<td>RTP</td>
<td>Real-Time Pricing</td>
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<tr>
<td>SEAI</td>
<td>Sustainable Energy Authority of Ireland</td>
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<tr>
<td>SEM</td>
<td>Single Electricity Market</td>
</tr>
<tr>
<td>SEMO</td>
<td>Single Electricity Market Operator</td>
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<tr>
<td>SOC</td>
<td>State Of Charge</td>
</tr>
<tr>
<td>SONI</td>
<td>System Operator Northern Ireland</td>
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<tr>
<td>SQL</td>
<td>Structured Query Language</td>
</tr>
<tr>
<td>TAO</td>
<td>Transmission Asset Owner</td>
</tr>
<tr>
<td>TCP</td>
<td>Transmission Control Protocol</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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</tr>
<tr>
<td>TLS</td>
<td>Transport Layer Security</td>
</tr>
<tr>
<td>TOU</td>
<td>Time-Of-Use</td>
</tr>
<tr>
<td>TSO</td>
<td>Transmission System Operator</td>
</tr>
<tr>
<td>V2G</td>
<td>Vehicle to Grid</td>
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</table>
Abstract

Due largely to a need to reduce both greenhouse gas emissions and fossil fuel dependence and to make the transport industry more sustainable, the use of electric vehicles is becoming more widespread. If the charging of a large-scale electric vehicle fleet is left unmanaged it will subject the electrical grid to large additional, undesirable and potentially damaging loads. This project examines the potential issues that may result from an unmanaged charging scenario and presents a potential solution in the form of a smart charging management system. The system utilises existing grid capacity and peaks in renewable energy to effectively integrate electric vehicles into the grid. Without the adoption of such a strategy, large-scale electric vehicle use may never become a reality. This solution was developed through a combination of research into the relevant subject areas, prototyping and simulations and was found to be capable of the successful integration of EV loads into an existing electrical grid.
Chapter 1: Introduction

1.1 Motivation
Many countries across the world are highly reliant on fossil fuels. Oil and gas, in particular, are two types of fossil fuels that are in high demand but much of the reserves of these fuels are located in politically unstable parts of the world meaning that prices are volatile. A major impact of this high reliance on fossil fuels is the emission of greenhouse gases with the emission of carbon dioxide ($CO_2$) being of particular concern. Greenhouse gas emissions are a major contributor to global warming and it is therefore desirable that they be reduced. Targets are being set in countries across the world to reduce the amount of $CO_2$ that they produce and to develop lower carbon, more sustainable economies. In Ireland, for example, it is aimed, by 2020, to reduce greenhouse gas emissions by 20% from 2005 levels [1]. In the UK, meanwhile, targets are in place to reduce $CO_2$ emissions by 80% with respect to 1990 levels by 2050 [2].

In order to meet these targets, the two main areas that are being addressed are those which are, at present, the primary users of fossils fuels – electricity generation and the transport sector. Plans are in place in many countries to make these industries more sustainable by way of increasing the proportions of renewable energy sources that are used for generation and increasing the prevalence of electric vehicles (EVs). In Ireland, for example, the government aims for 10% of the country’s vehicle fleet to be accounted for by electric vehicles by 2020 [3].

If the charging of a large-scale EV fleet is left unmanaged it will put a significant additional strain on the electrical grid and can potentially result in the failure and degradation of grid infrastructure as well as a reduction in power quality. In order to avoid such issues, grid operators face the choice of either upgrading infrastructure, an expensive, time consuming and disruptive operation or developing smart charging strategies to effectively manage the charging of EVs. This project examines the challenges that are faced as a result of the large-scale integration of EVs into an existing electrical grid and develops a charge management solution with the aim of ensuring that the resources of electrical grids are suitably utilised and protected.

1.2 Project Objectives
The primary goal of this project is the creation of a smart charging strategy that can effectively manage the integration of a significant electric vehicle charging load into existing electrical grids. In doing this, it is aimed to suppress the need for infrastructural updates while also mitigating the degradation of existing infrastructure. In addition, it is intended that the smart charging strategy that is developed will be capable of maximising the utilisation of the grid that exists and will also be able to respond to real-time system conditions and take maximum advantage of peaks in the availability of renewable energy.
1.3 Report Structure

Chapter 1: This chapter introduces the project and discusses the issue of increasing greenhouse gas emissions and alludes to some of the efforts that are being made to address this issue, in particular, the ways in which electric vehicles can contribute. The objectives of the project are also described.

Chapter 2: In this chapter, electric vehicle, battery and charging technologies and characteristics are examined. The state of EV use worldwide and the trends that are expected to emerge in the coming years are also described. In addition, the issues that may result from the charging of electric vehicles are discussed as are publications which present attempts at solving these issues using smart charging techniques.

Chapter 3: This chapter examines the smart charging system that was designed to address the electric vehicle charging problem. The architecture of the system is described at a high level and the most important aspects are discussed in further detail.

Chapter 4: This chapter looks at how the system described in the previous chapter was implemented and the technologies that were used. The problems that were encountered during the implementation phase of the project and the ways in which these problems were addressed are also discussed. Also included is a discussion of some of the software characteristics that are desirable in the implementation of the system.

Chapter 5: In this chapter, the outcomes of the project are discussed. An analysis of how well the project objectives were fulfilled is included as is a discussion as to what could have been improved upon. The implementation of the system is also evaluated in terms of its efficiency and how well it exhibits the desired software characteristics described in chapter 3.

Chapter 6: In this chapter, the conclusions that were reached through the completion of the project are discussed. The work completed during the project is reviewed and assessed and some possible areas of future work are discussed. Finally, a reflection on the experience of completing the project is included.
Chapter 2: State of the Art

2.1 Electric Vehicles
Electric vehicles (EVs) are those which use electric motors as their means of propulsion. They include vehicles as diverse as electric cars, electric aircraft, electric boats, electric trains, electric submarines and electric spacecraft and proposals are in place for the development of electric tanks. The focus of this report is electric cars and, from this point on, the term EV will refer only to electric cars unless stated otherwise. EVs are not a new concept. They have been in use since the late 19th century and have seen periods of significant interest and popularity interspersed with times of lesser usage. In the early 1900s EV penetration in the US reached 28% and EVs even held several vehicle speed and distance records. In recent years the popularity of EVs has again begun to grow thanks to the high and volatile price of oil and the need for countries to reduce their greenhouse gas (GHG) emissions as well as improvements in the areas of battery technology and power management. The electricity used to power EVs can be generated in many ways including the burning of fossil fuels, the use of renewable resources, nuclear power or a combination of these technologies. It can be stored using batteries, flywheels or supercapacitors. Typical internal combustion engines (ICEs), meanwhile, only burn fossil fuels. While the cost of EVs is higher than that of a conventional ICE vehicle they are significantly more efficient, fuel and maintenance costs are lower and air pollution and carbon emissions are greatly reduced.

2.1.1 Types of Electric Vehicle
EVs may be divided into several different categories based on their propulsion method. These categories are outlined below.

2.1.1.1 Battery Electric Vehicles (BEVs)
Battery electric vehicles are powered entirely by electricity. There is no ICE and thus the electric motor is entirely responsible for propulsion. BEVs produce no emissions but their range is reduced in comparison to ICE vehicles and other types of EV. They require an external electricity source to charge, a process which typically takes between 30 minutes – 20 hours depending on the type of charger that is used and the characteristics of the vehicle. Examples of a BEV include the Nissan Leaf and the Tesla Model S.

Figure 2.1 - Battery Electric Vehicle (BEV). (Source: [4])

2.1.1.2 Hybrid Electric Vehicles (HEVs) – Parallel Hybrid
Parallel hybrid electric vehicles use a traditional ICE supplemented by a battery-powered electric motor. The electric motor serves to improve fuel efficiency over a conventional ICE vehicle. Parallel HEVs can generate electricity using their ICE and use it either to recharge the battery or to run the electric motor
directly. No external electricity source is required. When the parallel HEV is idle, the ICE is powered off and is restarted only when needed. This helps to reduce idle emissions and is referred to as a start-stop system. The ICE of a parallel HEV is smaller than that of a typical ICE vehicle and thus it produces fewer emissions. The reduction in emissions is not as great as is the case with BEVs, however. Parallel HEVs have a significantly greater range than BEVs. The most popular of this type of HEV is the Toyota Prius with a total of around 2.8 million units sold.

![Hybrid Electric Vehicle](image1)

*Figure 2.2 - Hybrid Electric Vehicle (HEV). (Source: [4])*

### 2.1.1.3 Hybrid Electric Vehicles (HEVs) – Series Hybrid
Series hybrid electric vehicles, also referred to as extended-range electric vehicles (ER-EV) use both an ICE and an electric motor but only the electric motor is used to power the vehicle. The ER-EV works by using the ICE to run a generator. This generator is responsible for charging the battery and thus providing power to the electric motor. ER-EVs may also be charged via an external electricity source which improves the fuel efficiency of the vehicle. The ER-EV works in the same manner as a BEV for a given distance after which the ICE and the generator are used. The Chevrolet Volt is an example of an ER-EV.

![Extended-Range Electric Vehicle](image2)

*Figure 2.3 - Extended-Range Electric Vehicle (ER-EV). (Source: [4])*

### 2.1.1.4 Plug-in Hybrid Electric Vehicles (PHEVs)
Plug-in hybrid electric vehicles are similar to HEVs as they use both a typical ICE as well as an electric motor. The battery in the PHEV, however, is larger than that in the HEV (both parallel and series), increasing the cost of the vehicle. The battery can be recharged via an external electricity source. PHEVs further reduce emissions in comparison to ICE vehicles and HEVs. Running costs are also significantly reduced. In addition, PHEVs use energy more efficiently than HEVs. An example of a PHEV is the Ford C-MAX Energi plug-in hybrid.

![Plug-in Hybrid Electric Vehicle](image3)

*Figure 2.4 - Plug-in Hybrid Electric Vehicle (PHEV). (Source: [4])*
2.1.2 EV Usage
The ways in which vehicles are used is diverse and depends on a variety of factors. The needs of vehicle owners vary widely and are influenced by factors including distance of workplace from home, traffic on the routes that are taken, location and the type of use (e.g. private, commercial). With regard to EVs, the number that are in use and the usage patterns that exist are important in planning for the charging needs of the fleet. For this reason it is important to examine the current and expected usage patterns that may be seen.

2.1.2.1 Fleet Size
The size of the EV fleet in various countries shows vast variations. According to the Department of Transport, Tourism and Sport in Ireland, there were approximately 2.4 million registered vehicles in the country in 2011 [5]. The Irish government has a target of having EVs account for 10% of all vehicles in Ireland by 2020 [6]. This corresponds to about 250,000 vehicles. Other countries have set similar targets for increasing the numbers of EVs that are in use. In Germany, for example, it is hoped that, by 2020, EV sales will have reached about 250,000 each year and that there will be a total of approximately 1 million EVs in use. In the US it is expected that, by 2020, 10% of the country’s vehicle fleet will be EVs while Japan is aiming for EVs to account for 20% of their vehicle fleet by 2020 and 30-40% by 2030 [6]. Figure 2.5 depicts projected global sales of light duty vehicles (LDV) to 2050 according to fuel use. From this, it is clear that EV popularity is expected to grow while sales of ICE vehicles are expected to decrease dramatically.

![Figure 2.5 - Projected LDV sales to 2050 (Source: [7])](image)

2.1.2.2 Usage Patterns
Each vehicle owner has their own individual usage pattern involving factors such as annual and daily driving distance, driving time, driving behaviour, fuel use and vehicle type. EVs will introduce additional
factors to these usage patterns including charging start time and duration. As well as this, there are various factors which can modify a person’s vehicle usage pattern including the weather and the time of year. Due to this diversity it is impossible to find a single, common usage pattern. This section examines some usage characteristics that are often observed and ways in which these may be affected.

The typical distance that a person travels by car each day may be affected by the distance that they live from their workplace as well as other commitments such as collecting children from school and visiting parents. The Sustainable Energy Authority of Ireland (SEAI) estimated that private cars travelled an average of just over 19,000 km in 2010 [8]. This corresponds to an average of about 52.5 km each day. As well as this, it may be said that the majority of vehicle use takes place during the day. In the case of private vehicles the majority of journeys take place in the morning when people are travelling to work and in the evening when people are returning home from work. Regarding commercial vehicles, however, it is likely that journeys will take place at all times of the day.

As mentioned, vehicle usage characteristics are likely to be influenced in various manners. During winter and in bad weather, for example, it is likely that the amount of vehicle travel will increase while during better weather people may choose to walk to their destination thus decreasing the distance that is travelled in private vehicles each day.

With regard to EV charging time it is expected that the majority of vehicles will be plugged in in the evening time when people return home from work. Charging may also take place during the day if facilities are available at workplaces or if it is required to complete a long journey. The time at which EVs are plugged in to charge will be influenced by the times at which it is most convenient for the owner. It is hoped, however, that through careful planning, EV charging can be influenced by electric utilities and attracted to times that are most convenient to them. This idea is examined in detail later in this report.

2.1.3 EV Characteristics

EVs differ from traditional ICE vehicles in many ways including efficiency and range. In this section, these differences, amongst others, are discussed.

2.1.3.1 Efficiency

EVs are far more efficient in their use of energy than are ICE vehicles. ICE vehicles have an energy efficiency of approximately 15-20% with a great deal of energy being wasted as heat. EVs, meanwhile, have an energy efficiency of about 80%. While at rest, EVs do not consume any energy unlike ICE vehicles which continue to do so. In EVs, regenerative braking is used, i.e. some of the energy that is lost in braking is captured and reused. This can capture up to a fifth of the energy that is typically lost in braking.

Well-to-wheel efficiency addresses the production and distribution of energy as well as its use by the vehicle. The well-to-wheel efficiency of EVs is largely dependent upon the way in which the electricity that is used was generated. In countries where electricity is generated mostly from renewable sources the well-to-wheel efficiency of EV is quite low. In countries where electricity generation is highly reliant upon fossil fuels, however, it is closer to that of an ICE vehicle.
2.1.3.2 **Range**
The driving range of an EV or the distance that it is capable of travelling without being recharged is dependent upon various factors including the vehicle type, the battery characteristics and driving conditions. The Nissan Leaf (BEV), for example, has a driving range of 175 km while the range of the Tesla Model S (BEV) varies between almost 260 km and over 480 km depending on the battery that is used. With regard to HEVs and PHEVs, the distance that can be travelled using just the electric motor is less than is the case with a BEV. The total distance that can be travelled, however, is typically much greater. For example, a Toyota Prius (PHEV) is capable of travelling just 16-24 km using its electric motor alone. Combined with its internal combustion engine this vehicle has a range of 870 km. Similarly, the distance that can be travelled using the electric motor of an ER-EV is less than is possible with a BEV. The electric motor driving range of the Chevrolet Volt (ER-EV), for example, is close to 60 km while its total range is over 600 km.

Through examination of the driving ranges of this selection of vehicles it may be seen that there is great diversity in the distances that EVs are capable of travelling. While some are only suited for relatively short trips on a single charge, others are capable of travelling for much longer distances and can rival the travel potential of typical ICE vehicles.

2.1.3.3 **Battery Capacity**
Great diversity may also be seen in EV battery capacities. By examining the battery capacities of the vehicles mentioned in section 2.1.3.2 this diversity may be seen. This information is presented in Table 2-1 along with the EV ranges that were discussed previously.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Range (Approximate)</th>
<th>Battery Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nissan Leaf</td>
<td>175 km</td>
<td>24 kWh</td>
</tr>
<tr>
<td>Tesla Model S</td>
<td>260-480km</td>
<td>40-85 kWh</td>
</tr>
<tr>
<td>Toyota Prius</td>
<td>870 km total, 16-24 km electric motor</td>
<td>4.4 kWh</td>
</tr>
<tr>
<td>Chevrolet Volt</td>
<td>600 km total, 60 km electric motor</td>
<td>16.5 kWh</td>
</tr>
</tbody>
</table>

Table 2-1 - Range and battery capacity of various EV models

2.1.3.4 **Charging Time**
The time that is required to charge an EV also depends on a variety of factors. These include the battery characteristics, the initial SOC of the battery and the characteristics of the charging station. Charging an EV from 0% to 100% can take between half an hour and twenty hours depending on these factors. In section 2.3 the expected charging times when various types of charging facilities are in use is discussed.

2.1.4 **Barriers to Adoption**
In order for large scale EV use to become a reality there are several issues which must first be addressed. These issues are the main factors that discourage people from purchasing an EV in favour of a typical ICE vehicle. If left unaddressed, these may significantly impede the desired EV adoption rates in countries around the world. Some of these issues are discussed below.

2.1.4.1 **Lack of Charging Infrastructure**
At the moment, the charging infrastructure in many countries is not sufficient for a large number of EVs. While it is typical for EV owners to have charging facilities at their homes the shortage of public
infrastructure means that longer trips may not be possible. Many countries are making efforts to address this issue, however, and it is hoped that, in the coming years, EV charging facilities will be widespread. In section 2.3 the efforts that some countries are making to develop their EV charging infrastructure are discussed.

2.1.4.2 Limited Range
Many people are concerned that the range of EVs will not be sufficient for their needs and that they may end up stranded. This is known as “range anxiety” and is intensified by the issue of a lack of charging infrastructure that was discussed previously. According to Bill Reinhart, Toyota’s US National Manager of Advanced Technology, “The range anxiety will limit the ability of the electric car to be used in certain specific applications even if the price comes down” [9]. To help ease this problem it is necessary both that charging infrastructure is improved and that EV battery capacity and thus range is increased.

2.1.4.3 Cost
Cost is another issue that hinders the adoption of EVs. While it is true that the running costs of EVs are less than that of ICE vehicles the upfront cost is significantly greater. Prices for a 2013 ICE Ford Focus, for example, start at $16,200 [10]. Prices for an electric version of the vehicle, meanwhile, start at $39,200. EV batteries are a major component of this increased cost. As well as the initial cost of the EV, batteries must eventually be replaced, typically after about eight to ten years, giving rise to another cost for the potential owner to consider. The US Department of Energy estimates that, in order for EVs to fairly compete with ICE vehicles, battery prices must decrease by 50-80% [11]. To make EVs more appealing, prices must come down. Newer battery technologies are aiding in reducing costs but, in order for them to be reduced significantly, large scale production is required. This will not take place, however, until large scale EV use is a reality. It is therefore likely that EV prices will not come close to those of ICE vehicles until large numbers are already being sold.

2.1.4.4 Charging Time
As discussed in section 2.1.3, the amount of time required to recharge an EV is significantly greater than the time required to refuel an ICE vehicle. If the vehicle is being left to charge overnight a charging time of several hours may not be an issue. If, however, an EV needs to be charged in the middle of a journey, the owner may not be happy to wait this long before they can continue on to their destination. Fast charging and battery swapping are potential solutions to this issue but their use is not widespread. These are discussed in detail in section 2.3.
2.2 Batteries
As described previously, EVs typically rely on energy stored in a battery to drive an electric motor for at least part of its means of propulsion. These are rechargeable batteries and are typically the most expensive part of an EV. Other means of energy storage (flywheels or supercapacitors) may also be used. Battery and thus EV performance is highly dependent upon a number of factors including the depth of discharge of the battery, its temperature and the voltage at which it is charged. According to Bauer et al. [12] batteries must meet the following requirements in order to be acceptable for use in an EV.

- Long lifetime
- High charging and discharging efficiency
- High specific energy
- High specific power
- Minimal environmental impact upon disposal
- Safe to operate

These characteristics are discussed in section 2.2.1.

2.2.1 Battery Characteristics
In this section various characteristics of a typical battery are discussed as is the importance of these characteristics in the context of EVs. Batteries are composed of electrochemical cells. These transform chemical energy into electrical energy. Within each cell is an anode, a cathode and electrolyte. When a battery is discharging, a reduction reaction occurs at the cathode and an oxidation reaction occurs at the anode. When a battery is charging these reactions are reversed. The combination of an oxidation reaction and a reduction reaction is known as a redox reaction.

2.2.1.1 Battery Capacity
The capacity of a battery is the amount of charge that it is capable of storing. It is influenced by the amount of active material, or materials taking place in the redox reaction, that is present. The capacity specified by the manufacturer is the amount of charge that the battery can store under optimum conditions. The actual capacity is highly dependent upon its age and the charging and discharging that it has previously been subject to. To measure battery capacity either kilowatt hours (kWh) or ampere-hours (Ah) may be used. In this report battery capacity is measured in kWh.

2.2.1.2 State of Charge
The state of charge (SOC) of a battery refers to the amount of charge that is stored in the battery at any given time. It is given as a percentage and is calculated using the ratio of current charge to the battery capacity.

\[
SOC = \frac{\text{current charge}}{\text{battery capacity}} \times 100
\]

An SOC of 100% indicates that the battery is fully charged while an SOC of 0% indicates that the battery is fully discharged.
2.2.1.3 Depth of Discharge
The depth of discharge (DOD) of a battery refers to the amount by which the battery has been discharged at any given time, i.e. it is the inverse of SOC.

\[ DOD = 1 - SOC \]

A DOD of 100% indicates that the battery is fully discharged while a DOD of 0% indicates that the battery is fully charged.

2.2.1.4 Specific Energy
The specific energy of a battery is the amount of energy that it can hold per unit of mass. It is measured in units of Wh/kg. The higher the specific energy of a battery, the more energy it can store. It is important, therefore, that EV batteries have a high specific energy to ensure that the vehicle will have a suitable range.

2.2.1.5 Specific Power
The specific power of a battery is the amount of power that it delivers per unit of mass. It is measured in units of W/kg. A high specific power is desirable in an EV battery to aid in the vehicle’s acceleration.

2.2.1.6 Energy Efficiency
The energy efficiency of a battery refers to both the charging and the discharging efficiency and is the ratio of the energy that is output from the battery to the energy that is input to it. It is desirable that an EV battery have a high efficiency in both charging and discharging.

2.2.1.7 Cycle Life
The cycle life of a battery is the number of charge and discharge cycles that it is capable of undergoing before the time that is taken to discharge the battery reaches half of the initial value. It is desirable that the cycle life of an EV battery be as long as possible but this characteristic is highly dependent upon many factors. For example, high and low temperatures, deep discharge and high voltages (overvoltage) can reduce the lifetime of the battery. Participation in vehicle-to-grid, which is discussed in section 2.6, also serves to reduce lifetime.

2.2.1.8 Cost
As mentioned in section 2.1.4.3, the cost of EV batteries tends to be quite high and typically accounts for a large portion of the overall price of the vehicle. High battery prices are one of the main barriers to large scale EV adoption. Battery cost is of particular concern as, not only are batteries responsible for a high upfront cost, but they must also be replaced typically after eight to ten years though this varies greatly based on use.

2.2.2 Battery Types
Various types of battery, each having its own unique characteristics, are used in EVs. The battery types that are typically used are listed by Bauer et al. in [13]. An overview of each type is given below.
2.2.2.1 **Lead-acid**
Lead-acid batteries are the cheapest and most common type of rechargeable battery. They are often used as vehicle engine starter batteries. They have a low specific energy and a relatively high specific power. Deep cycle lead-acid batteries have traditionally been used in EVs primarily due to their low cost. These batteries do not have a long lifespan (500-800 cycles) and, in addition, make up approximately 25-50% of the total mass of the vehicle. Lead-acid batteries were used in General Motor’s EV I but are not regarded as a technology that is suitable for use in EVs in the future.

2.2.2.2 **Nickel Based**
Nickel based batteries, including NiCd and NiMH batteries, may also be used in EVs. NiMH (nickel-metal hydride) batteries have a charging efficiency of approximately 60-70% while that of NiCd (nickel-cadmium) batteries is approximately 70-90%. NiMH batteries also have a higher energy density than lead–acid batteries. Nickel based batteries have longer lifespans than lead-acid batteries with the NiCd variety having the longer of the two (~2000 cycles). A long lifespan is a characteristic that is desirable in an EV battery. NiMH batteries have proven more popular for use in EVs for several reasons including their typically higher capacity and also environmental concerns associated with the disposal of NiCd batteries. NiMh batteries are used in the Toyota Prius.

2.2.2.3 **Lithium Based**
Lithium based batteries, including Lithium-ion (Li-ion) and Lithium-polymer (Li-poly) batteries, are commonly used in consumer electronics and have come to be the most commonly used battery type in recent EVs. Currently, Li-ion batteries are being used in vehicles such as the Nissan Leaf and Li-poly batteries in vehicles such as Hyundai’s Sonata Hybrid. Reasons for their popularity include their high specific energies, relatively low mass and relatively long lifetime (>1000 cycles). There are, however, safety concerns associated with the use of lithium batteries if they are not treated correctly. Other lithium based batteries such as lithium-air batteries are also being developed. These have significant advantages including a very high energy density.

2.2.2.4 **High Temperature**
High temperature batteries such as the Sodium-nickel-chloride (NaNiCl₂) or ZEBRA battery have a relatively high energy density and, as they must be heated for use, are not greatly affected by cold weather. This heating wastes energy, however, and can cause issues with long-term charge storage. In addition, Zebra batteries have quite long lifespans (~3000 cycles) and have been used in vehicles such as the Iveco Daily and the 2007 Modec Electric Van.

2.2.2.5 **Metal Air**
Metal air batteries including Aluminium-air (Al-air) and Zinc-air (ZN-air) batteries are also used in EVs. These work by oxidising the metal with the oxygen that is in air in order to produce electricity. Both Al-air and Zn-air batteries have high specific energies and are inexpensive to make. They are not as efficient as other types of battery however. These battery types are still undergoing development and may, in the future, become commonly used in EVs.

Some of the characteristics of these battery types, as given by Valsera-Naranjo et al., are shown in Table 2-2 [13].
2.2.3 Lithium-ion Batteries

Due to its popularity and its use in many EVs including the Nissan Leaf and the Chevrolet Volt, the lithium-ion battery is that which will be considered in the remainder of this report. Li-ion batteries are relatively light, reducing the weight of the vehicle and thus improving its performance. Shown in Figure 2.6 [14], are the charge stages of a typical 4.20V/cell Li-ion battery. The battery is said to be fully charged when the supplied current drops to a given level and a specified threshold voltage is reached. While the battery remains connected to the charger, a topping charge may be applied to prevent significant discharge.
In order to charge an EV, alternating current (AC) from the electricity grid must be transformed into direct current (DC) by the charger. It is important to charge lithium based batteries at a moderate temperature. Charging at temperatures that are too low (below 0°C) can be damaging. At such temperatures the batteries appear to charge as normal but plating of metallic lithium can occur. This damage is permanent and increases the batteries’ susceptibility to failure.

An increase in the current that is supplied to a Li-ion battery will not significantly reduce the time taken to reach a full charge. The time taken to reach approximately 70% charge will be reduced but the time for the battery to become saturated after this point will not. It is not necessary for a Li-ion battery to be fully charged and it is typically not recommended. By fully charging such a battery it may be subject to undue stress. By either finishing charging before the saturation charge occurs or reducing the battery’s threshold voltage battery life will be extended but the lifetime between charges will be reduced. This is a trade-off that must be considered when using Li-ion batteries in EVs.

Lithium-ion batteries are not capable of absorbing any overcharge. For this reason the charging current is no longer supplied once the battery is fully charged. If any additional charging (trickle charging) were to be applied after this point, plating or deposition of metallic lithium can occur. This can cause the battery to become unstable. Prolonged overcharging can cause an increase in cell pressure which, if it becomes excessive, can result in fire. It is essential, therefore that the batteries are handled properly and that all charging equipment is designed to a high standard. Once the charging current has been stopped, the battery voltage will begin to decrease. While connected to the charger a topping charge may occasionally be applied to the battery in order to compensate for this self-discharge (see Figure 2.6, stage 4).

In addition to overcharging, over-discharging can also be an issue. To prevent a Li-ion battery from discharging too much, current is no longer drawn once a certain level of discharge is reached. If discharging were to continue the battery can enter a sleep state. Recharging a Li-ion battery that has entered this sleep state is not possible with a typical charger and instead specialised equipment must be used.
2.3 Electric Vehicle Charging
EVs may be charged at EV charging stations or EVSE (Electric Vehicle Supply Equipment). Different types of charging station are available to cater for different user requirements. Some are installed in public locations such as road sides and car parks while others are installed at homes. Some charging stations are capable of fast charging and others use inductive charging mats to charge the vehicles without a physical connection. Many charging stations have space for just one vehicle but some are capable of charging multiple vehicles at once. As discussed in section 2.1, there is a lack of EV charging infrastructure in many countries. Some of the EV charging systems that are in place around the world will be discussed in this section.

2.3.1 Standards & Safety
It is possible to charge an EV from a standard wall socket, however infrastructure designed specifically for charging EVs has additional safety mechanisms which make it more suitable for use. The European Automobile Manufacturers Association defined standard terminology for EV charging equipment that should be used [15] as shown in Figure 2.7. Safety mechanisms involve the ability to disconnect power when the connected EV is not charging. This is of particular importance due to the possibility that an EV owner may forget to disconnect their EV from the charging infrastructure before driving away. If this were to happen, the charging station could be damaged and electric conductors could be exposed. If such safety mechanisms were not in place this could be a very dangerous situation. There are two methods of determining whether the vehicle is charging. One uses physical sensor wires and the other monitors the EV’s power consumption. While sensor wires have a quicker reaction time they require special connectors. Power consumption monitoring, meanwhile, can be done with standard connectors.

As well as this, connection interlocks ensure that, no power is supplied to the connector when there is no EV connected [16]. Other safety considerations include ensuring that all charging infrastructure is installed by qualified personnel, that all equipment is handled correctly and not subject to any undue stress and that EVs may be safely charged in all weather conditions. Standards are in place to ensure that all charging equipment is subject to rigorous testing and is safe to use.

2.3.2 Modes of Charging
A set of standards known as IEC 62196 has been developed for EV connectors and charging modes by the International Electrotechnical Commission (IEC) [17]. The charging modes that are defined are described below.
2.3.2.1 Mode 1
Mode 1 charging involves the connection of the EV to the grid via a standard socket. The supply must not exceed 16 A and 250 V (single-phase AC) or 480 V (three-phase AC). No control pins are required for the connectors used for mode 1. To use this mode an earthing system must be in place. In some countries, including the U.S., this charging mode is not permitted primarily because some electrical installations do not have the required earthing.

2.3.2.2 Mode 2
Mode 2 charging involves the connection of the EV to the grid via a standard socket. The supply must not exceed 32 A and 250 V (single-phase AC) or 480 V (three-phase AC). For this mode a control pin is required on the EV. An earthing cable must be installed and a control function is added. In this mode a residual-current device (RCD) is used to protect against electric shock.

2.3.2.3 Mode 3
Mode 3 charging involves the connection of the EV to the grid via a dedicated EV charging station. The control equipment is permanently installed in the charging station. For this mode, control and signal pins are required on both the EV and the supply sides of the cable. No power is supplied to the socket if there is no EV present. In addition, a communication wire is present which allows for communication between the vehicle and the charging station. This allows for smart grid integration.

2.3.2.4 Mode 4
Mode 4 charging involves the connection of the EV to the grid via an external charger. The control equipment is again permanently installed in the charging installation. In this mode the AC power that is supplied from the grid is converted to DC in the charging station. As with mode 3, control and signal pins are required on the EV side and the supply side of the cable. Mode 4 charging equipment is significantly more expensive than mode 3 equipment, however. This mode of charging allows for currents up to 400 A to be used. Not all EVs are designed for such a high current, however, and a specific type of plug is used to ensure that those which are not designed to take such a current are not mistakenly connected to a mode 4 charging station.

2.3.3 Installed EV Charging Infrastructure
In many developed countries, the existing grid infrastructure is sufficient to meet potential large-scale EV charging needs provided the charging is properly managed. As the number of EVs that are in use grows, infrastructure must be put in place that can effectively utilise the electricity grid’s potential for charging. Some countries have seen widespread installations of EV charging infrastructure while others are trailing far behind. This section examines the charging infrastructure that has been installed in various countries around the world.

2.3.3.1 France
In France, public EV charging stations are being installed by Toyota and the electric utility Électricité de France (EDF). The French government plans to install 400,000 charging points across the country by 2015. Some parts of France are particularly innovative with regard to their charging infrastructure. In Nice, for example, a project called “Auto Bleue” [18], a self-service EV rental scheme is in operation. As
of December 2012 the system has a total of 139 EVs and 43 charging stations each with space for five vehicles.

2.3.3.2 United Kingdom
It is estimated that over 3,000 EV charging stations were installed in the UK by March 2012. These include domestic, workplace and public stations [19]. Around half of these have been installed as part of the ‘Plugged-in Places’ program [20]. This program is creating eight charging hubs across the UK including London, Milton-Keynes and Greater Manchester. The UK Committee on Climate Change has been advising the government on the installation of charging infrastructure capable of supporting 1.7 million EVs by 2020.

2.3.3.3 United States
As of January 2013 there were 15,461 public charging stations installed across the US [21]. These charging stations are not distributed equally amongst the states with large numbers being located in states such as California (3675), Texas (1320) and Washington (1077) and other states such as Montana (2) and Wyoming (0) having very few or even no installed stations. The US government has pledged $115 million to further the installation of EV charging stations in 16 areas of the country.

2.3.3.4 Finland
A significant expansion of the Finnish EV charging network is currently being planned. It is intended that the number of charging stations in the country will be increased from the current 150 to at least a thousand [22]. Finland uses both 16 A (220 V) charging stations and 250 A (400 V) fast charging stations [23].

2.3.3.5 Ireland
In Ireland, the Electricity Supply Board (ESB) is responsible for the installation of EV charging stations. The Irish government has set a target of having EVs account for 10% of all vehicles by 2020. The ESB aims to install sufficient infrastructure to meet the charging needs of this target. The first charging station in Ireland was installed in 2010 and, since then, they have been installed in many locations across the country. ESB’s targets for installation are:

- 2000 domestic charging stations
- 1500 public charging stations
- 30 fast charging stations

Extensive testing is being carried out both on the infrastructure that is being installed and on customer behaviour. As well as being responsible for the charging infrastructure the ESB is also developing the supporting payment and IT system.

As mentioned, the ESB has installation targets for three different types of charging station: domestic, public and fast. The characteristics of these are described below.

- **Domestic charging stations** – These are located on an external wall of a house and the existing domestic electricity supply is used to charge the vehicle. An EV can draw single-phase 16A
(3.6kW) when connected to such a station. These are mode 3 charging stations and allow the vehicle to be fully charged from 0% in 6-8 hours. A domestic charging station is shown in Figure 2.8.

Figure 2.8 - Domestic charging station (Source: [24])

- **Public charging stations** – These are located in places such as car parks and shopping centres as well as on-street. A three-phase electricity supply is used to charge the vehicle. These are also mode 3 charging stations and can fully charge a vehicle from 0% in 1-6 hours depending on its battery characteristics. A public charging station is shown in Figure 2.9a.

- **Fast charging stations** – These are primarily located close to motorways and national primary roads. They are capable of supplying EVs with a higher power meaning that they can be charged more quickly. A three-phase 63A AC (44 kW) or a 120A 400V DC (50 kW) supply is used to charge the vehicle. Using the DC 50 kW option it is possible to charge an EV from 0% to 80% in 20-30 minutes. Fast charging corresponds to charging mode 4 and uses a connector that was specifically designed for this purpose by the CHAdeMO Association. A fast charging station is shown in Figure 2.9b.

Figure 2.9 - (a) public charging station, (b) fast charging station (Source: [24])

Figure 2.10 shows the locations and types of the charging points that are currently installed in Ireland.
2.3.4 Battery Swapping

An alternative to charging EV batteries at home or at public charge points is battery swapping. At a battery switch station the discharged battery is removed from the vehicle and is replaced with a fully charged one. In such a situation the battery is owned by a battery switch company rather than by the EV owner. Battery swapping presents many advantages over traditional charging [26]. Some of these advantages are described below.

- **Short battery swapping time** - Owners do not have to wait for their vehicle’s battery to be charged. Batteries can be swapped in just a few minutes and the driver can even stay in their
vehicle while this happens. This is a significant difference to the several hours that people may have to wait if they were to charge the battery themselves.

- **Unlimited Range** - Provided there are a sufficient number of battery switch stations available it may be said that EV range becomes unlimited in a manner similar to an ICE vehicle. Rather than having to stop to recharge, the battery can simply be switched and the EV can continue driving.

- **Reduced capital cost** - The battery is one of the most expensive components of an EV. Using a battery switch station means that the owner has only to pay for the EV itself, significantly reducing capital cost.

- **Eliminate the need for customer battery replacement** - When a battery is continually charged and discharged its capacity gradually decreases. Eventually the battery must be replaced. This is very expensive for someone who owns a battery. By using battery switch stations the owner of the station replaces batteries resulting in no additional cost to the customer.

- **Increased resale value** - If an EV owner with their own battery decides to sell their vehicle before replacing the battery the degraded battery will reduce its resale value. If the owner does not have their own battery and instead uses battery switch stations the resale value is based only on the vehicle itself.

- **V2G participation** – At times when renewable energy resources are plentiful it can be stored in the batteries at battery switch stations. At times when the grid is in danger of a supply shortage some of the electricity stored in the batteries can be sent back into the grid to help meet demand.

There are also disadvantages associated with battery switch stations [27]. The main drawback is a lack of standardisation in EV design. Without having standards for battery access, attachment and type it is very difficult for battery switch stations to cater for all customers.

Currently, the main provider of battery swapping services is a company called Better Place [28]. So far, Better Place has installed battery switching stations in several countries including Israel, Denmark, Australia and the US. At present, the company is in some distress and is having difficulties raising funds.

### 2.3.5 Current Global State of EV Charging

Efforts are being made in many countries across the world to provide the growing EV fleet with a means of charging, but much work still needs to be done before infrastructure that is sufficient to cater for the charging needs of large-scale fleets will exist. The installation of such equipment may be expensive and thus the extent of the need must be carefully considered. The answers to questions such as who should be responsible for the installation and expense of charging infrastructure and where it should be located remain unclear. Many companies are entering the EV charging market and developing different charging solutions. Standards need to be put in place to ensure the safety of equipment and to ensure that the charging of any type of EV is possible in any location. While substantial charging point installation targets have been put in place in many countries, much work is needed before they will be met.
2.4 Electrical Grid
An electrical grid is responsible for the generation, transmission and distribution of electricity in a region. Such systems typically operate at a national level with the structure and operation varying in different countries. In this section, the high level operation of a typical electrical grid will be described. In addition, electricity generation and demand in the context of Ireland will be discussed. Finally, the characteristics of a typical load profile will be examined.

2.4.1 Operation of a Typical Electrical Grid
The purpose of an electrical grid is to generate electricity and to deliver it to consumers. The typical structure of an electrical grid is shown in Figure 2.11. Electricity can be generated from various renewable and non-renewable energy sources including wind power, nuclear power and the burning of fossil fuels. The electricity that is generated is three-phase AC. Once this leaves the power station it enters a transmission substation which steps up the voltage of the generated electricity to levels that are high enough for it to be transmitted over long distances. From Figure 2.11 it may be seen that these voltages may be in the range of 138-765 kV.

![Typical Electrical Grid Structure](image)

In some cases, the electricity that is carried by the transmission system is passed directly to large customers. Normally, however, it is stepped down to lower voltages and passed on to the distribution system. This stepping down of the electricity sometimes happens in several phases. It is at a power substation that the transition between the transmission and the distribution system occurs. As well as stepping down transmission voltages, power substations route the electricity in various directions. Voltages may be stepped down further within the distribution system where there is a need. The final voltage level of the electricity that is delivered is dependent upon the needs of the customer.

2.4.2 Irish Electricity System
In this section, the structure of the Irish electricity market will be described along with the features of the country’s generation, transmission and distribution infrastructure.
2.4.2.1 **Irish Electricity Market**

Prior to November 2007 there were two separate electricity markets in Ireland - the Republic which operated its own market and Northern Ireland which was part of the UK market. Since then, the Transmission System Operators (TSOs) of the two markets, Eirgrid and SONI (System Operator Northern Ireland), have come together to form a Single Electricity Market (SEM) for the whole of Ireland. The Market Operator (MO) of the SEM is the Single Electricity Market Operator (SEMO) [30].

The operation of the Single Electricity Market was described in the “SEM Trading and Settlement Code Helicopter Guide” that was published by the Commission for Energy Regulation (CER) and the Northern Ireland Utility Regulator in 2007 [31]. In summary, almost all of the electricity that is generated on the island is sold into a common pool. All producers that sell electricity into the pool receive the same base price for it and, similarly, all suppliers pay the same base price for electricity from the pool. These base prices may be subject to various additional costs. Suppliers then sell this electricity on to consumers. All electricity that is imported to and exported from Ireland is also sold into and bought from this pool. This market structure is depicted in Figure 2.12.

![Diagram of Electricity Market](image)

*Figure 2.12 - Buying and selling electricity into and from the common pool. (Source: [31])*

Each trading day (6am – 6am), all generators must submit an offer regarding the amount of electricity that it expects to generate.

2.4.2.2 **Electricity Generation**

The majority of Ireland’s electricity is today generated using non-renewable resources such as coal, oil and gas. Due to this great dependency on fossil fuels, renewable resources must be considered in order to ensure the security of the country’s electricity supply. In recent years, the percentage of renewable resources including wind and solar that contribute to Ireland’s generation profile has been increasing. In
2005 renewable energy sources accounted for 5% of Ireland’s electricity generation. As may be seen in Figure 2.13, this increased to 17% by 2011 [32].

The largest renewable contributor to electricity generation in Ireland is wind. As of September 2012, there was 1695 MW of installed wind generation capacity across the country. In addition to this, there was 237 MW of installed hydropower capacity and 68 MW of other renewable resources. The potential for using renewable energy in the generation of electricity in Ireland is significant. According to Eirgrid, with the currently installed infrastructure, wind has, at times, produced enough electricity to meet 50% of the demand. With regard to the total daily demand it has accounted for a record of 38% [32].

Plans are in place for Ireland to increase the amount of renewable resources that it uses in its electricity generation. The government aims to increase the proportion of the electricity demand that is met using renewable sources to 40% by 2020. This target is to be met primarily through wind generation. It has been estimated by Eirgrid that, in order to reach this target, an additional 3500 to 4000 MW of wind capacity must be installed in Ireland [33]. In addition to this, it is estimated that there will be a total of 2175 MW of renewable generation capacity installed in Northern Ireland by 2022. The strategies for meeting these targets, amongst others are set out in the Grid25 plan [34].

It is important to ensure that the grid can supply electricity reliably and that a sufficient amount of electricity can be generated to match the demand at any given time. As wind is an intermittent resource, it cannot be guaranteed that it will be available at the times it is needed. As shown in Figure 2.14 [35], it is not possible to exactly predict how much wind will be available and when it will be available although reasonable accuracy may be achieved. This indicates that, while wind can be an important contributor to the country’s electricity generation, it must be supported by alternative generation facilities to ensure that demand can be met at all times. Storage facilities can also aid in meeting the demand. The role that EVs can play in coping with the intermittency of wind is discussed in section 2.6.
2.4.2.3 Transmission System

As TSO of the Republic of Ireland, Eirgrid is responsible for the transmission of electricity from the power stations where it is generated to the distribution system in a safe, reliable and efficient manner. It is a state-owned company whose other roles include the general management of the Irish electrical grid and the undertaking of infrastructural projects including Grid25 and the East West Interconnector.

Ireland’s electricity transmission system is composed of about 6,500 km of 110 kV, 220 kV and 400 kV overhead and underground lines. In addition, there are over 100 transmission stations nationwide. Generated electricity is fed into the transmission system to be transmitted around the country. The electricity is transmitted at such high voltages to help reduce energy losses. When power substations are reached, the electricity that is carried by the transmission system is stepped down to the lower voltages of 38 kV, 20 kV and 10 kV. It is then passed on to the distribution system or, in some cases, directly to large customers.

ESB Networks Ltd. is the Transmission Asset Owner (TAO) in Ireland. Its responsibilities include the management of the transmission assets that are owned by ESB and ensuring that the TSO develops and maintains ESB’s infrastructure appropriately.

2.4.2.4 Distribution System

The management and maintenance of the Irish distribution system, or the network that is used to carry electricity to customers, is the responsibility of ESB Networks Ltd., the Distribution System Operator (DSO) in Ireland. The distribution network that is owned and managed by ESB Networks Ltd. includes distribution stations, poles and medium and low voltage overhead and underground lines.
2.4.2.5 Demand and Load Profile

The load profile of the electricity grid describes the amount of energy that is demanded by customers or the load that they put on the grid as a function of time. The data used in this section pertains to the Irish grid but the characteristics are typical of the load profiles that may be observed in many countries.

The electrical infrastructure in a country must be capable of meeting the demand of its population. Shown in Figure 2.15 is the weekly peak demand in Ireland between 2010 and 2012 [36]. The weekly peak demand is defined as the maximum demand on the system that was recorded in a given week. According to Eirgrid, the peak in the weekly demand most commonly occurs on Tuesdays, Wednesdays and Thursdays.

![Figure 2.15 - Weekly Peak Demand in Ireland (Source: [36])](image)

A similar demand pattern may be seen each year – higher demand during the colder weeks at the start and the end of the year and a much lower demand in the warmer summer months. The scale of the demand is affected by various factors, in particular temperature. At the beginning of 2010, for example, extraordinarily low temperatures were seen. Correspondingly, in Figure 2.15, a peak demand of around 5100 MW was seen that year which is significantly greater than the peaks at the corresponding times in the other years. It is important that, as well as being capable of serving the typical peak demands, the grid must be able to cope with the additional demand that comes with such unexpected occurrences. If such situations are not planned for, grid failures may occur.

The scale and timing of peaks and valleys in demand vary in different parts of the world. In the US for example, there is a significant load as a result of cooling during the summer months while in more temperate countries there are large heating loads during the winter months.
Patterns may also be seen in Ireland’s daily demand. Shown in Figure 2.16 is the load profile of Ireland’s electrical grid on 28th February 2013 [37]. The characteristics of this load profile remain fairly constant each day. As before, the characteristics are typical of those seen in other countries but the scale and the time at which various features are manifested may vary based on a multitude of factors.

Figure 2.16 - System demand, 28th February 2013 (Source: [37])

A valley in the demand profile can clearly be seen during the night time hours when the minimum amount of electricity is required. This is known as the off-peak time. Figure 2.16, shows that the least amount of electricity that was demanded at any time during this day was 2474 MW. This occurred at approximately 04:45. As morning approaches, the demand for electricity begins to increase as people travel to and arrive at work. This is the beginning of the on-peak time. Demand remains fairly constant for several hours with a reduction in demand seen in the late afternoon. The peak load on the electrical system typically occurs between 17:00 and 19:00 corresponding to the time when people typically arrive home from work. In Figure 2.16 it may be seen that the peak load on the system on the day in question was 4253 MW and occurred at 18:45. As the evening progresses, the demand on the system decreases until the off-peak night time valley is again reached.

At different times of the year the scale of the profile will differ. As was seen in Figure 2.15, peak demands tend to be high in winter and significantly lower during the summer months. The shape of the demand profile, however, remains quite constant throughout the year.

2.4.2.6 Carbon Dioxide Emissions and Intensity
To meet the demand that was discussed in the previous section, electricity is generated from a variety of sources. Electricity generation is a major contributor to the $CO_2$ emissions that are produced worldwide. The amount that is emitted is dependent upon the type of fuel that is used. By using more
renewable resources such as wind in their electricity generation, countries can reduce the amount of \( CO_2 \) that they emit into the atmosphere.

An important aspect that must be considered when discussing \( CO_2 \) emissions is the intensity of these emissions. \( CO_2 \) intensity is the amount of \( CO_2 \) that is emitted for each unit of electricity that is generated. The \( CO_2 \) intensity of the Irish electrical grid on 27\(^{th}\) February 2013 is shown in Figure 2.17 [38]. The unit that is used to measure \( CO_2 \) intensity is \( gCO_2/KWh \).

\[ \text{Figure 2.17 - } CO_2 \text{ intensity of the Irish electrical grid on 27th February 2013. (Source: [38])} \]

\( CO_2 \) intensity is, again, dependent upon the way in which electricity is generated. The production of electricity from fossil fuels is a significantly more carbon intensive activity than is the production of electricity from renewable sources. Through the comparison of Figure 2.17 and Figure 2.14b, the energy intensity and wind generation on the same day in Ireland, it can be seen that, at times when wind generation is higher, i.e. when there is a higher portion of renewable energy in the generation mix, the \( CO_2 \) intensity is lower and vice versa. It should be noted that a small increase in wind generation corresponds to a significant drop in \( CO_2 \) intensity, indicating the potential for this type of generation to reduce a country's \( CO_2 \) intensity. As mentioned, many countries are seeking to reduce \( CO_2 \) intensity and, from this, it is clear that the use of renewable sources of energy is an important aspect of doing this.

2.4.3 Review of Electrical Grids

From this section, several important points have emerged. It has been seen that electrical grids must be capable of handling the loads that they are subject to. For this reason, grids are built to handle the peak, meaning that much grid capacity is often not utilised. Though this is expensive, it is beneficial in enabling the grid to cope with additional EV loads that may be placed on it. It was seen that grid loads are both cyclic and predictable with a similar load pattern being seen each day. There may, of course, be some large, unanticipated load peaks but, provided the grid is managed properly, it should be possible to deal with these. An important part of this grid management is the encouragement of users to change their demand pattern in accordance to what suits the grid. This can be done by way of pricing incentives, a method which is discussed in section 2.6. In the same section, some ways to aid with the integration of EVs into the grid, as well as how EVs can be of benefit to the grid are discussed. In the next section, some of the negative impacts that EVs can have on an electrical grid if suitable management is not in place are discussed.
2.5 Impact of Growing EV Adoption

At low levels of penetration, the impact of EVs on the electrical grid, the typical load profile and the environment is negligible. As discussed in section 2.1.2.1, however, the number of EVs in use in countries across the world is growing. Due to the targets and incentives of various governments, it can be expected that, in the coming years, this number will increase significantly [13] [39] [40] and thus that the load that is placed on electrical systems will increase correspondingly. A study conducted by the Power Systems Engineering Research Centre [41] estimates that, if 10% of the US light vehicle fleet were PHEVs, an additional load of 31.35 GW would be put on the electrical grid. Due to this expected growth, it is important to consider the potential impacts that large-scale EV penetration may have on the grid, its load profile and the environment in order to ensure that the stability and the safety of the electrical system is maintained and that the sustainability of the system is not compromised.

2.5.1 Impact of EV Charging on Grid Load Profile

In section 2.4.2.5 the characteristics of a typical load profile were discussed and it was seen that the typical peak demand on electrical grids in Northern Europe occurs between 5 pm and 7pm as people arrive home from work and that the minimum load occurs during the night when people tend to be sleeping. Large scale EV usage will alter this typical load profile. The ways in which it is altered will be dependent upon various factors such as the size of the additional EV load, the times at which vehicles are charged and the length of time for which the vehicles are charging.

Several studies suggest that the most likely situation will be that in which people arrive home from work in the evening and immediately plug in their vehicle to charge [42] [43] [44], i.e. they will choose to charge their vehicles at a time that is likely most convenient for them. Assuming an uncontrolled charging scenario in which charging begins as soon as the vehicle is plugged in and continues until it is fully charged, this will introduce charging peaks at approximately 6pm – 8pm, coinciding with the existing peak in the typical load profile. The probability distribution of the times at which EVs begin to charge is illustrated in Figure 2.18 which shows the results of a study conducted by Arghandeh et al. in [45]. Ideally, charging should occur during the off-peak, night time hours rather than increasing the peak load on the electrical system. Methods of shifting the load to such times are discussed in sections 2.6 and 2.7.

![Percentage of PEVs Start to Charge vs. Time of Day](image-url)

*Figure 2.18 - Typical EV charging times. (Source: [45])*
The potential impact of wide-spread charging given this uncontrolled scenario is depicted in Figure 2.19. Shown in this diagram is a typical UK winter load profile as well as the expected changes to the load profile caused by the uncontrolled charging of a 10%, 20% and 30% EV penetration [46].

![Figure 2.19 - The impact of uncontrolled EV charging on a UK load profile (Source: [46])](image)

From Figure 2.19 it can clearly be seen that the majority of EV charging demand occurs at the same time as the existing peak demand with the additional load increasing as EV penetration increases. In this study [46], it was found that, for every 10% increase in EV penetration, the total electricity demand increased by approximately 18%.

What has been shown in this section is the worst case impact of EV charging. If charging was left unmanaged, as is the case here, many negative impacts, in particular infrastructural damage and thus an unreliable supply would result due to the large increase in load. Some of the possible impacts are discussed in the next section while some approaches to managing EV charging and avoiding any such issues are discussed in later sections. In managing charging, it is desired to shift the additional EV load away from the existing peaks and to instead utilise the low-demand, off-peak valleys.

### 2.5.2 Impact of EV Charging on Grid Infrastructure

Widespread EV adoption will place a large additional load on the electrical grid and the effects that this may have must thus be considered. According to Ford [47], this additional load will likely not have a substantial impact on the transmission system but, if loads are not properly managed, the impacts that it may have on the distribution system are significant. It is essential to realise, however, that if suitable provisions are put in place, any negative impacts of EV charging may be mitigated.
As discussed by Rahman et al., [48] EV load will not exhibit uniform geographical growth. Instead it is likely to be more concentrated in residential areas than in commercial or industrial areas. Even if total EV adoption is low there may still be very high adoption in some areas. For this reason, it is necessary to look beyond treating the electricity distribution system as a single entity. While the system as a whole may have sufficient capacity to meet EV demand the infrastructure may not be capable of coping with localised demand. It is important therefore, to examine the possible impacts of EV charging not just at the level of the full system but also at a lower, local, distribution infrastructure level.

The potential impacts of the new EV charging load on the distribution grid include accelerated transformer degradation and failure, degradation of power cables and issues relating to power quality [49] [42]. The extent to which impacts such as these are manifested is dependent upon factors such as EV penetration, the amount of energy that they consume and customer behaviour. Due to the uncertainty and variability of these factors worst case scenarios should be examined and contingency plans should be put in place to manage their possible occurrences. Some of these potential impacts are discussed below.

2.5.2.1 Power Quality
The increased load on the electrical system caused by EV charging can greatly impact the quality of electrical power if it is not sufficiently planned for and managed. This is significant as high power quality is essential to the reliability and security of the grid. Power quality is characterised by various parameters including:

- Harmonics
- Transient currents and voltages
- Voltage magnitude variation
- Reliability

It was mentioned in [50] that the chargers that are used for charging EV batteries are high-powered and non-linear. They are capable of introducing large amounts of current harmonics to the distribution system. These are introduced as a result of the process of converting AC power from the grid to DC to charge the vehicle [42]. The extent to which such harmonics are introduced will be influenced by EV charging patterns. As explained by Farmer et al. in [51], these harmonics can cause several issues including eddy currents and an increase in the temperature of transformer hot spots. It is intended that newer charger designs will reduce the amount of harmonic distortion that is produced. As well as this, it is likely that large-scale EV charging will result in power losses and significant voltage distortion.

2.5.2.2 Transformer Degradation
A distribution transformer serves the function of reducing electricity voltage to a level suitable for customer use. These are said to be the weakest part of the grid [50] and issues regarding them may be introduced as a result of EV loading. In America, it is typical for a transformer to supply between two and six homes while in Europe a transformer will often supply 20+ homes [49].

Distribution transformers are designed to cope with a certain load and, as has been seen, the addition of EV charging load to the electrical system will increase the loads that they are expected to handle. Figure
2.20, for example, depicts a scenario that may occur if all EVs that are served by a transformer are charged at the same time. It may be seen from this, that even a small number of EVs will significantly increase the load that the transformer is subject to. Exceeding the rated load of the transformer does not necessarily mean that it will fail. It will, however, contribute to reducing the transformer’s expected lifetime. This is known as loss of life. A study carried out in [52], for example, shows that, the addition of just three PHEVs to the load that is served by a distribution transformer, can reduce its lifetime by almost 30%.

![Transformer Load](image)

*Figure 2.20 - Residential load profile over a 24 hour period with additional EV load. (Source: [7])*

The major contributor to this reduction in lifetime is transformer heating, a result of both the additional current that passes through the transformer and the harmonics that were discussed in the previous section. As well as contributing to the aging of the transformer, heating can contribute to its mechanical degradation, in particular the degradation of components such as the transformer windings and tap-changers. Other contributors are moisture and oxygen content. The impact of these, however, is not as significant as that of temperature. In [53] it is explained that the temperature of the transformer is not constant throughout and that the location of the highest or hot-spot temperature is therefore where degradation will be most pertinent. The hot-spot temperature is a function of the transformer loading, the ambient temperature and several parameters of the transformer. The normal lifetime of a typical transformer is said to be its lifetime when a hot-spot temperature of 110°C is maintained. A typical life expectancy is just over twenty years.

2.5.2.3 Other Distribution Equipment Issues

As mentioned, EV charging can introduce harmonics to the distribution system. By carrying current with these harmonics both the ability to conduct and the life expectancy of electrical cables will be reduced. To control this impact, cables are derated or used at less than their maximum capacity. In addition to this, it is believed, according to the authors of [49], that harmonic distortion may reduce the ability of circuit breakers to interrupt the electricity supply. As the function of a circuit breaker is to interrupt the supply in order to protect the grid infrastructure from any damage that may be caused as a result of an
overload or a short circuit, it is of great importance that this be addressed. This is of particular concern as the methodology for protecting the grid from damage due to overloading is compromised by an additional load which may be the ultimate cause of an overload. As well as this, harmonic current can degrade the operation of the fuses in the system.

2.5.2.4 Reducing Infrastructural Impacts
Some of the impacts of the additional load on the electrical system as a result of EV charging have been discussed. As mentioned, these impacts can damage and reduce the expected lifetime of grid components increasing the frequency with which repairs and replacements must be carried out. Such measures, particularly with regard to transformers, are costly, time consuming and disruptive and it is therefore desirable to minimise the impacts that are described. To minimise these impacts, EV charging must be carefully controlled rather than simply allowing it to proceed unmanaged. The management of EV charging and the benefits that this may have are discussed in sections 2.6 and 2.7. If such measures are not taken the only remaining option is to reinforce the infrastructure of the grid, an expensive and disruptive operation.

2.5.3 Impact of EV Charging on Grid Carbon Emissions
As previously discussed, many countries are setting targets to reduce the amount of \( CO_2 \) that they emit. As low-emission vehicles, EVs will play a large role in meeting these emission reduction targets. In Ireland, it is expected that, by 2050, the country’s \( CO_2 \) emissions as a result of the light vehicle fleet will have been reduced by about 80% in comparison to 2011 levels even though the fleet size is expected to be significantly larger [54]. In the UK, it is expected that the use of EVs will result in an 80% reduction in the country’s total \( CO_2 \) emissions over 1990 levels by the same year [55]. The extent to which EVs can aid in emission reductions, however, is dependent upon the amount of renewables that are used in the generation of the electricity they require. If EV charging is uncontrolled, the use of electricity that is generated from renewable sources is entirely dependent upon the coincidence of the generation and the charging. If smart charging strategies are used, however, renewable generation can be taken advantage of and, through careful management, \( CO_2 \) emissions as a result of vehicles can be further reduced. Methods by which this may be achieved are discussed in section 2.6 and 2.7.

2.5.4 Review of the Impact of Growing EV Adoption
This section has discussed the likely impacts that EV charging will have on the typical load profile and the electricity grid of countries in which large-scale adoption becomes a reality. From this, it is clear to see that, if left unmanaged, the widespread charging of these EVs can cause significant, undesirable impacts. To avoid such impacts, a form of charge management must be put in place. As well as this, though the use of EVs can aid in the reduction of \( CO_2 \) emissions, the maximum potential for doing so and for maximising the utilisation of renewable electricity generation cannot be achieved by simply using uncontrolled charging. This will only be achieved through the careful management of EV charging. Sections 2.6 and 2.7 discuss some of the measures that may be taken to fulfil these goals while section 3 proposes a new system for the management of EV charging that takes the issues which are discussed here into consideration and attempts to integrate EVs into existing electrical systems in the most effective and advantageous manner possible.
2.6 EVs and the Smart Grid

As discussed, the charging needs of the growing EV fleet will have a significant impact on the electrical grid if left uncontrolled and unmanaged. The addition of supplementary generation capacity and upgrades to existing infrastructure is a potential method of addressing this, but such measures are not necessarily required. Instead, the additional load can be managed in a manner that will exploit the existing grid capacity and avoid the creation of new peaks in electricity demand. By doing this, electrical grids will be able to support much larger loads than would otherwise be possible. According to the US Department of Energy’s Pacific Northwest Laboratory (PNNL), the existing American power grid is capable of meeting the charging needs of approximately 158 million EVs or about 73% of the country’s light vehicle fleet without the addition of generation facilities [56]. This is a clear indication of the potential for existing grid infrastructure to support the charging of increased numbers of EVs. In order to properly manage EV charging, the utilisation of smart grid ideas is essential, to provide the necessary control for ensuring that generating capacity is used effectively and to alleviate the negative EV load impacts that could otherwise result. Through effective integration with smart grid technology, EVs can even be of benefit to the grid by helping both to balance power supply and demand and to facilitate the increased use of renewable energy sources in the generation portfolio of the grid.

2.6.1 Smart Grid

A smart grid is an electrical grid which makes use of communications and information technologies to monitor and automatically respond to supplier and consumer behaviour. By doing this, the generation and distribution of electricity can be made more efficient and reliable. The use of smart grid technologies can help reduce a grid’s peak load which contributes to the lowering of electricity prices. As well as this, a smart grid will aid in the integration of renewable energy into the electricity system and will also ensure that infrastructural issues can be dealt with quickly and with minimal interruption to supply. Both demand side management (DSM) and demand response (DR), which are discussed below, play a major part in achieving these benefits. Smart grid projects are underway in many parts of the world including Europe, the US and China [57]. In the following sections some of the advantages of the integration of smart grid and EV technologies are discussed.

2.6.2 Demand Side Management

In an electrical grid it is important that supply and demand be kept in balance. Traditionally, this has been achieved by varying the supply to match the load, i.e. during times of heavy load, additional generation capacity is brought online to meet the increased demand and, when the load on the system is lighter, some generation capacity is taken offline. Alternatively, consumer demand can be modified to match supply conditions, through the employment of various measures including education and financial incentives, an idea known as demand side management (DSM). The idea of DSM is that consumers are encouraged to reduce their energy usage during high demand on-peak times (peak shaving) and to shift their use to more lightly loaded off-peak hours (valley filling). By doing this, not only will peak loads be reduced, so too will the need for infrastructural upgrades.

DSM aids in the flattening of the grid load profile, reducing the need to use additional carbon intensive generation plants during on-peak times. As well as this, the use of DSM can aid in reducing carbon emissions and in the integration of renewable electricity generation into the grid. It can make sure that
times of plentiful renewable energy are taken advantage of and that demand can be reduced during times of lesser availability. A method by which EVs can contribute to this integration is described in section 2.6.4.

Some approaches to DSM include time-of-use (TOU) pricing, real-time pricing (RTP) and critical peak pricing (CPP). TOU pricing involves selling electricity for lower prices during the off-peak, night time hours. Such an approach is examined in a study by Ramchurn et al. [58] where it is found that TOU pricing can introduce significant additional peaks at the start of the off-peak period. In the same study, the advantages of using RTP, where electricity prices differ between given time periods (typically thirty minutes) and are provided at least several hours ahead of time is also examined. RTP is found to perform better than TOU pricing in allowing consumers to avoid times of expensive electricity, i.e. peak times, by dynamically modifying their demand. This too can create new peaks during off-peak times. CPP, for the most part, uses TOU prices but at given peak times generating costs are reflected in the price. This has been used to control air conditioning units in parts of the US but has also been found to create additional peaks in demand.

In Ireland, some DSM measures are already in place [59]. For example, ESB Networks provides lower electricity prices during night time hours to encourage a reduction in peak demand. As well as this, a Winter Peak Demand Reduction Initiative is run by Eirgrid which encourages large customers to reduce their electricity consumption during the winter periods, in particular during the peak hours of 5pm – 7pm. Other initiatives have been put in place by the country’s various electricity suppliers. In addition, DSM programs are in effect around the world in places such as the UK, Canada and Vermont in the US. These programs are proving successful in their aims but have the potential to achieve further benefits.

Combining the use of DSM with a growing EV population creates new opportunities for helping to reduce variations in electricity supply and demand by shifting EV charging to times which are beneficial to the grid (see section 2.6.5) and by using vehicle-to-grid, a system described in section 2.6.4.

2.6.3 Demand Response
Demand response (DR), a subset of DSM, refers to the use of price signals from the electric utilities to encourage customers to dynamically change their electricity use in response to supply conditions. This allows for short-term reductions in electricity consumption to be achieved. Though DR often involves customers being encouraged to reduce their demand and thus the peak electricity demand (peak shaving), it may also involve encouraging them to increase demand at times of excess electricity production or low demand. In this way, DR can aid in smoothing the demand curve, balancing supply and demand and integrating renewable sources of electricity generation into the grid. DR typically uses financial incentives to achieve its goals. Incentives may include the increase of electricity prices at times when load is to be shed or compensation for customers that opt to move loads to different times.

Though DR has typically been used for large customers rather than for individual users its use in controlling EV charging was examined by Shao et al. in [60]. In this study, customer response to various pricing schemes is investigated and it is concluded that the reduction and thus the inevitable deference of some loads to off-peak times can cause new load peaks. It was also determined that, if peak prices
are set too high, customer participation may be so high that, again, new peaks result. In addition, a study conducted by Arghandeh et al. [45] examined the barriers that exist to the implementation of DR programs. The main issues were found to be low adoption of the advanced metering infrastructure (AMI) and uncertainty as to the number of customers that will participate.

An application of DR in terms of EVs is vehicle-to-grid. This is discussed in detail in the next section.

2.6.4 Vehicle-to-grid
As mentioned, many countries are increasing their use of renewable energy resources as part of their attempts to reduce greenhouse gas emissions. Due to their inherent intermittency, the production of electricity from renewable sources cannot be accurately predicted as was illustrated by Figure 2.14. On a small scale, this intermittency is tolerable but as the proportion of electricity that is generated by renewable sources increases, it can become a major problem. Wind energy may be plentiful at off-peak times when it is not needed and may be scarce at on-peak times when demand is high. To alleviate this issue of being unable to match supply to consumer demand without the aid of fossil fuel generation, grid energy storage solutions including pumped storage and flywheels are utilised. Due to the increasing number of EVs that are in use and the growing prevalence of the smart grid, however, a new energy storage solution known as vehicle-to-grid (V2G) has been developed. V2G, an application of DR, provides a method of exploiting the distributed electricity storage resources that are present in EVs and is aided by the fact that most vehicles are parked and potentially plugged in for a large portion of the time. In this way, the EV fleet can provide ancillary services such as operating reserves and frequency regulation to the electrical grid and can also help counter the unreliability of renewable energy. By doing this, they are aiding in the facilitation of an increased amount of electricity generation from renewable sources. The concept of V2G was explained diagrammatically by Kempton et al. in their 2005 paper [61]. This diagram is shown in Figure 2.21.

![Figure 2.21 - Concept of V2G. (Source: [61])](image)

The idea is that EV batteries are charged during times of plentiful renewable energy and send power back into the grid when it is required. Figure 2.21 shows how the components of the grid interact with one another to achieve this. Generated electricity flows through the grid until it reaches the EVs where it is stored until needed. Upon request from the grid operator (labelled ISO or Independent System
Operator in this depiction) the EVs send electricity back into the grid. This request may be sent to a single EV or to a group of vehicles. In this way, the EVs can help to reduce variations in electricity supply and demand. By taking advantage of the distributed storage capacity that is provided by EVs there is a reduced need to rely on fossil fuels to meet peak demands. In addition, this distributed electricity storage can act as reserves in the case of a power failure. V2G can also provide backup power to the home of the vehicle owner if needed.

According to Kempton et al. [62] EVs must be equipped with three elements in order to participate in V2G. These elements are:

- A connection to the electrical grid that allows for bidirectional electricity flow.
- The capability to communicate with the grid operator.
- The ability to meter the flow of electricity.

Much research has been conducted to analyse the potential benefits of V2G. A study conducted by Mets et al. [63] for example, shows that, when using V2G, significant reductions in peak load can be obtained. In their study, it was found that peak load as a result of EV charging was reduced by 33%, 63% and 81% with penetration levels of 15%, 45% and 75% respectively. In [64], Lund et al. examines how V2G can facilitate the integration of renewable energy into the electrical grid and the transport sector. The authors conclude that the use of V2G will successfully aid in this integration and, as a result, will reduce the $CO_2$ emissions of the electrical system and increase its efficiency. It is also noted that V2G has significant potential in providing stability for the grid.

White et al. studies the financial benefits of using V2G [65]. It is found that using it solely for peak reduction does not provide a significant financial gain for the vehicle owner. A much larger gain is possible if V2G is used for frequency regulation. These two uses are not mutually exclusive. Both are of benefit to the grid and it is important that there be some financial incentive to encourage participation.

Kempton et al. examined the potential for V2G use in various countries [61]. It was found that, if the entire Irish light vehicle fleet was electrified it could potentially produce about 846% of the country’s average load. In Portugal, the same circumstances were estimated to produce 1740% of the average load. Another study by Kempton [66] suggests that if 3% of the US light vehicle fleet took part in V2G with the aim of regulating wind and another 8-38% were to provide storage for electricity produced by wind, then the large-scale integration of wind power could be stabilised.

While V2G can provide significant benefits to the electrical grid there are some concerns which must be addressed. The most pertinent of these is the impact of V2G on EV battery life. As discussed in section 2.2, batteries have limited cycle lives. Participation in V2G will increase the number of charge and discharge cycles that batteries are subject to, thus decreasing their lifetime. This will increase the frequency with which batteries must be replaced which, as has been seen, is a significant expense. This may make many vehicle owners hesitant to partake in V2G schemes, an issue that can only be resolved by a reduction in battery prices or developments in battery technology. Without efforts to address this issue and to incentivise participation, it is likely that widespread V2G use may never become a reality and that the benefits that it can provide will not be utilised.
2.6.5 **Smart Charging Strategies**

It was seen in section 2.5.1 that uncontrolled EV charging is likely to coincide with and increase the existing demand peak. Using the ideas described in this section, amongst others, more intelligent methods of EV charging can be developed. Smart charging strategies can alleviate both the additional load peaks that may otherwise result from EV charging and potential damage to grid infrastructure. Adopting a smart charging strategy will shift the EV charging load away from the times of existing high loads and will instead utilise the off-peak capacity in the grid and fill the valleys that exist, effectively flattening the demand curve. By doing this, the grid load profile can be altered from that shown in section 2.5.1 to look more like that in Figure 2.22.

![Figure 2.22 - The impact of controlled EV charging on a grid load profile](image)

From Figure 2.22 it may be seen that the EV charging load has been shifted away from the existing peak into the off-peak night time hours. This is known as valley filling and is a preferable scenario to that of uncontrolled charging. In this diagram, the non-EV load is comprised of actual figures from Eirgrid. The effect of adding EV load has been extrapolated based on the desired scenario.

By making suitable use of methods such as DSM and DR, EV charging can be integrated into an electrical grid without any of the negative impacts that were described in section 2.5. Creating a smart charging strategy can mitigate the need for infrastructural upgrades and can even be of great benefit to the grid. Without enforcing such a strategy, large-scale EV adoption can cause major issues for electrical utilities and may never become a reality. Various methods of approaching the EV charging problem have already been considered and a review of some existing approaches is presented in section 2.7.

2.6.6 **Privacy Concerns and Security**

The use of smart grid technologies is a cause for concern amongst many parties, in particular with regard to data protection. In the case of EV charging, customers may be required to provide various pieces of potentially sensitive information including account numbers and vehicle information. There is potential for such data to be exploited and suitable security measures must be taken. Communications are inherent to smart grid technologies and it must be ensured that all communications are encrypted and authenticated. Such issues must be addressed in order for smart charging to be successful. The security considerations for the system proposed in this project are presented in chapter 3.
2.7 Smart Charging Strategies
As discussed, in order for the successful integration of a large scale EV fleet with an existing electrical grid, it is necessary that smart charging strategies be developed. This section examines various types of charging strategy that may be used and reviews some existing attempts at creating such a strategy. It should be noted that, although various strategies have been proposed in literature, very little of this field has actually been implemented.

2.7.1 Categories of Smart Charging Strategy
There are many potential categories of smart charging strategy though it is important to note that a given strategy will not necessarily fall into a single category but may instead include aspects of several. The charging strategies aim to fulfil a given objective or set of objectives. The aim of some strategies, for example, is to avoid the degradation of grid infrastructure [67], [68] while others aim to minimise power losses [69]. In [70] and [71], price based solutions are presented which aim to minimise charging costs for the vehicle owner. Solutions such as those in [69] and [71] attempt to maximise the utilisation of the grid’s capacity. A method of minimising the time until a vehicle can be charged is presented in [72] and a method of reducing the time taken to charge an EV is discussed in [73]. In some proposed charging strategies, the primary goal is the maximisation of renewable energy use. Such strategies are presented in [74] and [75]. Some charging solutions also consider V2G [76].

Several of these proposed strategies are discussed in section 2.7.2. Described below are the two broad categorisations of charging strategy – centralised and decentralised.

2.7.1.1 Centralised EV Charging Strategies
Centralised EV charging strategies are those which require a centralised control centre or hub to gather information pertaining to EVs and manage charging based on this information. The majority of the communications that take place in the system are routed through this central hub. Some of the benefits and disadvantages of using a centralised system are discussed by Richardson et al. in [77]. Advantages include the ability to access information about all parts of the system to aid in decision making and an enhanced utilisation of the capacity that is available in the grid. Disadvantages include the need for communicating a large amount of data and the heavy reliance on the central control. If there is an issue at the control, the entire system may be affected. Several centralised charging strategies have been proposed including those in [70] and [71].

2.7.1.2 Decentralised EV Charging Strategies
Decentralised EV charging strategies are those in which the EVs are connected by a network which allows them to coordinate their actions and share resources. There is no central control that makes decisions for the whole system. Advantages and disadvantages of such a system are also discussed in [77]. Advantages include a reduced need for communications and a greater robustness than centralised systems due to the lack of reliance on a central control. Disadvantages include an increased difficulty in diagnosing faults in the system and lesser control over the charging of the vehicles. An example of a decentralised EV charging strategy is discussed in [67].
2.7.2 Existing EV Charging Strategies

In this section, some existing strategies for the implementation of a system to manage EV charging loads are described as are their merits and weaknesses. These strategies each have a major focus including cost minimisation and the maximisation of the use of grid capacity but may also incorporate several other of the objectives described in section 2.7.1.

Cost is a powerful factor in influencing behaviour and it is reasonable to assume that EV owners would like their vehicles to be charged at the lowest possible price. This idea is utilised in many existing EV charging strategies including that presented by Mahat et al. in [70]. This is a centralised algorithm that makes use of real-time pricing to simply charge EVs at times when electricity is available at a low cost. To do this, it is assumed that a reasonably accurate forecast of the available electricity and the associated price for the coming 24 hours is available. Consideration is also given to the issue of transformer overloading that was discussed in section 2.5.2. As part of their strategy, Mahat et al. introduce a priority system which, for an additional cost, allows customers to have their vehicles charged as quickly as possible if required.

From their research, Mahat et al. [70] concluded that, while a real-time pricing system can be an important aspect in developing an EV charging schedule this alone is not sufficient. Scheduling based solely on pricing can result in serious issues such as transformer overloading and measures to avoid such problems must therefore be taken. In addition, it is noted that customers must be treated fairly.

Another centralised, price-based approach to managing the charging of EVs is presented by Cao et al. in [71]. In this strategy, TOU pricing is considered and focus is also put on the maximisation of the use of existing grid capacity. The authors attempt to both minimise the cost of charging and to flatten the typical load profile that was examined in section 2.4.2.5. The strategy that is presented is tailored for use in a regulated electricity market or a market in which the government sets electricity prices which remain unchanged for a significant amount of time, potentially for as long as several years. Such a market structure may be seen in the Chinese electricity market.

Unlike the strategy that was discussed in [70], this proposal attempts to mathematically minimise charging costs rather than scheduling based on predicted prices. Where possible, EVs were also charged at the maximum possible power. The authors of [71] carried out simulations to test their strategy and found that, as expected, not only did a significant reduction in charging costs result, but that a shift of charging load away from on-peak times to the more lightly loaded off-peak times was also seen, i.e. the valley in the load profile was filled. This study highlights the importance of utilising the capacity that is already available in the grid and supports [70] in showing the advantages of using price-based scheduling.

In a study conducted by Flath et al. [68], revenue management ideas are used to develop a potential solution to the EV charging problem with focus being put on the protection of local transformers and ensuring that they are not subject to strain as a result of EV charging. In this case, it is assumed that the capacity of the transformer creates a bottleneck in the grid, i.e. in the capacity of the system.
In this EV charge management system, two types of charging demand are assumed, similar to the situation in [70]—regular charging demand where owners return home and charge their EVs after work and spot charging demand where owners spontaneously decide to charge their EVs. In terms of charging, the difference between the two types of demand is in price, i.e. the cost of spot demand charging is greater than that of regular demand charging.

The authors of [68] propose two variations of a charging scheme to manage the demand. In the first scenario, all capacity is first made available to regular demand meaning that none may be available for spot demand. In this case, the utilisation of grid capacity is maximised but the distribution of capacity is unfair. In the second scenario a protection level is introduced to ensure that some capacity is reserved for spot demand. In this case, the distribution of charge is fairer as it is ensured that both types of demand have the opportunity to be served. The use of available capacity may not necessarily be maximised, however. In the case of no spot demand some capacity is still protected and cannot be used by regular demand so it is wasted. In addition, the profits of the generators are increased in this scenario. This study highlights the fact that, in a charge management system, compromises and trade-offs are inevitable.

In [73], Shao et al. discuss the use of stagger charging, a DSM strategy, to manage the EV charging load. Similar to [71], the aims of this strategy involve the flattening of the load profile. It is also ensured that no new transformer load peaks are introduced. By doing this, the need for infrastructural upgrades and premature replacements is avoided. These aims are achieved by allowing EVs to charge only if the current load on the transformer is less than the existing peak load. If this is not the case, charging is deferred until a time of lighter loading. The authors of [73] ran a simulation in which the effect of using this strategy to manage the charging of PHEVs from a distribution transformer was examined. It was found that, as desired, some smoothing of the demand profile resulted and no new load peaks were created. Figure 2.23 shows the results of this simulation.

![Figure 2.23 - Stagger charging strategy proposed by Shao et al. (Source: [73])]({})

Though this strategy succeeds in avoiding new load peaks it is not concerned with the speed of charging. No schedule is created to lay out when a vehicle is to charge but rather the decision as to whether to charge at a given time is made based on the real-time state of the system. The management of charging in this way provides the owner with no indication as to when charging will be complete, i.e. no consideration is given to customer time constraints. While grid requirements of smoothing the load
curve are served well the requirements of customers are not. This is particularly true in the case of a customer who wishes to have their vehicle charged quickly. The stagger charging method of Shao et al., therefore, lacks in the area of customer satisfaction and highlights the importance of ensuring that charging strategies do not focus solely on the needs of one actor but that the needs of all actors in the system are fairly addressed.

As an alternative to the method of stagger charging, Shao et al. also proposed household load control, another DSM strategy, as a means of managing EV charging [73]. Using this method, non-critical household loads such as clothes driers are deferred to allow for EV charging to occur. Unlike the stagger charging approach, this method takes user time constraints into consideration and ensures that owners can expect to have their vehicle charged when it is needed. Fast charging is supported with this method provided that sufficient household loads are shed. In [73] a simulation of the fast charging of PHEVs using this method was carried out, the results of which are shown in Figure 2.24.

![Figure 2.24 - Household load control strategy proposed by Shao et al. (Source: [73])](image)

From the simulation, it was found that the household load control strategy allowed for vehicles to be charged quickly and avoided the potential for owners to have to wait for several hours before charging began and ensured that vehicles would be charged within a given, expected time. This strategy, therefore, is an improvement over the stagger charging alternative in terms of meeting customer needs. The same advantages are not seen in terms of smoothing the demand curve, however, as, in the case of fast charging, new peaks were seen. This, again, fulfils the desires of only one actor in the system. This is indicative of the likelihood that difficulties and conflicts will occur when devising such a system and that it may not be possible to fulfil the needs of all actors.

In their study on the management of distributed loads over a network Murthy et al. [78] also examine the use of DSM techniques in the form of DR. The main focus of this study is the management of laptop charging within a building but given the mobile nature of laptops and the uncertainty surrounding their charging conditions, many parallels can be drawn with the EV charge management problem. Two scenarios are examined – a “classic demand response scenario” and a “continuous demand response scenario”. The aim of the classic scenario is to ensure that charging demand does not exceed the available supply. This involves the reduction of electricity consumption in response to a DR event or signal when the grid is in danger of being overloaded. The continuous scenario, meanwhile, involves the fitting of the load to the available renewable electricity supply in continuous time. Simulations of both
the classic and the continuous DR scenarios were carried out by the authors of [78] to examine their effectiveness. In the classic scenario it was found that electricity demand was successfully reduced to an acceptable level. In the continuous scenario the use of available renewable energy sources was optimised. If similar approaches were applied to the EV charging problem it is expected that the same outcomes would be seen. The optimal utilisation of renewable energy is an important concept that should be considered in a smart EV charging strategy.

In [67], Stüdli et al. proposed a distributed method of addressing the EV charging problem. The objectives of this approach are to minimise impacts on grid infrastructure, to achieve fairness in charging and to ensure that the EV owner can charge their vehicle at their convenience. In this strategy, user requirements are regarded to be of greater importance than was the case in the other strategies that have been discussed. It may sometimes be desired that an EV be charged as quickly as possible while at other times the minimisation of cost may be more important. Sometimes a trade-off between these two factors may be more suitable. In this strategy, it is ensured that such requirements are taken into account. The aims of the strategy are achieved through the modulation of the power supplied to EVs in response to factors such as the number of vehicles charging and the power that is available. In agreement with [70], this strategy indicates the importance of treating customers fairly but it also strives to meet the objectives of more than one actor in the system.

From this review of some of the existing EV charge management proposals that are available in literature, it has been seen that a wide variety of approaches are possible. Most of the proposals make use of centralised systems in favour of decentralised systems indicating that centralised solutions provide greater demand control benefits. In addition, most strategies aim to fulfil the requirements of just one actor in the system. The most common goals of the examined strategies were the avoidance of grid damage and the utilisation of available capacity. Some were also concerned with ensuring that customer constraints were met. It was found, however, that quite a small proportion of the existing strategies consider the maximisation of renewable energy use. By addressing this, additional benefits such as improved capacity utilisation and increased GHG emission reductions could have been achieved. This is a major goal of this project. The ways in which this, amongst other goals, is addressed is discussed in chapter 3.
Chapter 3: Design

In this chapter, the proposed EV smart charging strategy is presented. The aims of the system are discussed and a realistic system model is developed. Each part of the system, in particular the charge scheduling algorithm, is described in detail. In addition, the security considerations that must be accounted for in the design of such a system are discussed.

3.1 System Objectives

The strategy described in this chapter offers a potential solution to the EV charging problem, addressing many of the possible issues and taking customer constraints into consideration. Influence is drawn from several existing algorithms, some of which have been discussed previously. It is a centralised solution (Figure 3.1) in which focus is put on the utilisation of off-peak capacity in the electricity system and peaks in electricity production from renewable sources. Though centralised solutions can suffer from robustness issues as a result of their reliance on a central hub, this approach was chosen as it allows access to information about all parts of the system which allows for greater control over the scheduling of EV charging. The cost of electricity tends to reflect its availability meaning that prices will be lowest during the off-peak night-time hours and during times of increased electricity production as a result of renewable sources, e.g. wind as may be seen in Figure 3.2. Electricity prices therefore play a major role in the algorithm that has been developed with charging being scheduled during the least expensive time periods available. By exploiting these lower priced times, EV load will be drawn away from the heavily loaded peak hours and towards the more lightly loaded off-peak hours. As a result, the load profile flattens and the utilisation of the grid is enhanced. The system also aims to ensure that the impact of EV charging on the grid is minimised and that issues such as transformer overloading are avoided. As well as this, the scheduling system is flexible enough to allow owners to specify constraints and have some control over the schedule that is created for their EV. The system was also designed in such a way that it is simple and intuitive to use. This means that customers don’t need to have prior experience using such a system. They simply need to plug in their vehicle and indicate their preferences.

![Control Centre](image)

*Figure 3.1 - Centralised System*
In summary, the strategy that is proposed aims to fulfil the requirements of all actors in the system. For the generators of electricity the aim is to match the demand to the available supply as closely as possible. As part of this, the use of electricity generated from renewable sources is maximised. EVs are also used to aid in coping with the intermittency of renewable energy by way of V2G. These measures help to maximise generator profits by reducing the need for electricity generation from fossil fuels, i.e. there is a reduced need to bring additional generation capacity online. For the distribution system operator, the aim is to minimise peak loads and to minimise infrastructural impacts. Finally, for the EV owners the aim is to minimise the cost of charging and to ensure flexibility and fairness in the scheduling of charging. To achieve these goals, an initial charging schedule is created for each vehicle which may later be modified based on real-time conditions in the system.

3.2 System Model
Discussed in this section are some of the assumed features and constraints of the system for which the EV charge scheduling algorithm has been designed. These include EV and charger specifications as well as expected customer behaviour and the capabilities of the installed grid infrastructure.

3.2.1 Vehicles
Due to their popularity, the EVs that are used are assumed to be the Nissan Leaf [79]. The Leaf has a lithium-ion battery with a capacity of 24 kWh. It has a power output of more than 90 kW and is capable of a range of around 175 km (dependent upon driving behaviour). The maximum speed that can be reached by the Leaf is 145 km/h. Under fast charging conditions the vehicle can be charged from 0% to 80% in a time less than 30 minutes. Using a domestic charger, a full charge from 0% can be achieved in less than 8 hours. A summary of these specifications is given in Table 3-1.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Nissan Leaf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery type</td>
<td>Lithium-ion</td>
</tr>
<tr>
<td>Battery capacity</td>
<td>24 kWh</td>
</tr>
<tr>
<td>Power output</td>
<td>&gt;90 kW</td>
</tr>
<tr>
<td>Full recharge time (domestic charger)</td>
<td>&lt; 8 hours</td>
</tr>
<tr>
<td>Range</td>
<td>175 km</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>145 km/h</td>
</tr>
</tbody>
</table>

Table 3-1 - EV Specifications

3.2.2 Chargers
The chargers that are considered are those which are currently being installed across Ireland by ESB ecars. These have previously been described in section 2.3 and therefore just a brief summary of their specifications is given in Table 3-2. Some of these specifications will, of course, vary depending on the EV that is connected.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Domestic</th>
<th>Public</th>
<th>Fast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to Charge</td>
<td>(0-100%) 6-8 hours</td>
<td>(0-100%) 1-6 hours</td>
<td>(0-80%) 20-30 minutes</td>
</tr>
<tr>
<td>Phase</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Max. Current Rating</td>
<td>16 A</td>
<td>32 A</td>
<td>63 A (AC) / 120 A (DC)</td>
</tr>
<tr>
<td>Max. Power Rating</td>
<td>3.6 kW</td>
<td>22 kW</td>
<td>44 kW (AC) / 50 kW (DC)</td>
</tr>
</tbody>
</table>

Table 3-2 - EV Charger Specifications
3.2.3 Control Centre
The control centre is the central hub of the system and has a great deal of responsibility. It is this that creates EV charging schedules and negotiates them with the customers while providing them with the flexibility to specify preferences and influence their schedule. In addition to this, it is responsible for controlling the overall EV load and ensuring that it does not put a strain on the grid. The control centre also has the responsibility of effectively responding to real-time conditions in the system. Finally, it is responsible for generating customer billing data.

3.2.4 Database
A database exists which contains information regarding customers and EVs that are registered with the system. It also contains charging point information and all charging requests that have been made and charging schedules that have been created. In addition, the database contains day-ahead predictions of the availability and price of electricity in half hour time periods. This data is obtained from the website of the Single Electricity Market Operator (SEMO) [30] and is used as the basis for creating charging schedules. An example of such data is shown in Figure 3.2. The database can be accessed by the control centre and the charging points.

![Figure 3.2 - Day-ahead system load and electricity prices for a spring day in Ireland as predicted by SEMO (Source: [30])]()

3.2.5 System Constraints
The system looks at EV load in a localised area and thus the characteristics of a local distribution transformer must be examined. The power that the transformer is capable of supplying is denoted as \( P \). As this EV charging system will deprive transformers of their usual overnight cooling time it is assumed that \( P \) is less than the actual rated capacity of the transformer, i.e. transformers are not used at their full capacity so that they will not experience as much heating and will thus be able to cope with a reduced opportunity for cooling. An amount \( \Delta \) of \( P \) is reserved for uses other than EV charging, i.e. the non-EV load. The power available for EV charging is given as \( P_{\text{available}} \) as shown.

\[
P_{\text{available}} = (1 - \Delta)P
\]
During each time period $T$, the power that is available for EV charging [68], is given as $P_T$ (see Figure 3.3).

$$P_T = P_{\text{available}} T$$

The charge scheduling algorithm is designed in such a way as to ensure that the power being demanded by EVs at any given time will not exceed that which is available to them. The constraints of $P_{\text{available}}$ and $P_T$ are respected and the power designated for EV charging will be suitably divided amongst the connected EVs. This is important in ensuring that issues such as transformer overloading that were described in section 2.5 do not materialise.

As was the case in the system described by Stüdli et al. [67], the power $P(t)$ that is being used for the purpose of EV charging at any time instance $t$, is expressed as shown below with $N(t)$ being the number of EVs charging at time $t$ and $c_i(t)$ being the charging rate of EV $i$.

$$P(t) = \sum_{i=1}^{N(t)} c_i(t)$$

The constraints that are placed on the system due to the EV batteries are based on those described by Cao et al. in [71]. The power that is required by an EV to achieve a full charge over a time period $T$ is given as shown below where $SOC_0$ is the $SOC$ of the battery at time $t_0$ and $C$ is the EV battery capacity.

$$\int_{t_0}^{t_0+T} P(t) dt = (1 - SOC_0)C$$

In order to maximise the lifetime of the EV battery, the power $P_s$ that is supplied to it must not exceed some maximum value $P_{\text{battery}}$ as below.

$$0 \leq P_s \leq P_{\text{battery}}$$

In addition, the charging point is capable of supplying a power of $P_{\text{charge pt.}}$. The actual maximum power $P_{\text{max}}$, that should be supplied to an EV is therefore the minimum of these two values.

$$P_{\text{max}} = \min\{P_{\text{battery}}, P_{\text{charge pt.}}\}$$
3.2.6 Assumptions

Several assumptions are made in the formulation of this solution. These are outlined below.

- Time is divided up into periods of length 30 minutes.
- All EVs are charged at a constant rate for the duration of each time period.
- The charge rate of EVs may be varied between time periods. Depending on the charging demand it may not be possible to charge all EVs at the maximum allowed rate during all scheduled time periods. EVs must therefore accept a partial charge.
- The initial SOC is known. This is necessary in order to schedule sufficient charging time for the vehicle.
- The control centre has access to reasonably accurate day-ahead predictions of the availability and the price of electricity. These predictions are made by SEMO [5] as previously described.
- Both the control centre and the charging points have access to the information that is stored in the database.

3.2.7 Customers

Due to the diversity of people, different EV owners will have different requirements with regard to charging their vehicles. This diversity includes the times for which their EVs will be available for charging, their driving behaviours, their financial situations and their environmental concerns. Based on these individual needs an appropriate charging schedule can be compiled for each EV.

The system attempts to model the situation in which EV owners arrive home from work in the evening and immediately plug in their vehicles to charge. It is expected, therefore, that the peak time for the connection of EVs to the system will be approximately 18:00 and that the number of vehicles connecting will be fewer when this time is further away as was the expectation in [71]. A Gaussian distribution with $\mu = 18:00$ and $\sigma = 5$ is used to model this scenario. This distribution may be seen in Figure 3.4. In addition, it is expected that most customers will leave their EV plugged in until morning.

$$f(t; \mu, \sigma^2) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2}(\frac{t-\mu}{\sigma})^2}$$

![Figure 3.4 - Distribution of EV connection times](image)
As well as this, battery SOC upon connection will vary between customers depending on the distances that they have driven and their driving habits. Nissan recommends allowing the SOC to drop below 80% before charging [80] and, in addition, it is expected that most owners will charge their EVs before the SOC reaches as little as 20%. For these reasons it is assumed that the SOC will typically be between 20% and 80% when an EV is plugged in for charging. The initial SOC of an EV battery is thus modelled using a Gaussian distribution with $\mu = 50$ and $\sigma = 30$.

$$f(soc; \mu, \sigma^2) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2}(\frac{soc-\mu}{\sigma})^2}$$

In addition to connection times and SOC, EV owners may have different preferences regarding the charging of their vehicle. It may, for example, be important for some customers to charge their vehicles at the lowest cost possible while for others speed of charging is of greater importance. The charge scheduling system provides the flexibility for these customer preferences to be taken into consideration and to be integrated into the development of a suitable charging schedule. To avail of this flexibility, customers must provide the system with certain information upon the connection of their vehicle. The information that may be specified is described below.

1. **Availability (Required)**
   The customer must specify the hours for which their EV will be available for charging so that charging time may be allocated to it. Availability is expressed in the form “hh:mm – hh:mm”.

2. **Maximum Cost (Optional)**
   The customer may specify a maximum price that they do not wish their total charging cost to exceed.

3. **Desired SOC (Optional)**
   The customer may specify a SOC that they wish to be achieved.

Taking these specifications into consideration, a suitable charging schedule may be developed for each EV.

### 3.3 Proposed EV Charge Scheduling Algorithm

Described in this section is the process of connecting an EV to the charging infrastructure, supplying the required information, using this information to create a charging schedule and negotiate it with the EV owner and, finally the charging of an EV according to this schedule. This is depicted, in detail, by the diagram in Appendix A.

#### 3.3.1 Connecting to the Infrastructure

Upon connection of an EV to the charging infrastructure the owner, as described in section 3.2.7, is prompted to supply the availability of their EV, and, optionally, the maximum allowed charging cost and the desired SOC of the vehicle. This information, along with information about the status of the EV, is packaged into a scheduling request and sent from the EV to the charging point. The contents of a scheduling request and the origin and requirement for each item are shown in Table 3-3. Additional items required for communication are also included in the request. These are described in chapter 4.
When the scheduling request is received by the charging point the actual charging power, $P_{max}$ that may be supplied to the EV is determined as was described in section 3.2.5. If necessary, the charging point modifies the request to contain the new maximum power. In addition, it adds its own ID to the request. This is then forwarded to the control centre. The new scheduling request as updated by the charging point is shown in Table 3-4.

<table>
<thead>
<tr>
<th>Information</th>
<th>Origin</th>
<th>Required/Optional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charging Point ID</td>
<td>Charger</td>
<td>Required</td>
</tr>
<tr>
<td>EV ID</td>
<td>EV</td>
<td>Required</td>
</tr>
<tr>
<td>Current SOC</td>
<td>EV</td>
<td>Required</td>
</tr>
<tr>
<td>Battery Capacity</td>
<td>EV</td>
<td>Required</td>
</tr>
<tr>
<td>Max. Charging Power, $P_{max}$</td>
<td>Charger</td>
<td>Required</td>
</tr>
<tr>
<td>Availability</td>
<td>Customer</td>
<td>Required</td>
</tr>
<tr>
<td>Max. Cost</td>
<td>Customer</td>
<td>Optional</td>
</tr>
<tr>
<td>Desired SOC</td>
<td>Customer</td>
<td>Optional</td>
</tr>
</tbody>
</table>

*Table 3-4 – Scheduling Request sent from Charging Point to Control Centre*

When the control centre receives this scheduling request it attempts to create a charging schedule for the EV that will adhere to the customer constraints based on both the received information and information pertaining to the predicted electricity costs and availability that is stored in the database. The method of doing this is described in the following section. The communications described in this section as well as all other communications involved in creating a schedule and charging based on it are shown in Figure 3.5.

### 3.3.2 Creating the Charging Schedule

The charging schedule that is created upon the connection of an EV to the charging infrastructure aims to charge the EV at the lowest possible cost to the owner while ensuring that issues such as transformer overloading are avoided. To achieve these goals EVs are scheduled to charge at the cheapest times during the specified availability provided capacity is available to do so. Once a schedule is created, it is offered to the EV owner and, if accepted, is used to charge against. The schedule may be modified in response to real-time conditions such as changes in renewable generation.
Upon receipt of a scheduling request, the control centre searches the electricity price predictions that are stored in the database for the time period within the specified availability during which the price is lowest. Provided that all transformer capacity for that time period has not already been allocated, the EV will be scheduled to charge during that time. If sufficient transformer capacity is not available to charge the EV at full power it must accept a partial charge for that time period. There is a lower limit on the partial charge that may be accepted. If there is no available capacity or if a sufficient amount of charging time has not yet been scheduled for the EV, the algorithm moves on to the next cheapest time period and repeats this capacity check and assign process.

The user specified constraints determine when the scheduling process is complete. If EV availability is the only constraint that was specified then the algorithm will attempt to fully charge the vehicle within the given timeframe. If both EV availability and maximum cost are specified the algorithm will schedule charging until that cost has been reached. It will then cease no matter what SOC the schedule will provide. Similarly, if both EV availability and desired SOC are specified, the schedule will attempt to schedule enough charging time for that SOC to be reached. If a sufficient availability has been specified scheduling will cease when the SOC can be reached. If availability, maximum cost and desired SOC have all been specified, then, provided the availability is sufficient, scheduling will cease either when the maximum cost has been reached or when enough time has been scheduled for the desired SOC to be reached. Once confirmation is received from the customer that the schedule is acceptable the charging
process can begin. This method for creating a charging schedule for a single EV is shown diagrammatically in Figure 3.6 and is explained in detail below.

Each of the steps described below refers to a number in Figure 3.6.

1. This step involves the calculation of the remaining battery capacity \( RC \) that needs to be charged up. This is determined by multiplying the total EV battery capacity \( EVC \) by the amount by which it is to be charged up. For example, if the initial SOC is 20\% \( (SOC_0 = 20) \) and it is desired that the battery be charged up to 100\% \( (finalSOC = 100) \) then, assuming a battery capacity of 24 kWh, \( RC \) is calculated as:

\[
RC = EVC \left( \frac{finalSOC - SOC_0}{100} \right)
\]

\[
RC = 24 \text{ kWh} \left( \frac{100\% - 20\%}{100} \right)
\]

\[
RC = 19.2 \text{ kWh}
\]

Thus enough time must be scheduled so that 19.2 kWh of battery capacity may be charged up. By default, the desired SOC \( (finalSOC) \) is 100\% but may be altered by the customer as described previously.

2. The time period is set to that, within the availability specified by the customer, which has the lowest predicted electricity price.

3. This step checks whether time has been scheduled for all of the remaining battery capacity to be charged. If so, the scheduling will finish. Otherwise it will proceed to step 4.

4. In this step, the total transformer load for time period \( L(t_i) \) is compared with the transformer capacity \( TC \). If the load, which is composed of the predicted non-EV load and the already scheduled EV load for this time period, is less than 80\% of the transformer capacity, it is concluded that there is sufficient capacity for the EV to be charged during time period \( t_i \) and the algorithm proceeds to step 5. Otherwise it proceeds to step 9. The transformer is only loaded to 80\% capacity to avoid overheating as mentioned in section 3.2.5.

5. If this step is reached it has been accepted that the EV will charge during time period \( t_i \). The charging rate has yet to be decided, however. This step calculates the amount of the transformer capacity \( TC \) that is available for charging EVs \( rem \). To do this, the predicted system load for the current time period, \( L(t_i) \) is subtracted from 80\% of the transformer capacity:

\[
rem = 0.8TC - L(t_i)
\]
Figure 3.6 - Algorithm to schedule charging for a single EV (See Table 3-5 for an explanation of the symbols used).
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC</td>
<td>Transformer Capacity – the amount of electricity that can safely be supplied by the transformer.</td>
</tr>
<tr>
<td>EVC</td>
<td>EV Battery Capacity</td>
</tr>
<tr>
<td>CR</td>
<td>Charge Rate – maximum rate at which EV can be charged.</td>
</tr>
<tr>
<td>RC</td>
<td>Remaining Capacity – the EV battery capacity that is yet to be assigned charging time. Initially $RC = EVC \left( \frac{finalSOC - SOC_0}{100} \right)$.</td>
</tr>
<tr>
<td>$i$</td>
<td>Time period within specified availability - ordered from least ($i = 0$) to most expensive ($i = i_{max}$).</td>
</tr>
<tr>
<td>$t_i$</td>
<td>Time period $i$.</td>
</tr>
<tr>
<td>$L(t_i)$</td>
<td>Total load on transformer during time period $i$.</td>
</tr>
<tr>
<td>cost</td>
<td>Aggregate cost of charging.</td>
</tr>
<tr>
<td>maxCost</td>
<td>Maximum charging cost constraint (specified by customer).</td>
</tr>
<tr>
<td>$cost(t_i)$</td>
<td>Cost of electricity in time period $i$.</td>
</tr>
<tr>
<td>finalSOC</td>
<td>Desired final battery SOC. Default value is 100% but this can be charged by the customer.</td>
</tr>
<tr>
<td>rem</td>
<td>Capacity available for charging EVs in the current time period.</td>
</tr>
</tbody>
</table>

Table 3-5 - Explanation of Symbols used in Figure 3.6

6. At this point, it is determined whether the maximum possible charging rate of the EV, $CR$ is less than or equal to the capacity available for EV charging in time period $i$ ($rem$), i.e. if the EV can be charged at the maximum charging rate or if it must accept a partial charge. If it is possible to supply the full rate the algorithm proceeds to step 7a. Otherwise it proceeds to step 7b.

7. In this step, the load on the transformer ($L(t_i)$), the remaining EV battery capacity to be charged ($RC$) and the total cost values are updated. In step 7a these are updated using the maximum charge rate value, $CR$ while in step 7b they are updated using the $rem$ value (if step 7b is reached $rem$ is taken to be a reduced charging rate). Assuming step 7a the values are updated as shown below.

To update the load value, the charge rate is added to it, adding a new EV load to time period $i$ i.e.

$$L(t_i) += CR$$

To update the RC value, the charge rate is subtracted from it reducing the EV battery capacity that charging time is yet to be scheduled for, i.e.

$$RC -= CR$$
To update the total cost of charging, the predicted price of electricity during time period \( i \) and the rate at which the EV is charging during that time period is required. The predicted electricity prices are provided in units of €/MWh and are thus converted to €/kWh by dividing the cost by 1000. This value is then divided by 2 in order to obtain the cost of electricity over a half hour period rather than an hour. The value added to the cost in each half hour charging period is thus

\[
\text{cost} += \frac{\text{cost}(t_i) \times CR}{2000}
\]

8. This step involves updating the charging schedule of the EV and the total transformer load for this time period in the system database.

9. At this point, it has been decided whether the EV will charge in the current time period and, if so, the rate at which it is to be charged has been determined. This step, therefore, moves the algorithm on to examine the next cheapest time period, i.e. \( t_i \rightarrow t_{i+1} \).

10. This step checks if the last time period in the customer specified availability has been checked. If so, the scheduling will finish. Otherwise it will proceed to step 11.

11. In this step, the algorithm checks if the maximum cost, as specified by the customer, has been reached. If so, the scheduling will finish. Otherwise the algorithm may continue. From here it proceeds to step 3.

12. This step indicates the end of the scheduling process. It may be reached in any of three ways – if enough charging time has been assigned to charge the vehicle to the desired SOC, if all time periods within the customer availability have been checked or if the customer specified maximum cost has been reached. The charging schedule is now complete and may be offered to the customer.

### 3.3.3 Negotiating the Schedule

Once a schedule has been created it is offered to the user as is shown in Figure 3.5. This offer contains details of the schedule that has been created, the charging cost and the SOC that can be reached. Upon receipt of the offer the customer is given four options. These options are outlined below.

- **Accept**
  The offer is acceptable. The scheduling process is complete and the schedule that was created is used to charge the vehicle.

- **Modify Constraints**
  The offer is not acceptable. The EV owner modifies their constraints of availability, maximum cost and desired SOC. A new charging request is sent to the control centre and a new schedule is created and offered. This option may be selected if, for example, the initial constraints were
unreasonable and could not all be satisfied, e.g. if both availability and maximum cost are specified and it is determined that it is not possible to fully charge the vehicle within this timeframe and cost.

- **Reschedule**
  If this option is chosen another EV is selected for rescheduling so that a better offer may be made to the current customer. This option may be chosen if, for example, the EV owner needs their vehicle charged quickly. The charging of another vehicle can be deferred to a later time and the new EV can use the previously scheduled charging time. The owner of the EV that requested the reschedule is accountable for any additional cost incurred by the rescheduling of another EV. The owner of the rescheduled EV pays the initial price that they agreed with the control centre.

- **Decline**
  The EV owner may choose not to accept the offer. In this case, the charging schedule is discarded. If a public charging point is being used the owner must disconnect their EV.

### 3.3.4 Charging the EV

Once the charging schedule has been agreed upon, it is the responsibility of the charging point to charge the EV according to the schedule. While the customer constraints have not yet been met, i.e. while the agreed SOC has not yet been reached, the charger will query the database at the start of each 30 minute time period to check whether the connected EV is scheduled to charge during that time. If there is an entry in the database schedules table stating that the EV is to charge at this time, the rate at which it is to charge will be retrieved and charging may commence. In addition, the electricity price for the time period is retrieved. The current cost is updated every minute and, along with the current SOC, is displayed to the customer.

### 3.3.5 System Dynamics

It cannot be assumed that everything in the system will, in practice, go according to the initial plan. Scenarios such as EVs being disconnecting early or an unexpected peak in electricity generation from renewable sources must be dealt with in a suitable manner. This is important to ensure both the safety of the system and that the available capacity and infrastructure are adequately utilised.

If an EV is disconnected before its scheduled charging has been completed, steps must be taken to ensure that it is no longer taking up any capacity or infrastructural resources. Upon disconnection, the charging point sends a notification to the control centre. The control centre will then delete the schedule for the EV that is concerned from the database and will also update the transformer load values to reflect the removed EV load. EVs that connect to the infrastructure after this may therefore make use of this newly available capacity.

Given the intermittency of renewable sources it is likely that there will be times during which electricity generation from these sources will significantly exceed that which has been predicted. Similarly, there will be times during which renewable generation is much lower than the predicted amount. It must be ensured that such scenarios are appropriately dealt with. In this system situations like these are dealt with using DSM techniques and V2G. Customers can opt to partake in these schemes.
In the case of an increase in electricity production from renewable sources, utilities will look to utilise the excess. Otherwise it will be wasted. The EV load can be throttled to make use of this excess energy. To do this, the excess energy is offered to newly connecting EVs at a lower price to incentivise its use. EVs may also be rescheduled to avail of the newly available supply. The lower price of the excess energy is used to incentivise EVs to modify their existing schedules and to utilise the newly available energy. This is a form of DSM.

In the case of a decrease in electricity production from renewable sources, meanwhile, utilities will seek to reduce consumption. To reduce the EV load, price breaks are offered to incentivise EVs to modify their charging schedules to attract charging away from the times of lesser electricity availability. If necessary, the vehicles of customers who have not opted to partake in DSM schemes will be forced to reschedule to further reduce capacity. These customers will not avail of the price break, however.

In addition to the DSM techniques discussed, EV owners may choose to partake in V2G. By doing this, the EVs can help cope with the intermittency of renewable energy by storing excess energy at times of increased renewable generation and selling it back into the grid at times of lesser generation. This is advantageous to all actors in the system.

Engaging in the methods of managing system dynamics that have been described in this section facilitates the use of an increased amount of renewable sources for electricity generation and ensures that electricity generated in this way is utilised.

3.4 Security Considerations

In any system there are potential vulnerabilities which must be addressed. In the case of this particular system users are required to provide various pieces of potentially sensitive information including account numbers for the purpose of billing as well as vehicle and location information. There is potential for such data to be exploited and suitable measures must therefore be taken to aid in keeping data secure. There is also the possibility that the system database may be compromised and thus, again, measures must be taken to mitigate this risk. Other vulnerabilities such as electricity theft also exist. In this section the security considerations of the proposed EV charge scheduling system are discussed as are possible countermeasures. Aspects of both communication security and system security are examined.

3.4.1 Communication Security

The goals of communication security are confidentiality, data integrity and peer entity authentication. There are several ways in which each of these may be compromised in this system by way of both active and passive attacks. With regard to passive attacks it is possible that an attacker may simply intercept and read charging requests off the network and obtain potentially sensitive information that may have been sent. In this way, the vehicle owner’s confidentiality is compromised. In addition, database queries may also be intercepted.

As well as simply reading data off the network attackers can launch active attacks. An example of such an attack is a message insertion attack. In this type of attack the attacker creates a message and injects it into the network, typically with a spoofed source address. In the context of this system it is possible
that an attacker may create a charging request and insert it into the network to be sent to the control centre. This would cause the control centre to create a charging schedule for a vehicle that is not connected meaning that it is left waiting for confirmation that will never be received. Many such insertions would constitute a form of denial-of-service (DoS) attack on the control centre. Some methods of attempting to protect against such an attack are described later in this section. A message insertion attack such as this compromises the goal of peer entity authentication which is aimed for as part of communication security.

Another potential active attack that the system may be subject to is message deletion. It is possible that an attacker may delete a charging request to the control centre or a charging offer to the EV. In either case the vehicle is left waiting for an offer that will never be received due either to the offer being deleted or to it never having been created. In a scenario such as this, the vehicle is denied the ability to charge, another denial-of-service.

In addition to the above, an attacker may also modify a message. It is possible that the attacker may remove a charging request from the network, modify it so that it contains the details of the charging point to which their own EV is connected and their vehicles state of charge but leaving the remainder of the EV information and the billing information the same. They can then send the modified request on to the control centre so that a charging schedule may be created for the attacker’s vehicle. In this way, the EV of the attacker is charged at the expense of someone else and the person that initially made the request is left waiting for an offer. An attack such as this compromises the integrity of the messages that are being sent.

In order to initiate communications EV owners must authenticate with the system. In order for a user of the system to be authenticated they must be in possession of a correct username and password and smart card combination. Using a username and password alone presents a vulnerability due to their potential weakness and by way of password sniffing. Combining this with a smart card means that the owner must not only know the password but must also be in physical possession of the card. The smart card contains the private key of the EV owner which is beneficial as the owner can connect their EV to any charging point.

To provide protection against the attacks that were described above all traffic in the system, including traffic between the EVs, the charging points, control centre and the database must be secured. Securing traffic involves authentication, ensuring that integrity is not compromised and encrypting traffic. In this system, TLS (Transport Layer Security), a protocol specifically designed to provide secure communications, is used. As part of this, asymmetric or public key cryptography is used to authenticate the communicating parties while symmetric cryptography is used to encrypt the data that is sent between the parties after authentication. The secret key for this data encryption is a session key, i.e. single use and is negotiated as part of the TLS handshake protocol. By using TLS it is ensured that the connection is reliable and that message confidentiality and integrity are maintained.
3.4.2 Systems Security

In addition to communication security there are also many aspects of systems security which should be
addressed in a system such as this. Systems security involves the protection of both data and machines.
Machines should only be available for use by specific, authorised people for specific purposes. Attackers
can undermine system security in several ways such as gaining unauthorised access to a system or by
making resources unavailable to authorised users. The major aspects of system security to be addressed
in this system pertain to the protection of the database and of the charging infrastructure.

A major area for concern with regard to systems security is data protection. In this system much
potentially sensitive customer information is stored in a database. The aggregation of information in
the database aggravates the need to keep it secure. Databases present many vulnerabilities which
should be addressed. Some of the most pertinent vulnerabilities and manners in which they may be
addressed are discussed below.

A potential attack that databases are vulnerable to is an SQL injection attack. Such an attack involves
the injection of a malicious SQL command into a system which fails to properly deal with the command.
SQL injection attacks are often used to elevate user privileges giving the attacker unauthorised access to
various parts of the database. One potential method of mitigating such attacks includes the use of
parameterised statements so that the malicious command is rejected as an invalid input. Patches may
also be released to protect against vulnerabilities to SQL injections. The electrical utility must ensure
that these are applied as quickly as possible.

It must also be ensured that database privileges are appropriately managed. In the smart charging
system privileges are assigned based on roles such as vehicle owners and system administrators. Roles
are provided with only the minimal privileges that they require. Assigning privileges in this way makes
them far easier to manage than if privileges were granted on a per user basis.

Another concern in database protection is the potential for buffer overflows. A buffer overflow involves
data input which is longer than the expected input, i.e. the buffer is overrun and adjacent memory is
overwritten. By doing this it is possible to crash the system, denying EVs of charging services. In
addition, it is possible to include malicious code in the input. This could lead to issues such as a loss of
data or the compromise of the system. The most up-to-date database patches should be applied to
provide protection against buffer overflow attacks.

It was mentioned previously that communication channels to the database should be encrypted. It is
important too that the information stored in the database is also encrypted. Therefore, if an attacker
manages to gain access to the database, they will not be able to understand the data that is stored there
without significant efforts to break through the encryption. Storing information in the database in clear
text provides no data protection once the database itself has been compromised.

It is also possible that a denial-of-service attack may be launched on the system’s database, i.e. it is
made unavailable to the intended users by sending a flood of traffic to the database and consuming
resources so that it unable to deal with legitimate queries. Vulnerabilities to such attacks are often
addressed by way of patching the database. It is important, therefore, that the electric utility ensures that database patches are up-to-date.

The database is not the only part of the system that is vulnerable to denial of service attacks. As mentioned previously, message modification and deletion attacks can result in a denial-of-service to EV owners as they are denied the ability to charge their vehicles. Larger scale denial-of-service attacks may result in the control centre being unable to cope with the legitimate charging requests that it receives leaving vehicles waiting for charging schedules that cannot be created. It can be difficult to protect against denial-of-service attacks as source addresses can be spoofed or many machines can be used meaning that it can be hard to identify which traffic is legitimate and which is not. The use of a firewall is a potential method protecting against this threat. Encrypted messages may also be digitally signed to reduce the threat of denial-of-service attacks. It is also possible for the control centre to be subject to buffer overflow attacks as were described above.
Chapter 4: Implementation

This chapter looks at how the system proposed in chapter 3 was implemented. The technologies that were used are discussed as are challenges that were encountered and the ways in which these were addressed. The system was implemented as three object oriented, multi-threaded applications – EV, charging point and control centre – which were written in Java. The Eclipse IDE was used for the development of the applications. In addition, SQL was used for database queries, insertions and updates.

4.1 Software Requirements
In the implementation of the system described in chapter 3, there are several characteristics which were desired including extensibility, robustness, scalability and usability. These characteristics, amongst others, are important not just in the implementation of this system but in software in general. A brief explanation of each of the desired characteristics is given below and, in chapter 5, a review of how well the system exhibited these characteristics is provided.

4.1.1 Extensibility
Extensibility refers to how easily a computer system can be extended by way of adding functionality or by modifying existing functionality. It should be possible to extend a system without harming existing functionality. This is important in the EV charge scheduling system as it may, at some point, be desired to add functionality such as more sophisticated DSM schemes.

4.1.2 Robustness
Robustness refers to how well a computer system can handle abnormalities such as unexpected input and errors in execution. The better a computer system can cope with such abnormalities the more robust it is said to be. In the EV charge scheduling system, robustness is important in ensuring that EVs are effectively served and that faults which may arise will not critically affect the system’s performance.

4.1.3 Scalability
Scalability refers to a system’s ability to handle an increasing amount of work or to be expanded to cope with increased work. A system that exhibits the ability to do this is referred to as a scalable system. It is important that the EV charge management system be scalable so that it will be able to cope with the needs of growing EV fleets.

4.1.4 Usability
Usability refers to the ease of use of a system. A system should be intuitive and there should not be a significant learning curve associated with its use.

4.2 Communications
Given its basis on smart grid ideas, the system that was designed required a significant amount of communications between the various entities. This section discusses how these communications were achieved and the considerations and challenges that were faced.
4.2.1 TCP Sockets
TCP (Transmission Control Protocol) sockets were used for the majority of the system’s communications. It was these that were responsible for communicating information between the three Java applications. TCP was used in favour of another protocol as it ensures reliable communications.

4.2.2 Data Serialisation
In order to send data across the sockets mentioned in the previous section it was first serialised. Serialisation involves the transformation of an object or a data structure into a format that is suitable for transmission. Upon receiving serialised data it may be translated back to its original format by way of deserialization.

In implementing the system, JSON (JavaScript Object Notation) was used for data serialisation. JSON is “a lightweight data-interchange format” [81] which was designed with the aim of being easy for both humans and machines to understand and work with. Though it was derived from JavaScript, JSON is language independent. JSON parsers exist for many languages indicating its versatility. As well as this, JSON is platform independent, a property which makes it suitable for use in the transmission of data between different machines. JSON, rather than XML, was chosen primarily due to its simplicity.

To translate Java objects to JSON for transmission and back to their original form upon receipt Gson was used. Gson is an open-source Java library that was developed by Google specifically for this purpose. Originally it was developed for internal use but was made available for public use in 2008. Gson is capable of supporting complex objects and is simple to use with the methods toJSON() and fromJSON() being provided for conversion between Java and JSON.

All data that was communicated over sockets was serialised in this way. An example of the JSON format in which messages were transmitted is shown in Figure 4.1. The content of these messages is discussed later.

Figure 4.1 - Messages serialised to JSON – (a) charging request sent to control centre, (b) offer made by control centre
4.2.3 Database Communications

Communications between the Java applications and the database were also necessary. To achieve this, JDBC (Java Database Connectivity), a Java API developed by Oracle was used. JDBC can be used with various types of databases and other tabular data to query and manipulate the data contained in them via Java. It is most commonly used with relational databases. JDBC provides three functions to Java applications – the ability to connect to a database, the ability to query the database and manipulate the data stored in the database through the creation of SQL statements and finally, the ability to process the results of a database query.

Some difficulties were encountered in enabling use of JDBC as most of the available tutorials are complicated and contain many steps which are superfluous to the process. Once set up, however, the use of JDBC to access the database was quite straightforward.

4.3 Database

As mentioned in chapter 3, a database was used to store information about the system including information about EVs, their owners, charging points, charging requests and charging schedules. A relational database was used for this information along with MySQL, an open source relational database management system (RDBMS) now owned by Oracle [82]. MySQL has become the most popular open source RDBMS available since it was released in 1995. While it is used by many large companies and organisations including Wikipedia, Google, Twitter, WordPress and MyBB, MySQL is also suitable for use in applications of a smaller scale such as this project. The proven success of MySQL in these large-scale applications indicates that the same technology would be suitable for use if an EV charge management system such as that which has been proposed were deployed at a national level. The default MySQL interface is a command line but many third party GUIs have been developed to enhance and simplify user experience. It is also possible to use MySQL on cloud computing platforms. MySQL forms part of the LAMP (Linux, Apache, MySQL, Python/Perl/PHP) open source software stack.

As discussed in section 4.2.3, JDBC is used to communicate with the database via Java.

4.3.1 Database Design

The first step in designing the database involves determining the entities that are required and their associated attributes. The relationships between the various entities were also determined. Using this information, an entity relationship diagram (Figure 4.2) was created.

The next step in the design of the database was to map the entity relationship diagram to an outline relational schema which is shown in Figure 4.3. This depicts all of the tables in the database, the attributes contained in them, the primary key of each table (underlined attribute) which uniquely identifies all entries or tuples in the table and the foreign keys which depict the relationships between the tables (depicted by arrows).
Figure 4.2 - Database entity relationship diagram
Having created the relational schema for the database the tables could be created. As can be seen from Figure 4.3, seven tables are contained within the database. These tables are briefly described below.

- **account** – ev owner account information. Includes account number, balance and the number of EVs associated with the account.
- **charging_station** – information regarding all charging stations connected to the system. Includes ID, location and type of charging station.
- **ev** – information regarding the EVs registered with the system. Includes registration number and owner account number.
- **owner** – information regarding the EV owners that are registered with the system. Includes account number, name and contact details.
- **predictions** – predicted day-ahead electricity prices and system load. These are actual predictions taken from the website of the Single Electricity Market Operator (SEMO) [83].
- **requests** – charge scheduling requests made by EV owners. Includes vehicle availability and maximum allowed cost.
- **schedules** – EV charging schedules that have been created based on requests and predictions. Includes EV ID, time periods during which EVs are to charge and the level at which they are to charge.

The contents of these tables are updated as the state of the system changes.
4.4 User Interface

The user interface (UI) aspect of the system is comprised of two components – a control UI which displays information to system administrators and charging point/EV UIs which display information to the vehicle owners. These were created using Swing, a Java GUI toolkit [84]. This, along with AWT (Advanced Window Toolkit) and Java 2D, forms the Java Foundation Classes (JFC). Swing was designed in order to improve on the functionality offered by AWT. It is more flexible and provides many complex components that are not available with AWT. Swing was written in Java and is platform independent, another improvement over AWT. The components that Swing provides are highly customisable which allows for great variety in the GUIs that can be created with it.

To create basic UI components the Google Web Toolkit (GWT) designer was used [85]. This is a Java UI designer that provides assistance in creating and laying out simple Swing components such as buttons and text fields. The implementation of these components was therefore very straightforward. More complex components, such as tables, maps and graphs, however, were not directly supported by the GWT designer and proved significantly more challenging to implement. Section 4.4.1 describes the more complex components that were used and some of the challenges that were faced.

The UIs that were created were equipped with various listeners so that actions may be performed in response to certain events. These are discussed and various aspects of the UI are shown throughout the remainder of chapter 4.

It was important that the UIs be simple and intuitive to avoid frustrating the user. They should not be cluttered or difficult to navigate and, in addition, there should be no significant learning curve that must be overcome to allow for their use. The UIs were carefully designed based on these considerations.

4.4.1 Complex UI Components

The complex UI components that were implemented were tables, maps, and graphs. Each of these components presented their own challenges which are discussed below.

4.4.1.1 Tables

To create a table with Swing the JTable class is used. In this system, a table is located at the control centre UI and contains information about the EVs that are currently connected to the infrastructure. The creation of a simple table proved to be a relatively straightforward task. When it came to programmatically adding data to a table, however, information was not being put into the expected table location. This caused issues in accessing the table data at a later time. To resolve this issue, the expectation of what was to be in a given row was simply disregarded. Rather than looking for certain information in a given row the table rows were searched for the desired entry.

4.4.1.2 Maps

A map was integrated into the control centre UI to depict the locations of all charging points in the system as well as all vehicles that had been connected. In a real world implementation of the system only vehicles that were connected to the infrastructure at any given time would be displayed on the map. For the purpose of examining various scenarios that may occur in the system, however, the
location of EVs as they drove around, unconnected to the charging infrastructure was still visible in this implementation.

The maps used in the UI are from OpenStreetMap (OSM), a project that began in 1994 and aims to create an editable world map through the collective efforts of individuals around the world. The incentive for this project is the limited availability of maps in many parts of the world. OSM currently has over one million contributors. These contributors gather data in various manners including the use of aerial photography and GPS devices. While the data that has been gathered is typically of a high standard, much work is still needed in some countries. OSM data has been put to use in a variety of applications including websites such as Wikipedia, Flickr and Foursquare as well as other applications such as GPS receivers and humanitarian aid. A RESTful API and a Java OpenStreetMap editor (JSOM) are available for interacting with the data in the OSM database allowing users to edit maps. A Java API also exists to allow the use of OSM data in Java applications. It was this API, in particular the JMapViewer component that was used to integrate OSM data into the UI of this system.

The OSM Java API is not directly available from the Swing toolkit. Instead, the JMapViewer jar must be packaged into the application. The use of this API to display and interact with a map proved to be the most problematic aspect of the UI implementation. This was largely due to the fact that the API was very poorly documented. In order to implement the map correctly it was necessary to examine fragments of code that were found online as well as the API class files to piece together what was needed. Such measures were required in order to obtain and display map data and to interact with the map by way of placing markers on it. Significant difficulties were encountered in moving the markers around the map in order to depict a moving vehicle. If a “vehicle” was to travel along a route it would simply jump straight from the first to the last location on the route. To address this issue, a swing worker thread was used to run the map updates as a background task.

OSM does not use static maps. Instead, map data is downloaded upon request meaning that any updates that are made to the map will automatically be made available to the application. This allows for the map area that is in view to be changed to suit the needs of the viewer.

Google Maps was considered as an alternative to OSM but due to the increased freedom with the use of OSM data and the lack of restrictions in how its maps may be used and displayed it was decided that OSM was a more suitable choice.

Shown in Figure 4.4 is the OSM map that was implemented into the control centre UI. Charging stations and connected EVs may be seen marked on the map.
4.4.1.3 Graphs
Graphs depicting the state of charge of each EV were also created. As with maps, no direct Swing support for creating graphs is available. Instead, an external Java chart library known as JFreeChart was used. This library is provided by JFree.org and can create Swing components of various types of chart including pie charts and line graphs. In this case, quite thorough documentation is provided. Despite this documentation, however, several issues were encountered, particularly with regard to modifying the axes and scaling the graph. The solutions to these issues were again pieced together by examining various fragments of code that were found online. In order to scale the graph an obscure function call that was not present in the JFreeChart documentation was required. Figure 4.5 shows an example of a graph that was created.
4.5 Components of the Design

In this section, the way in which the various components of the design were made to interact with one another using the technologies described in this chapter in order to create the system described in chapter 3 is discussed.

4.5.1 EV Implementation

As mentioned, EVs were simulated by a Java application. If the system was to be implemented in a real world situation, the EV program would be loaded on to each vehicle and would execute upon the connection of an EV to a charging point. For the purpose of simulation, however, the operation of the application had to be modified. When the application is started a prompt is first given to specify the number of EVs that are to be charged (see Figure 4.6) and the corresponding number of simulated vehicles is created. In a real world implementation of the system, user constraints and EV parameters including the EV ID and battery SOC would be aggregated to create a charge scheduling request. In the simulation of the system, user constraints such as availability and EV parameters such as SOC were generated based on various probability distributions. In either case, once a charging request has been created it is serialised to JSON and sent to the appropriate charging point via a TCP socket.
4.5.2 Creating a Charging Request

Charging points were also simulated by a Java application. In a real world implementation of the system the program would be installed on each charging point in the system. The charging points listen for EV connections on a TCP server socket. Upon receiving a charging request from an EV the charging point deserialises it to a Java object, adds its own ID to the request as well as several pieces of configuration information. The request is then serialised to JSON once more. A sample JSON charging request is shown in Figure 4.1a. The components of this request are described below.

- **ID** – the ID of the EV that is making the charging request.
- **percentageCharge** – the current SOC of the EV.
- **battery_capacity** – the capacity of the EV battery.
- **max_power** – the maximum power at which the EV can be charged.
- **availability** – times between which the EV will be plugged in and available for charging.
- **maxCost** – the maximum amount of money that the EV owner wishes to spend on charging.
- **desiredSOC** – the SOC that the EV owner wishes to be obtained.
- **dates** – the dates spanned by the specified availability.
- **dialogue** – specifies whether a charging schedule should be agreed on automatically or if dialogues should be displayed for the EV owner to go through the acceptance process manually. This option is available only for simulation purposes. In a real world implementation of the system the owner must always manually navigate the process.
- **chargerID** – ID of the charger to which the EV is connected.
- **updatePort** – port number used for further communications between the charging point and the control centre.
- **time** – time of EV connection.

Having constructed the JSON charging request it is displayed to the EV owner as in Figure 4.7 before being sent to the control centre.

![Figure 4.7 - Charging request](image)

Once this dialogue is dismissed the charging request is sent via TCP socket to the listening control centre where a charging schedule is created.
4.5.3 Creating a Charging Schedule

The final Java application, the control centre, continually listens on a TCP server socket for incoming charging requests. Each time a request is received a new thread is spawned to deal with it. By doing this, multiple charging requests may be handled simultaneously, improving the efficiency of the system. The new control thread deserialises the received charging request to Java and the details of the request are entered into the requests table of the database. The control thread may then begin the process of creating a charging schedule for the EV that made the request. To do this, the availability specified by the vehicle owner is divided into thirty minute time periods and the predictions table of the database is queried to determine the predicted electricity cost for each time period. Once this information is known scheduling may begin.

To create the charging schedule the least expensive time period within the specified availability is selected and the predicted load for this time period is read from the database. If sufficient capacity remains, charging is scheduled during this time period. This process repeats until a sufficient amount of charging time has been scheduled or until all of the specified availability has been used up. Once the schedule is complete it is inserted into the schedules table of the database. At this point, the availability of the EV and the times within that availability for which charging is scheduled (marked in blue) are shown in a Swing dialogue. If it was attempted to schedule an EV during a time period in which the load was already too high the corresponding period is marked in red (see Figure 4.8).

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Figure 4.8 - Charging schedules. All time periods within the customer specified availability are shown. Times marked in blue have been chosen as part of the charging schedule. Times marked in red have reached the allowable load limit.
It should be noted that, in a real word implementation of the system, this dialogue would not be displayed. It is simply a visual aid to show what is happening in the system and to make it clear how various scenarios affect the charging schedules that are made.

### 4.5.4 Making an Offer to the Vehicle Owner

Having created a charging schedule based on the customer constraints and on the predicted grid load and electricity prices, an offer may be made to the owner of the vehicle. This offer is sent, in JSON, to the waiting charging point via a TCP socket. A sample JSON offer may be seen in Figure 4.1b. The components of this offer are described below.

- **cost** – the amount of money that it will cost to charge the EV against the created schedule.
- **SOC** – the SOC that can be obtained given the constraints that were provided.
- **response** – customer response to be filled in at control centre.
- **rescheduleID** – ID of rescheduled vehicle. This only has a value if the reschedule option was previously selected.
- **additionalCost** – additional cost that the EV owner is accountable for due to the rescheduling of another vehicle. This only has a value if the reschedule option was previously selected.

Upon receiving the offer, the charging point deserialises it and a Swing dialogue is created to display it to the owner as shown in Figure 4.9. The schedule that was created is read from the database and also displayed. The EV owner must select the option that they wish to avail of. The chosen option is inserted into the response field of the offer which is serialised once more and returned to the control centre.

![Figure 4.9 - An offer to the EV owner](image)

### 4.5.5 Interpreting the Response

Depending on the option that is selected by the EV owner in response to the offer that was made the control centre will react in a particular manner. The ways in which the various options are responded to are described below.
### 4.5.5.1 Offer Accepted

If the customer chooses to accept the offer, the details of the vehicle are added to the table of connected EVs that is displayed at the control centre. As well as this, the EV is marked on the map that is also displayed at the control centre and the appropriate charging point is marked occupied. The information table and map are shown in Error! Reference source not found.a and 4.10b respectively.

By clicking on a table row or on a map marker a dialogue containing additional information about the vehicle including the charging schedule that was created for it and a Swing graph component showing the SOC is displayed. An example of such a dialogue is shown in Figure 4.12.

In addition, by hovering over a map marker, the name of the appropriate EV owner is displayed as may be seen in Figure 4.11.

Having accepted the schedule that was created for it the EV may now begin to charge as described in section 4.5.6.

### 4.5.5.2 Constraints Modified

If the customer instead chooses to modify their specified constraints the initial schedule is discarded. A new request, schedule and offer are made in the same manner as has been described and the acceptance process is
once more completed.

4.5.5.3 Reschedule Request
If the customer chooses the reschedule option in order to obtain a better charging schedule, one of the already connected EVs must be selected for rescheduling. The vehicle with the longest specified availability is initially chosen. If this vehicle is scheduled to charge during the first available time period of the new EV it’s charging is deferred so that this time period is no longer used. Otherwise another EV is chosen. A new schedule may then be made for the newly connected EV. The time period that has been made available may now be utilised and the offering and acceptance process that has been described can once more be completed.

4.5.5.4 Offer Declined
If the customer chooses to decline the offer, the charging schedule is discarded, communication channels are closed and, in the case of a public charging point, the owner must disconnect their vehicle.

4.5.6 Charging the EV
The charging of the vehicle is managed by the charging point. At the beginning of each half-hour time period, the charging point queries the database via JDBC to check if the connected EV is scheduled to charge during that time. If so, the SOC of the vehicle is increased based on the agreed upon charging level throughout the time period. This simulates the drawing of electricity from the grid to charge the vehicle. In addition, real-time updates of the EV’s SOC are sent to the control centre via TCP socket. The cost of charging is also updated based on the predicted electricity prices. Information regarding the current state of the EV and the charging process is displayed at the charging point for the EV owner to view. An example of what may be displayed is shown in Figure 4.13.

![Charging point UI](image)

*Figure 4.13 - Charging point UI*

It may be seen from Figure 4.13 that the EV owner is presented with information regarding the charge status of their vehicle, its current SOC, the level at which it is currently charging, the time, the price per kWh of electricity in the current time period and the total cost of charging so far.
By pressing the disconnect button, the owner can disconnect their EV from the charging system. This would be the equivalent of unplugging the vehicle in a real life scenario. In the system that was implemented, this will send a signal to the control centre indicating that the EV is no longer connected. The EV will set off to drive along a route using up the charge that it has been given. This was depicted by moving the map markers along a specified route using the Swing worker threads that were discussed previously. When the EV returns to a charging point, the charge button may be pressed to initiate the creation of a new charging schedule in the same manner as has been described.

4.5.7 System Parameter Changes
As mentioned in chapters 2 and 3, renewable sources of energy are intermittent, meaning that their use in electricity generation can cause unanticipated peaks and lows in supply. At these times, EV charging can be rescheduled to make use of the excess electricity or to reduce the charging load as necessary. In this system, such scenarios are reflected by a change in the price of electricity. If EVs are to be rescheduled, the control centre broadcasts a reschedule request signal to all of the charging points. Upon receipt of such a request, a random number is generated for each vehicle and returned to the control centre. The decision to reschedule a vehicle is based on the value that they return. If, for example, it is desired that 30% of vehicles be rescheduled, EVs that returned a number greater than 0.7 will be selected for rescheduling. If an insufficient number of vehicles return an appropriate value, some will be forced to reschedule. In a real world implementation of the system EV owners could set the number manually based on their willingness to have their vehicle rescheduled, i.e. a lower number indicates an increased reluctance to partake.

4.6 Accelerated Time
As was discussed in section 2.1.3.4, EV charging can take many hours to complete. For the purpose of simulation, a method of accelerating time was implemented so that the entire EV charging process could be seen in a short amount of time. To do this, a system clock was implemented, the update frequency of which was based on a scale factor. This scale factor was set via a slider that was located at the control centre.

A challenge involved with implementing this feature was ensuring that the time was kept in sync across each of the different Java applications. If the times were not properly synced the charging point and the control centre would have different ideas of when charging should take place based on their mismatched times. To solve this issue, each time the slider at the control centre is changed, i.e. when the rate at which time passes is changed, a broadcast signal is sent to all of the charging points in the system to inform them of the change and to allow them to update their clocks accordingly. In addition, messages that are sent are time-stamped which aids the various components of the system in ensuring that their clocks are kept in sync.
Chapter 5: Evaluation

In this chapter, the project is reviewed and evaluated against the objectives that were discussed at the beginning of this report. The benefits of the proposed solution as well as some ways in which it could be improved are discussed. In addition, the performance of the implemented solution is examined and the system is evaluated against the desired software characteristics that were discussed in chapter 4.

5.1 Project review

In this section the various successes and limitations of the proposed system and its implementation are reviewed.

5.1.1 Successes

A system was designed which fulfils the objectives of the project. A smart charging strategy with the capability of effectively integrating EV charging load into existing electrical grids was developed. This strategy can mitigate any negative grid impacts which may result if this additional load was left unmanaged and can also respond to real-time grid conditions and take advantage of peaks in the available renewable energy. From these successes, it is clear that the system that was developed is a distinct improvement over the uncontrolled charging scenario that was discussed in chapter 2.

The system that was developed exhibits some benefits over existing solutions such as those that were discussed in sections 2.6 and 2.7. In these existing solutions, optimisation is usually done from a single perspective with just one objective. In other words, the solutions aim to fulfil the objectives of just one actor in the system. For example, some solutions aim to minimise distribution grid impacts for the DSO, some aim to minimise the cost of charging for the vehicle owner and others aim to maximise the utilisation of the available grid capacity and to match the demand to the supply as closely as is possible for the electricity generators. Other objectives did exist but these were found to be the predominant goals in the literature that was reviewed. Rather than looking at the problem from one perspective, the solution proposed in this project aims to fulfil the objectives of all actors in the system without compromising the others. In addition, the proportion of the available literature that addresses the maximisation of the use of renewable sources of energy and thus low carbon electricity is quite small. This was a major goal of this project as it maximises the effectiveness of EVs in reducing carbon emissions and may be seen to be a significant benefit over other solutions.

The implemented system works as intended and shows that the solution is capable of meeting its goals. The system allows for the simulation of EVs and charging points as well as the intelligent creation of charging schedules and the simulated charging of vehicles. It is also capable of effectively responding and adapting to changes in the system. Many scenarios were simulated and it was found that, for the most part, the desired results were obtained. Scenarios in which this was not the case are discussed in section 5.1.2. Shown in Figure 5.1 is a sample of a charging profile that was created by the charge scheduling system.
It may be seen from this that, as expected, even though the EV was connected to the system in the early evening, charging did not commence until 1am. From this charging profile, the operation of the strategy and its success in fulfilling its goals are clear. The EV charging load was attracted away from the times of peak loading and was attracted to the more lightly loaded off-peak hours to utilise the available grid capacity that existed at these times. As previously described, this modification of customer demand was achieved through price incentives, a clearly successful DSM technique.

Similar results were seen in scenarios of increased and decreased amounts of renewable energy. For simulation purposes the amount of electricity generated from renewable sources that was available could be varied. When increased with respect to the predicted value, it was found that, as desired, the charging load was attracted to the times of increase. Conversely, when decreased, the charging load at the times of decrease was reduced and redistributed to other time periods.

5.1.2 Limitations
Due to time constraints, the V2G component of the project was not implemented meaning that the system could have been improved in terms of its facilitation of renewable sources of energy. Despite its absence from the implementation, V2G was present in the system design and the expected benefits of this have been discussed in chapters 2 and 3.

Another limitation was in the scenario of allowing an EV owner to opt to have another EV rescheduled in order to free capacity and obtain an improved charging schedule. While this worked as intended, it is likely that this option would have to be more complex in real life. It was found that, if no capacity remained to charge an EV in a given time period, as a result of non-EV load, a customer who needed to urgently charge their vehicle had no way to do so, i.e. the option works only if there is EV load to be moved. To solve this issue, use could be made of the household load control techniques that were discussed by Shao et al. in [86].
A third limitation associated with the development of this system was the inability, as a sole developer, to thoroughly test the system. To complete adequate testing on a system such as this, much larger simulations than were possible with the available hardware would be required so that the system behaviour with a large number of connected vehicles could be observed. In addition, field testing would be required to ensure that the system operates as desired. Without such testing it is difficult to identify aspects of the system that require improvement and issues that may require attention.

5.2 Performance Testing
The performance testing of the system was carried out on a 64-bit Windows 7 PC with a 2.5 GHz Intel Core i5 processor with 4GB RAM.

A major aspect to be addressed regarding the performance of the system is the speed of schedule creation. This is of importance both in the initial creation of schedules, in particular when there are many concurrent requests and in the rescheduling of EVs in response to various system dynamics. The time that is required to create a schedule is largely dependent upon the number of database accesses that are required. The number of required accesses is influenced by various factors including the length of the specified availability and the amount of time for which the EV is to be scheduled.

The time taken to create 25 schedules and insert them into the database was measured and used to determine an average schedule creation time. As expected, variation was seen in these measurements though the extent of the variation was greater than anticipated. The maximum, minimum and average values of the results that were obtained are shown in Table 5-1.

<table>
<thead>
<tr>
<th></th>
<th>Maximum</th>
<th>Minimum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.75s</td>
<td>0.13s</td>
<td>1.17s</td>
</tr>
</tbody>
</table>

Table 5-1 - Schedule creation and insertion times

The experiment was repeated with just the schedule creation times being measured, i.e. the time taken to insert them into the database was disregarded. In this case, significant variation was again seen but it was found that times were noticeably lower than was previously the case. The maximum, minimum and average values of the results that were obtained are shown in Table 5-2.

<table>
<thead>
<tr>
<th></th>
<th>Maximum</th>
<th>Minimum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.6s</td>
<td>0.12s</td>
<td>0.97s</td>
</tr>
</tbody>
</table>

Table 5-2 - Schedule creation times

While these creation times may be sufficient for an individual that is requesting a charging schedule they are somewhat long for a case where the rescheduling of a large number of EVs is required. If this system were to be used in a real world situation it is likely that some optimisation would be required so that the number of vehicles that could be served is maximised.
The charging of EVs was also examined. This process put somewhat of a strain on the PC that was used and slowed it down considerably due to many database accesses amongst other factors. While this is an issue in the simulation of the system it would not be relevant in a real world implementation.

5.3 Evaluation of Software Characteristics
In this section, the implementation of the system is evaluated against the desired software characteristics that were discussed in section 4.1.

5.3.1 Extensibility
The EV charge management system is quite extensible. This is demonstrated by the way in which the system was developed. At the beginning, a simple system that was capable of communication was developed. Over time, the various functionalities such as schedule creation and vehicle rescheduling were added. Each function that was added served to enhance the system and did not compromise the other features. The code that was written was thoroughly commented to explain its functionality. This would be a good aid for someone involved in the further development of the system.

5.3.2 Robustness
Throughout the implementation phase of the project, the system was not always sufficiently robust. During the implementation of some features, faults were introduced to the system which made it prone to crashing. In each case, it was ensured that these faults were corrected and that the system was stabilised before the process of adding another feature was begun. At the time of writing, there are no known, critical bugs in the system.

Based on the simulations and testing that was carried out, the system appears reasonably robust. It is inevitable, however, that in larger-scale and real life scenarios, bugs will be found that did not present themselves in the smaller simulations that were run as part of this project. To address these, robustness would likely have to be improved somewhat.

The use of a decentralised system rather than a centralised system could have provided greater robustness. This was a trade-off, however, as a decentralised system would have allowed for less control over the various aspects of the system.

5.3.3 Scalability
As was seen in section 5.2 there is potential for the speed of the implemented control centre to be improved. This would be important as EV populations grow and as the use of the system increases. If the system were used in a real world scenario, however, the control centre would have significantly more hardware to utilise than was available for this project. This should render the system capable of handling large numbers of requests within a reasonable time.

It was mentioned in chapter 4 that MySQL was used to manage the database. Given its successful use in large scale applications by Google and Wikipedia amongst others, it has been proven that MySQL is capable of scaling to the needs of the charge management system as it grows to accommodate large EV fleets.
5.3.4 Usability
The best measure of a system’s usability is in the form of user feedback. Unfortunately, in this project, no user feedback was obtained. Though it was aimed that the system be intuitive and that, in the case of EV owners, no training be required to use it, there are, doubtless, aspects that could be improved. The usability of the system could, in the future, be improved based on user input.

5.4 Overview
In this chapter, the design and implementation of the system has been evaluated. It was found that all of the objectives of the project were met. In terms of the implementation of the system, however, some areas for improvement, particularly with regard to performance, were identified.
Chapter 6:  Conclusion

Many countries around the world have set targets to reduce the amount of greenhouse gases that they emit. As part of this, the use of electric vehicles is being encouraged in an attempt to make the transport industry more sustainable. In addition, the proportion of renewable energy sources that are used in the generation of electricity is being increased. The combination of these efforts has the potential to play a large role in meeting emission reduction targets but there are several outstanding issues that must be addressed before this contribution can be made.

To have a substantial impact in the reduction of greenhouse gas emissions EV penetration must increase. Some governments are providing financial incentives to encourage adoption but for such schemes to be successful there are some issues that need to be overcome, particularly regarding the availability of charging infrastructure and EV cost. Improvements in battery technology to provide an increased range and lifetime are also desirable. In addition to this, there are concerns regarding the charging of large EV fleets. Widespread, unmanaged EV charging is expected to increase peak loads and result in the degradation of both grid infrastructure and power quality. For large-scale EV adoption to be successful, methods of mitigating these impacts must be developed.

Some approaches to EV charge management or smart charging strategies have already been proposed each with its own strengths and weaknesses. Many of these, however, are limited to a single objective aiming to fulfil the requirements of just one actor in the system. In addition, very few consider the optimal utilisation of renewable energy and the benefits that this can provide. These strategies are presented in literature but very little in the way of charge management methodologies have actually been implemented for use.

In this project, a solution to the EV charging problem is proposed which has the capabilities of effectively integrating EV charging into existing electrical grids while making efforts to fulfil the needs of all actors in the system. The proposed system was shown to be capable of mitigating negative grid impacts and ensuring that grid resources, with particular regard to renewable energy, are effectively utilised. A smart charging strategy such as this is essential to ensuring that large-scale EV use can become a reality and that the potential of EVs for reducing greenhouse gas emissions and achieving more sustainable societies is utilised.

6.1 Future Work

There is much potential for further work to be done on the system. For example, V2G could be implemented, along with more sophisticated DSM techniques to further the utilisation of renewable energy and to allow for increased influence over customer demand. Doing this, would allow for the minimisation of greenhouse gas emissions as a result of the EV charging process. In addition, the system could be modified to give EVs with low initial SOCs a higher charging priority until they reach a given SOC to ensure that they are available for emergencies. As well as this, the system could be optimised in terms of performance and simulations could be carried out on a larger scale to further refine operation.
6.2 Reflection on the Project

Prior to completing this project I had an interest in the area of EVs and the benefits that they can provide but had no substantial knowledge or understanding of the issues that are involved with their large-scale use. In completing the project, I have gained much knowledge and awareness of these topics, amongst others, and hope that this will be of use in future projects.

In addition, this project allowed me to improve my technical abilities. In particular, my knowledge of working with databases and of GUI development has improved as have my programming abilities. I have learned about several new programming concepts and techniques, some of which are specifically related to Java and others which are applicable across many languages. As well as this, the project involved learning about and using new technologies which will be very advantageous in future projects that are undertaken.

In completing a project of this scale I have also come to learn a lot about the way that I work and about how my abilities could be improved for future projects. The main thing learned in this regard is the importance of carefully planning what to do before rushing into the implementation of a solution so that work can be completed more efficiently and to a higher standard.
Source Code

The accompanying project source code may be found on the attached CD.
Bibliography


Appendix A