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University of Liège- School of Engineering and Computer Science

Modelling of Charging Systems for Electric Vehicles and Assessment of Charging Scenarios

Masterʹs thesis carried out to obtain the degree of Master of Science in

Mechanical Engineering by Karim Koujou

Academic Supervisor: Pierre Duysinx

Academic year 2022-2023

ABSTRACT

This Master’s Thesis focuses on modeling, simulating and assessing various charging scenarios, charger types and methods for a Nissan Leaf equipped with different battery sizes. This research aims to determine charging losses and time needed to evaluate whether larger batteries are an effective solution to range anxiety. Conductive charging is influenced by factors such as converter inefficiency, connector and cable losses in addition to battery internal resistance. Whereas inductive charging is mainly affected by misalignment and air gap between the charger and EV, resonant circuit losses and coil and ferrite losses. Both charging methods are influenced by the battery's state of charge and health, ambient temperature, and varying charging powers.

Two different driving routines were simulated, a long trip and a daily commute to work. The long trip simulation highlighted the effects of using DC fast chargers and their main influence on battery degradation, results showed that the 100 kW DC Level 2 fast charger was more efficient than the 50 kW DC Level 1 fast charger. The urban commute simulation suggested an optimal charging strategy when the State of Charge drops between 40-60%, maximizing efficiency and battery life. Moreover, results indicated that the 22 kW AC Level 2 charger was the most efficient charger compared to other AC chargers. An overall simulation was conducted comparing the 40 kWh vs 62 kWh. The findings suggest that instead of investing in larger battery packs for EVs, investing in advanced charging infrastructures, battery enhancements against degradation and especially in wireless charging promises a more sustainable EV future.

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ACKNOWLEDGMENTS

First and foremost, I would like to express my deepest appreciation to Professor Dr. Pierre Duysinx for offering me this captivating topic that extremely expended my knowledge in this interesting field of electric vehicles. He has been also the driving force behind my education in the automotive domain. It is under his guidance that I have come to understand the complex world of automotive technologies, particularly EVs, which served as the backbone for this thesis.

I must also extend my deepest appreciation to Romain Vanderbeeken. Romain has been an instrumental figure throughout this project, being there for me at every step forward taken, and at any time needed. His profound knowledge and great understanding in this field were invaluable, and his patience and friendliness made the process so much smoother and beneficial.

To my family, your endless support has been and will always be the key for my success, motivation and strength. Your faith in me has been the foundation of my journey. Thank you for always being there for me.

Lastly, and most profoundly, I thank God. In moments of doubt and struggle, through every step of this journey, it was His steady guidance and strength that consistently lit up my path, ensuring that I found my way to the finish line. To Him, I owe endless thanks for the resilience He gifted me during this journey.

1 INTRODUCTION

1.1 Study overview and objective

Electric Vehicles are a liberating technology for people all around the world, and the automotive industry has played a crucial role into every person's daily life basic needs. During the last decade, Electric Vehicles have become extremely popular and a leading research topic in this field, and it is expected that by 2030, around 40% of the vehicles will be electric, and the goal is that by 2040, mostly all vehicle will be electric (1). However, EVs are not without their challenges, charging times and losses remain high, and the cost and weight of large battery packs represent crucial issue to overcome.

This thesis aims to address some of these challenges by exploring, modeling, and assessing various EV charging scenarios like the basic home or work conductive charging, and the new technology of wireless charging. Methodologically, this thesis will start by having a deep understanding of the different charging methods used nowadays and identify the different types of chargers and charging powers, such as AC Level 1&2 which are the common chargers types found in homes and DC Level 1&2 fast chargers mostly available in charging stations.

When charging your EV, one notices that the energy transferred from the grid is not equal to the amount of energy received to the vehicle; this difference represents the energy loss during the charging process due to inefficiencies in chargers and many other factors. This research will highlight the reasoning behind these losses for both conductive and inductive charging, by identifying factors such as materials, power, temperature, state of charges and infrastructure which can significantly influence battery life, charging speed, vehicle performance, and overall efficiency.

While electric vehicle are currently a main research topic in automotive engineering, and having an increase of literature and investigation in this field, what sets this research apart is its focus on charging systems and losses, an area in this domain that currently lacks extensive research. A real-life simulation of a normal person usual driving routines will help up visualize and quantify the major aspects of the charging types and losses used nowadays.

The first case scenario held in this thesis will simulate a real-life long trip, assuming one of the frequently traveled routes in Europe (>300km), this scenario will help us understand the need of understanding your EV range and pre-locating charging stations, in addition, the use of DC Fast chargers for this purpose.

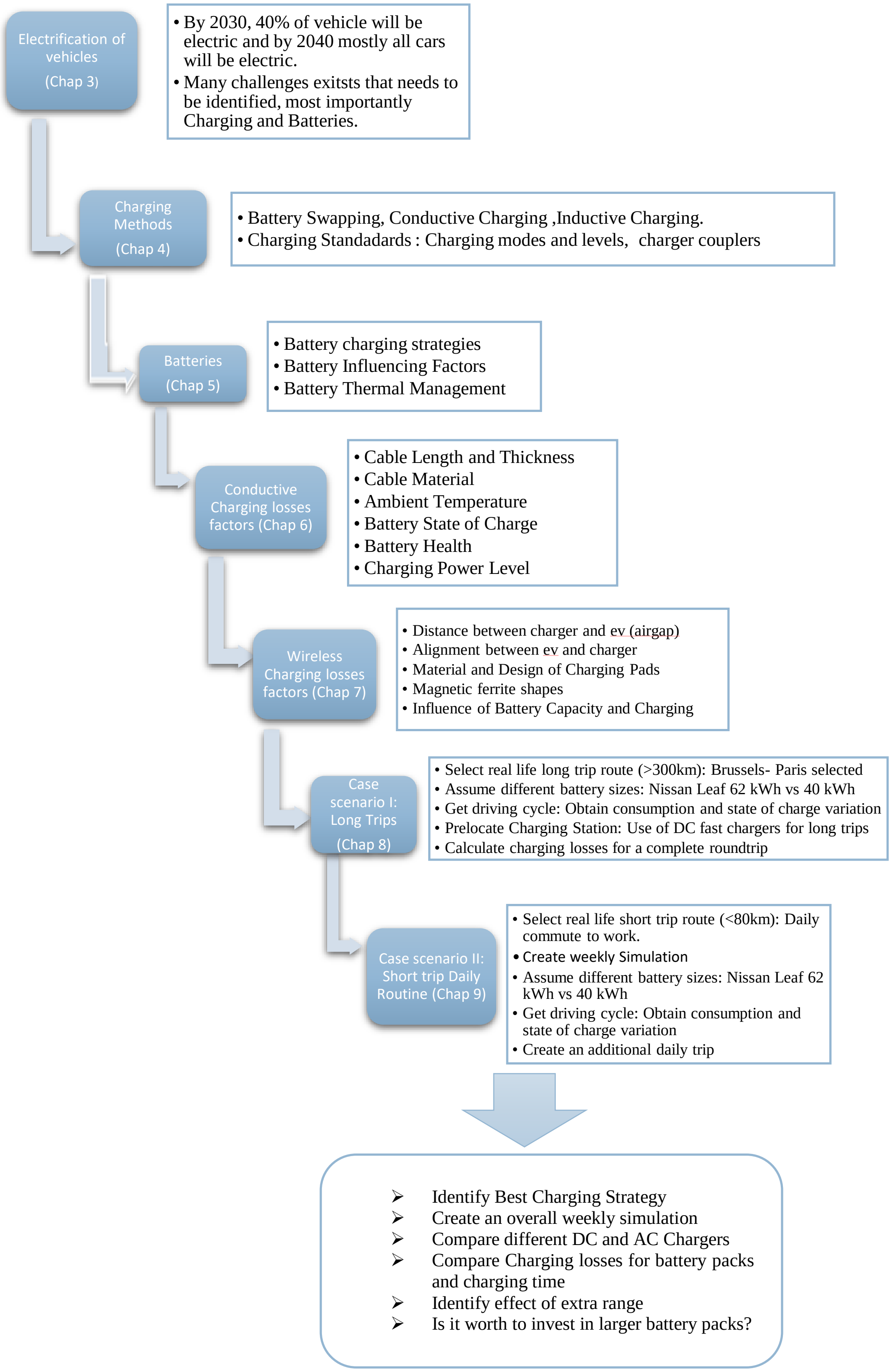
The second case scenario will simulate an everyday routine short trips (<80km) for a usual vehicle owner going to work and other places as well, which will let us understand the behavior of an EV in urban applications and the use of AC chargers. Both journeys will be initiated in a Nissan Leaf, offering varying battery capacities of 40kWh, or 62kWh.

Combining all these different aspects will offer an interesting and wide range of analysis, setting up different features for comparison by understanding the charging losses and times for different types of chargers, having different trip scenarios, using different battery sizes on different state of charges.

In addition, this research will help us understand the best charging strategy that a user could follow in order to charge his EV, as well as the best charger types. By recognizing and identifying the inefficiencies in power transfer during the charging process, these aspects will help promote the widespread adoption of electric vehicles, and would contribute in a better understanding on charging behavior in general. By identifying the charging losses and charging times and stops needed for different battery packs this would help us understand if larger battery size would be the best solution to solve range anxiety which is one of the main goals of this research as larger battery packs could offer more range, but have several drawbacks.

As electric vehicles are projected to be the future of the automotive industry, we finally aim to make a significant contribution to the current and future research in EV technologies and challenges, especially for charging systems and strategies, offering a valuable reference for further academic studies.

1.2 Thesis methodology and layout



Electrification of vehicles (Chap 3)

- By 2030, 40% of vehicle will be electric and by 2040 mostly all cars will be electric.
- Many challenges exitsts that needs to be identified, most importantly Charging and Batteries.

Charging Methods (Chap 4)

- Battery Swapping, Conductive Charging ,Inductive Charging.
- Charging Standadards : Charging modes and levels, charger couplers

Batteries (Chap 5)

- Battery charging strategies
- Battery Influencing Factors
- Battery Thermal Management

Conductive Charging losses factors (Chap 6)

- Cable Length and Thickness
- Cable Material
- Ambient Temperature
- Battery State of Charge
- Battery Health
- Charging Power Level

Wireless Charging losses factors (Chap 7)

- Distance between charger and ev (airgap)
- Alignment between ev and charger
- Material and Design of Charging Pads
- Magnetic ferrite shapes
- Influence of Battery Capacity and Charging

Case scenario I: Long Trips (Chap 8)

- Select real life long trip route (>300km): Brussels- Paris selected
- Assume different battery sizes: Nissan Leaf 62 kWh vs 40 kWh
- Get driving cycle: Obtain consumption and state of charge variation
- Prelocate Charging Station: Use of DC fast chargers for long trips
- Calculate charging losses for a complete roundtrip

Case scenario II: Short trip Daily Routine (Chap 9)

- Select real life short trip route (<80km): Daily commute to work.
- Create weekly Simulation
- Assume different battery sizes: Nissan Leaf 62 kWh vs 40 kWh
- Get driving cycle: Obtain consumption and state of charge variation
- Create an additional daily trip

- ➢ Identify Best Charging Strategy
- ➢ Create an overall weekly simulation
- ➢ Compare different DC and AC Chargers
- ➢ Compare Charging losses for battery packs and charging time
- ➢ Identify effect of extra range
- ➢ Is it worth to invest in larger battery packs?

2 ELECTRIC VEHICLE – AN OVERVIEW

2.1 History and challenges

The automotive industry has become lately one of the main leading industries in the world due to its huge impact on the human daily lifestyle, where most of population is now dependent on the use of vehicles. This industry has shown increasingly its importance in the research and development industry while also having a huge impact on an economic level. However, the increase of vehicular usage over the years has led to major effects on air pollution levels, having road transport accounting for over 22% of the total CO2 emissions (2).

Therefore, in order to avoid major environmental penalties that will surely affect both human and planet health, authorities are now encouraging the use of Electric Vehicles as an eco-friendly alternative, particularly in developed countries. What makes EVs special is that they promise zero emissions, they have simpler engines compared to internal combustion engines and require cheaper maintenance, and greater reliability, in addition, the energy cost per kilometer is significantly lower than traditional vehicles. Another major advantage of the use of EVs is comfort, where an electric motor cancels vibrations and noise compared to an ICE engine (3).

As driving range is not a main issue in ICE vehicles, knowing that the user can refill his car anytime having a huge distribution of gas stations all over the city, range is still a major challenge in the Electric vehicles industry. EVs are typically limited with a range of 200-400 km with a full charge and companies are continuously improving this aspect, for example, a Tesla Model S can reach high ranges of around 500 kilometers and maybe more depending the driving situation (4), and a Nissan Leaf have a driving range that might reach 364 kilometers (5).

As authorities are focusing on increasing the numbers of EV users, the number and distribution of charging stations is increasing from day to day. However, EVs are not without their challenges, charging times remain high, and the cost, bulk, and weight of large battery packs represent substantial issue to overcome.

Therefore, researchers in the Automotive industry are mainly focusing on improving all the weak aspects that an EV has and the main topics are now dedicated on improving the charging processes and time, battery technology and battery efficiencies that leads to higher driving range and lower charging times taking power losses, cost, efficiency as main considerations.

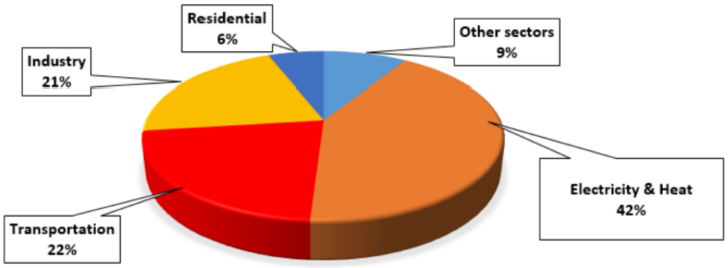


Figure 1: CO2 emissions by different sectors (6)

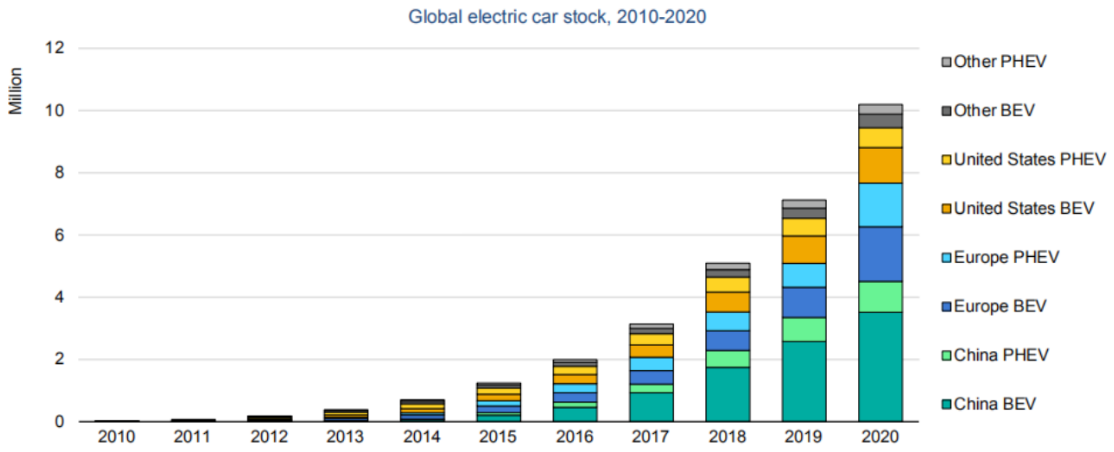


Figure 2: Global EV stock 2010-2020 (7)

2.2 Electric vehicle technologies

The principal concern with Internal Combustion Engine (ICE) vehicles as mentioned is their dependency on fossil fuels and its environmental impact. Vehicle technology is generally categorized into four main types, each one of them representing an increased level of electrification. These types starts with the ICE as the reference vehicle, then with the electrified versions like Hybrid electric vehicle (HEV), Fuel Cell vehicle and last but not least the fully electric vehicle.

Each type of technology presents its unique advantages and challenges, and a having a deeper understanding of each type gives us a fundamental part of our exploration of electric vehicle charging systems and their efficiencies.

Hybrid Electric Vehicles, as the name define itself combine an internal combustion engine and battery at the same time, having both components work simultaneously in order to propel the vehicle. HEV are ideal for urban application as we have frequent start-and-stops, the technology relies on recapturing the vehicle’s kinetic energy and stores is back to the battery pack using “regenerative braking” technology. Since fully EVs are still in early development and many aspects are still under investigation in order to improve every drawback the technology has, HEVs currently stands as the best cost-effective solutions for this period of time. The key advantages of HEVs include that the technology uses both battery and engine in the most optimized and efficient way to reduce CO2 emissions. Other advantages include a reduction in fuel consumption, the use of existing fuel stations that reduces infrastructure concerns, but the disadvantage stands mainly in the higher initial cost due to the battery (8).

Fully Electric Vehicles is the most electrified version of vehicles, which rely on a battery power pack to drive the vehicle, making them superior to HEVs in terms of combating global warming. EVs mainly utilize the battery pack in order to operate the motor, which propels the vehicle. Similar to hybrid electric vehicles, they are also equipped with a regenerative braking system; this ability to recapture energy during frequent starts and stops also makes EVs as a more suitable option for urban driving.

Therefore, EVs in general operate in two modes. The first mode in acceleration, which involves the battery propelling the vehicle whenever it needs to move. The second mode, "Deceleration or Braking," comes into play when the vehicle slows down or brakes where in this mode we take advantage of the regenerative system to restore energy into the battery pack (6).

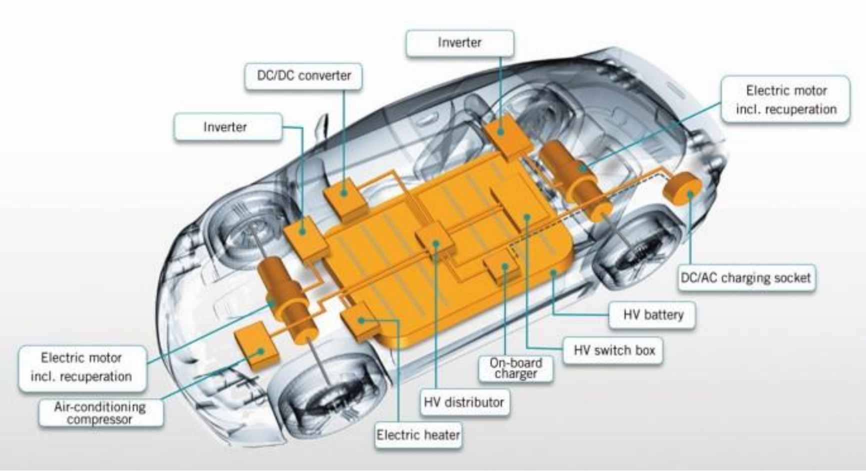


Figure 3: Battery Electric Vehicle layout and components (9)

3 CHARGERS

3.1 EV charging methods

There exist mainly three charging methods used to charge an EV, the first one being conductive charging, which is the commonly most used charging method by EV owners and in charging stations nowadays. The second one is Battery swap station (BSS) which relies on renting fully charged batteries from companies or stations that is implementing this method. And the third one is a new charging technology that researchers believe that it will be the future of EV charging, which is Wireless charging where there will be no need for connectors to charge your EV. These methods are summarized below in Figure 4.

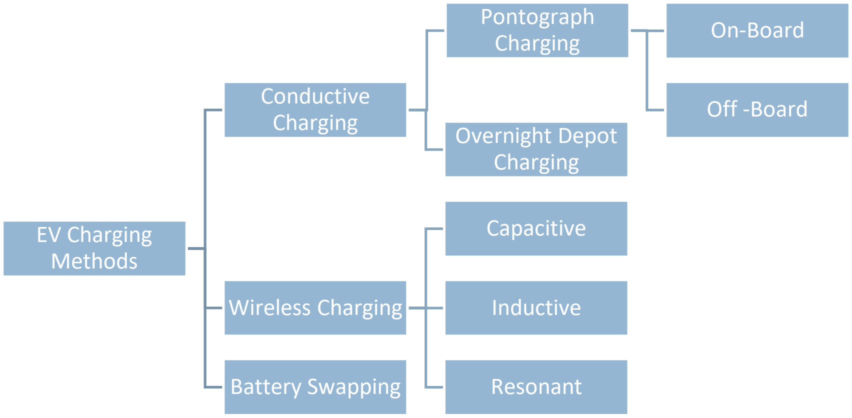


Figure 4: EV charging methods

3.1.1 *Battery swap station (BSS)*

The battery swapping method is a charging method that mainly operates on a way where users pay a monthly rent for the battery to the Battery Swapping Station owner, this method is illustrated in Figure 5. This method, that generally uses a slower charging process, tends to extend battery life knowing that fast charging methods for batteries lead to battery degradation over the years. Battery swapping station are implementing the use of Renewable Energy Sources (RESs) like solar and wind as environmental considerations are always a key factor in any type of charging method.

A significant advantage of this method is that the EV user does not need to think about charging his vehicle and can easily replace his depleted battery without leaving his vehicle. Additionally, the batteries kept at the station can take advantage of vehicle-to-grid (V2G) technology.

However, as this method sounds simple and reliable, it carries some drawbacks. High monthly rental fees from the BSS owner can make this charging technique costlier than fueling an Internal Combustion Engine (ICE) vehicle. Another potential issue is the compatibility of batteries, knowing that not all EVs have the same battery pack, and battery technologies differ from a model to another, so a battery swapping station might not have a compatible battery for you vehicle, which is not that convenient (6).

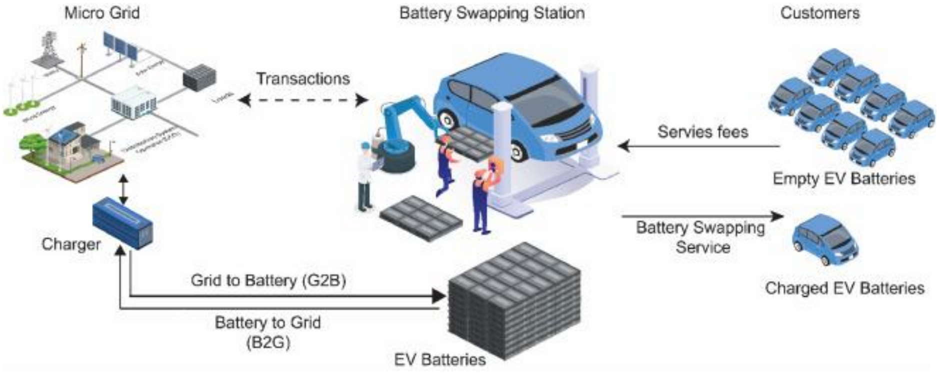


Figure 5: Battery swapping station process (10)

3.1.2 Conductive charging

Conductive charging is mainly the most used charging method by EV users, which involves a direct electrical connection between the vehicle and the charging inlet, offering various charging levels. In general, public charging stations typically use high power charging levels, while slower charging levels are normally used in home charging. As shown in Figure 6, this method supports the vehicle-to-grid (V2G), which is a technology that allows energy to flow back from the battery to the grid, helping to reduce grid loss, maintain voltage levels, and prevent grid power overloading (6).

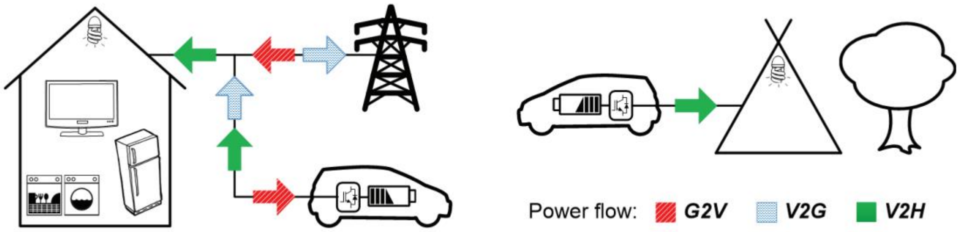


Figure 6: Concepts of the bidirectional battery charger with G2V, V2G and V2H technologies (11)

Onboard chargers: Onboard chargers come equipped with two different power transfer capabilities, bidirectional, which its name define itself, having the capability of transferring power from grid to vehicle and vice-versa, and unidirectional having the power flow in one direction. They are primarily compatible with Level 1 and Level 2 chargers, constrained by their limited size, weight, volume, and power. These chargers mainly use two-stage converter topologies; an AC-DC stage at the front end and a DC-DC stage at the back end, where this conversion mainly affect the overall charging efficiency and contributes a big percentage of power loss. The configuration of an onboard charger is shown in Figure 7.

However, compared to offboard chargers, onboard charging provides lower power transfer, which results in longer charging times. Despite this issue, even if charging time of an EV is a crucial aspect to look up to, onboard chargers remain an important component of electric vehicle charging infrastructure (12).

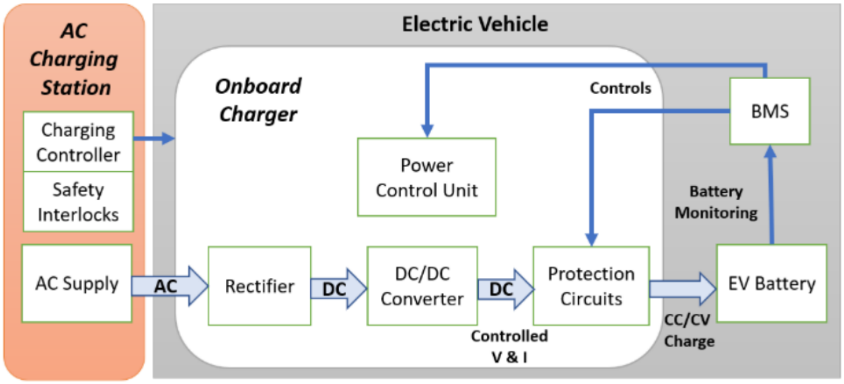


Figure 7: Configuration of conventional onboard EV (13)

Off-board Chargers: Offboard chargers are mainly used in DC fast charging systems than allows higher power flow for chargers with a power more than 20 kW between the grid and battery. They adhere to Level 3 or Level 4 DC fast charging.

The power conversion stage of this type of charger is mainly located externally to the EV, resulting in significant reductions in the charger's cost, volume, size and weight compared to its onboard counterpart. The offboard charger involves two converter stages: AC-DC and DC-DC, for regulating the DC current before it reaches the EV as shown in Figure 8 (14).

Recent advanced technologies in offboard chargers are capable of providing over 350 kW power to the EV battery for ultrafast charging, and many studies are focusing on not only delivering higher power chargers, but also in designing higher efficiency chargers as well, and these ultrafast chargers are projected to be compatible with 800 V EVs in the future (15).

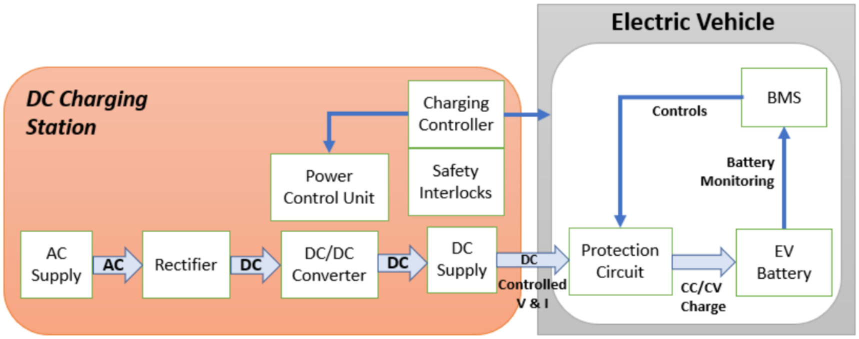


Figure 8: Configuration of conventional offboard EV (13)

For vehicles with larger battery capacity, rapid charging needs and high daily use like buses and trucks, two predominant charging methods are typically used: Overnight Depot Charging and Pantograph Charging.

Overnight Depot Charging is a charging method that can be used for both slow or fast charging applications and is typically set up at the end of the lines for nighttime charging. Slow charging is preferable due to its minimal impact on the distribution grid and can reduce battery degradation over time, making it favorable for high-capacity batteries with quick charging needs (16).

Pantograph Charging on the other hand offers a significant opportunity for charging. It is useful for high capacity and high-power demand applications such as buses and trucks. This method reduces investment in the bus battery, which is a main issue in Electric busses technologies that uses extremely big battery packs, thus it contributes in decreasing the bus investment cost, but it increases the charging infrastructure cost (17).

Pantograph Charging is mainly subdivided into two types:

1. Top-down Pantograph: Mounted on the bus stop roof, this off-board method provides high power direct current and has been demonstrated in countries like USA and Germany
2. Bottom-up Pantograph: This method, where charging equipment are already installed in the bus, is suitable for certain applications. It is also known as an on-board bottom-up pantograph (18).

Figure 9: Pantograph system (19)

3.1.3 Wireless Charging

Wireless Power Transfer (WPT), an alternative technology to the conventional charging method widely used, is a futuristic charging technology, which is based on the principle of charging your vehicle without using cable chargers, this method has recently received increased attention in EV applications. Charging stations are starting to implement this method, but it is still under a wide range of testing and improvement, WPT enhances safety and convenience for EV charging. One can distinct different forms of wireless charging based on their application scenarios: the first one being stationary charging, where the vehicle is at rest, typically parked. Second one is opportunistic charging, which happens when the vehicle is briefly stationary, such as at traffic signals, and the last one, which might revolutionize the EV industry is dynamic charging, which occurs while the vehicle is in motion, typically along a specific charging track (20).

One of the most important aspects in implementing this charging technology is for being spark-free, due to the lack of electrical contact between the vehicle and grid, it adds a higher level of safety, which is always a crucial factor in engineering innovation. It is also user-friendly, where drivers only need to ensure that their vehicles are aligned with the charging zone for the charging process to begin. WPT transfers power with high efficiencies when air-gap and alignment to the charging pad is perfectly respected (21).

Using a time-varying currents and voltages at high power levels in WPT systems may present health and safety risks that needs to be prevented in order to implement this technology. These risks, such as electromagnetic field exposure and electrical shocks needs to be addressed (22). To decrease radiated fields and losses, shielding and magnetic field cancellation methods can be employed, they can be passive methods using ferromagnetic materials or conducting materials that create an opposing magnetic field (23).

3.1.3.1 WIRELESS POWER TRANSFER TECHNOLOGIES

Inductive power transfer: IPT, an old power transfer concept that was discovered by Nikola Tesla in 1914, enables the wireless transfer of power. This method has been adapted to a variety of charging structures for electric vehicles allowing wireless power transfer from the charging pad to the vehicle with powers ranging from milliwatts to kilowatts.

Figure 10 shows a schematic diagram of traditional IPT system, the primary coil, also known as a charging pad, is inserted into the vehicle's charging port. The secondary coil, situated within the vehicle, then receives power, enabling the EV charging process. The unique type of charging is what makes it unique, as it allows eliminating the need for physical contact during the charging process and allows the driver to stay in the vehicle when intending to charge (24).

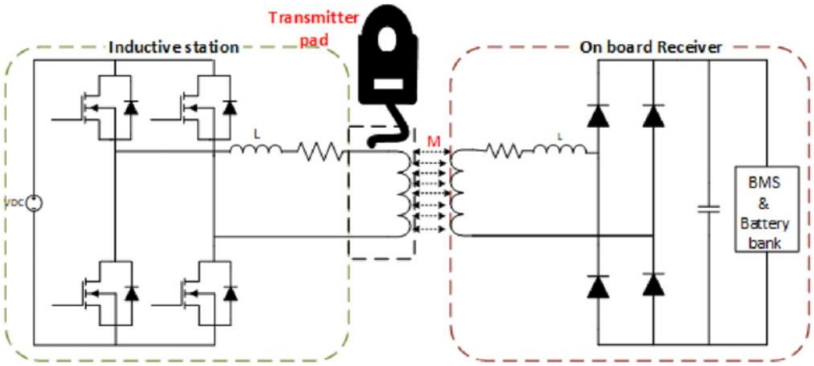


Figure 10: Schematic Diagram of traditional inductive power transfer (25)

Capacitive Coupled Power Transfer: CCPT is a cost-effective and simple approach for power transfer in low-power applications, due to its use of innovative geometric and mechanical structures of coupling capacitors as shown in Figure 11. CPT wireless charging mainly transfers energy through an electric field, enabling it to penetrate metal materials which is contrary to IPT systems that uses a magnetic field,.

In a typical CPT system, the main alternating current (AC) voltage is applied to an H-bridge converter, which typically generates a high frequency AC that passes through the coupling capacitors on the receiving side, which simplifies the charging process and power transfer between the charging pad and the vehicle battery (26).

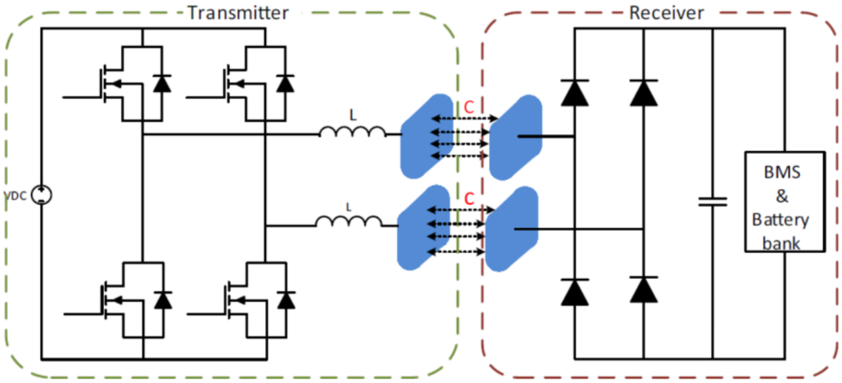


Figure 11: Schematic Diagram of traditional CCPT (25)

Magnetic gear wireless power transfer: MGWPT system is different than the other wireless power transfer methods that have been mentioned, instead of using a coaxial cable as in most wireless electric vehicle charging systems, MGWPT employs two synchronized permanent magnets that are facing each other as demonstrated in Figure 12. The charging process begins when the primary source of power is applied to the transmitter winding, creating a mechanical torque on the primary PM. This torque causes the primary PM to rotate which will then induce a torque on the secondary PM.

In this system, there is a primary PM that operates as a generator, and a secondary PM operating as a receiver which will then deliver it to the battery through battery management system and the power converter (24).

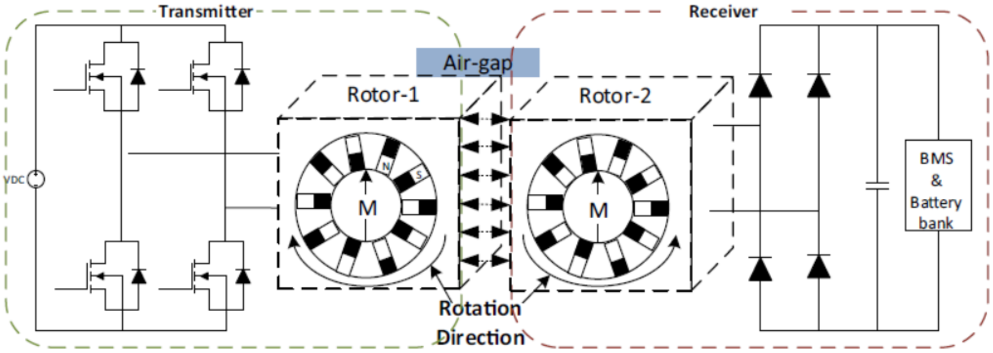


Figure 12: Schematic Diagram of magnetic gear based WPT (25)

Resonant inductive power transfer: This wireless power transfer technique is considered as the most advanced WPT system where the primary mechanism remains the same, with the main AC voltage converted into a high-frequency AC source. The secondary coil will receive power via fluctuating magnetic fields and is then converted into DC for the electric vehicle battery pack, the configuration of this technique is shown in Figure 13. When comparing RIPT to the IPT system, additional compensation networks added in series and/or parallel configurations to both the primary and for the secondary windings, which help establish the resonant case and minimize additional losses. Thus, this power transfer method offers a more efficient and advanced approach to wireless power transfer (27).

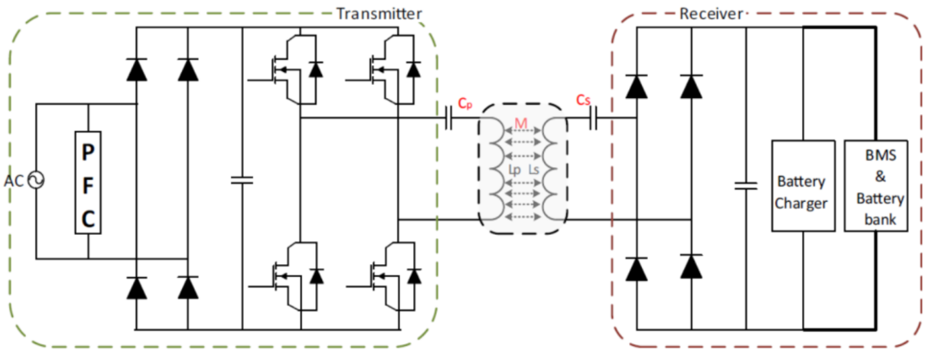


Figure 13: Schematic diagram of Resonant Inductive Power Transfer (25)

Table 1 shows a comparison of different aspects between WPT methods.

Table 1: Overview of deferent methods of Wireless Power Transfer (WPT) for EVs (25)

WPT methods	Performance			Price	Size/ Volume	Complexity of design	Power Level	Suitability for WEVCS
	Efficiency	EMI	Frequency range (kHz)					
Inductive	Medium/High	Medium	10–50	Medium/High	Medium	Medium	Medium/High	High
Capacitive	Low/Medium	Medium	100–600	Low	Low	Medium	Low	Low/Medium
Permanent magnet	Low/Medium	High	0.05–0.500	High	High	High	Medium/Low	Low/Medium
Resonant inductive	Medium/High	Low	10–150	Medium/High	Medium	Medium	Medium/Low	High

3.1.3.2 STATIC & DYNAMIC WIRELESS ELECTRIC VEHICLE CHARGING SYSTEM

Static Wireless electric vehicle charging system

The implementation of wireless charging infrastructure ideally should be integrated into areas where vehicles tend to park for extended periods. A few strategic locations that could maximize the benefits of static and opportunistic wireless charging could be at residential areas and workplaces where user can simply park his EV in his garage, or near his house and even at his workplace and then leaves his car immeadtly ensuring that charging will start without thinking about plugging any cables.

Another location that would be suitable is airports and train stations where they have long term parked card ensuring the user will get back to his fully charge vehicle. Implementing wireless charging for taxi and bus stops sounds also as an interesting location as these types of vehicles have high daily energy consumption rates and parks multiple times per day waiting for the next trip.

For some opportunistic charging scenarios, traffic lights and drive-thru services would be a great and interesting idea to have wireless chargers beneath them, though this would require more rapid charging technology.

When comparing WPT to normal conductive charging system, we can simply conclude that it is safer and simpler, especially with the new existence of extremely high current DC fast charger.

Moreover, this new advanced technology can last longer as studies showed that it needs less maintenance. Just like how people love wireless charging for phones, EV users will most likely love it for cars too. However, for this to take off, we need better infrastructure and support from cities and businesses, knowing that the implementation of its infrastructure will at the moment cost much more than normal chargers (28).

Dynamic wireless electric vehicle charging system

Dynamic wireless charging is an exciting new technology in the field of electric vehicles; it aims to solve the two main issues in this field, cost and range. Currently, to achieve a longer driving range, EVs have either to charge multiple times or to be equipped with larger, heavier and a more expensive battery pack.

The proposed dynamic wireless EV charging system is a highly advanced technology for the future that presents an innovative solution that embeds primary coils into the roadway at certain intervals as shown in Figure 14. These embedded coils, connected to a high voltage and high-frequency AC source will create a magnetic field, which a secondary coil mounted under the vehicle picks up as it passes over. This magnetic field is then converted into DC power to charge the battery. This concept in-motion charging significantly reduces the battery capacity required by EVs, estimated to be around 20% less compared to current EVs.

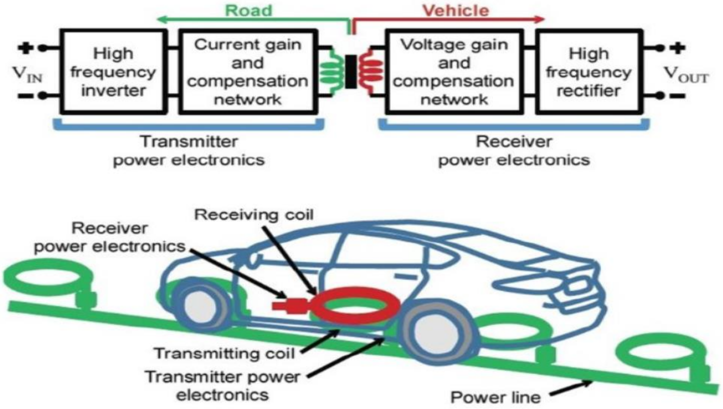


Figure 14: Dynamic WPT system (29)

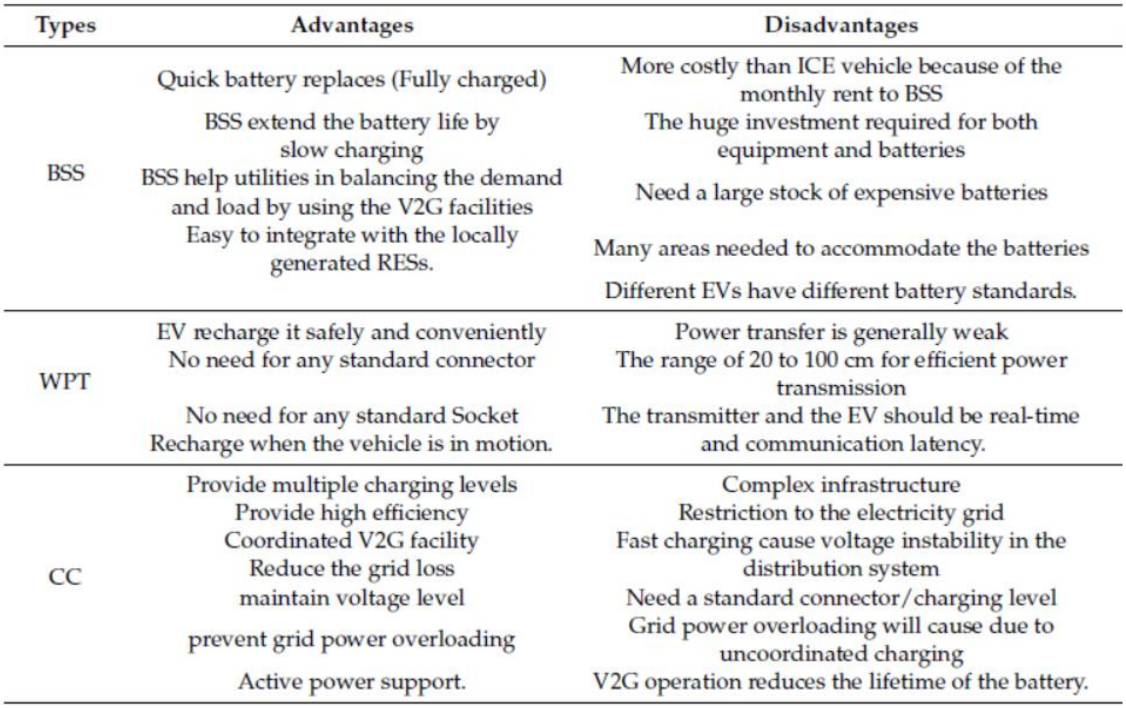
However, this technology is not of course without its challenges, because implementation such in-road charging system would definitely require significant infrastructure changes, including the installation of transmitter pads and power supply segments along specific routes with extremely high installation and maintenance costs.

Moreover, precise alignment between the transmitter and receiver coils is crucial for optimal power transfer efficiency. This might necessitate the use of self-driving cars in the future, but it will definitely be a promising prospect for a wide range of EV applications, including light-duty vehicles, buses, rail, and rapid transport.

In conclusion, while DWC holds the potential to revolutionize the EV industry, it is still a work in progress and under research investigation with many technical, logistical, and infrastructural obstacles to overcome. Nevertheless, once fully realized, this technology could completely transform our approach to EV charging and usage (25).

After going through the different types of charging methods used to charge an electric vehicle, Table 2 shows the advantages and disadvantages for Battery swapping stations, Wireless power transfer and Conductive charging.

Table 2: Advantages and Disadvantages comparison of different Charging methods



Types	Advantages	Disadvantages
BSS	Quick battery replaces (Fully charged) BSS extend the battery life by slow charging BSS help utilities in balancing the demand and load by using the V2G facilities Easy to integrate with the locally generated RESs.	More costly than ICE vehicle because of the monthly rent to BSS The huge investment required for both equipment and batteries Need a large stock of expensive batteries Many areas needed to accommodate the batteries Different EVs have different battery standards.
WPT	EV recharge it safely and conveniently No need for any standard connector No need for any standard Socket Recharge when the vehicle is in motion.	Power transfer is generally weak The range of 20 to 100 cm for efficient power transmission The transmitter and the EV should be real-time and communication latency.
CC	Provide multiple charging levels Provide high efficiency Coordinated V2G facility Reduce the grid loss maintain voltage level prevent grid power overloading Active power support.	Complex infrastructure Restriction to the electricity grid Fast charging cause voltage instability in the distribution system Need a standard connector/charging level Grid power overloading will cause due to uncoordinated charging V2G operation reduces the lifetime of the battery.

3.2 EV charging standards

In order to effectively manage the electric vehicle charging process, comprehensive classifications and regulations have been instituted in Europe and North America. These standards ensure the seamless, safe, and efficient operation of the EV charging infrastructure (30).

The SAE J1772 standard by SAE International governs the essential physical, electrical, and functional specifications for conductive charging of EVs in North America. SAE international terminology as “Charging Levels” is defined in order to classify between different charging powers, consisting of four charging levels: AC Level 1 and 2, and DC Level 1 and 2. The charging levels and specifications for SAE J1772 standards are summarized in Table 43.

IEC 61851-1, a standard published in 2017, defines four distinct charging modes in countries outside of North America. In Europe and other countries, IEC uses “Charging modes” as terminology consisting of also four different modes for charging powers, having Mode 1, Mode 2, Mode 3 and Mode 4, these modes specifications are found in Table 44 (31).

There also exists China GB (Guo Biao) standards (32). For Wireless charging several standards exist from societies like IEC, SAE and IEE and are summarized in Table 45.

As for charger couplers, several standards govern these connectors. The Society of Automotive Engineers (SAE) handles this in the US and parts of the Pacific, the IEC takes care of much of the world, predominantly Europe and Guobiao Standards (GB) looks after standardization in China. Specifications of different AC and DC charging connectors are found in Table 46 and Table 47.

4 BATTERIES

In the context of electric vehicles, batteries have a crucial role, as they are the primary source of power. The operation of batteries mainly operates by electrochemical reactions, involving a positive electrode (cathode), a negative electrode (anode), and an electrolyte that facilitates the flow of ions between these electrodes.

Electric Vehicles are typically equipped with two different battery types; the first type is called the high-voltage or 'traction battery', and the second one being the low-voltage battery. The traction battery serves as the main power source, fueling the electric traction motor through a three-phase power inverter. This battery, which in general relies on Lithium-ion technology, can be recharged via AC current as we have seen previously by an onboard charger or directly through DC current supplied by fast-charging stations. On the other hand, a 12 V lead-acid battery is used to power the vehicle's auxiliary loads. This battery is recharged from the high-voltage battery through a DC-DC converter (33).

The traction battery is an assembly of individual cells combined into modules that are grouped to form as known as the high-voltage battery. The design of these battery cells might differ from an electric vehicle to another and is guided by factors like energy density, heat dissipation, manufacturing cost and weight (34).

Some of the most common types of EV batteries include Lead-acid, Nickel-metal hydride (NiMH), Lithium-ion (Li-ion). Lead-acid batteries, though cost-effective, suffer from low energy density and shorter lifespan. NiMH batteries fare better in terms of lifespan and can deliver higher power, but they are still eclipsed by Li-ion batteries in most performance aspects. The main advantage of Li-ion batteries is that they have high energy density, long lifespan, and relatively fast charging times. Their only major disadvantage is that they have higher cost and some safety concerns related to overheating. Electric vehicles batteries specifications are summarized in Table 48.

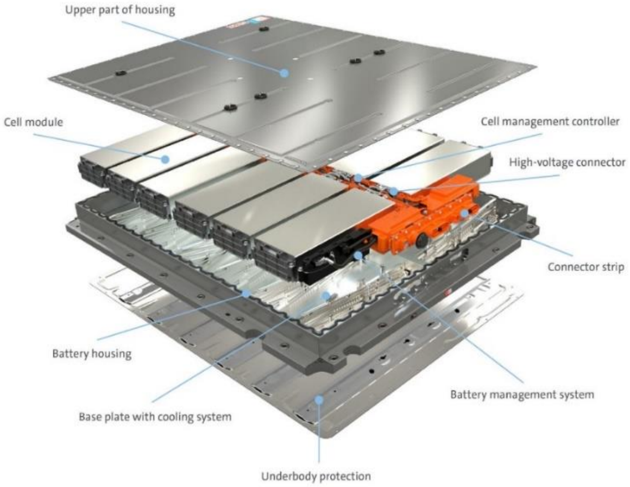


Figure 15: EV high voltage battery components (35)

4.1 Battery Terminologies

Terminologies of a battery are used to describe some important aspects that leads for a better understanding of its characteristics and functioning, they are described as following (36):

Energy Capacity: This term refers to the total energy storage potential of a battery, usually measured in kilowatt-hours (kWh) or Joules (J). It essentially indicates how much electric energy a fully charged battery can deliver before it needs recharging. This parameter is critical in electric vehicles as it largely determines the driving range and it can be express by:

$$EC(T) = \int_0^T v(\tau)\, i(\tau) d\tau$$

With v(t) and i(t) instantaneous voltage and current

Rated Voltage: This is a cell or battery's benchmark voltage, often known as the "Normal" voltage. It is the voltage value when the battery is at roughly 50% state of charge (SOC).

Cut-Off voltage: This is the lowest voltage limit when a battery is considered fully discharged. This limit varies based on the type of battery and its usage.

Rated Capacity (Cn(%)): This is the amount of ampere-hours (Ah) a battery can provide in a single discharge, from 100% SOC to the cut-off voltage under specified conditions. It is influenced by several factors such as discharge current, electrolyte type and density, separator design, temperature, battery age, usage history, electrode design and dimensions. We can also express battery capacity in watt-hours (Wh) or kilowatt-hours (kWh) in the given Equation.

Rated Capacity (Wh) = Rated Capacity (Ah) x Battery Rated Voltage (V)

Charge rate (C-rate): This describes the speed at which a battery is discharged relative to its total capacity. For instance, a 1C rate means that a fully charged battery will be depleted in one hour.

Discharging/charging current: The capacity of a battery is typically determined through a process known as constant current discharge-charge tests. In these tests, a battery is initially fully charged to a voltage equivalent to its open-circuit voltage (V0c). A constant current is then applied to discharge the battery and after a certain time (discharge time), the voltage drops below the cut-off voltage and the battery is empty. Both energy capacity and coulometric capacity can vary based on the discharge current, operating temperature, and the battery's age.

State of Charge: This is expressed as the percentage of the battery's current capacity compared to its total capacity. It is affected by the discharging current, the operating temperature and ageing.

$$q(t) = SOC = \frac{Q(t)}{Q_0(t)}$$

The SOC can be estimated by integrating the battery current over time to quantify the change in battery capacity.

$$SOC(t) = SOC(t0) - \int_{t0}^{t} \frac{Ib}{3600Cn} dt$$

with *SOC(t0)* being the SOC initial value, *Cn* the battery rated capacity and *Ib* the battery current

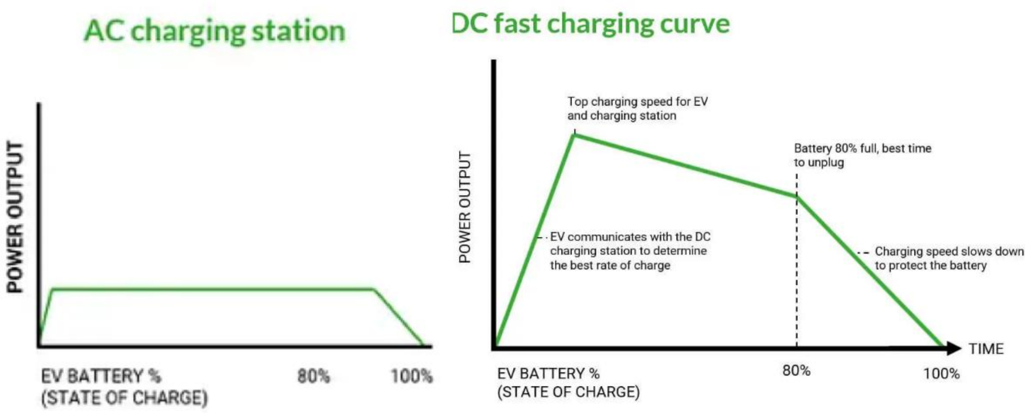


Figure 16: Understanding the charging curve for AC and DC (kW vs SoC) (37)

Internal resistance: This is the cumulative resistance within the battery, which accounts for the ohmic contributions of various components. This resistance is influenced by the SOC of the battery and can fluctuate with temperature.

State of Health: This is a measure of the maximum available battery charge compared to its rated capacity. The SOH is a critical for evaluating the remaining lifespan of the battery and understanding its performance degradation level.

$$SOH(\%) = \frac{Battery\ Available\ Capacity}{Rated\ Capacity}$$

4.2 Charging strategies for EV batteries

Several factors of the battery such as longevity, efficiency, and safety of a battery are mostly affected by the techniques adopted for charging and discharging it, these charging strategies are explained below (36):

Constant Voltage (CV): This is a charging strategy used where a battery is charged by sustaining a constant voltage across its terminals while the battery current is gradually decreasing until it reaches zero. However, this method has a downside in that it demands a high current at the beginning of the battery charging process, which could be managed by reducing the CV value. This charging method is used in any type of battery.

Constant Current (CC): This strategy is used in charging/discharging electric vehicle batteries. The method tries to keep the battery's current constant with a fixed C-rate as the battery voltage increases until it reaches its maximum charge value.
Constant Current–Constant Voltage (CC-CV): As shown in Figure 17, this dual-stage charging technique consists of two stages: a CC Stage and a CV Stage. In the first stage, the battery is

charged at a constant current, until the battery voltage attains the full charge voltage. In the second stage, the battery voltage is held constant until the current decreases to the cut-off current.

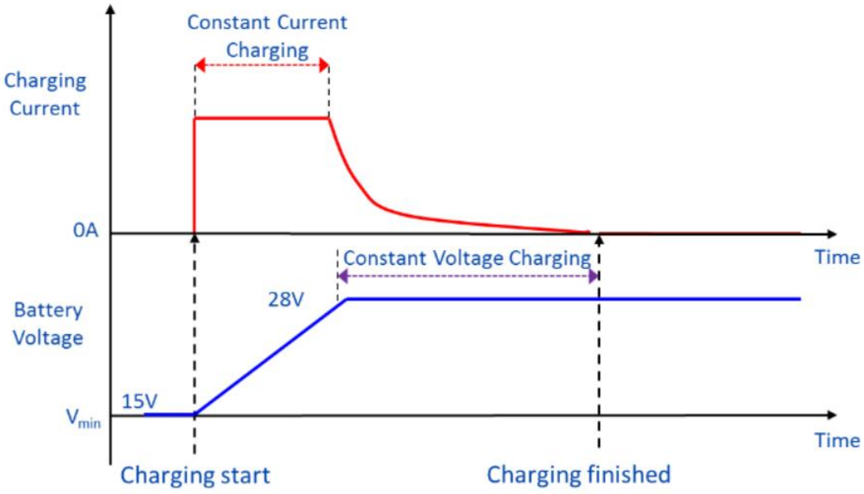


Figure 17: Constant current-constant voltage battery charging (38)

Multi-stage Constant-Current (MCC): This method a fast charging technique for batteries that in general consists of multiple constant-current levels. The set C-rate diminishes progressively at each CC stage to reduce the battery's temperature and charging duration, this method is shown in Figure 18.

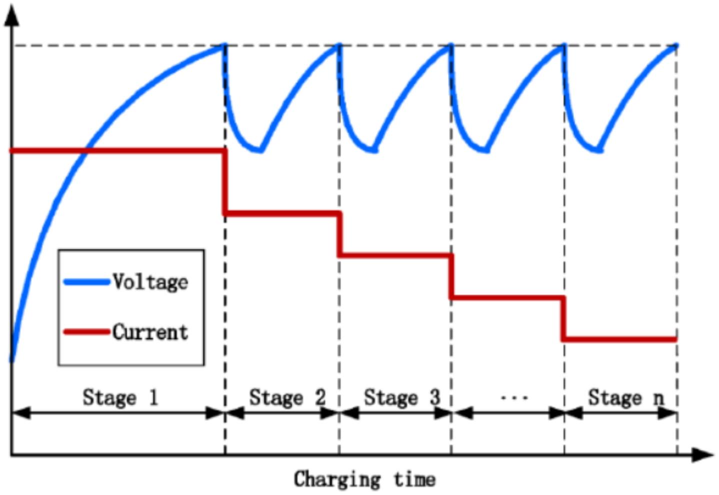


Figure 18: Profile of the Multi-stage Constant-Current battery-charging strategy (36)

Pulse charging and Negative Pulse Charging are also some charging techniques that were initially created to boost the efficiency of charging converters for lead-acid batteries and are now applied to lithium-ion batteries as well.

4.3 Battery Influencing Factors

In the context of charging an electric vehicle, in order to have better understanding of losses in the battery, we need to identify the several factors that influence the battery. These factors leads to major decrease in the overall efficiency of the charging process, therefore, a major increase in charging losses (39).

4.3.1 Capacity

Battery capacity naturally degrades over time due to chemical side reactions like lithium-plating, solid-electrolyte-interface creation, pore clogging, and surface cracking. This degradation is influenced by environmental temperature, cut-off voltages, and charging and discharging currents. Therefore, if we have an 80% state of health, this means that we have only use 80% of the battery overall capacity, which can significantly affect its efficiency and lead to more losses, particularly in cold temperatures.

4.3.2 Lithium plating

The deposition of lithium-ions on the graphite layer of a cell's negative electrode is a major influencing factor that can have an impact battery efficiency. This process indirectly has impacts on charging efficiency by influencing the battery's ageing, internal resistance, and usable capacity. Under ideal conditions, lithium-ions intercalate into the anode's grid structure. However, factors such as temperature, upper cut-off voltage, and charging current can cause lithium plating, which leads to more power losses in the overall system.

4.3.3 Open-circuit voltage

OCV is parameter that depends on the battery state of health that in general represents the battery's electrical output when we have no applied load, illustrating the ideal voltage behavior without losses. Open circuit voltage is mainly influenced by factors such as capacity, side reactions, state of health, current direction, and battery temperature, open-circuit voltage helps the BMS assess the current SOC when the battery is not under load.

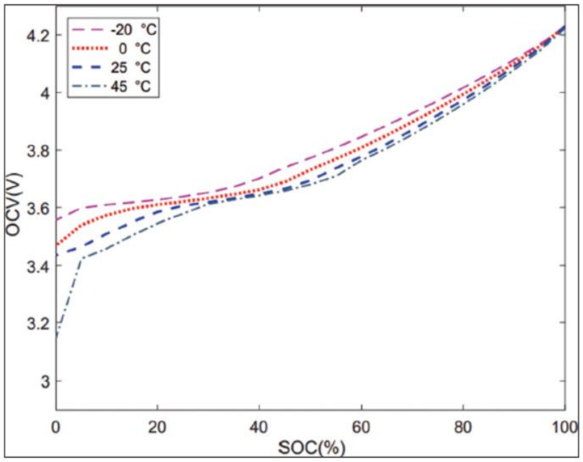


Figure 19 Discharge OCV curve over the SOC for different temperatures (39)

4.3.4 Cell and Ambient Temperature

Both cell and ambient temperature significantly affect a battery's energy. Manufacturers usually recommend specific temperature ranges for operation and storage. The performance and usability of a battery are highly influenced by its operational temperature, where battery and charging operates differently under extremely cold vs extremely hot weathers. Higher temperatures promote aging and influence both the OCV and internal resistance of a battery, thereby directly affecting its efficiency that will also lead to higher power losses in the system.

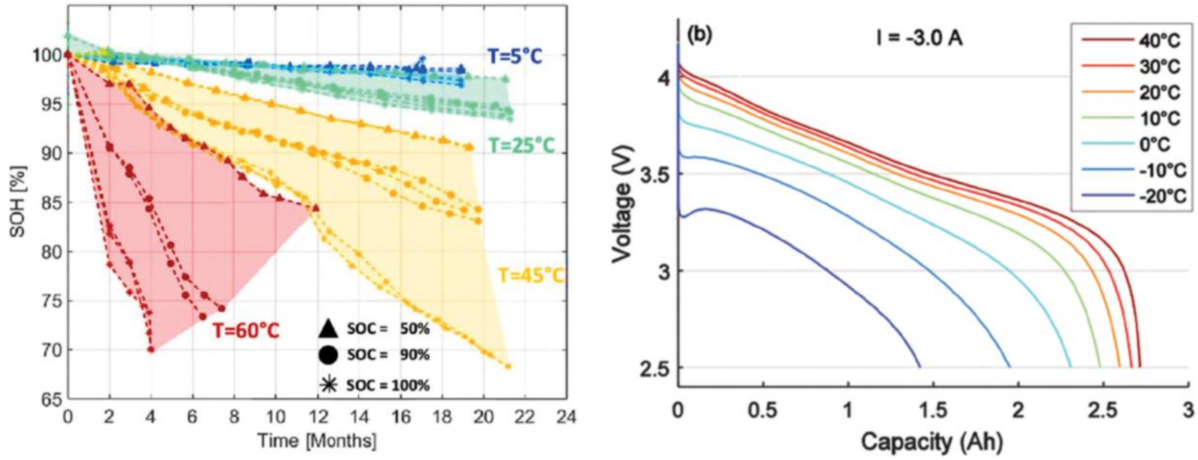
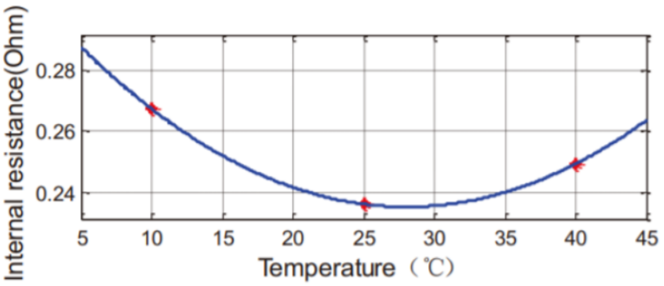


Figure 20: Calendric ageing of a commercial 16 Ah cell at different temperatures and different SOC values + Discharged capacity at different cell temperatures with the correlating terminal voltage of a 2.8 Ah Panasonic NRC18650PD cell (39)

4.3.5 Internal Resistance

The internal resistance of a battery cell plays a significant role in determining power losses, heat generation, extractable energy, and the overall performance of an electric vehicle system. Factors such as temperature, current SOC, and SOH, as well as both calendar and cyclic aging, affect the internal resistance. Therefore, the internal resistance influences the battery's pulse load capacity, cold or hot start characteristics, and the removable capacity in the load case.



Internal resistance (Ohm) in function of battery temperature (40)

4.3.6 Battery Management Systems (BMSs)

Battery Management Systems are in general devices in the battery that monitor and regulate individual battery cells or the entire battery systems. It mainly plays a crucial role in protecting functions that leads to extending the health of the individual cells. External imbalance might occur due to uneven heat distribution or power consumption from protection integrated circuits.

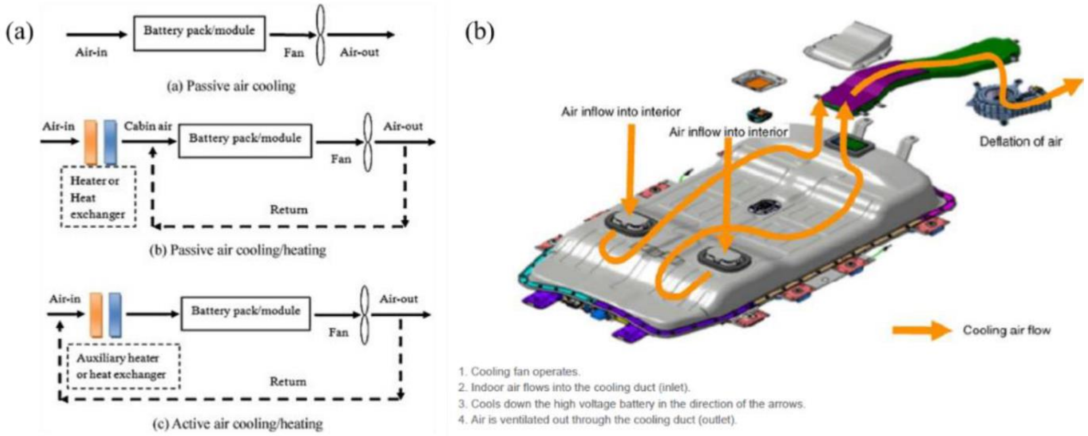
There are active and passive balancing methods, passive balancing is a less costly and simpler method and it is widely used. However, it results in energy losses, and active balancing can be more effective in preventing battery aging. Active balancing, while more effective, is also more complex and expensive. So regardless which of these methods is used, both strive to mitigate capacity losses, prolong battery life, and ensure consistent performance.

4.4 Battery Thermal Management

The charging and discharging processes and specially while varying the input power can generate substantial amounts of heat that will majorly influence the overall charging efficiency and even cause permanent damage to cells. This is why thermal management of the battery is a major system that needs to be implied to prevent any type of physical or performance damage. Thermal management in batteries addresses two key issues: excess heat generation during operation and uneven temperature distribution. Overheating could lead to melting of the electrolyte between the electrodes, leading to reduced power output, internal short circuits, or even explosions in extreme cases. Uneven temperatures within a battery pack can also accelerate degradation of battery cells.

There are three key techniques for battery thermal management (38):

Air Cooling: Air cooling methods are simple, cost-effective, and easy to maintain. This technique allows for direct contact with battery cells and carry no risk of leaks. However, they are not the most efficient means of removing heat due to the small heat capacity of air and challenges in maintaining uniform temperature. Figure 21 illustrates a typical air cooling system.



1. Cooling fan operates.
2. Indoor air flows into the cooling duct (inlet).
3. Cools down the high voltage battery in the direction of the arrows.
4. Air is ventilated out through the cooling duct (outlet).

Figure 21: (a) Mechanism of air-cooling battery thermal management system and (b) the air-cooling system onboard the Kia Soul EV

Liquid Cooling: This is another type of BTM illustrated in Figure 22, while more complex and costly compared to air-cooling, it offers more effective heat transfer due to the larger heat capacity of liquids. However, these systems demand more maintenance and parts. They can use a variety of cooling fluids, like water and glycol solutions, or dielectric mineral oil, each with its own pros and cons.

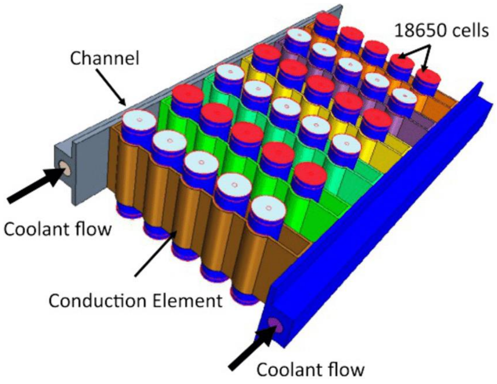


Figure 22 Schematic of liquid cooled BTMS with conduction elements (41)

Phase Change Materials: PCM-based systems are a type of cooling systems for the battery that manly use a patented wax-graphite material that absorbs heat from the cell and transforms from a solid to a liquid state, effectively removing heat and limiting the battery's temperature rise. Once the battery is no longer in use, the PCM rejects the stored heat to the environment and returns to a solid state at ambient temperature, ready for reuse. This type of technology can prevent cascading failure if a single cell overheats. One of the main advantages of this system is that it is affordable, lightweight, and low-maintenance solution with high thermal conductivity and heat capacity that allows efficient heat transfers.

5 CONDUCTIVE CHARGING

This thesis aims in modeling and simulating different charging strategies and scenarios for an EV, to do so, we need to have a good understanding of charging losses and chargers efficiencies. There are three main sources of power loss during conductive charging: Converter Inefficiencies, Connector and Cable Losses, and Battery Internal Resistance. Each source overall contribution depends on various factors such as the state of the battery (SOC & SOH), the battery technology as well as the charging rate.

Around half of the charging losses are due to converter losses, modern AD-DC converters and onboard chargers have efficiencies around 90%, various components in this conversion contributes in these losses such as Diodes, switching devices, Inductors and Transformers, Capacitors and other components as well. (42).

Connector and Cable losses contributes in around 10-15% on these overall losses, they are primarily due to resistive heating , and many factors are included that may lead in varying these types of losses such as cable material, length and thickness, power rates and ambient temperature. Similar to cable losses, there is also a contribution at around the same percentage in losses due to Battery internal resistance, these losses can be higher during fast charging and when the battery's state of charge is very low or very high. Other remaining factors that contribute in theses loses in small percentages include Battery management system, knowing that the BMS have some components that consumes power leading in small contribution of losses, we also have cooling system losses specially during fast charging to keep the battery temperature in check and other influencing factors to the battery seen in chapter 4.

The first approach aimed to try to theoretically compute these losses and specially for the converter inefficiencies, but most of the literature found for EV charging losses mainly compute and evaluate these losses experimentally, as there exists limited literature covering all different aspects of charging and especially charging losses. Almost all authors mainly measure experimentally for different conditions (temperatures or SOC), the total power or energy delivered from the grid and the power or energy received by the vehicle and by that they would be able to identify the losses and conclude the charger efficiency (43). After investigating in most of the existing literature regarding charger losses, there was one article found proposing the calculation models to compute the power losses of a fast charger, the authors were only able to theoretically quantify the conduction and switching for MOSFETs and Diodes which represent only 1-3% of the charger overall power losses percentage (44). Therefore, experimental data will be collected from different tests found in literature regarding charging curves and efficiency tests on different state of charges done for several models of the Nissan leaf in order to obtain accurate real-life results of charging losses using mathematical modeling and curve fitting approximations. By navigating through these stages, the goal is to provide a comprehensive understanding of losses in conductive EV charging.

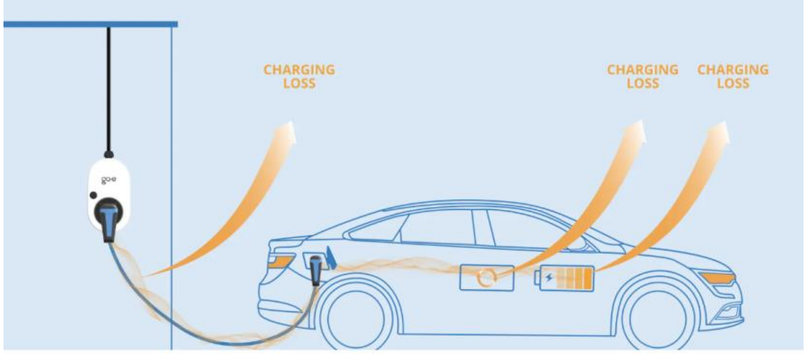


Figure 23: Conductive charging power losses

5.1 Cable Length and Thickness

Cable length and thickness, also known as cable gauge, play an influencing factor in conductive charging for electric vehicles. They essentially determine the resistance encountered by the current as it moves from the charger to the battery. According to Ohm’s law, the resistance (R) of a uniform conductor (such as a wire) is directly proportional to its length (L) and inversely proportional to its cross-sectional area (A), which is determined by the cable thickness. This relationship is expressed as R=ρ*(L/A), where ρ is the resistivity, a property of the material used in the wire.

The longer the cable or the thinner it is, the greater the resistance, which therefore leads to greater power losses. These losses primarily occur in the form of heat, generated by the electrical current's interaction with the resistance of the cable, which can also present a safety issue due to the heat generated.

The power loss in a cable due to electrical resistance is given by the following formula (45):

$$P = I^2 * R = \rho.(L/A).I^2$$

The thickness of an EV charging cable depends on the power level of the charger, and it can be determined by using the AWG chart for choosing the correct wire size, as for a given wire thickness, it can withstand a maximum amount of current. Here are the typical ranges for different types of chargers:

1. AC Level 1 (1.5-2 kW): It would be typically a cable with a cross-sectional area of about 1.5 to 2.5 square millimeters (mm²), corresponding to an American Wire Gauge (AWG) size of around 14 to 12.
2. AC Level 2 (3-20 kW): For a level 2 charger, the cable typically has a cross-sectional area of 2.5 mm² (lower power end, AWG 14) to 50 mm² (higher power end, AWG 1/0).

3. DC Level 1 (Up to 50 kW): DC fast charging is more variable because it can deliver very high currents. For a DC Level 1 charger delivering up to 50 kW of power, cables might range in size from 25 mm² (AWG 4) to 50 mm² (AWG 1/0), or possibly larger.
4. DC Level 2 (Up to 400 kW): For ultra-high-power DC Level 2 charging, cables can be as large as 120 mm² (approximately 250 MCM in AWG).

The following graph (Figure 24) shows the effect of varying the cable length on power loss for different charging levels. Looking into the loss variation, we can see that the power loss in general isn't that big with respect to the overall power delivered, knowing resistive losses due to the cable approximately represents around 10% of the overall losses.

However, analyzing within its margin, changing the cable length from 6 meter to 10 meters can increase the power losses by 40% for Ac level 2 charging. Whereas for cable thickness, there are limits of AWG for different currents in order to choose the right size, these limits are found in Table 49 and Table 50. Looking at Figure 29, if the cable length is assumed to be 7.5 meters, for a DC level 1 charger with a current of 100 A, increasing the thickness from 4.2 mm2 to 5 mm2 can lead to a reduction of Power Losses by approximately 15%.

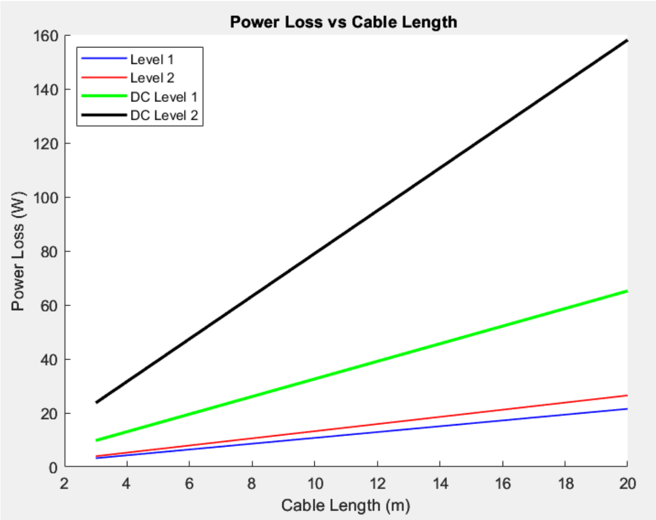


Figure 24: Power Loss in conductive charging with respect to Cable length for different charging levels

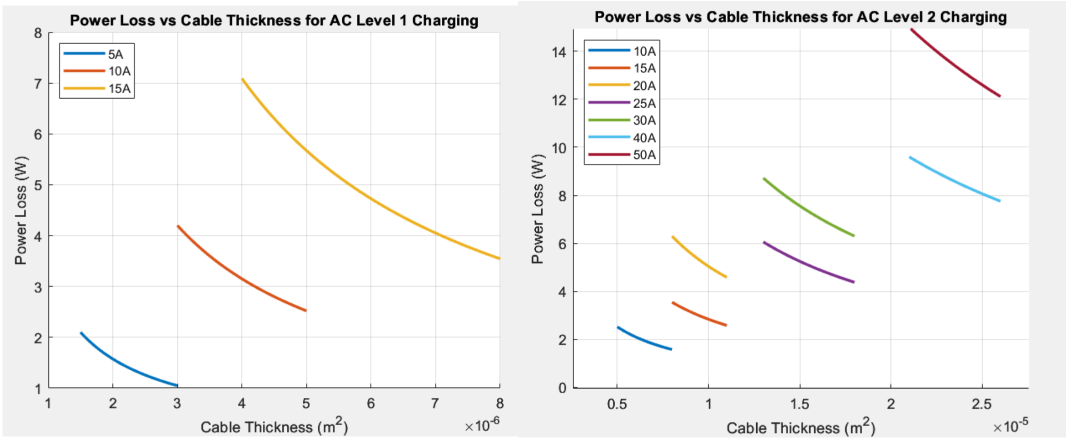


Figure 25: Power Loss in conductive charging with respect to Cable Thickness for AC Level 1&2 Charging

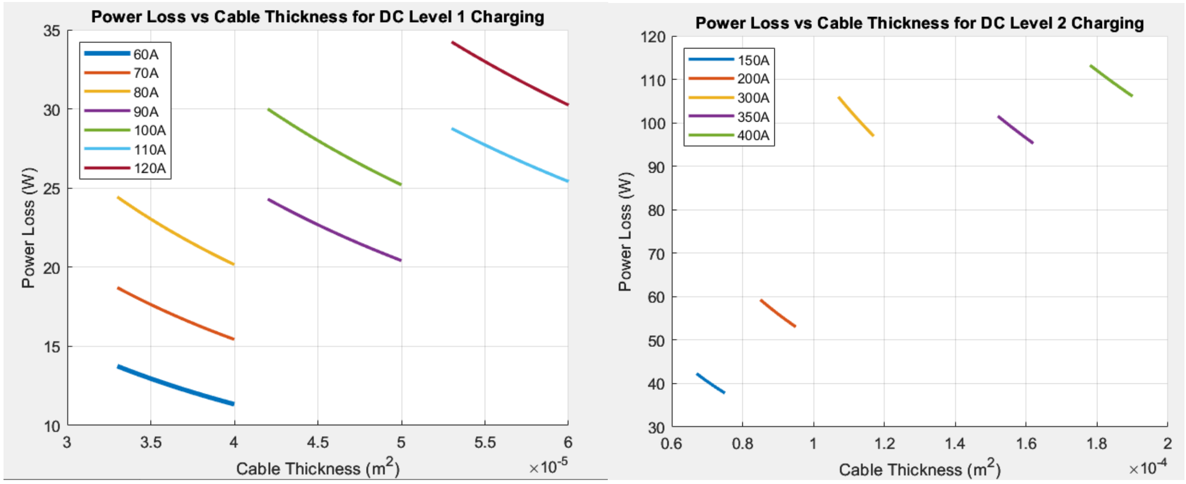


Figure 26: Power Loss in conductive charging with respect to Cable Thickness for DC Level 1&2 Charging

5.2 Cable Material

The choice of cable material is a crucial factor in determining the efficiency of conductive charging in electric vehicles. The type of material used to construct the cable can greatly affect its electrical resistivity, which in turn influences the power loss experienced during charging. Common materials used in charging cables include copper, aluminum, and sometimes silver, each with varying degrees of resistivity.

Copper, with its low resistivity of 1.68 x 10^-8 Ω.m at room temperature, is the most commonly used material in EV charging cables. It offers a good balance between cost, conductivity, and durability. On the other hand, aluminum, while cheaper and lighter than copper, has almost twice the resistivity (2.82 x 10^-8 Ω.m), leading to greater power loss for a given cable length and thickness. Silver, while having the lowest resistivity of all (1.59 x 10^-8 Ω.m) (46), is not that great of an option having approximately the same amount of power loss as Copper but with a huge difference of cost, which justifies why it is not used in typical application. For example, looking at Figure 27, by comparing for an AC Level 2 charger, the use of copper only leads to 5% more power loss than using silver; however, using Aluminum leads to 40.5% more power loss than for using Copper.

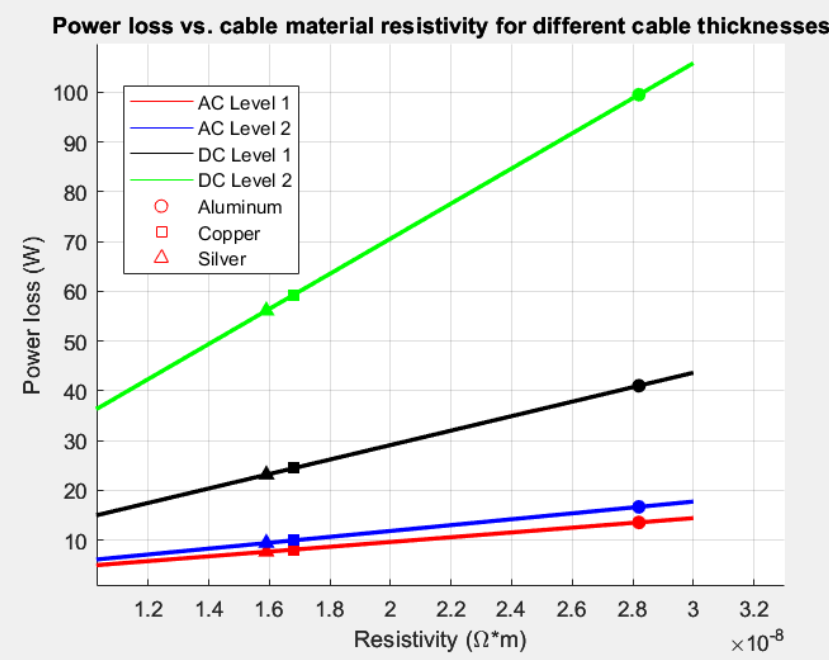


Figure 27: Power Loss in conductive charging with respect to Cable Materials for different charging levels

5.3 Ambient Temperature

Ambient temperature plays a pivotal role in conductive charging systems for electric vehicles. The resistance of both the charger's components and the cable varies with temperature, typically increasing with the rise in ambient temperature. This leads to higher power losses, as defined by Joule's Law ($P=I^2R$). . However, the resistance of a material changes with temperature, and this relationship is given by the equation:

$$R = R\_0 * (1 + \alpha * (T - T\_0))$$

where R is the resistance at temperature T, R_0 is the resistance at a reference temperature T_0 (often 20°C), α is the temperature coefficient of resistance, and T is the temperature in °C. So the power loss equation becomes:

$$P = I\hat{}2 * R\_0 * (1 + \alpha * (T - T\_0))$$

which shows how the power loss increases with temperature due to the increased resistance of the cable, therefore higher ambient temperatures increase the cable's resistance, which, in turn, theoretically leads to a rise in heat generation, and consequently further efficiency loss. Looking further into the results shown in Figure 28, there is a difference in power loss while increasing the ambient temperature, but it not that significant, as for varying the temperature from -10 degrees to 20 degrees, only increases the power loss by 12.4%. However, we cannot generalize that temperature does not have an overall effect on the whole charging system, because this variation of power loss only represents the resistive losses in the cable. While as mentioned previously, temperature has a major influence on the battery, the charger efficiency and even the vehicle energy consumption.

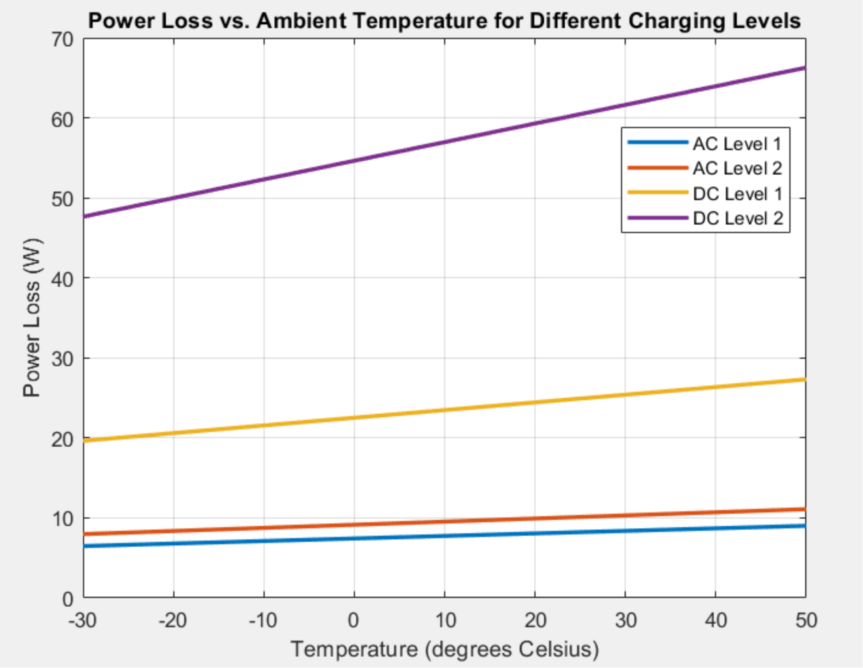


Figure 28: Power Loss in conductive charging with respect to Ambient Temperature for different charging levels

5.4 Battery State of Charge

The state of charge (SOC) of an electric vehicle's battery is a crucial determinant of power loss during the charging process. SOC refers to the current energy level of the battery relative to its capacity - with 0% indicating a fully discharged state and 100% representing a fully charged state. The relationship between the battery's SOC and its charging efficiency is nonlinear and varies throughout the charging process, with efficiency typically decreasing at extremely low and high SOC levels.

During the initial charging phase, often referred to as the constant-current phase, when the battery SOC is low, the battery can absorb energy more efficiently. However, as the battery approaches its full capacity, the charging process enters the constant-voltage phase, where the battery's ability to absorb energy diminishes, causing decrease in efficiency. This phase usually starts when the battery's SOC reaches about 70-80%. That is why every EV user has to know the importance of respecting the 20-80% rule of state of charge, not respecting this range will lead to high losses of power, a great decrease in the battery efficiency, and major effects on the battery state of health. Looking at the charging speed curve in Figure 29 for an actual Nissan Leaf experimental data using a 50 kW DC fast charger, it perfectly aligns with the theoretical DC charging curve. It is shown that the power is stepped down as the battery becomes fuller at around 60%, after that when it reaches 80% SOC, one can visualize a sharp decline in the charging power until it reaches 100% (47).

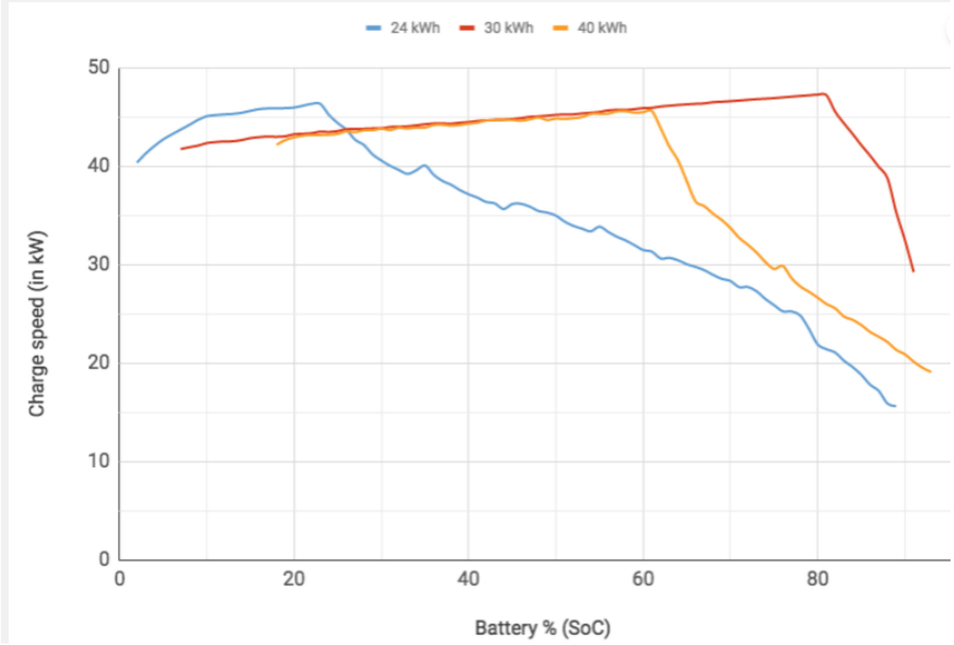
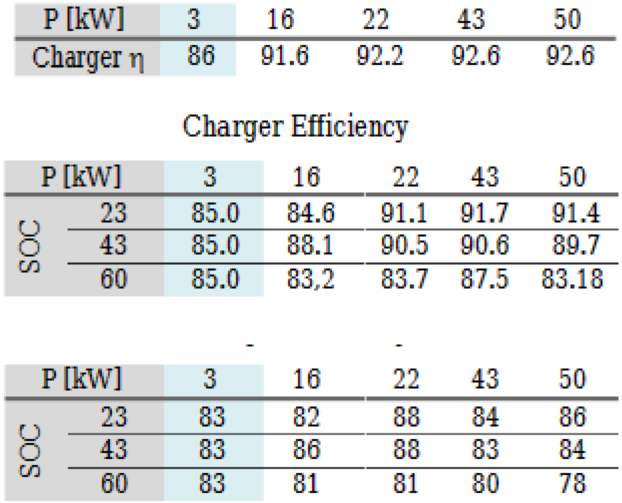


Figure 29: Charging Speed (in Kw) with respect to Battery % SOC for different Nissan Leaf Battery capacities (24kWh, 30kWh, 40 kWh)

An experimental study made by ENEA Research lab, highlighting the effect of SOC% on the overall efficiency of the charging process, the experiment was conducted on a 24 kWh Nissan Leaf on different charging powers (3kW, 16 kW, 22kW, 43kW and 50kW). The efficiency of the battery after charging and discharging was obtained, in addition to the efficiency of the charger at different SOC% (23%, 43% and 60%), and the overall efficiency vs power and initial SOC was calculated by multiplying the battery and charger efficiency. The results are summarized in figure 30 showing that the overall efficiency at low SOC% increases with the increase of the power delivered, except for the 22kw charger, which shows the highest efficiency compared to other power delivered. For the lowest power delivered, the efficiency is pretty much constant along different SOC%, which typically represents an AC level 1 and is also confirmed by other literature, moreover, the overall efficiency is decreasing with the increase of SOC% by getting closer to 60% (48).



P [kW]	3	16	22	43	50
Charger η	86	91.6	92.2	92.6	92.6

Charger Efficiency

	P [kW]	3	16	22	43	50
SOC	23	85.0	84.6	91.1	91.7	91.4
	43	85.0	88.1	90.5	90.6	89.7
	60	85.0	83,2	83.7	87.5	83.18

	P [kW]	3	16	22	43	50
SOC	23	83	82	88	84	86
	43	83	86	88	83	84
	60	83	81	81	80	78

Figure 30: Battery Efficiency, Charger Efficiency on different power and SOC, Overall Efficiency on different power and SOC (48)

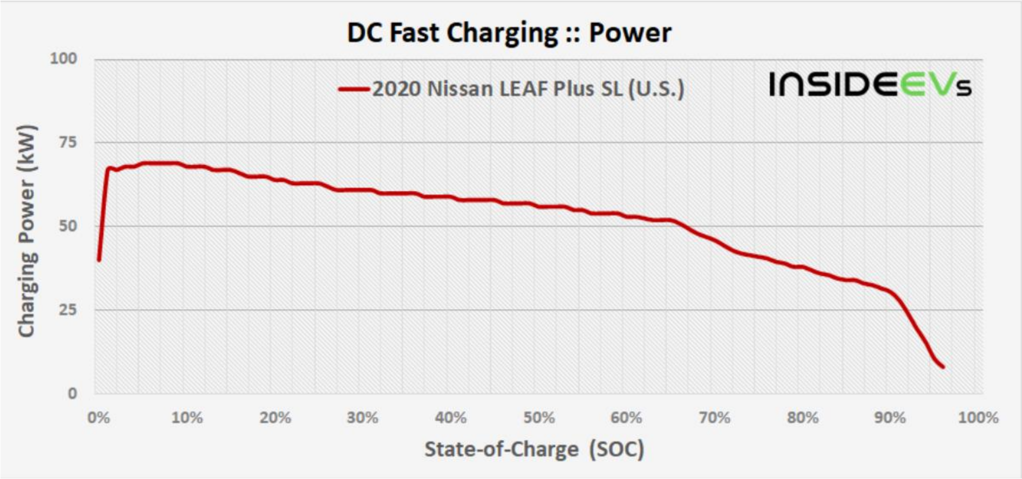
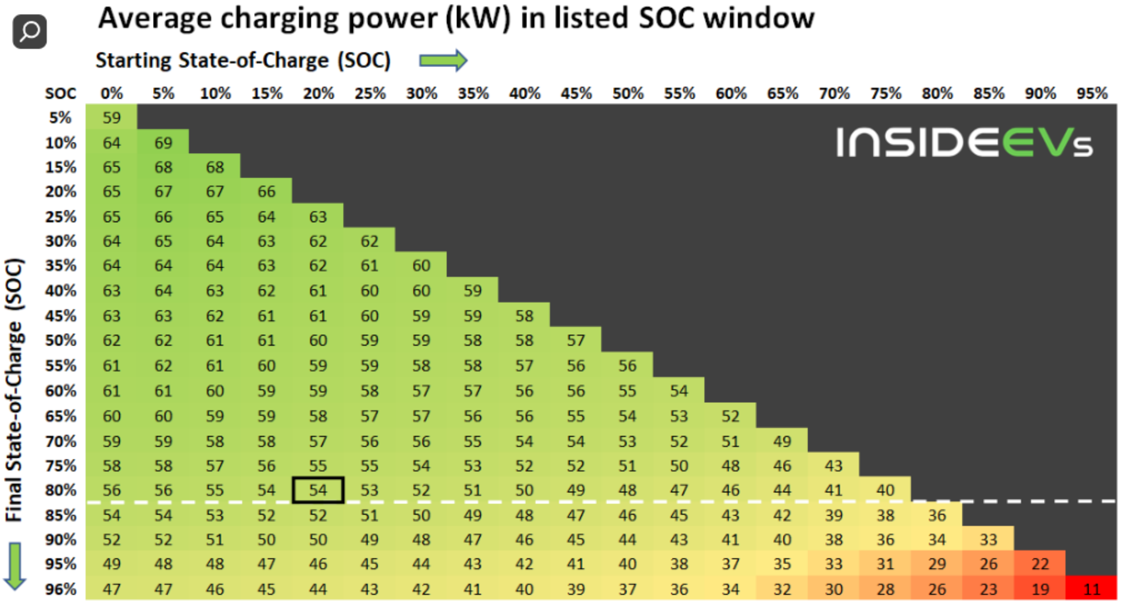


Figure 31: Charging Power with respect to battery SOC% for Nissan Leaf 62 kWh (49)

This graph shown in Figure 31 represent the power charging curve for a bigger battery pack Nissan Leaf, this experiment was conducted by INSIDEVs (49), as they conduct hundreds of experiments on different electric vehicles models. This shows an interesting curve of charging the 62 kWh Nissan Leaf Plus with a 100kw charger, this graph shows that the power peaks at around 69 kW, charging from 20% to 80% took them around 35 mins, which is logical for this type of chargers with this battery pack. Other experiments were conducted, measuring the charging power with different starting SOC% and different desired SOC% shown in the Figure 32, the average power from 20% to 80% is 52 kW that is around 78% of its peak value. Understanding the impact of SOC on charging efficiency can help optimize charging strategies to minimize power loss and enhance the overall charging efficiency. This is particularly important in managing fast charging systems, where managing heat and minimizing energy loss during the constant-voltage phase can be challenging.



Average charging power (kW) in listed SOC window

Starting State-of-Charge (SOC)

Final State-of-Charge (SOC)

SOC	0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%
5%	59																			
10%	64	69																		
15%	65	68	68																	
20%	65	67	67	66																
25%	65	66	65	64	63															
30%	64	65	64	63	62	62														
35%	64	64	64	63	62	61	60													
40%	63	64	63	62	61	60	60	59												
45%	63	63	62	61	61	60	59	59	58											
50%	62	62	61	61	60	59	59	58	58	57										
55%	61	62	61	60	59	59	58	58	57	56	56									
60%	61	61	60	59	59	58	57	57	56	56	55	54								
65%	60	60	59	59	58	57	57	56	56	55	54	53	52							
70%	59	59	58	58	57	56	56	55	54	54	53	52	51	49						
75%	58	58	57	56	55	55	54	53	52	52	51	50	48	46	43					
80%	56	56	55	54	54	53	52	51	50	49	48	47	46	44	41	40				
85%	54	54	53	52	52	51	50	49	48	47	46	45	43	42	39	38	36			
90%	52	52	51	50	50	49	48	47	46	45	44	43	41	40	38	36	34	33		
95%	49	48	48	47	46	45	44	43	42	41	40	38	37	35	33	31	29	26	22	
96%	47	47	46	45	44	43	42	41	40	39	37	36	34	32	30	28	26	23	19	11

Figure 32: Average Charging Power needed (in kW) for Nissan Leaf having Initial and Final SOC% (49)

Whereas for AC charging, the power variation over state of charge is mainly constant, as it was shown in the previous chapter how the charging curves of DC and AC typically look like. In order to justify it by experimental measures, a study was made by charging a Nissan Leaf with an AC Level 1 charger, the author have measured the power at various measuring points (50). Looking at the results shown in Figure 33, real-life measure shows that the Power fluctuation for an AC charger is almost constant over all the charging process except when it nearly reaches 100%.

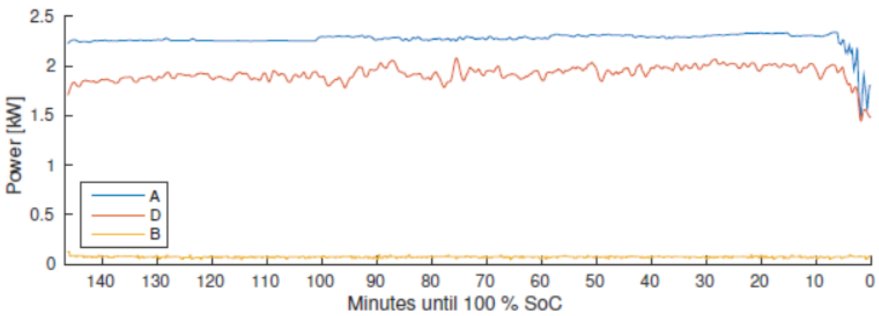


Figure 33: Charging Power until 100% SOC using AC charger for Nissan Leaf (50)

5.5 Battery Health

The health of the battery, known as State of Health (SOH), is a significant determinant in the efficiency of conductive charging for electric vehicles. SOH is a measure of a battery's current condition compared to its ideal state when it was new. This encompasses various aspects such as battery capacity, impedance, and the number of charge-discharge cycles the battery has undergone.

The overall efficiency of charging is negatively impacted as the SOH of the battery degrades over time. This happens due to a range of factors that were discussed in previous chapter. Each of these factors can contribute to increased losses during the charging process.

GEOTAB, a world leading company in connected transportation solutions based in Canada have conducted several results showing the battery degradation over a long period of time, with different scenarios (51).

The graph in Figure 34 shows the battery variation SOH over the years for two vehicles, one that drives a high range distance per year (>20000 km) compared to a low use EV (<8000km per year), exclusively operating in hot climates without a use of DC fast charger and charging with a Level 2 charger. After two years, it is shown that there is a small difference of 90% vs 92% degradation which let us conclude that a high or low use of vehicle doesn’t effect that much the vehicle SOH% as much as other factors.

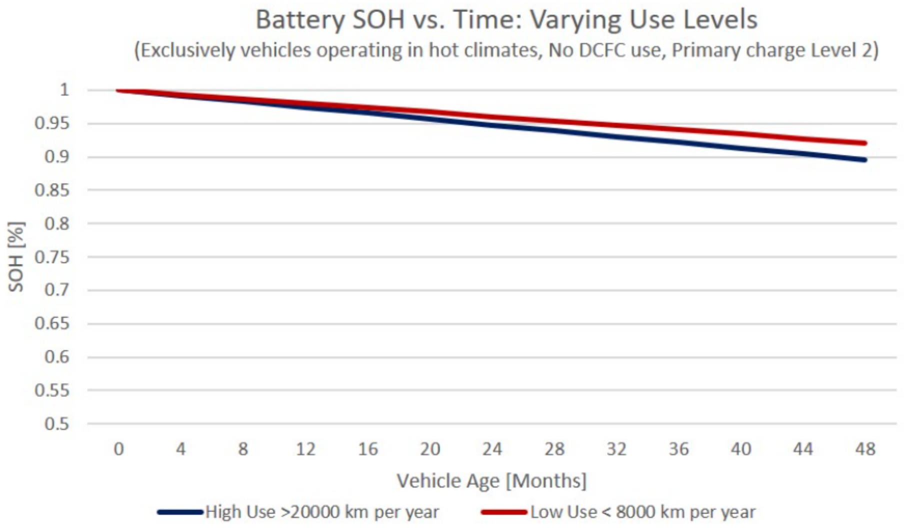


Figure 34: Battery degradation effects over time for high vs low vehicle usage (51)

Another interesting graph in Figure 35 shows the battery SOH variation with respect to time for a vehicle with High use of range over the years that uses Level 2 charger and no DC fast charging for different climates. After two years, a huge difference of around 6-7% of battery degradation is shown between hot and average climates, which lead to the conclusion that high ambient temperatures have major influence on battery performance, and will lead to huge drop in the charger efficiency and will increase the power losses after a few months.

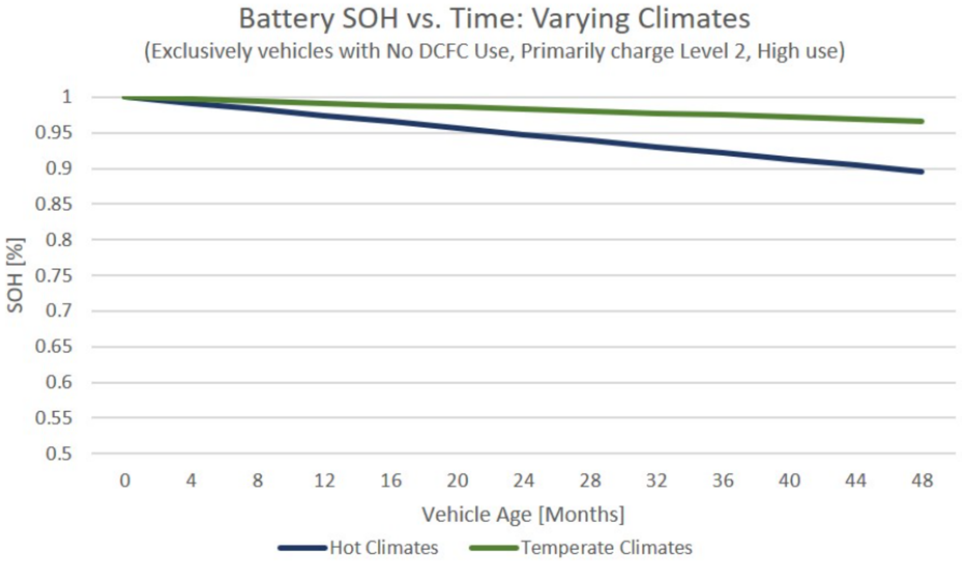


Figure 35: Battery degradation effects over time for hot vs Normal climates (51)

Looking at Figure 36, the graph shows the variation of battery degradation of the years with using different types of chargers. The difference in degradation between charging the vehicle using Level 1 and Level 2 charging is significantly low showing a 1-2% difference over the use after a period of time.

Nevertheless, what interests us the most in this research is to visualize and have a great understanding on the effect of DC fast charging on the battery degradation, the graph shown in Figure 37 shows this effect for a vehicle that normally uses AC Level 2 charger with a high driving use over the year. The results were compared for using DC fast charging over three times per month, using fast charging between 0-3 times per month and never use fast charging, the results shows a huge difference in degradation of 5% between each case. If DC fast charging is never used, the approximate battery SOH after two years will be around 90%, while if DC fast charging was used over 3 times per month, the battery SOH drops to 80% after two years, which is a huge difference and quantifies as major increase in power losses in the overall system.

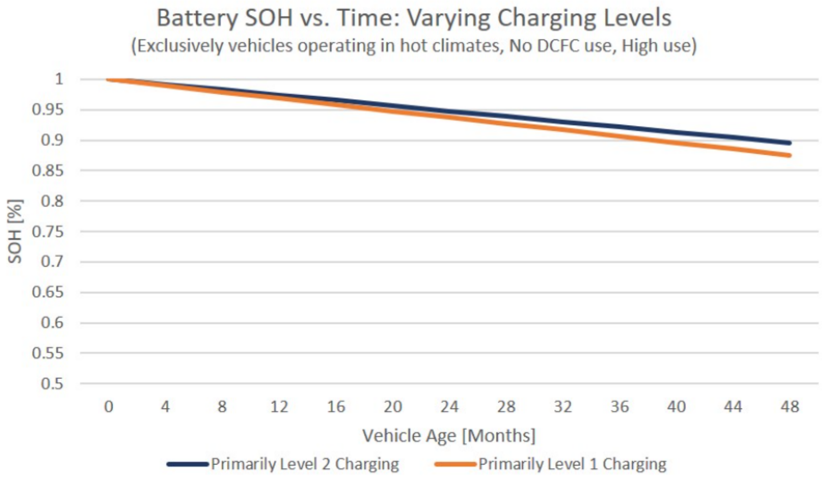


Figure 36: Battery degradation effects over time varying Charging levels (Level 1 vs Level 2) (51)

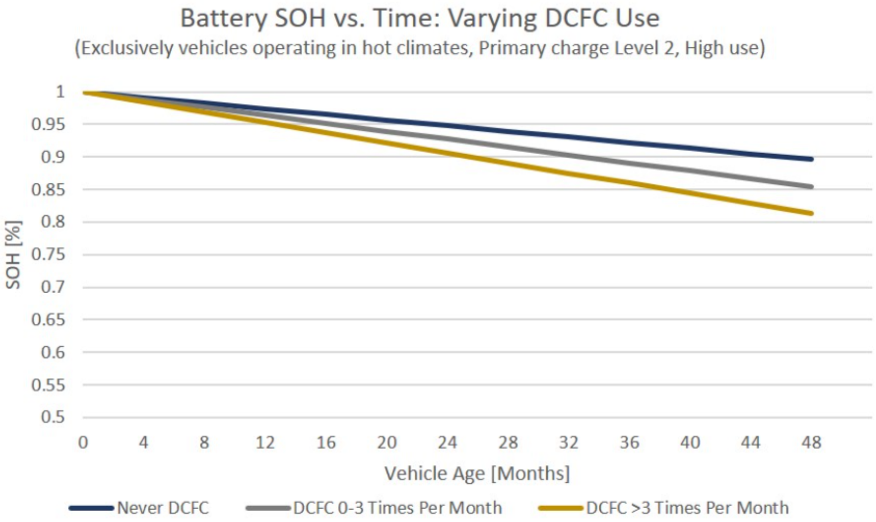


Figure 37: Effect of DC fast charging on Battery degradation over time (51)

Understanding battery health and its impact on charging efficiency is critical. It not only guides the design of efficient charging infrastructure but also the development of strategies for prolonging battery lifespan and thus enhancing the sustainability of electric vehicles.

5.6 Charging Power Level

The charging power level of an electric vehicle has a profound influence on the overall efficiency of the conductive charging process. It is typically classified into three broad categories: Level 1, Level 2, and DC fast charging. Each level represents a different power rating and, consequently, the rate at which an EV can be charged.

In conductive charging, it is essential to realize that higher power levels are not always characterized with better efficiency. As power levels increase, charging tends to generate more heat due to higher current flow, leading to increased losses in the form of thermal dissipation. The previous subsections have shown the effect of using different chargers having different charging power levels, each one of them having different power losses and efficiencies.

6 INDUCTIVE CHARGING

Traditional charging systems, also known as conductive charging systems, have their limitations. They rely on heavy charging wires and connectors, and the charger must be manually connected to both the power supply and the device being charged. Safety concerns also arise if the charging wire insulation deteriorates due to high temperatures, friction with the ground, or problems within the charging device itself. These issues can lead to short circuits or even potentially lethal electric shocks.

One can distinct different forms of wireless charging based on their application scenarios: stationary or static charging, where the vehicle is at rest, typically parked, opportunistic charging or quasi-static, which happens when the vehicle is briefly stationary, such as at traffic signals, and dynamic charging, which occurs while the vehicle is in motion, typically along a specific charging track. The methods method of wireless power transfer have been already discussed in this previous chapter by going through Inductive, resonant, capacitive and magnetic power transfer, and this chapter will focus on identifying the most widely used new techniques implemented by startups companies to emerge this promising charging technique with the identification of losses that might occur while wirelessly transferring power.

6.1 Technology implementation: Witricity

Despite the significant potential of wireless charging, its challenges remain a barrier for companies and charging stations to implement this technology. Witricity is one of the main leading companies in EV wireless charging, this section will describe the challenges and methodology from a company point of view for implementing such charging system. When considering WiTricity's wireless charging approach, it is important to note that this method eliminates the need for an On-Board Charger (OBC) in the vehicle, thereby simplifying the charging process.

Moreover, wireless charging operates within a narrow band of efficiency (between 88-93%) that is comparable to Level 2 plug-in charging. It has the added advantage of saving time since it eliminates the need for physically plugging and unplugging the vehicle.

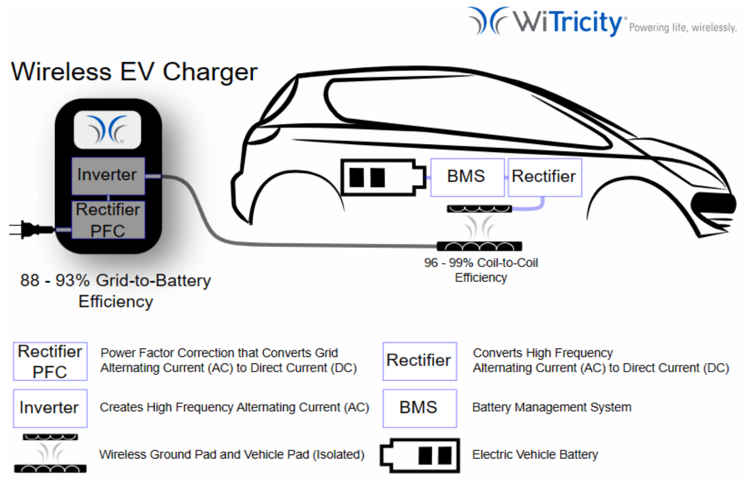


Figure 38: EV wireless charging (52)

From the Witricity official page, they have published a Whitepaper by Dr. Morris Kesler, giving an overview background around the idea of implementing this new technology and describing the system's functioning (53).

The system, as seen in Figure 39, is designed to convert the input power (which is usually AC power from a wall socket or DC voltage from a battery) into a radio frequency (RF) voltage waveform. This conversion is done by a high-efficiency switching amplifier.

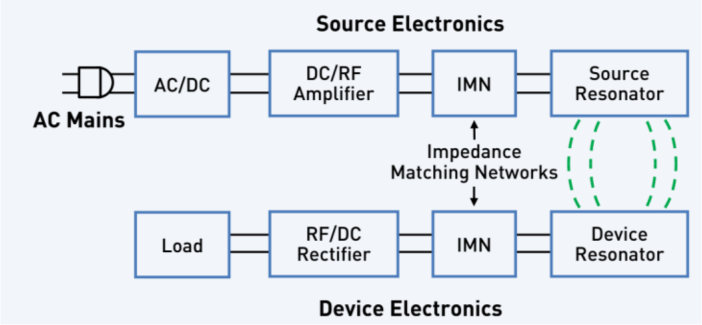


Figure 39: Block diagram of a wireless energy transfer system (53)

In Figure 40, there is a schematic representation of how inductive coupling works. By tweaking the value of Mg, you can get the input impedance you want, considering the load on the source resonator. Likewise, the device resonator's load can be controlled by adjusting ML, the mutual coupling to the load.

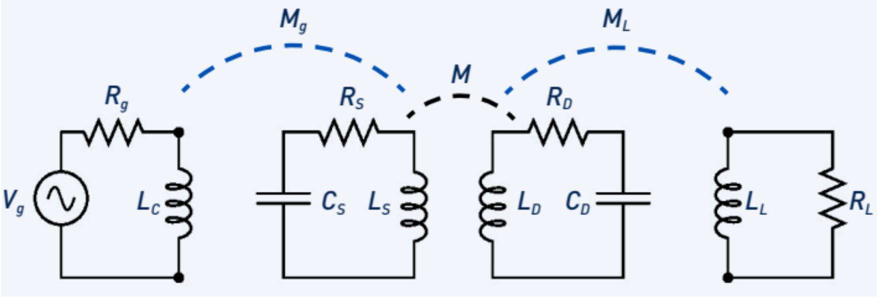


Figure 40: Schematic representation of inductively coupling into and out of the resonators (53)

Now, any standalone resonator can be described by two key parameters: its resonant frequency, denoted by ω0, and its inherent rate of energy loss, Γ. The ratio of these two parameters gives us the quality factor, or Q, of the resonator. This Q-factor tells us how good the resonator is at storing energy.

An example of an electromagnetic resonator is a simple circuit with an inductor, a capacitor, and a resistor, as shown in Figure 41. In this circuit, energy alternates at the resonant frequency between the inductor (where energy is stored in the magnetic field) and the capacitor (where energy is stored in the electric field), and energy is lost in the resistor.

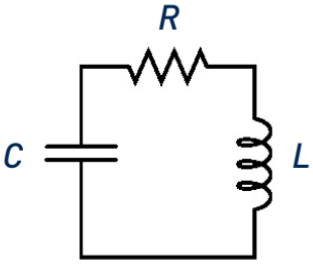


Figure 41: Circuit equivalent of an electromagnetic resonator (53)

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$Q = \frac{\omega_0}{2\Gamma} = \sqrt{\frac{L}{C}}\frac{1}{R} = \frac{\omega_0 L}{R}$$

The formula for the quality factor (Q) tells us that when the loss in the circuit is reduced, meaning when the resistance (R) is decreased, the quality factor of the system increases.

In systems that use highly resonant wireless power transfer, the resonators in the system need to have a high quality factor to ensure energy is transferred efficiently. High-Q electromagnetic resonators are usually constructed from conductors and components that have low absorption losses.

If we have two resonators, and we place them near each other. This leads to an interaction, a connection between them that is called "coupling." This connection allows them to swap energy back and forth.

To illustrate this, one can think of a series resonant circuit, as shown in Figure 42. In this Figure, the generator, which is a sinusoidal voltage source, has an amplitude of Vg and frequency ω, and a generator resistance of Rg. The source and device resonator coils, represented by the inductors LS and LD, are connected through the mutual inductance M ($M = k\sqrt{L_S L_D}$.) Each of these coils has a capacitor to form a resonator. The resistances RS and RD are the unwanted resistances, including both ohmic and radiative losses, of the coil and resonant capacitor for the respective resonators. Finally, the load is represented by an equivalent AC resistance RL.

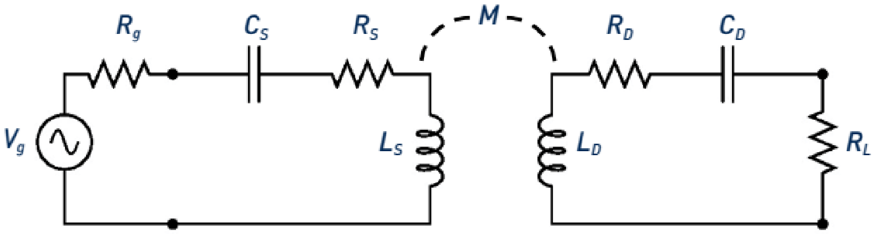


Figure 42: Equivalent circuit for the coupled resonator system (53)

By analyzing this circuit, we can calculate the power that is delivered to the load resistor, compared to the maximum power the source can give when both the source and device resonate at ω, as shown in equation Pl/Pg & U

$$\frac{P_L}{P_{g.max}} = \frac{4.U^2.\frac{R_g}{R_S}.\frac{R_L}{R_D}}{(\left(1+\frac{R_g}{R_S}\right)\left(1+\frac{R_L}{R_D}+U^2\right)^2}$$

Where $U = \frac{\omega M}{\sqrt{R_S.R_D}} = \frac{\kappa}{\sqrt{\Gamma_S.\Gamma_D}}$

This offers the flexibility to select the generator and load resistances that could give the best performance of the system. Alternatively, we can use a network that transforms impedance to align with other resistance values. If we select $\frac{R_g}{R_S} = \frac{R_L}{R_D} = \sqrt{1+U^2}$

Then the efficiency of the power transmission as defined above is maximized and is given by: $\eta_{opt} = \frac{U^2}{(\left(1+\sqrt{1+U^2}\right)^2}$

Referring to Figure 43, it is clear that systems with high values of U can achieve highly efficient energy transfer. This resistance essentially adds an additional term, Γw, to the unloaded device object's energy loss rate ΓD. Hence, the overall energy loss rate is expressed as: $\Gamma'_D = \Gamma_D + \Gamma_W$

and that the efficiency of the power transmission is maximized when:

$$\frac{\Gamma_W}{\Gamma_D} = \sqrt{1+\left(\frac{k^2}{\Gamma_S\Gamma_D}\right)} = \sqrt{1+k^2\mathrm{Q}_S\mathrm{Q}_D} = \sqrt{1+U^2}$$

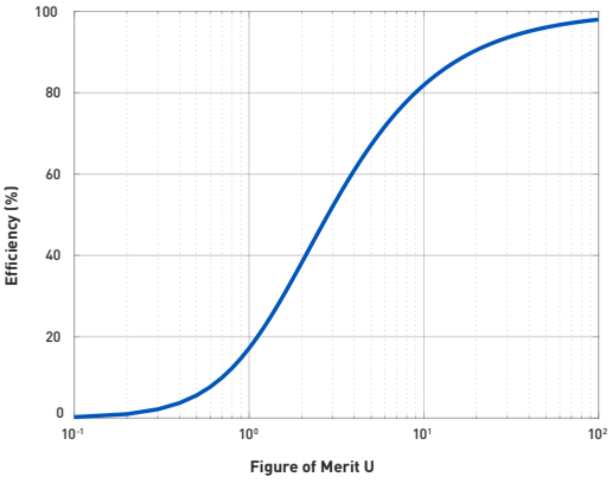


Figure 43: Optimum efficiency of energy transfer as a function of the figure-of-merit, U. (53)

It is important to point out that the highest efficiency achievable in a wireless power transmission system is purely dependent on the system's figure-of-merit. This figure-of-merit can also be expressed in relation to the magnetic coupling coefficient between the resonators (symbolized by 'k') and the unloaded quality factors of the resonators, represented as QS and QD.

$$U = \frac{\omega M}{\sqrt{R_S . R_D}} = k\sqrt{Q_S Q_D}$$

Understanding the quality factors of the resonators and the extent of magnetic coupling between them for a specific use case allows us to use the equation of η_{opt} to find out the highest efficiency the system can possibly achieve.

The magnetic coupling coefficient, a dimensionless parameter, signifies the proportion of magnetic flux that is coupled between the source and device resonators. Its magnitude can range between zero (meaning no coupling at all) and one (meaning all flux gets coupled). The coupling is dependent on the resonators' relative sizes, their distance apart, and their relative orientation.

Wireless power transmission systems based on conventional induction are typically designed for higher coupling values. As a result, they demand close spacing and precise alignment between the source and device.

6.2 Power Losses

Similarly to what was seen in Chapter 5 for conductive charging, inductive charging like all energy transfer mechanisms is subjected to inefficiencies in its overall system. While wireless power transfer eliminates the wear and tear for cables and connectors, however, it introduces its own set of inefficiencies and challenges. The main sources of losses in such systems are mainly contributed from three different factors: Misalignments and air gap between the transmitting and receiving coils, which these factors do not exactly contribute in power losses in the normal sense, but they contribute in loss of efficiency in the power transferring process. One other major factor that contributes in power losses for wireless chargers is Coil and Ferrite losses, where coil windings have resistance that leads to resistive losses as well as for Ferrite losses that are used to guide magnetic fields, can lead to hysteresis and eddy current losses. The last major loss contribution found in such systems are resonant circuit loses, for components found in the circuit such as capacitors and inductors. Other minor factors could be the presence of electromagnetic interference that can negatively influence the overall efficiency of wireless power transfer between the transmitting and receiving coils.

These factors are major factors only found in this technology, however it is still a charging process for an electric vehicle including power transfer to the battery, so converter and control circuitry losses are still a major effect in the overall charging inefficiencies. Moreover, common factors between conductive and inductive charging would still be the same with approximately the same amount of contribution to power losses in the system, such as influence of ambient temperature, charger's power output and influence of battery capacity and charging rate.

6.2.1 *Distance between charger and EV & Coil design*

One of the most important influencing factors when it comes to Wireless power transfer efficiency and power losses is the air gap, or the distance between the charger and the EV. Wireless charging systems in general work based on the principle of electromagnetic induction, where an alternating magnetic field generated by the charger induces an electromotive in the receiver coil in the vehicle.

Increasing this gap will highly affect the coupling coefficient of the system, where the coupling coefficient has a linear relationship with the mutual inductance that leads to a huge decrease in the efficiency of the wireless charger. In addition to air gap, one has to note that the coil design also has an impact on that coupling coefficient and therefore the system efficiency, different coil shapes have been studied in order to conduct the best-optimized shape to reach the highest efficiencies. A study was conducted in order to quantify the effect of air gap between the charger and the EV on the wireless charger, this study made a simulation for two different coil shapes, rectangular coils and circular coils, the results between the two designs while varying the air gap are shown in Figure 45 (54).

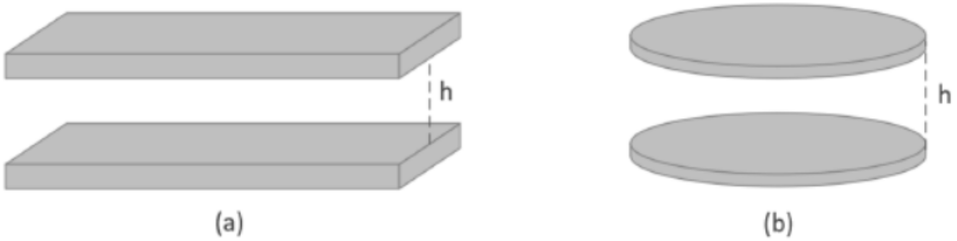


Figure 44: Perfectly aligned coils: (a) rectangular coils, (b) circular coils. (54)

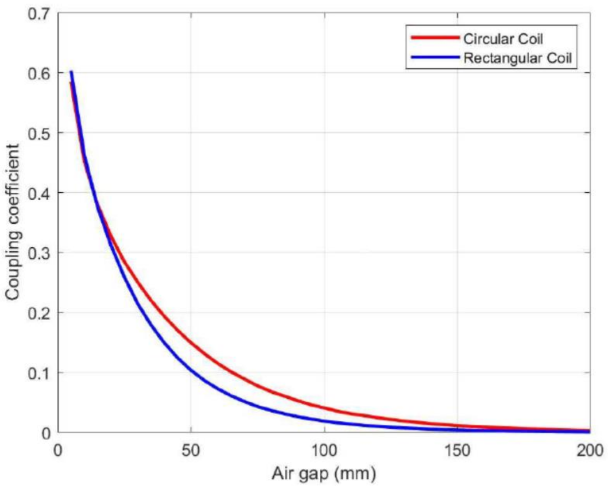


Figure 45: Circular and rectangular pads coupling coefficient for different Air gap (54)

6.2.2 *Alignment between EV and charger*

Alignment, or the relative positioning between the charger and the EV, plays also a huge influencing factor on wireless charging efficiency. In an ideal scenario, both the transmitter and receiver are perfectly aligned, and for this new technology of wireless chargers, companies are doing their best in order to minimize as much as they can the error in misalignment between the charger and the EV. This alignment ensures maximum coupling between the two coils, and hence, optimal energy transfer. However, in real-world scenarios, perfect alignment is difficult to achieve consistently, owing to various factors such as parking inaccuracies or irregularities on the parking surface. Therefore, automotive companies are now investigating in autonomous self-aligning systems for EVs where the vehicle itself can identify the location of the first and secondary coils and self-align without the user's effort to do so.

Misalignment, can be defined in different forms, such as longitudinal, lateral, rotational and angular misalignment which results in lower coupling and consequently, lower energy transfer efficiency. The energy is instead dissipated in directions other than the receiver coil, leading to losses. Different types of misalignments are shown Figure 46 and Figure 47, and the results of varying the different types of misalignment and their effect on the coupling coefficient therefore, the system efficiency are shown in Figure 48.

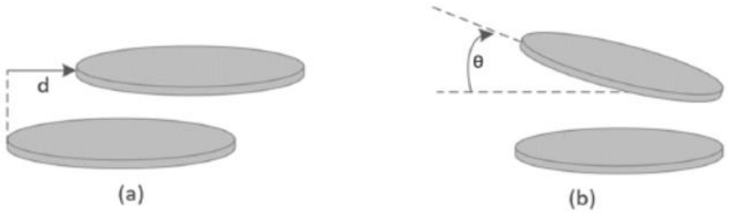


Figure 46: Misalignment in circular coils: (**a**) translational, (**b**) angular. (54)

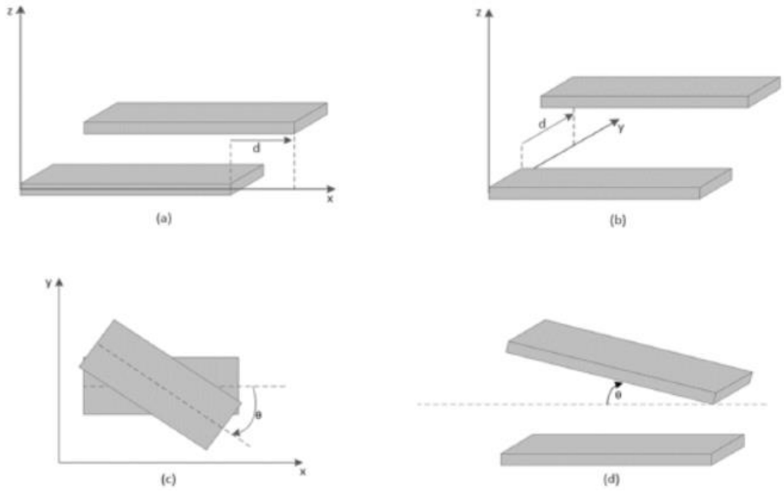


Figure 47: Misalignment forms of rectangular coils: (**a**) longitudinal, (**b**) lateral, (**c**) rotational, (**d**) angular. (54)

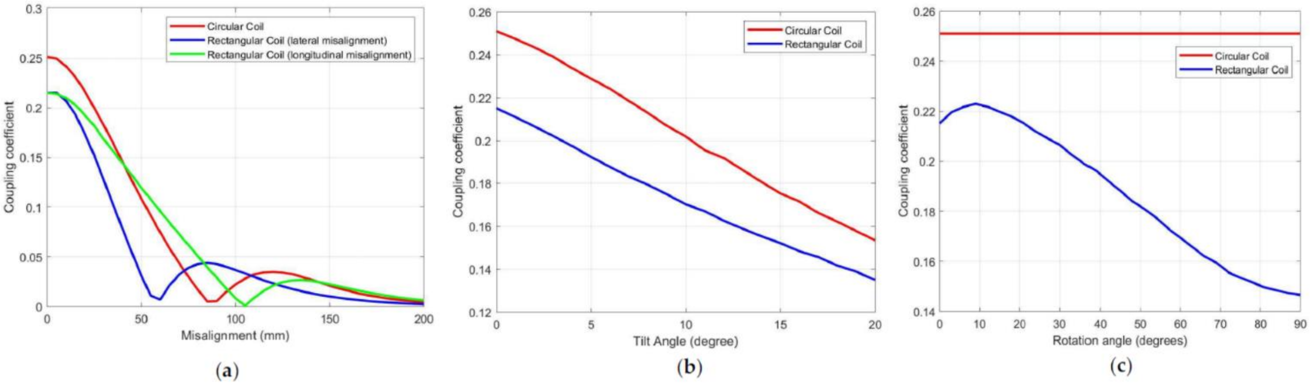


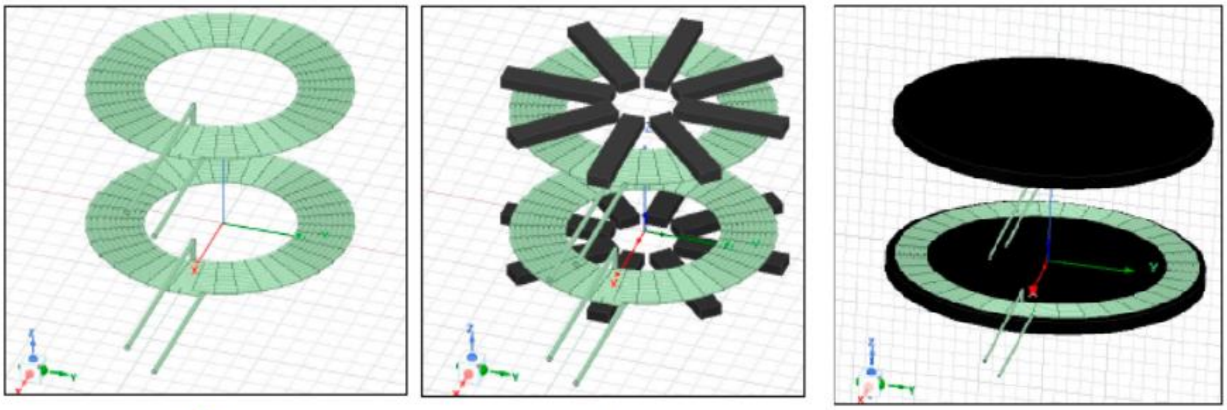
Figure 48: Circular and rectangular pads against different types of misalignments: (**a**), lateral and longitudinal displacement (**b**) angular misalignment, (**c**) rotational misalignment (54)

6.2.3 Magnetic ferrite shapes

The wireless transformer used in Wireless Electric Vehicle Charging Systems relies heavily on a magnetic ferrite structure. This structure helps to direct the magnetic field between the coils and strengthens the field at the receiver and it therefore minimizes leakage, which leads to a higher performance wireless charger. It is very important to control this flux to both maintain safety standards and optimize the coupling efficiency between the transformer's windings, so without proper shielding, leakage fluxes could decrease the system's performance. Ferrite in general reduces Eddy current losses, which are mainly currents caused by changing magnetic fields that can create energy loss due to heat (55).

As the same concept of coil design and shape and their effect on the coupling coefficient, ferrite shapes also plays a role into enhancing the charger overall efficiency, different ferrite shapes exists and were studied to show their effect on the overall system such as circular, square, rectangular ,T-core , U-core , E-core, and Double U shaped ferrite (25).

One study have shown the effect of using ferrite and its effect on the coupling coefficient with varying different air gaps (56), where a coreless model was put into the study as a reference comparison model, with two different ferrite topologies, one a circular model using ferrite bars, and the other using ferrite plates as shown in the figure below. The results shown in Table 3 shows a huge difference in the coupling coefficient comparing the coreless model and the models that used ferrite, and it also shows that using a ferrite plate leads to greater efficiencies for the system compared to using ferrite bars.



(a) (b) (c)

Figure 49: Circular models: (**a**) circular coreless model; (**b**) circular model using ferrite bars; (**c**)circular model using a ferrite plate (56).

Table 3: The coupling coefficient values for three cases with variation of the gap from 100 mm to 200 mm (56)

Gap Variation (mm)	The Coupling Coefficient		
	Case 1	Case 2	Case 3
100	0.254742	0.369677	0.385042
120	0.209370	0.305432	0.316385
140	0.173810	0.253880	0.261800
160	0.145391	0.212085	0.217908
180	0.122344	0.178019	0.180967
200	0.103442	0.149973	0.153215

7 CASE SCENARIO I: LONG TRIP

In the realm of electric vehicle studies, in order to have a clear and better understanding of the charging scenarios and techniques that were explained in the previous chapters, a real-life simulation of a usual normal person driving routines will help up visualize and quantify the major aspects of the charging types and losses used nowadays. Such simulations not only gives a realistic view of energy consumption and charging losses but also enable researchers and developers to make informed decisions and improvements in the design and utilization of EVs.

The first case scenario held in this thesis will simulate a real-life long trip, assuming one of the frequently traveled routes in Europe, the AutoRoute from Brussels to Paris, making it an exemplary choice for such a study. By considering this route, the analysis can represent a long highway journey's challenges and benefits in an EV.

For the purpose of this study, the journey will be initiated in a Nissan Leaf, offering varying battery capacities of 40kWh, or 62kWh. The exact locations assumed for this trip are Brussels-Midi Station as the starting point, arriving to Paris Porte de La Chapelle as the final destination, this trip represents a 315-kilometer journey.

The first simulation in this case study will be carried out with a bigger battery pack in order to check the energy consumption along the whole journey and to have a clear understanding of the route. Nissan Leaf 62 kWh average consumption data is available on the web, as we know, this consumption differs from many factors, such as driving cycle, slope inclination, accessories, temperature, this data will only give a preliminary estimation of the driving range of the Nissan leaf in order to pre locate a charging station before stating the trip.

Utilizing Google Maps, exact distances between the starting point, charging station and destination will be determined, ensuring precision in subsequent calculations. Complementing this, the OsmAnd maps is a software that the user defines real life route, and it provides an approximate driving cycle graph, which will incorporate real-life speed limits and occasional stops along the route. Several influential factors will be considered to determine the energy consumption during the journey. These parameters will assist in deducing the Nissan Leaf's total energy consumption for the trip, typically represented as kWh.

Before starting the journey and leaving home, it will be assumed that the user leaves the starting point with a battery with full capacity of 100%. As we know that charging the battery to a 100% SOC is not the ideal condition by explaining the effect of degradation and power losses in the previous chapters. However, such long trips are not that that frequent for a human’s normal lifestyle, they are mainly occasional trips that might be in the scenario of a vacation, work purposes and others. EV manufacturers explains that charging to 100% is of course not prohibited, but it is preferred not to be done often to avoid future damage to the batter. Subsequently, energy consumption will be calculated from our starting position until we reach the charging station in order to compute the SOC% at the charging station and upon arrival; charging losses at this point will be computed, emphasizing the efficiency of the fast charging process and by obtaining real-life data of charging curves for these Nissan Leaf models.

The main goal of this method is to closely examine the results. This will help us better understand how efficiently EVs charge, how different driving conditions affect them, and how good the chosen charging spots are. By comparing our findings with what is expected from theory and other studies, we can see how EVs really perform in everyday situations. At the end of the study, we will suggest the best ways to charge EVs, check for the best choice of batteries and point out areas that could be looked into more in future research.

After evaluating the Nissan Leaf range data for highway driving, we can estimate when and where to stop at a charging station and pre locate its address on the map. The chosen stop for recharging is the "Last Mile Solutions Charging Station." This station is located on the highway, 176 kilometers from the starting point which a fully charged 62 kWh Nissan Leaf can cover this distance while staying in the 20-80% range. In addition, upon arrival to the charging station, we will assume different types of chargers to compare their charging times losses. To evaluate the real-life decision we made, this exact charging station offers a 22 kW Type 2 charger, a 50 kW ChAdeMO and a 160 kW CCS charger, which is a great variety of options for a real life scenario. Figure 50 shows the trip route on google maps, with the location of the charging station.

Figure 50: Last Mile Solution Charging Station location on the map during the trip

The Nissan Leaf data are found in Table 4. One has to note that for a bigger battery pack, there is a weight penalty for the vehicle where a 62 kWh Leaf weights around 1780 kg while a 40 kWh Leaf weights 1610 kg, this makes a difference of 170 kg which theoretically will affect the energy consumption of the vehicle and will be shown later, the other data were assumed the same for both models.

Another important factor to highlight is that for any type of electric vehicle, the battery capacity shown on the vehicle data is not the accurate capacity to carry out calculation with. For EV batteries, there is something called the gross capacity, as it is the theoretical capacity that a battery can hold, and there is the net capacity, which is the actual useable capacity that the user can use.

The usable capacity is something that is not that easy to determine, so different useable batteries for this model are suggested on data sheets found on the web. Myev shows that the useable battery for a 62 kWh Nissan Leaf is 56 kWh (57), ev-database shows that the useable battery is 59 kWh, a forum discussion on abetterrouteplanne found out that it is 60 kWh (58), and others suggests it is around 58 kWh, so for our study we will assume an average of these data and take it as 58 kWh. Same goes for the 40 kWh battery pack, as the same sources suggests different useable batteries of 39 kWh, 36 kWh and 37 kWh, therefore an assumed average of 38 kWh will be taken into consideration.

Table 4: Nissan Leaf II Data

VEHICLE DATA		
Drag coefficient	Cx	0.29
Frontal area	S	2.19 m2
Air density	ρ	1.22 kg/m3
Tire size	205/55 R 16 91 H	
Effective rolling radius	Re	0.31
Tire rolling resistance	frr	0.0136 + 0.4 10−7V 2 (with V in km/h)
TRANSMISSION		
Single reduction ratio	i	8.19
Transmission efficiency	ηt	0.97
ELECTRIC MOTOR		
Maximum power	Pmax	110 kW
Maximum Torque	Cmax	320 Nm
Base speed	Nb	3282 rpm
Maximum speed	Nmax	10300 rpm
Moment of inertia	Jm	0.01 kg.m2
GEOMETRY AND MASS PROPERTIES		
Length	Lh	4.49 m
Width	Wh	1.788m
Height	Ht	1.530m
Curb weight	mc	1610/ 1780 kg
Driver mass	md	75 kg
Total Mass	m	1685 kg/ 1855 kg
Wheelbase	L	2700 mm
Weight distribution : 50/50	b	L/2
	c	L/2
Elevation of center of gravity	h	0.508 m

In order to calculate the energy required to refill the vehicle and obtain charging losses, it is essential to evaluate the SOC% of the vehicle upon arrival to the charging station, to do so we need to calculate the energy consumption of the vehicle over the driving cycle. The energy power output is equal to the power required divided by the overall efficiency of the electric motor (motor + inverter) (59).

$$P_{bat}^{out} = \frac{P}{\eta_{inv}(C,\omega)\eta_{mot}(C,\omega)} = \frac{P}{\eta_m(C,\omega)}$$

The power supplied by the engine can be obtained by dividing the tractive power by the efficiency of the transmission:

$$P = \frac{P_t}{\eta_t}$$

From the tractive power, we can make appear the tractive force.

$$P_t = vF_t$$

Newton's equation of motion is expressed as:

$$m_e a_x = m_e \frac{dv}{dt} = F_t - F_{RES}$$

and shows that the acceleration of the vehicle is a function of the excess of the tractive force and resistive forces, called the net propulsive force. The effective mass is introduced in order to take into account the inertia of the drive train components and the engine elements, therefore the expression will be expressed as:

$$F_t = F_{res} + m_e \frac{dv}{dt}$$

The total resisting force is influenced by the rolling resistance, the slope and the aerodynamic forces. The expression of total resisting force is expressed as:

$$F_{res} = f_{RR}.mg.cos\theta + mg.sin\theta + \frac{1}{2}\rho S C_x V^2$$

Putting all these elements together, we get:

$$P_{bat}^{out} = \frac{v}{\eta_t \eta_m(C_m,\omega_m)}\left(f_{RR}.mg.cos\theta + mg.sin\theta + \frac{1}{2}\rho S C_x V^2 + me\frac{dV}{dt}\right)$$

expressed in [W]. We can introduce the energy consumption of the axillary accessories:

$$P_{bat}^{out} = \frac{v}{\eta_t \eta_m(C_m,\omega_m)}\left(f_{RR}.mg.cos\theta + mg.sin\theta + \frac{1}{2}\rho S C_x V^2 + me\frac{dV}{dt}\right) + P_{aux} \text{ [W]}$$

With

$$\gamma = 1 + \frac{I_w}{m_e R_e^2} + \frac{J_m}{m_e R_e^2} i^2 = 1.04 + \frac{J_m}{m_e R_e^2} i^2$$

$$m_e = \gamma m_e + m_d$$

$$f_{RR} = 0.0136 + 0.4.10^{-7} 3.6^2 v^2$$

At constant speed, the energy consumption can be somewhat simplified since there is no acceleration:

$$P_{bat}^{out} = \frac{1}{36v} \left(\frac{v}{\eta_t \eta_m (C_m, \omega_m)} \left(f_{RR}.mg.cos\theta + mg.sin\theta + \frac{1}{2} \rho S C_x V^2 \right) + P_{aux} \right) \text{ [kWh/100km]}$$

Figure 51 shows the energy consumption of the Nissan Leaf [kWh/100km] at constant speeds.

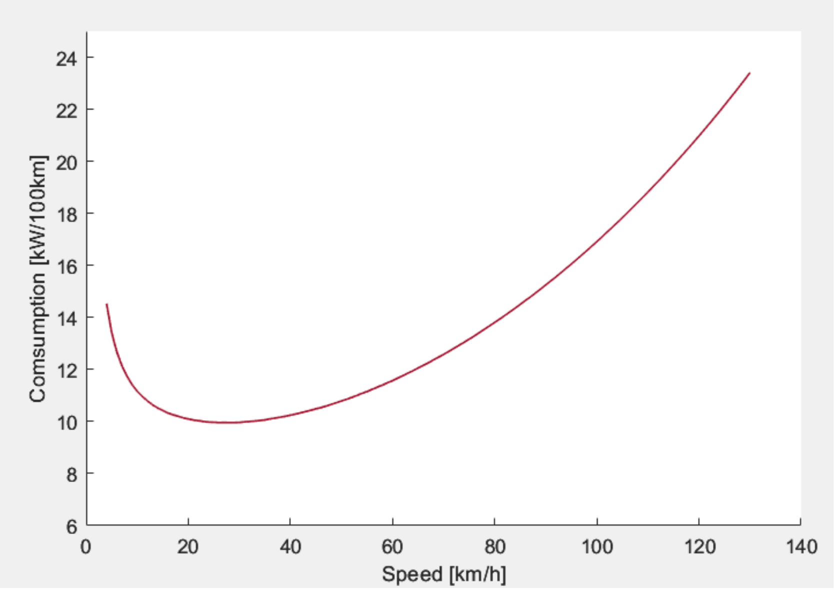


Figure 51: Energy consumption [kWh/100km] at constant velocities

If the driving cycle is given, one can estimate the total energy consumption by summing the integrating of the power leaving the battery and the power entering the battery over time. Knowing that the power entering the battery is negative due to regenerative braking. The net energy consumption is therefore expressed as follows:

$$E_n^{out} = \oint_{Pt>0} P_{bat}^{out} dt + \oint_{Pt>0} P_{bat}^{in} dt$$

With

$$P_{bat}^{out} = \frac{v}{\eta_t \eta_m (C_m, \omega_m)} \left(mgf.cos\theta + mg.sin\theta + \frac{1}{2} \rho S C_x V^2 + \gamma m \frac{dV}{dt} \right) > 0$$

$$P_{bat}^{in} = \alpha.\eta_t \eta_m V \left(mgf.cos\theta + mg.sin\theta + \frac{1}{2} \rho S C_x V^2 + \gamma m \frac{dV}{dt} \right) < 0$$

The braking factor α shows how much energy is restored when braking. Here, we use the common value of 0.3 for it. In addition, an efficient engine and transmission help cut down on how much the vehicle uses. What is different at constant velocities consumption is the term taking into account the acceleration and effective mass of the vehicle:

$$\gamma m \frac{dV}{dt} \text{ with } \gamma = mcar\left(1.04 + \left(\frac{Jm}{Re^2.mcar} i^2\right)\right) + \ m_{driver}$$

This term contributes strongly to the increase in consumption during acceleration.

7.1 62 kWh Battery

Using the OsmAnd Maps application setting the starting point as Brussels-Midi and destination of the charging station, we obtain the driving cycle of this first journey, having this curve, we will be able to calculate the P_{bat}^{out} and P_{bat}^{in} along the journey and estimate the total energy consumption in kWh. As shown in the Figure 52, there is a point where the vehicle speed drops the 0, which means that the vehicle stopped, for clarification, this stop represents the motorway toll “péage” where the user stops on the highway to pay and passes through the tollgate.

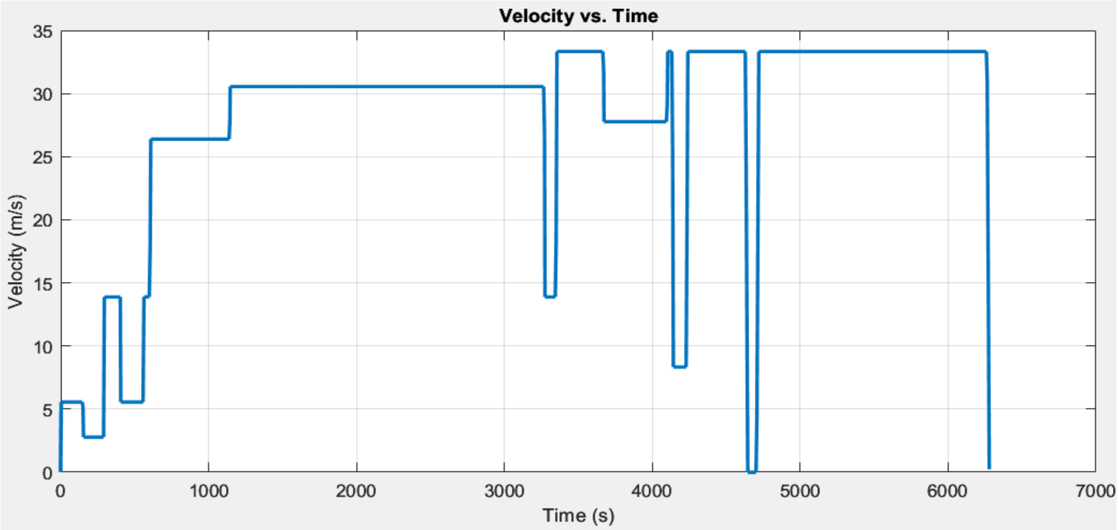


Figure 52: Driving cycle from Starting point (Brussels) to Charging Station

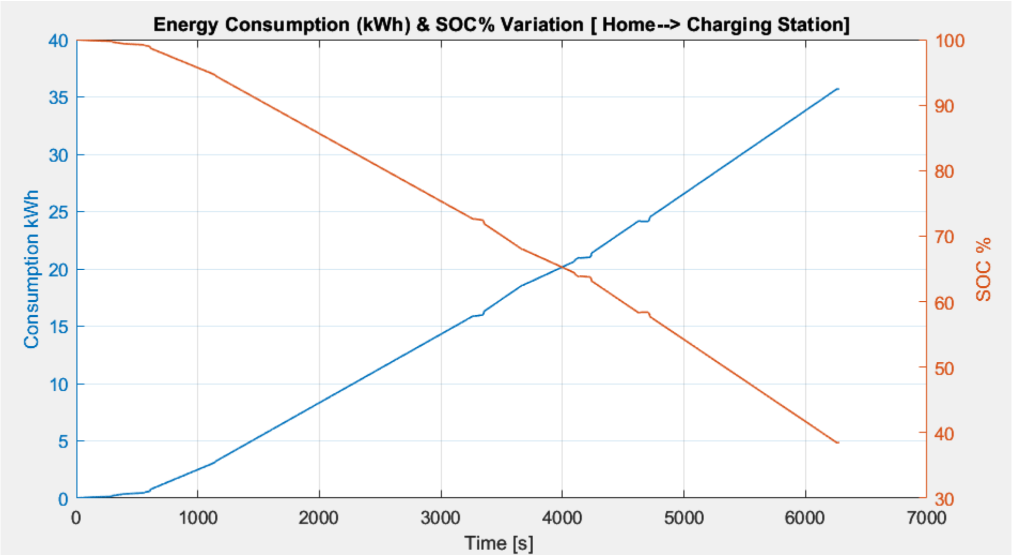


Figure 53: Consumption (in kWh) and SOC% variation for 62 kWh battery from Starting point to Charging station

Figure 53 shows the variation of consumption and state of charge during the first trip. The total energy consumption of the first trip, of 176 kilometers, with an approximate average speed of 110 km/h is 36.08 kWh, which represents a consumption of 20.48 kWh/100km, which is compatible to the Leaf highway tested data found in literature, the SOC% varied from 100% leaving home, and arrived to the charging station at approximately 38% SOC. Then when we arrive at the charging station, we will calculate the needed energy to refill the vehicle back to 80% with its charging time and charging losses. After that, we continue our trip to reach the final destination, Figure 54 shows the driving cycle from the Charging station to Paris, as we can see it is mainly a constant speed curve knowing it is a highway.

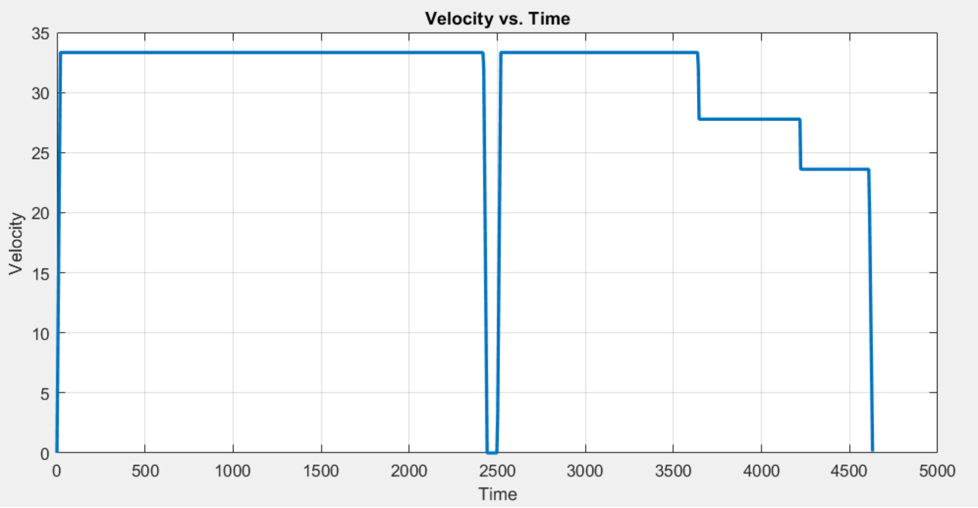


Figure 54: Driving Cycle from Charging station to End point (Paris)

After charging the EV to 80% at the charging station, we continue by simulating the second journey of our long trip, going from the Charging station to the final destination, a 138-kilometer highway trip with an approximate average of 120 km/h. Looking at results shown in Figure 55, the total energy consumed by the vehicle was 30.68 kWh, which means that the average energy consumption was 22.23 kWh/100km, which is very close to the energy consumption of the vehicle at constant speeds for 120 km/h. Moreover, the SOC% leaving the charging station was 80% and dropped to 27% when arrived to final destination.

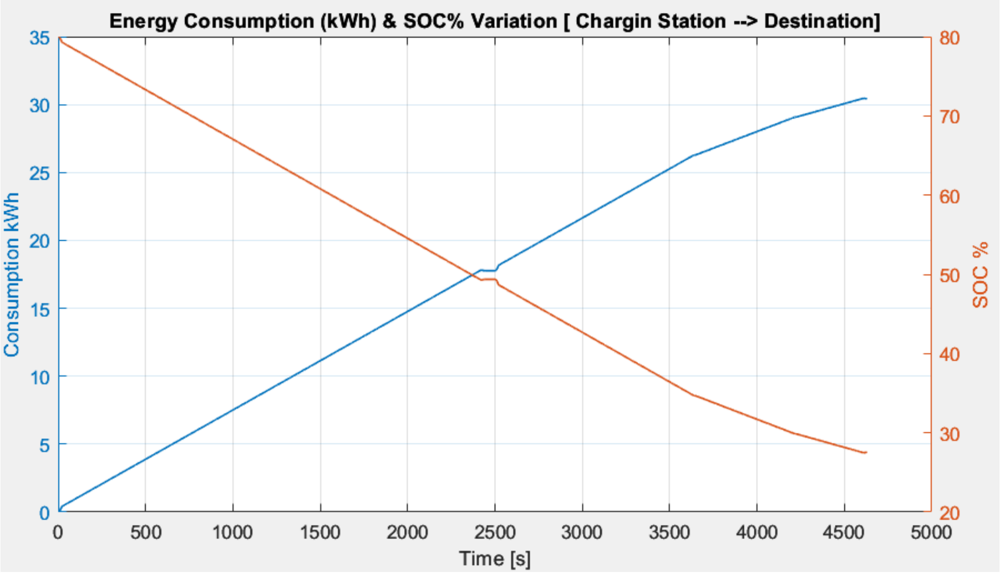


Figure 55: Consumption (in kWh) for 62 kWh battery from Charging station to End Point

The variation of state of charge and the energy consumed by the vehicle at different locations are summarized in Table 5.

Table 5: SOC% and Consumption on different locations of the trip going to the destination

Location	SOC %	Distance (km)	Consumption kWh
Home (Brussels-Midi)	100%	0	0
Charging Station	37.8%	177 km	36.08 kWh
End Point (Paris)	27.08%	315 km	30.68 kWh

Now for the second part of the simulation, after obtaining the different state of charges at different locations, we are able to assume the charging strategies and types in order to refill the vehicle up to the desired SOC. In order to be able to quantify the charging losses and charging time, the need of real-life data charging curves is crucial in this study to obtain the most accurate real values.

As we know from previous chapters, the DC charging speed curve is a varying curve of kWs with respect to the battery state of charge, opposite to the AC charging curve, which is mostly a constant curve over SOC. So for this reason the need of charging speed curve is needed in our study, because for a 50kw charger, we cannot assume that the grid is delivering a 50 kw constant power during the charging process due to many discussed factors. Moreover, real-life curve will demonstrate this inaccuracy showing different powers delivered peaking at around 47 kW and dropping to much lower powers.

The experimental data was obtained and plotted in order to perform a curve fitting to have an approximation function of the Power delivered by the grid with respect to the Battery State of Charge. By checking the distribution of power delivered from experimental data, a 6th order polynomial would be a good approximation to have an accurate fitting of the data.

Figure 56 and Figure 57 show the real experimental data of a 100 kW and 50 kW fast charging curves for a 62 kWh Nissan Leaf, the range of interest mainly drops between 20-80%, as this is the range of state of charge that we will try to maintain during the charging/discharging processes.

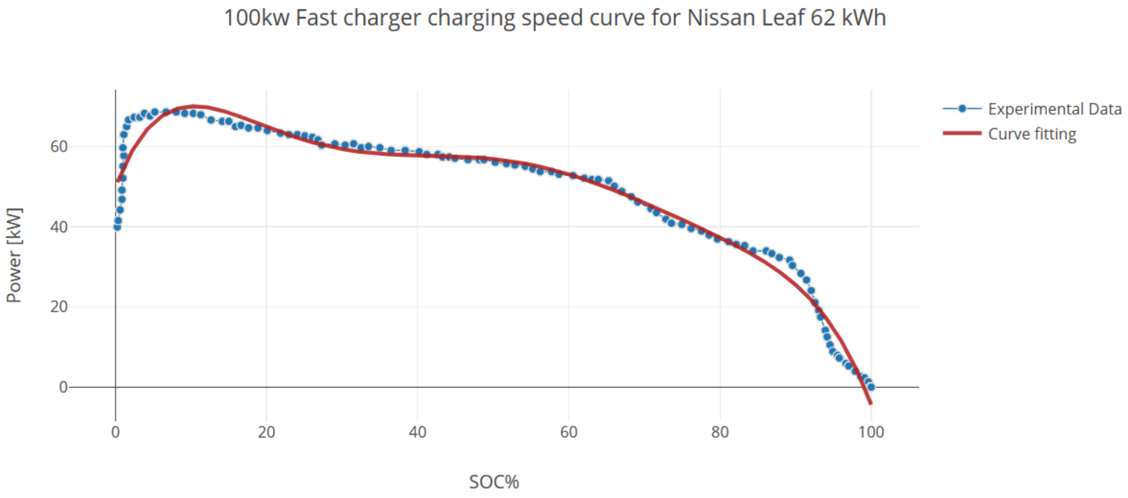


Figure 56: 100kw Fast charging curve fitting for 62 kWh Nissan Leaf

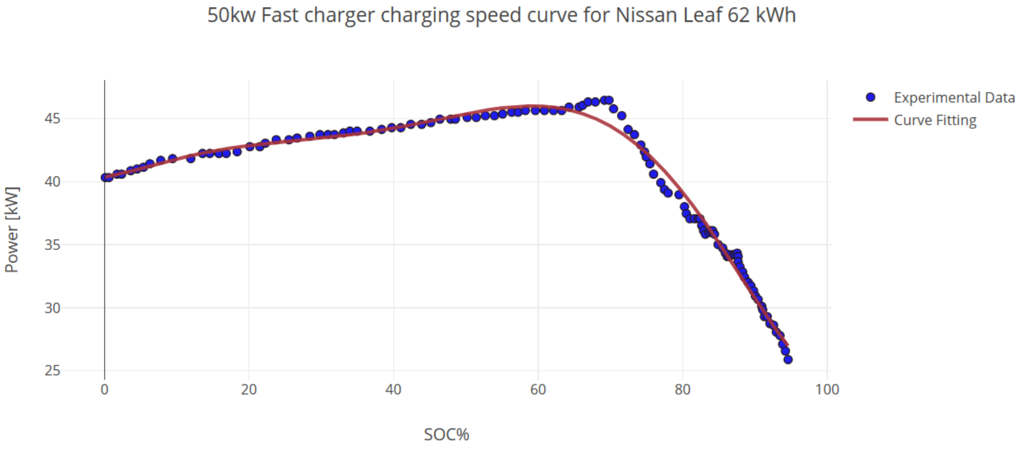


Figure 57: 50kw Fast charging curve fitting for 62kWh Nissan leaf

The following table (Table 6) shows the constants values for the curve fitting for both 50 kW and 100 kW charging curves for the Nissan leaf 62 kWh.

$$P(SOC) = a + bSOC + cSOC^2 + dSOC^3 + eSOC^4 + fSOC^5 + gSOC^6$$

Table 6: Constant values for curve fitting order 6

Constant	Value for 100kw	Value for 50kw
a	49.95390368998815	40.35021480549581
b	4.9159169581302455	0.10139335756070977
c	-0.4095358162507603	0.010461271909698235
d	0.014098051637287013	-0.0008237741027203284
e	-0.00023797111431617923	0.00002293995980498069
f	0.0000019397366337036646	-2.6608592794617785e-7
g	-6.148854299511115e-9	1.0597328298263343e-9

After obtaining the P(SOC%) function, we will now be able to proceed with our calculation, by having the initial state of charge for starting the charging process, and defining an 80% desired SOC, we will be able to know the required energy to fill the EV. As a reminder, for this battery pack, our total battery capacity is being taken as 58 kWh as the useable capacity of the vehicle.

As mentioned in chapter 5, the efficiency of the charger is not a constant value over all state of charge, the efficiency differ at different SOC, as it have seen that is drops at higher SOC, approximately at 60%, and for each type of chargers having different power supplied, which will be taken into account in the calculation modelling.

By summing up all these info, we can now assume different types of chargers and start simulating the charging process for each one of them. Knowing that the user is going on a long trip, and he would like to charge his EV mid-trip at charging station, it would not be logic to include AC Level 1 & Level 2 low power chargers, because they would need excessive time to charge such EV with big battery pack. Basic relations will be used in the calculation process:

$$Charging\ Time\ [h] = \frac{Energy\ [kWh]}{Power\ delivered\ [kw]}$$

$$Energy\ required\ to\ fill\ EV = \frac{Desired\ SOC\% - Initial\ SOC\%}{100} * Battery\ Useble\ Capacity$$

$$Energy\ Required\ from\ grid\ [kWh] = \frac{Energy\ required\ to\ fill\ EV\ [kWh]}{Efficiency\ \%}$$

$$Energy\ Loss = Energy\ required\ from\ grid - Energy\ required\ to\ fill\ EV$$

The results in Table 7 shows the charging process for three different types of conductive chargers at the Charging station, a 22kW AC Level 2 charger, and a 50 kW & 100 kW DC level 1 fast chargers. In addition, there exists multiple fast wireless charger, offering different power rates, but as wireless chargers are still a technology under large amounts of testing and investigation, we were able to get the data for only a 50 kW wireless charger made by Momentum, where its efficiency was experimentally tested by Bjørn Nyland and found out to be 86% (60). In regards of the charging curve, the curve that we were able to obtain was primarily a reflection of the battery's charging characteristics and the charging strategy determined by the vehicle's battery management system, rather than the type of charger (conductive vs. wireless). Therefore, by using the same battery and vehicle, the charging curve should remain largely the same.

Efficiencies variation on different SOC% are taken into account with the calculation, with simulating the Energy loss on each increment of state of charge at different charger efficiencies and power supplied from the grid. With this calculation model, we are able calculating the total charging time with the charging from 37.8% until 80%, which then enable us to conclude the total energy lost from the grid as well as the total Power lost during every charging process.

Table 7: Charging Losses and Charging Time for different Charging types at Charging Station

Charging Type	**Charging Power**	**Charger efficiency**	**Desired SOC 80%**	**Required kWh**	**Charging time**	**Energy loss**
AC Level 2	22kw	~81-88%	46.4 kWh	24.48 kWh	~66 mins	4.47 kWh
DC Level 1	50 kw	~78-86%			~34 mins	5.76 kWh
DC Level 2	100 kw	~80-88%			~28 mins	5.03 kWh
Wireless Charging	50kw	~82-86%			~34 mins	4.7 kWh

After obtaining the Energy and Power losses for different charging techniques at the charging station, we will continue our calculation in order to obtain the overall losses for the whole trip. We will now set that the EV user has arrived to the destination having 27% state of charge.

Many scenarios might differ when arriving depending the trip purpose, if the user has an important meeting and is going for a short period of time, he might need to also fast charge his vehicle. Another purpose might be to spend the day there or even spend the night, which in that case it will be preferable to use AC chargers and prevent DC fast charging, because as mentioned before of its effects on battery degradation where until now with the current technology, DC charging should be only used when needed.

Also for this part, there exists multiple wireless chargers at different power rates, for example, Witricity offers a 3.7 kW and 11 kW chargers, Toshiba and BOSCH has 7 kW wireless chargers and there is even 22 kW wireless charger. Given the limited amount of literature found about their overall exact efficiencies and power variation, we were able to find some data for the 7 kW charger having around 87% efficiency (61).

Therefore, we will simulate different charging scenarios for any type of purpose needed. The desired SOC% will remain 80% for charging. These results are shown in Table 8.

Table 8: Charging Losses and Charging Time for different Charging types at Destination

Charging Type		Charging Power	Charger efficiency	Desired SOC 80%	Required kWh	Charging time	Energy loss
DC Level 1		50 kw	~78-86%	46.4 kWh	31.28 kWh	~43 mins	6.87 kWh
DC Level 2		100 kw	~80-88%	46.4 kWh	31.28 kWh	~35 mins	5.96 kWh
AC Level 2 charging	16 A	7 kw	~80-85%	46.4 kWh	31.28 kWh	4.39 hr	6.42 kWh
	32 A	11 kw	~81-86%			2.79 hr	5.96 kWh
	32 A	22 kw	~81-88%			1.39 hr	4.97 kWh
Wireless Charging		7 kW	~83-87%	46.4 kWh	31.28 kWh	4.3 hr	5.45 kWh
		50 kW	~82-86%			~42 mins	5.85 kWh

After arriving to the current destination, we will continue our assumption and carry out further analysis for the whole journey and make it a round trip, assuming that the user finished his tasks in Paris, charged his EV back to 80% and now it’s time to get back home. After checking the way back on maps software, we concluded that it is exactly the same route and distance as going to the destination, and even the same charging station on the same address have two parallel stations on each way of the highway. With that, we can immeadtly get the SOC% on different location of the way back, but with now assuming that the starting point is Paris and the Destination is Brussels, and we start out trip with an 80% state of charge. The state of charge and consumption variations for the way back are shown in Table 9.

Table 9: SOC% and Consumption on different locations of the trip going back from destination

Location	SOC %	Distance (km)	Consumption kWh
Starting Point (Paris)	80%	0	0
Charging Station	27.1%	138 km	30.68 kWh
End Point (Brussels)	17.9%	315 km	36.08 kWh

On the way back, we arrive at the charging station that is now 138 km away from the departing point with a State of Charge of 27.1%, we set this SOC as our initial charging state of charge, and the desired state of charge will be 80% in order to proceed with the charging calculations. After completing the following table, we will be able to conclude the total energy losses of a complete round trip. The charging losses and charging time at the charging station on the way back are shown in Table 10.

Table 10 : Charging Losses and Charging Time for different Charging types at station on the way back

Charging Type	**Charging Power**	**Charger efficiency**	**Desired SOC 80%**	**Required kWh**	**Charging time**	**Energy loss**
DC Level 1	50 kw	~78-86%	46.4 kWh	30.7 kWh	~41 mins	6.71 kWh
DC Level 2	100 kw	~80-88%			~35 mins	5.82 kWh
Wireless Charging	50 kw	~82-86%			~40 mins	5.74 kWh

7.2 40 kWh Battery

In the previous section of this study, the simulation of a long trip (315km) with a 62 kWh battery pack vehicle was conducted. This first simulation used only a single charging stop along the highway, giving us a great approximation of the charging strategies and losses for larger battery capacities. As we advance in our study, the next simulation of this research focuses on performing a parallel simulation for also a Nissan Leaf but with a 40 kWh battery.

This secondary simulation focuses on figuring out the effects of battery size on EV travel and charging strategies. By comparing the same vehicle with a smaller 40 kWh battery against the previously analyzed 62 kWh version, we aim to analyze not only the possible requirement for additional charging stops but also the consequential impact on charging efficiency, losses, and overall power management.

In planning a 315km trip from Brussels to Paris using a Nissan Leaf with a smaller battery pack of 40 kWh battery, where 38 kWh are usable capacity, we face an interesting challenge; for the first simulation, using range data found on the web, we were able to predict the location of the charging station before starting the trip. For this smaller battery, after simulating the first scenario, now we have an overall idea of the consumption of the Nissan Leaf along this chosen highway. The projected consumption for this trip was around 66 kWh, a figure that exceeds the battery's total capacity. Assuming the same energy consumption for this scenario, is just an approximation value to predict the number of stops required for this vehicle, even though we know that the total consumption of both vehicles will differ, especially for having less car weight due to the battery.

To start, let us break down the usable capacity for each charging segment within with also leaving the house with a 100% SOC, but after that, we need to keep a 20-80% capacity range. As we leave with a 100% state of charge, but then when we need to recharge, our aim will be to refill to 80%, we will assume a usable battery capacity ranging from 20%-80% for the trips leaving the charging station with 80% SOC:

- Usable Capacity: 80% - 20% = 60% of 38 kWh, which equates to 22.8 kWh.

Since the entire trip requires around 66 kWh, and each charge segment allows for only 24.7 kWh, we can determine the total number of necessary charging stops:

- Total Number of Charge Segments Needed: 66 / 22.8 ≈ 2.89.

Since it is impractical to make a fraction of a stop, at least three charging stops will be required.

To pinpoint the optimal distances for these stops, we must consider the vehicle's range with the usable capacity of 22.8 kWh, as well as the overall consumption rate for the journey:

- Consumption Rate: 66 / 315 ≈ 0.209 kWh/km
- Range Per Segment: 22.4 / 0.209 ≈ 107 km .

This calculation forms the basis for a pre planning of the charging stations along the highway, ensuring not only the feasibility of the journey but also the efficiency in accordance with best practices in EV charging. These calculation let us understand that we will need a total of three stops along the journey, including the arrival at destination which is considered a stop, and during the trip we have a range of 107 km to find a charging station from one to another. But we should note that because the user leaves the depart location with a 100%, he will have a small additional range during the first segment of 107km during the first trip from home to the first charging station, as this calculation is for a 20-80% usable capacity.

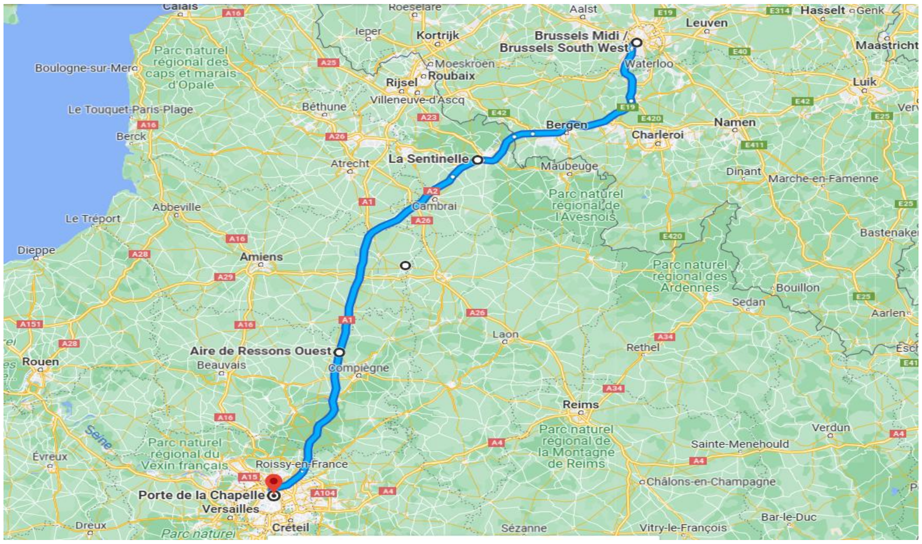


Figure 58: Google Maps route from Starting point to destination showing two charging stations

With the use of these calculations, we were able to pre locate using maps software two existing charging stations, the first one being 108 kilometers away from our starting location. On this address, there actually exists two different charging stations located next to each other, “ENGIE Charging station” and “Last Mile Solutions Charging Station” that offers many charging powers, but we will remain with assuming our own chargers.

The second charging station is located at 115 km away from the first one, and finally our destination will therefore be 92 km away from the second charging station. The range per segment calculate in order to stay in the 20-80% range was 107 km, and the distance between the first and second charging station is 115km as we couldn’t locate a more optimal charging station location, which will be acceptable as this distance added won’t largely drop the SOC to extremely low state of charge. The route and charging stations for this case are shown in Figure 58.

By using OsmAnd Maps, and locating the first charging station while setting up our depart point, we were able to get the driving cycle from our depart point to the 1st charging station. The driving cycle is shown in Figure 59.

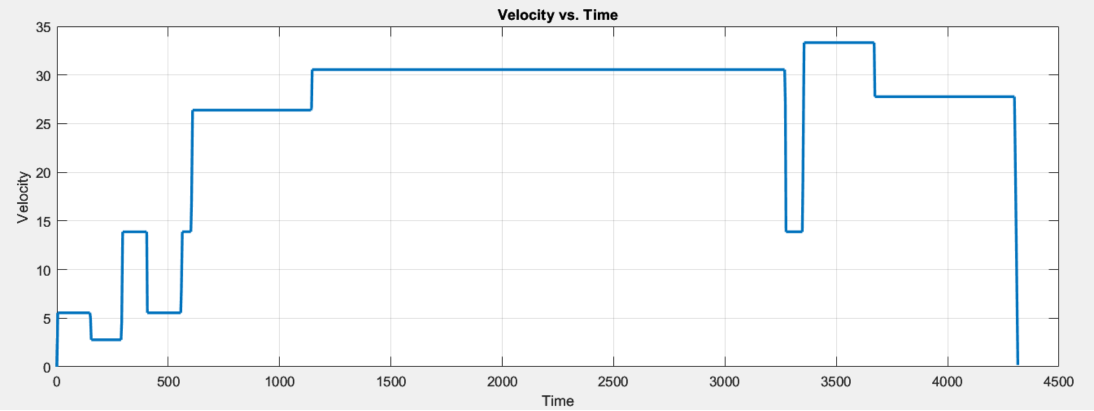


Figure 59: Driving cycle from Starting point to 1st charging station

By checking the results obtained shown in Figure 60, the total energy consumption of the first trip, of 108 kilometers is 21.01kWh, which represents a consumption of 19.4 kWh/100km, which is compatible to the Leaf highway tested data found in literature, the SOC% varied from 100% leaving home, and arrived to the first charging station at approximately 44.71% SOC.

Knowing that we will have two stops for charging during the trip before leaving the starting, it would have been logically preferable to leave home at 80% to always stay in the 20-80% range and knowing that the vehicle could have reached the charging station at an SOC% higher than 20%. However, the decision of leaving at 100% was only made to be able to compare our results with the first case scenario of a larger pack that left the house at 100%, to insure consistency in comparison.

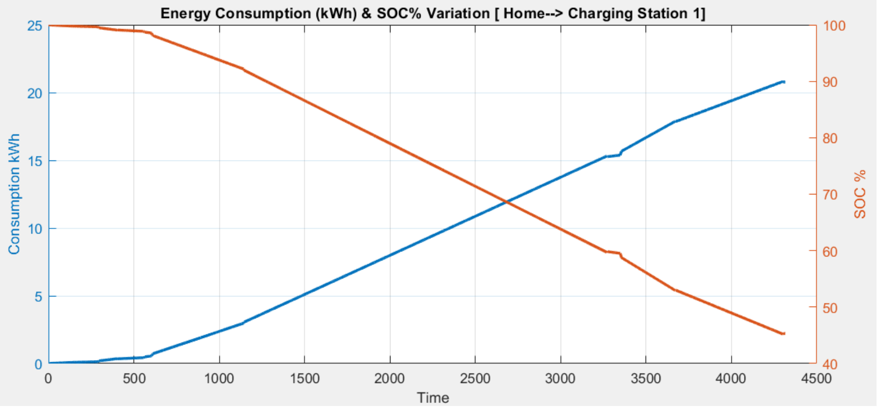


Figure 60: Consumption variation from starting point to 1st charging station

After charging the vehicle at the first charging station to 80%, we will continue the trip until we arrive to the second charging station. The figure below (Figure 61) shows the driving cycle from the first charging station until the second charging station.

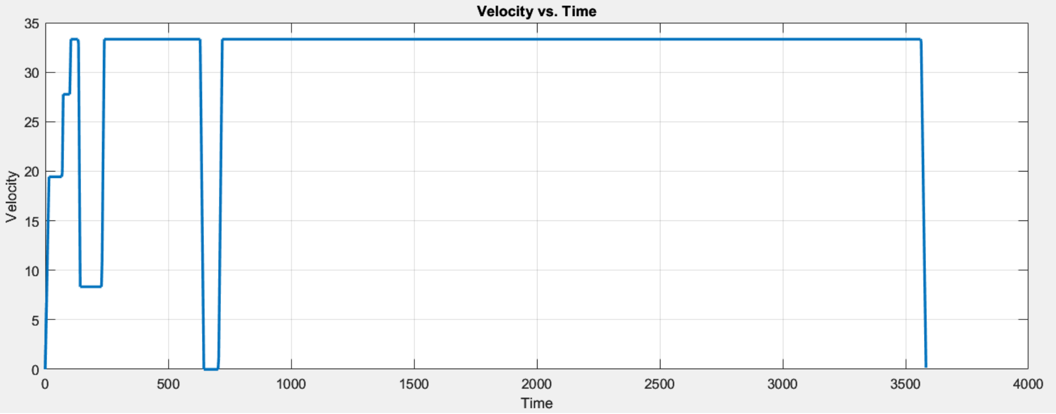


Figure 61: Driving Cycle from 1st Charging station to 2nd Charging station

The total energy consumption of the second first trip, of 116 kilometers is 24.33kWh, which represents a consumption of 20.9 kWh/100km, which is compatible to the driving cycle for such trip, the SOC% varied from 80% leaving the first charging station, and arrived to the second charging station at approximately 16.36% SOC. The variation of state of charge and consumption during the second trip are illustrated in Figure 62.

We were expecting a drop of SOC% under 20% while presuming the locations of the charging station, as the distance of 116 km was higher than our permitted range per segment of 107 km, however 16% is acceptable and will not cause that much of a damage for the overall performance of the battery.

After arriving to the second charging station, we will set a starting state of charge of 16.3% and a desired SOC% of 80% to refill the battery pack.

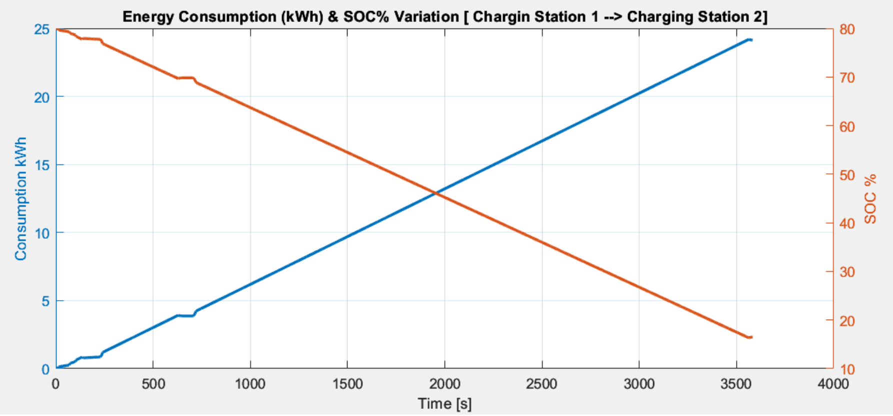


Figure 62: Consumption variation from 1st Charging Station to 2nd Charging Station

After charging the vehicle at the second charging station to 80%, we will continue the trip until we arrive to the final destination. The figure below (Figure 63) shows the driving cycle from the second charging station until our final destination.

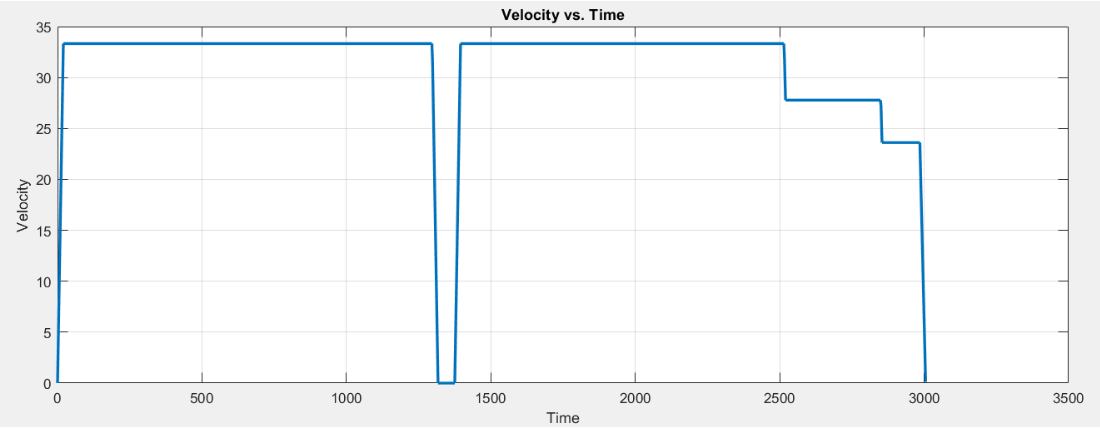


Figure 63: Driving cycle from Second Charging Station to destination

The total energy consumption of the third trip, of 92 kilometers is 19.63kWh, which represents a consumption of 21.33 kWh/100km, which is compatible to the driving cycle for such trip, the SOC% varied from 80% leaving the second charging station, and arrived to the final destination with a state of charge of 28.33%.

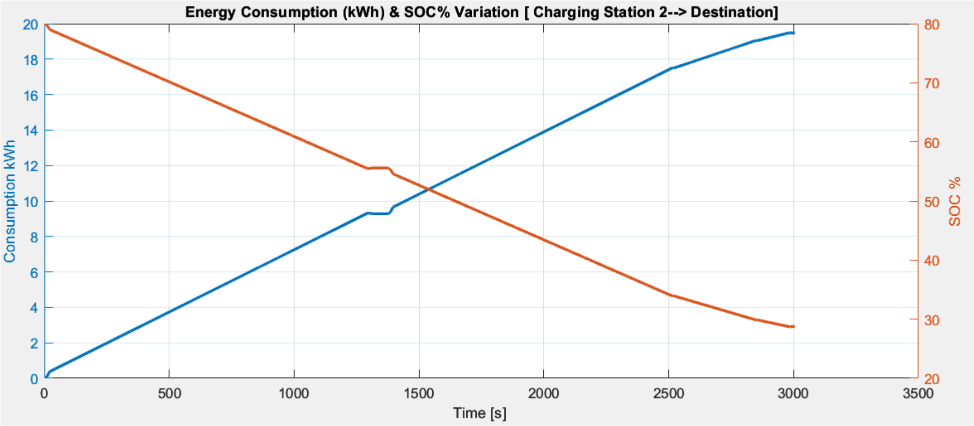


Figure 64: Consumption variation (kWh) from second charging station to destination

The following table (Table 11) will summarize the variation of state of charge and the energy consumed by the vehicle at different locations.

Table 11: SOC% and Consumption on different locations of the trip going to the destination

Location	SOC %	Distance (km)	Consumption kWh
Home (Brussels-Midi)	100%	0	0
Charging Station 1	44.71%	108 km	21.01 kWh
Charging Station 2	16.36%	223 km	24.33 kWh
End Point (Paris)	28.33%	315 km	19.63 kWh

As done in the previous simulation, the real-life experimental data was also found for charging a 40 kWh Nissan Leaf with a 50 kW DC fast charger, the first battery pack had in addition data for a 100 kW, however, this model of Nissan Leaf having a smaller battery pack only supports a maximum charging power of 50 kW.

The experimental data was obtained and plotted in order to perform a curve fitting to have an approximation function of the Power delivered by the grid with respect to the Battery State of Charge. By checking the distribution of power delivered, a 6th order polynomial would be also a good approximation to have an accurate fitting of the data.

The graph in Figure 65 shows the real experimental data of a 50 kW fast charging curves for a 40 kWh Nissan Leaf,

$$P(SOC) = a + bSOC + cSOC^2 + dSOC^3 + eSOC^4 + fSOC^5 + gSOC^6$$

Table 12: Power fitting constants values

Constant	Value
a	-30.561749549172614
b	12.62106436931728
c	-0.8192776460561217
d	0.02572141383078904
e	-0.0004123172044933469
f	0.00000323076190299812
g	-9.83029960358867e-9

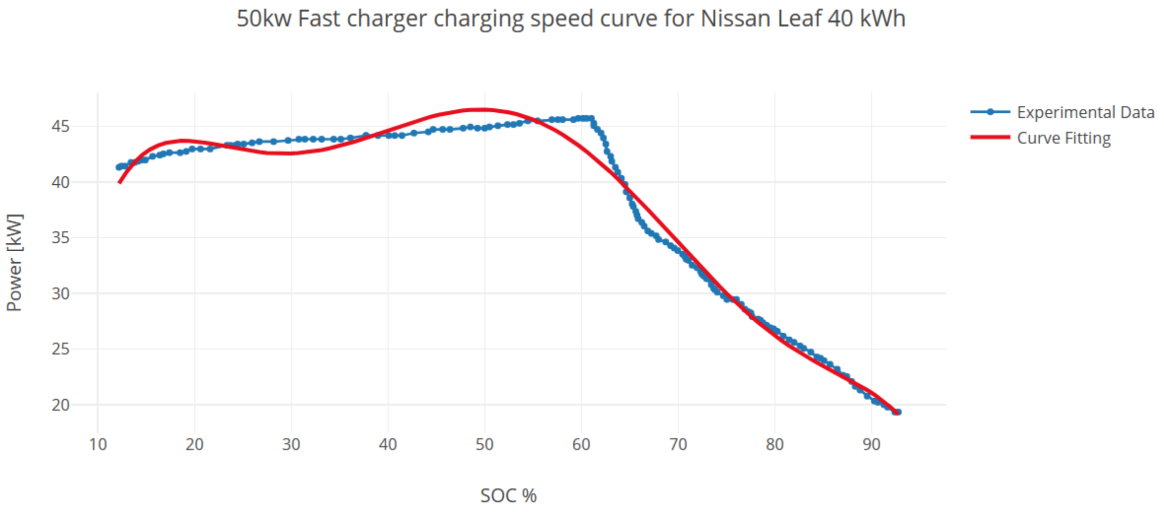


Figure 65: 50kW DC fast charging speed curve for Nissan Leaf 40 kWh

After obtaining the P(SOC%) function, we will now be able to proceed with our calculation, by having the initial state of charge for starting the charging process, and defining an 80% desired SOC. The following table (Table 13) will show the charging process for three different types of chargers at the first Charging station, a 22kW AC Level 2 charger, and a 50 kW DC level 1 fast charger. Efficiencies variation on different SOC% are taken into account with the calculation. The initial state of charge at the 1st charging station is 44.71% to start the charging process.

Table 13 : Charging Losses and Charging Time for different Charging types at First Charging Station

Charging Type	**Charging Power**	**Charger efficiency**	**Desired SOC 80%**	**Required kWh**	**Charging time**	**Power loss**
AC Level 2	22 kw	~81-88%	30.4 kWh	13.68 kWh	~36 mins	2.34 kWh
DC Level 1	50 kw	~78-86%	30.4 kWh	13.68 kWh	~22 mins	3.30 kWh

After identifying the losses and charging time while charging the vehicle at the first charging station, the same thing will be done by reaching the second charging station; Results in Table 14 show the charging losses and charging time using the same types of charger used in the first charging station. The vehicle arrives to the 2nd charging station at 16.36% state of charge and will be charged until the desired 80% SOC.

Table 14 : Charging Losses and Charging Time for different Charging types at 2nd Charging Station

Charging Type	**Charging Power**	**Charger efficiency**	**Desired SOC 80%**	**Required kWh**	**Charging time**	**Power loss**
AC Level 2	22 kw	~81-88%	30.4 kWh	24.33 kWh	~66 mins	3.81 kWh
DC Level 1	50 kw	~78-86%	30.4 kWh	24.33 kWh	~36 mins	5.08 kWh

After obtaining the Energy and Power losses for different charging techniques at the second charging station, we will continue our calculation in order to obtain the overall losses for the whole trip. As done in the previous section, we will also simulate different charging scenarios for any type of purpose needed when the user arrives to his destination. The desired SOC% will remain 80% for charging and the initial state of charge is 28.33% to start the charging process. Results of charging losses and charging time for different charging types at the destination are shown in Table 15.

Table 15: Charging Losses and Charging Time for different Charging types at Destination

Charging Type		Charging Power	Charger efficiency	Desired SOC 80%	Required kWh	Charging time	Power loss
DC Level 1		50 kw	~78-86%	30.4 kWh	19.66 kWh	~30 mins	4.44 kWh
AC Level 2 charging	16 A	7 kw	~80-85%	30.4 kWh	19.66 kWh	2.8 hr	4.09 kWh
	32 A	11 kw	~81-86%			1.79 hr	3.81 kWh
	32 A	22 kw	~81-88%			~53 mins	3.19 kWh
Wireless Charging		7 kW	~83-87%	30.4 kWh	19.66 kWh	2.8 hr	3.51 kWh

The simulation of the way back home will also be carried out in order to complete a full study as the previous section for an entire round trip, in order to then compare both battery packs results having the exact simulation for both cases. The following table (Table 16) will summarize the SOC% and consumption on different locations while going back to Brussels, in addition the charging losses and time at different charging stations on the way back are shown in Table 17.

Table 16: SOC% and Consumption on different locations of the trip going back home

Location	SOC %	Distance (km)	Consumption kWh
Stating Point (Paris)	80%	0	0
Charging Station 1	28.34%	92 km	19.63 kWh
Charging Station 2	16.33%	207 km	24.33 kWh
End Point (Brussels)	24.7%	315 km	21.01 kWh

Table 17: Charging Losses and Charging Time for different Charging types on the way back at 1st & 2nd charging stations

Location	Charging Type	Charging Power	Charger efficiency	Desired SOC 80%	Required kWh	Charging time	Power loss
Charging station 1	AC Level 2	22 kw	~81-88%	30.4 kWh	19.66 kWh	~53 mins	3.19 kWh
	DC Level 1	50 kw	~78-86%	30.4 kWh	19.66 kWh	~30 mins	4.33 kWh
Charging station 2	AC Level 2	22 kw	~81-88%	30.4 kWh	24.33 kWh	~66 mins	3.81 kWh
	DC Level 1	50	~78-86%	30.4 kWh	24.33	~37 mins	5.08 kwh

8 CASE SCENARIO II: DAILY DRIVING ROUTINE

For the methodology of this thesis, as we have mentioned, understanding the real-life energy consumption and charging behavior of an EV is crucial. While theoretical approximations can give us a good understanding of the general behavior of an electric vehicle, real scenarios simulations will let us evaluate accurately the charging losses.

The aim of this second part of the study is to reflect the typical daily usage of an EV; a case scenario will be created in order to simulate a daily lifestyle of most of vehicle owners. In addition, as mentioned in the literature, EVs technology comes in use in these urban situations where we have an added value of regenerative braking.

Therefore, for the second case scenario we will assume a starting point from home with 80% Battery in order to always respect the 20-80% range, contrarily to the previous simulation where we were constrained by leaving with a 100% SOC due to the huge distance that needed to be traveled.

As we are aiming in simulating the daily lifestyle of a vehicle owner, the best approach that could be done is to create a daily commute to work and going back home, as this scenario represents the biggest percentage of vehicle use in the world, it might be going to either work or school. The departure for this simulation will continue the assumption of leaving from Brussels Midi, representing the home location. The chosen destination is Zaventem (assumed to be Toyota Motor Europe NV on the map), where many big companies are located there, it is around an 18km route that may represent an average distance for a typical worker. This journey will encompass different driving conditions such as city traffic and highway driving, all of which could significantly influence power consumption.

The first approach will only simulate going on a daily basis to work and coming back home. An additional trip will be then introduced, as we know that many people during the week are only busy with work or school, but at the same time, there are different types of users where they go during the week either to gym, the restaurant, see friends or family, many scenarios. For this part, we will assume that the user goes on a daily basis to the gym after finishing work and gets back home. This will let us analyze two scenarios, revealing how additional outings affect energy consumption, and would be interesting to compare battery packs size for a whole weekly scenario.

The scenario assumes the availability of charging stations at both the workplace and home. Depending on the type of charger available (slow or fast), the energy and losses involved in each charging session will be calculated, providing practical insights into daily charging habits.

In order to obtain a great understanding of a typical user consumption and losses of the EV, instead of just analyzing a single trip, the simulation will replicate a typical workweek, making the simulation along the whole working week from Monday until Friday.

Our main goal in this section is to be able to identify the best charging strategy that a user can follow during his week, different strategies will be compared, where one would be that the user keeps on using his EV until the battery SOC reaches 20% and then his refills it back to 80%. Another interesting scenario to compare would be where the user charges everyday his EV after coming back home and other charging strategies would be added where the user charges twice or three times per week which would be in general a charging from mid valued state of charges (40%-60%).

In this case scenario, the same comparison of Nissan Leaf battery packs will be used and compared in the simulations, using the same maps software and calculation strategies as the section before.

Figure 66 shows the route on google maps from Home to Work, with showing in red high traffic zone, in orange medium traffics, and in blue no traffic at all, and it is a total of 18-kilometer trip, which would be a good approximation of an average work travel.

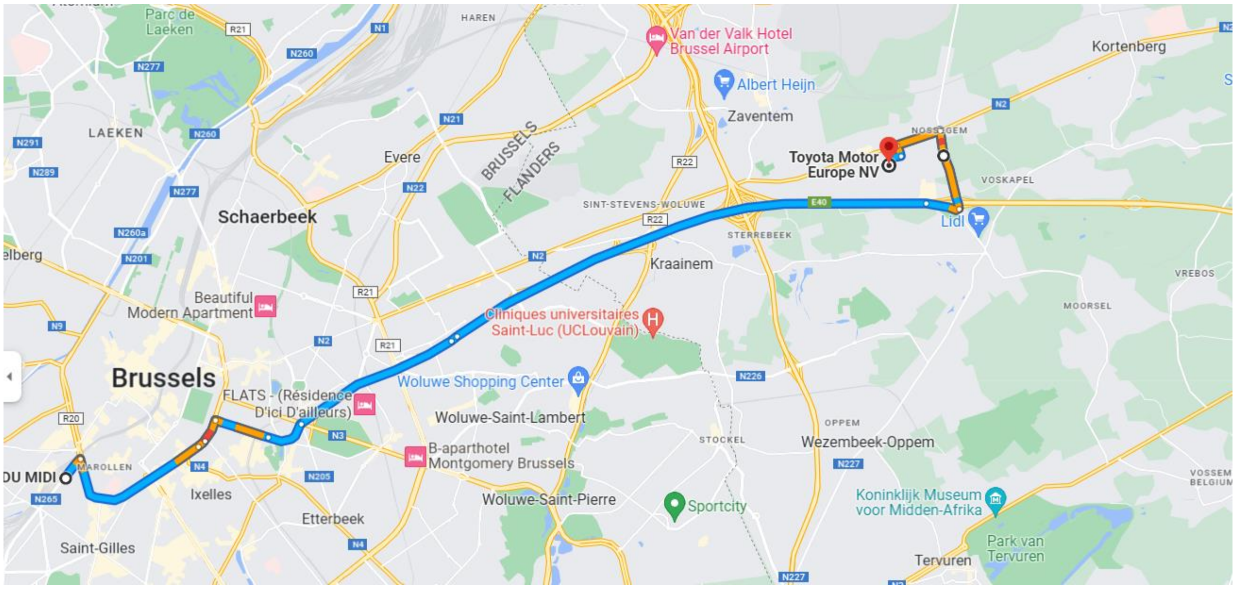


Figure 66: Google Maps route from Home to Work

Using the same software and before, OsmAnd maps was able to give use the driving cycle from Home to Work (Figure 67) by setting up the exact addresses of both points, It also takes into consideration the exact speed limits on these actual roads. As we can see there are three points where the vehicle speed is zero, which means that the car is stopping, which are in reality traffic lights.

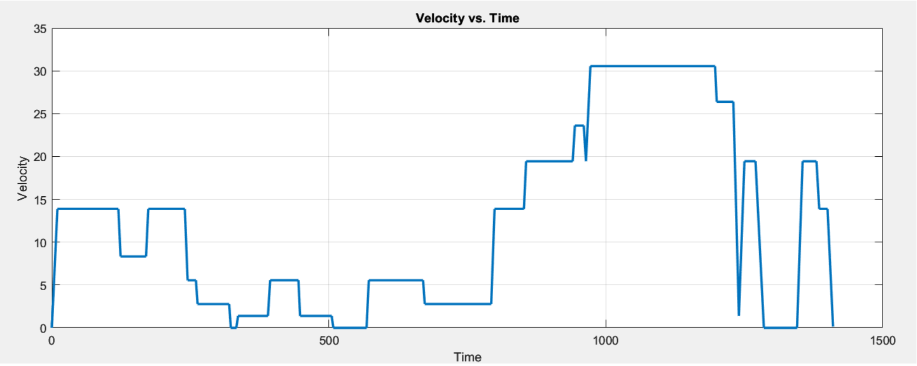


Figure 67: Driving cycle from Home to work

The way back from work to home is not the same route as going to work, there, another driving cycle will be also obtained for the way back home as shown in Figure 69 , having an approximate distance of 20.5 kilometers which is around 2.5 kilometers more than going to work.

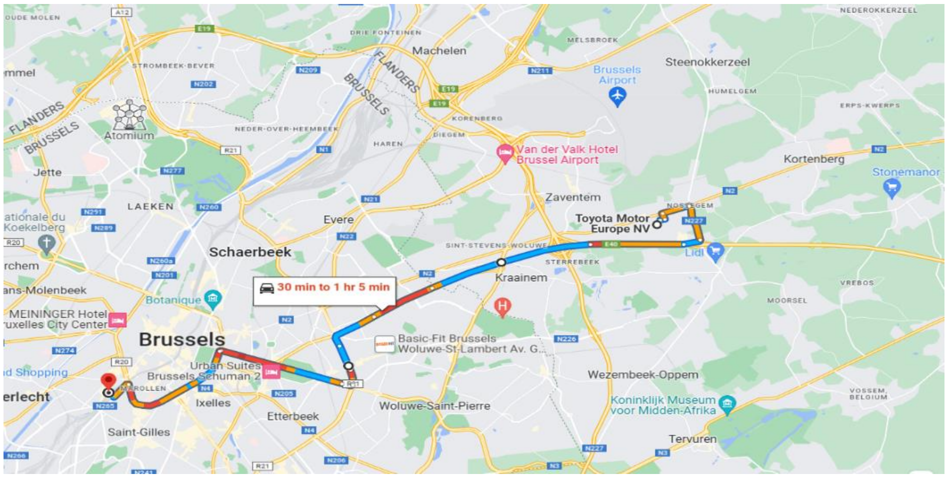


Figure 68: Google maps route from Work to Home

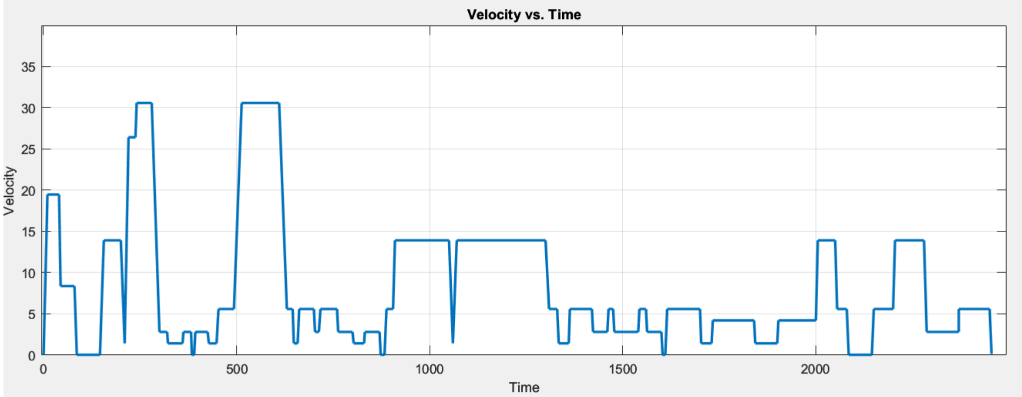


Figure 69: Driving Cycle from Work to Home

8.1 62 kWh Battery

In this case scenario, the same comparison of Nissan Leaf battery packs will be used during this simulation, as we have seen differences in battery pack size during long trips; it would be interesting to also identify the difference for urban daily routine trips.

As shown in the Figure 70, we also obtained the energy consumption of the first trip going from home to work in order to check the SOC% variation. The total energy consumption of this trip, of 18 kilometers is 3.23kWh, which represents a consumption of 17.9 kWh/100km, which is compatible to combined urban highway energy consumption for a Nissan Leaf; the SOC% varied from 80% leaving home, and arrived to work with a state of charge of 74.4%.

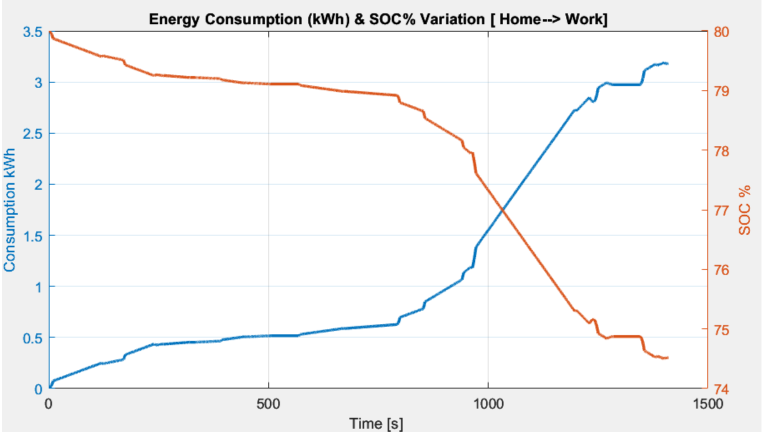


Figure 70: Consumption (in kWh) and SOC% variation from Home to Work

After arriving to work and it is time to come back home, we are going then to identify different charging strategies during the week by either charging at home or at work, so for the first approach we will assume that the user have not charged his vehicle at work. So coming back home, the total energy consumed was 3.53 kWh over a 20.5km distance, which represents a consumption of 17.2 kWh/100km. The user has left work with a state of charge of 74.4% and reaches home with 68.2% SOC.

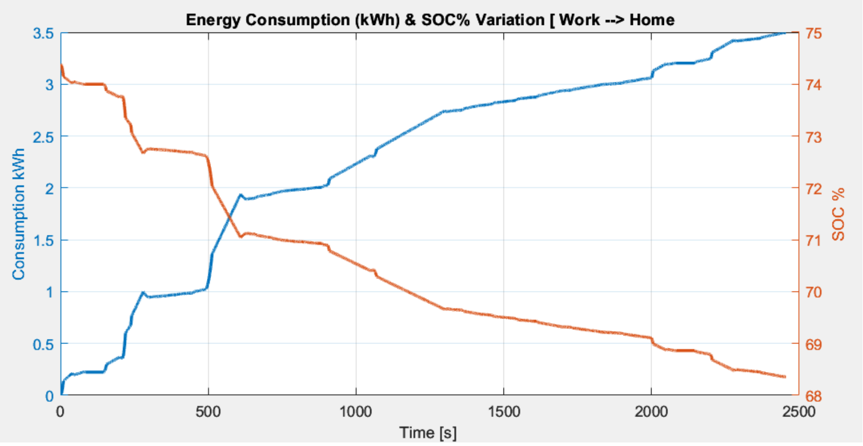


Figure 71: Consumption (in kWh) and SOC% variation from Work to Home

After obtaining the energy consumption and SOC% variation for the Nissan Leaf by going from Home to work and vice versa, we are now able to construct the variation over the week by going every day to work. By checking this weekly variation shown in Table 18, we are able to simulate different charging strategies in order to conclude the most suitable strategy for an EV user to use. The first strategy that will be identified will let the user keep on going back and forth to work until his battery reaches 20%, when it reaches this state of charge it will be time to charge. Using a 62 kWh battery, it looked like the user was able to go every day to work and come back home without the need of charging his vehicle all week long, where he reaches 20.6% SOC on Friday after coming back home.

Table 18: SOC% variation over the week going from Home to Work and Work to Home without Charging

Day of the week	SOC % Home	SOC% Work
Monday	80%	74.4%
Tuesday	68.2%	62.5%
Wednesday	56.24%	50.62%
Thursday	44.36%	38.74
Friday	32.48%	26.87
Friday night	20.60%	

In the previous chapter of simulating the charging types for long trips, the use of DC fast chargers was crucial in order to not waste time at the charging stations. Moreover, as we have discussed in previous chapters, it is not recommended to use DC fast charging frequently and only for important applications when needed due to its major effects on battery degradation.

For daily-routines where the user is staying for around 8 hours at work/school and is staying overnight at home, AC Level 1 and 2 are the most suitable chargers to use. The following table (Table 19) will show the calculations for different types of chargers for charging one time per week starting at 20.6% as starting SOC and 80% as our desired state of charge.

Table 19: Charging Losses and Charging Time for different Charging types (One time per week)

Charging Type		**Charging Power**	**Charger efficiency**	**Desired SOC 80%**	**Required kWh**	**Charging time**	**Power loss**
AC Level 1 charging	10 A	2.3 kw	~81%	46.4 kWh	34.45 kWh	14.97 hr	8.08 kWh
	16A	3.68 kw				9.36 hr	8.08 kWh
AC Level 2 charging	16 A	7 kw	~80-85%	46.4 kWh	34.45 kWh	4.92 hr	7.23 kWh
	32 A	11 kw	~81-86%			3.132 hr	6.73 kWh
	32 A	22 kw	~81-88%			1.566 hr	5.49 kWh
Wireless Charging		7 kW	~83-87%	46.4 kWh	34.45 kWh	4.92 hr	6.168 kWh

After calculating the charging time and losses for this first charging strategy, we will look into identifying another charging strategy. The second charging strategy will simulate that the user waits until his vehicle drops between the 40-60% state of charge range and refills his vehicle back to 80%. Looking at Table 20, the user has charged his vehicle the first time on a Tuesday night when the vehicle reached 56.2% SOC, and the second time at the end of week on a Friday night when his battery reached 44.4% SOC, which in conclusion required two times charging per week.

Table 20: SOC% variation over the week going from Home to Work and Work to Home with Charging twice a week

Day of the week	SOC % Home	SOC% Work	SOC% Home night
Monday	80%	74.4%	68.2%
Tuesday	68.2%	62.5%	56.2%
Wednesday	80%	74.4%	68.2%
Thursday	68.2%	62.5%	56.2%
Friday	56.2%	50.6%	44.4%
Refill	80%		

The following table (Table 21) will show the calculations for different types of chargers for charging twice per week starting at 56.2% and 44.4% as starting SOC and 80% as desired state of charge.

Table 21: Charging Losses and Charging Time for different Charging types (Twice per week)

Charging Day	Charging Type		**Charging Power**	**Charger efficiency**	**Required kWh**	**Charging time**	**Power loss**
TUESDAY	AC Level 1 charging	10 A	2.3 kw	~83%	13.78 kWh	6 hrs	4.028938
		16A	3.68 kw			3.75 hrs	3.23 kWh
	AC Level 2 charging	16 A	7 kw	~80-85%	13.78 kWh	~2 hrs	3.13 kWh
		32 A	11 kw	~81-86%		1.25 hrs	2.92 kWh
		32 A	22 kw	~81-88%		~38 mins	2.69 kWh
	Wireless Charging		7 kW	~86%	13.78 kWh	~2 hr	2.448 kWh
FRIDAY	AC Level 1 charging	10 A	2.3 kw	~83%	20.64 kWh	9 hr	4.84 kWh
		16A	3.68 kw			5.63 hr	4.84 kWh
	AC Level 2 charging	16 A	7 kw	~80-85%	20.64 kWh	2.96 hr	4.31 kWh
		32 A	11 kw	~81-86%		1.84 hr	4.01 kWh
		32 A	22 kw	~81-88%		0.94 hr	3.60 kWh
	Wireless Charging		7 kW	~86%	20.64 kWh	2.9 hr	3.69 kWh

After obtaining results for the second charging strategy that required to charge twice per week, another strategy will be identified in order to have a good margin of comparison. The Third charging strategy we will simulate is that the user waits until his vehicle drops around 60% state of charge range and refills his vehicle back to 80%, so trying to keep the vehicle in the 60-80% range. Looking at Table 22, the user has charged his vehicle the first time on Tuesday at work, when the vehicle reached 62.5% SOC, with the assumption that there exists an EV charger at work.

The second time, the user charged his vehicle on Thursday also at work when the vehicle has reached 56.4% SOC. And the last time needed to refill the vehicle was at the end of week on a Friday night when the battery reached 62% SOC, which in conclusion required three times charging per week.

The results in Table 23 will show the calculations for different types of chargers for charging three per week starting at 62.5%, 56.4% and 44.4% as starting SOC and 80% as desired state of charge.

Table 22: SOC% variation over the week going from Home to Work and Work to Home with Charging three times per week

Day of the week	SOC % Home	SOC% Work	SOC % Leaving Work	SOC% Home night
Monday	80%	74.4%	74.4%	68.2%
Tuesday	68.2%	62.5%	80%	73.8%
Wednesday	73.8%	68.2%	68.2%	62%
Thursday	62%	56.4%	80%	73.8%
Friday **Refill**	73.8% 80%	68.2%	68.2%	62%

Table 23 Charging Losses and Charging Time for different Charging types (3 times per week)

Charging Day	Charging Type		**Charging Power**	**Charger efficiency**	**Required kWh**	**Charging time**	**Power loss**
TUESDAY	AC Level 1 charging	10 A	2.3 kw	~83%	10.15 kWh	4.41 hr	2.38 kWh
		16A	3.68 kw			2.76 hr	2.38 kWh
	AC Level 2 charging	16 A	7 kw	~80-85%	10.15 kWh	1.45 hr	2.45 kWh
		32 A	11 kw	~81-86%		55 min	2.38 kWh
		32 A	22 kw	~81-88%		27 min	2.22 kWh
	Wireless Charging		7 kW	~83-87%%	10.15 kWh	1.45 hr	1.81 kWh
THURSDAY	AC Level 1 charging	10 A	2.3 kw	~83%	13.68 kWh	~5.9 hr	3.2 kWh
		16A	3.68 kw			3.7 hr	3.2 kWh
	AC Level 2 charging	16 A	7 kw	~80-85%	13.68 kWh	~1.95 hr	3.08 kWh
		32 A	11 kw	~81-86%		~1.2 hr	2.88 kWh
		32 A	22 kw	~81-88%		~ 37 mins	2.66 kWh
	Wireless Charging		7 kW	~83-87%%	13.68 kWh	~1.95 hr	2.44 kWh
FRIDAY	AC Level 1 charging	10 A	2.3 kw	~83%	10.44 kWh	4.53 hr	2.44 kWh
		16A	3.68 kw			2.83 hr	2.44 kWh
	AC Level 2 charging	16 A	7 kw	~80-85%	10.44 kWh	1.49 hr	2.52 kWh
		32 A	11 kw	~81-86%		~56 min	2.44 kWh
		32 A	22 kw	~81-88%		28.2 min	2.29 kWh
	Wireless Charging		7 kW	~83-87%%	10.44 kWh	1.49 hr	1.87 kWh

After simulating these charging strategies, we have obtained the results of charging losses and time for charging the vehicle once, twice and three times per week. The last charging strategy, which will be an important strategy for comparison, will be an everyday charging which would be a five times charging per week. The user will go every day to work and get back home, and will refill his vehicle back to 80% at night, as shown in Table 24. The results found in Table 25 shows the charging losses and time for an everyday charging starting 68.2% SOC.

Table 24: SOC% variation over the week going from Home to Work and Work to Home with daily charging at home

Day of the week	SOC % Home Morning	SOC% Work	SOC% Home Night
Monday→ Friday	80%	74.4%	68.2%

Table 25 Charging Losses and Charging Time for different Charging types (Charging everyday)

Charging Type		**Charging Power**	**Charger efficiency**	**Desired SOC 80%**	**Required kWh**	**Charging time**	**Power loss**
AC Level 1 charging	10 A	2.3 kw	~83%	46.4 kWh	6.84 kWh	~3 hr	1.6 kWh
	16A	3.68 kw				1.85 hr	1.6 kWh
AC Level 2 charging	16 A	7 kw	~80-85%	46.4 kWh	6.84 kWh	~1 hr	1.93 kWh
	32 A	11 kw	~81-86%			~38 mins	1.81 kWh
	32 A	22 kw	~81-88%			~ 19 mins	1.711 kWh
Wireless Charging		7 kW	~83-87%%	46.4 kWh	6.84 kWh	~ 1 hr	1.22 kWh

After calculating the charging losses for different charging strategies, a comparison of results will be done in order to understand which strategy would be the best to use on a daily basis for charging an EV from a charging loss point of view.

The results will be compared for the same charging type, in our case, a 7kw AC Level 2 charger will be selected for comparison throughout the different charging strategies to have an understanding of the differences.

The results found in Table 26 summarize the obtained results for different charging strategies. We will compare the total energy lost from the grid for these different strategies in order to come up with a conclusion. For the first strategy used was waiting until the vehicle reaches 20% state of charge which required only one charge per week to complete the weekly roundtrip to work. This charging strategy had the least amount of energy lost from the grid with a 7.23 kWh total energy loss.

In contrary, the charging strategy where the user charged everyday his vehicle which accumulated a total of 5 times charging per week, charging the vehicle from a 70% to 80% each time he gets back home was the worst one where we have obtained the highest amount of energy lost with 9.65 kWh, and the reason behind that is that the efficiency of the charger shows a big decrease when getting closer to 80%, which in conclusion should be the least preferred way to charge your vehicle.

The other two strategies showed close results, where one was to consider recharging the EV when the state of charge drops between 40-60%, where it gave very close results to the first strategy having 7.44 kWh of total energy lost from the grid. Moreover, the last one was charging where we were charging the vehicle when the SOC was close to 60% keeping the vehicle in an approximate 60-80% range had the second most amount of energy lost by 8.05 kWh. The two strategies with the least amount of energy lost from the grid where charging from 20-80% and charging when the vehicle is in the 40-60% state of charge range.

As the one time charge per week seems like the optimal strategy, we need to get back to some fundamentals explained in previous chapters, where we have seen that discharging the battery too often, will increase the chances of higher battery degradation. Some authors suggests that it is not preferable to continuously let your battery discharge for state of charges lower that 30%, comparing these two strategies, we only have 2.8% more energy loss difference.

This leads us to the conclusion that charging the vehicle when the initial state of charge is between 40-60% is the best strategy that could be used, for two main factor: Decrease in the energy lost from the grid where the charger shows great efficiencies between these SOC, and for battery health as it is an optimal state of charge to stay between and decreases the chances of battery degradation.

In addition, after choosing this ideal strategy, by comparing it by the worst one, one can conclude that charging the vehicle at high state of charges (~70%) to 80% will lead to an increase of 25% in the total energy lost compared to the best charging strategy chosen.

Table 26: Total Energy Loss over the week for different charging strategies

Charging Strategy	Everyday	One Time	Two Times	Three Time
Total Energy Loss	9.65 kWh	7.23 kWh	7.44 kWh	8.05 kWh

Additional Daily urban trip

As there exists a big percentage of workers that only goes to work during weekdays, there is also a big percentage of people that also goes out at night when they are finished with their responsibilities; it might be several urban locations like a restaurant, gym, café... For that reason, an additional trip will be introduced, we will assume that the user goes on a daily basis to the gym after finishing work and gets back home.

A gym was located on the map being 7 kilometers away from the Home location, which is a good average distance for an additional daily urban trip. It will be assumed that the user goes in the morning to work and gets back home, and then he goes out to the gym. The driving cycle was obtained for this route, and as the way back will be exactly the same route and distance, there was no need obtain a driving cycle for the way back. Therefore, the consumption and SOC% variation will be the same for this round trip.

The following Figure (Figure 72) shows the route on the map from Home to the selected gym, and the driving cycle is shown In Figure 73.

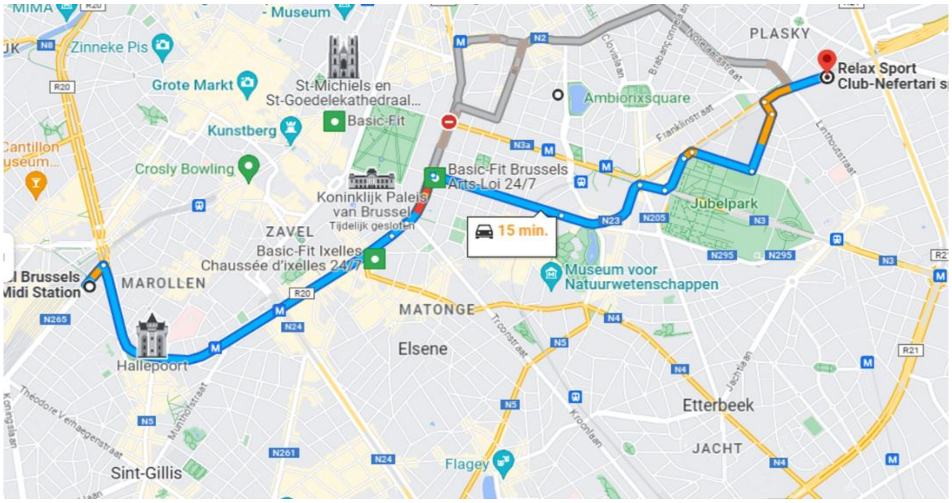


Figure 72: Route from Home to the Gym

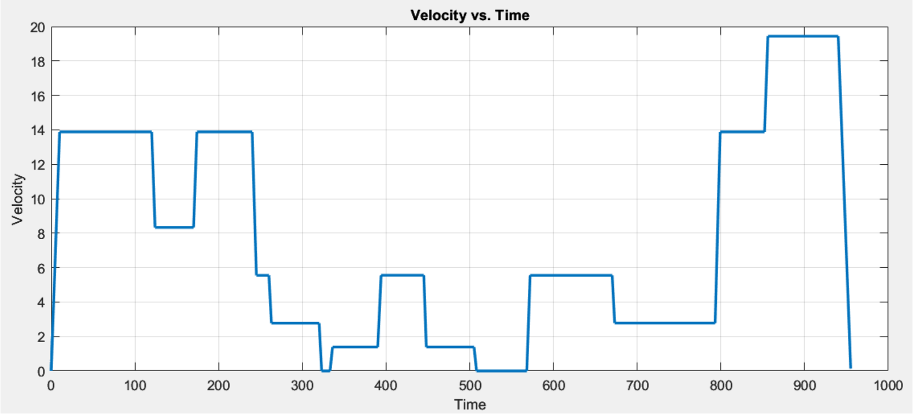


Figure 73: Driving Cycle from Home to Gym

As shown in the Figure 74, we were able to calculate the energy consumption of the additional going from home to gym in order to check the SOC% variation. The total energy consumption of this trip, of 7 kilometers is 1.09 kWh, which represents a consumption of 15.57 kWh/100km, which is suitable for urban trips for a Nissan leaf, the SOC% varied from 68.2% leaving home, and arriving to the gym at 66.2%. Then the same consumption will be consumed by getting back home, whereas the state of charge will vary from 66.2% leaving the gym arriving at home with a 64.2% state of charge.

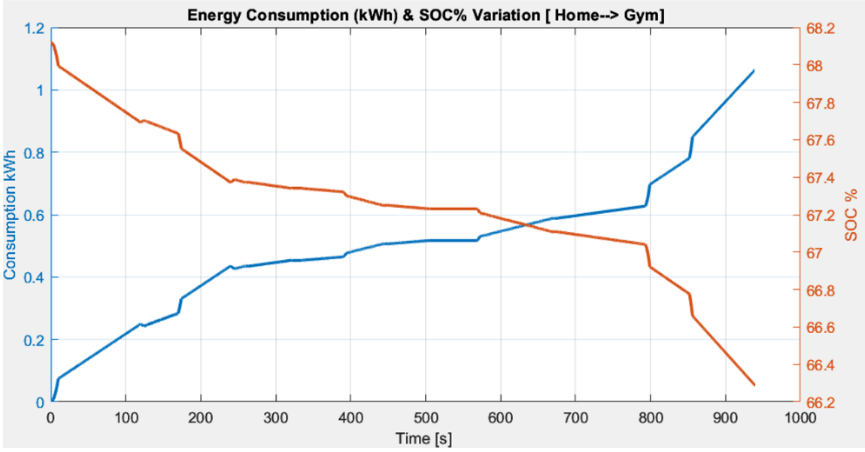


Figure 74: Consumption variation from Home to Gym

First of all, for this additional trip, we will check the state of charge variation without charging the vehicle at all just to visualize the difference between a weekly daily routine of the user with and without an additional trip. The additional trip has led to a daily drop of 4% in the battery state of charge. A visualization of the state of charge variation during the week with the additional trip is shown in the Table 27; we will of course not let the user continue his trips with state of charges under 20%.

Table 27: SOC% variation over the week at different locations (Home, Work, Gym)

Day of the week	SOC % Home in the morning	SOC% Work	SOC% Home At night	SOC% Gym
Monday	80%	74.4%	68.2%	66.2%
Tuesday	64.2%	58.6%	52.4%	50.4%
Wednesday	48.4%	42.8%	36.6%	34.6%
Thursday	32.6%	27%	20.8%	18.8%!
Friday	16.8%!	11.2%!	5%!	3%!
Friday Night	1%!			

After concluding the best charging strategy in the previous section, by charging between the 40-60% range, we will implement this strategy to the weekly simulation with adding the additional trip to the daily routine. This implementation will let us compare the results of the charging losses of the weekly routine with and without an additional trip, and will later let us compare this weekly simulation between different Nissan Leaf Battery Packs.

The table below (Table 28) shows the variation of state of charge during the week with implementing the best charging strategy, the vehicle was recharged the first time on Wednesday at work, charging the vehicle from 42.8% state of charge, and the second time was at the end of the week on Friday night, charging the vehicle from 38.2% starting SOC%. Adding an additional trip did not increase the number of charging times during the week.

Table 28: SOC% variation over the week at different locations (Home, Work, Gym)

Day of the week	SOC % Home Morning	SOC% Work	SOC% Leaving work	SOC% Home At night	SOC% Gym
Monday	80%	74.4%	74.4%	68.2%	66.2%
Tuesday	64.2%	58.6%	58.6%	52.4%	50.4%
Wednesday	48.4%	42.8%	80%	73.8%	71.8%
Thursday	69.8%	64.2%	64.2%	58%	56%
Friday	54%	48.4%	48.4%	42.2%	40.2%
Friday Night	38.2% → 80%				

The following table (Table 29) will show the calculations for different types of chargers for charging twice per week starting at 56.2% and 44.4% as starting SOC and 80% as desired state of charge.

Table 29: Charging Losses and Charging Time for different Charging types with an additional trip

Charging Day	Charging Type		**Charging Power**	**Charger efficiency**	**Required kWh**	**Charging time**	**Power loss**
WEDNESDAY	AC Level 1 charging	10 A	2.3 kw	~83%	21.57 kWh	9.3 hr	5.06 kWh
		16A	3.68 kw			5.63 hr	5.06 kWh
	AC Level 2 charging	16 A	7 kw	~80-85%	21.57 kWh	3 hr	4.48 kWh
		32 A	11 kw	~81-86%		1.96 hr	4.17 kWh
		32 A	22 kw	~81-88%		0.98 hr	3.73 kWh
	Wireless Charging		7 kW	~83-87%%	21.57 kWh	3 hr	3.86 kWh
FRIDAY	AC Level 1 charging	10 A	2.3 kw	~83%	24.244 kWh	10.54 hr	5.68 kWh
		16A	3.68 kw			6.58 hr	5.68 kWh
	AC Level 2 charging	16 A	7 kw	~80-85%	24.244 kWh	3.44 hr	4.97 kWh
		32 A	11 kw	~81-86%		2.19 hr	4.62 kWh
		32 A	22 kw	~81-88%		1.09 hr	4.08 kWh
	Wireless Charging		7 kW	~83-87%%	24.244 kWh	3.44 hr	4.34 kWh

8.2 40 kWh Battery Pack

In the previous section of this study, the simulation of daily routine trips with a 62 kWh battery pack vehicle was conducted. After conducting the best charging strategy, the first simulation with a big battery pack needed to be charged twice a week, giving us a great approximation of the charging strategies and losses for large battery capacities.

This secondary simulation focuses on figuring out the effects of battery size on EV daily routine urban travel and charging strategies. By comparing the same vehicle with a smaller 40 kWh battery against the previously analyzed 62 kWh version, we aim to analyze the state of charge variation and the charging losses over the week with and without the additional daily trip.

For a 40 kWh Nissan Leaf, the total energy consumption going from home to work, of 18 kilometers is 3.09kWh, which represents a consumption of 17.1 kWh/100km, which is compatible to combined urban highway energy consumption for a Nissan Leaf, the SOC% varied from 80% leaving home, and arrived to work with a state of charge of 71.8%. The figure below (Figure 75) shows the variation of SOC% and consumption during the trip.

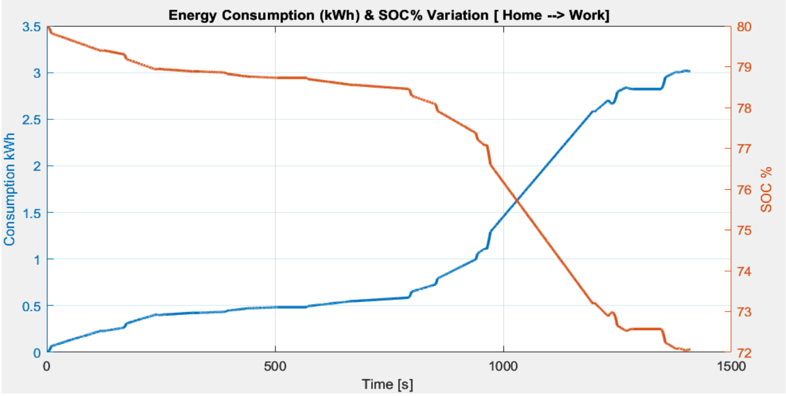


Figure 75: Consumption and SOC% variation from Home to Work

Whereas, the graph in Figure 76 shows the variation of consumed energy and SOC while coming back home, the total energy consumed was 3.42 kWh over a 20.5km distance, which represents a consumption of 16.6 kWh/100km. The state of charge varied from 72% leaving work and arriving home with 63%.

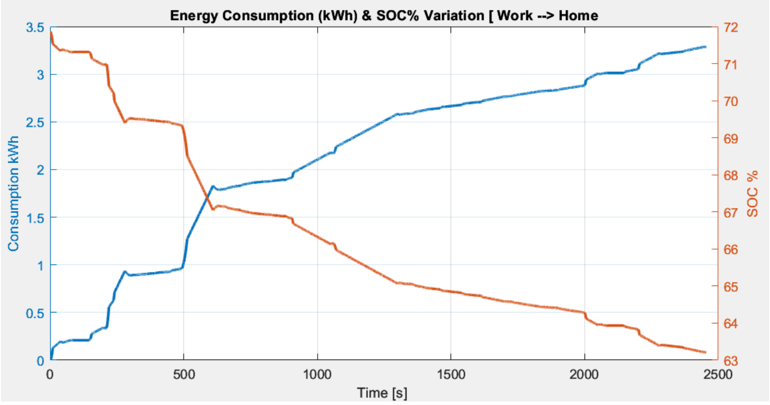


Figure 76: Consumption and SOC% variation from Work to Home

First, for this smaller battery pack, we will check the state of charge variation without charging the vehicle at all just to visualize the difference variation between a larger and smaller battery pack. A visualization of the state of charge variation during the week with the additional trip is shown in the table below (Table 30); we will of course not let the user continue his trips after the state of charge has dropped under 20%. It even turned out that the user cannot even complete a whole working week without charging his vehicle, contrary to the 62 kWh Leaf that was able to get back home on Friday night with a 20% state of charge.

Table 30: SOC% variation over the week going from Home to Work and Work to Home without Charging

Day of the week	SOC % Home	SOC% Work
Monday	80%	72%
Tuesday	63%	55%
Wednesday	46%	38%
Thursday	29%	21%
Friday	12%	4%

After concluding the best charging strategy in the previous section, where it was to charge the vehicle when the state of charge was dropping between 40-60%, we will implement this strategy to the weekly simulation with adding the additional trip to the daily routine.

Table 31 shows the variation of state of charge during the week with implementing the best charging strategy, the vehicle was recharged the first time on Tuesday night, charging the vehicle from 46% state of charge. The second time the vehicle was charged was on Thursday at work charging it from a 55% initial SOC%, and the last time was on the last day, which was Friday night, charging the vehicle from 54%. Three times was the number of charging needed during the week using the best charging strategy, which is one time more than using a bigger battery pack.

Table 31: SOC% variation over the week going from Home to Work and Work to Home using best charging strategy

Day of the week	SOC % Home	SOC% Work	SOC% Leaving Work	SOC% Home night
Monday	80%	72%	72%	63%
Tuesday	63%	55%	55%	46%
Wednesday	80%	72%	72%	63%
Thursday	63%	55%	80%	71%
Friday **Refill**	71% 80%	63%	63%	54%

The following table (Table 32) will show the calculations for different types of chargers for charging three times per week the 40 kWh Nissan leaf starting at 46% and 55% and 54% as starting SOC and 80% as desired state of charge.

Table 32: Charging Losses and Charging Time for different Charging types using best charging strategy

Charging Day	Charging Type		**Charging Power**	**Charger efficiency**	**Required kWh**	**Charging time**	**Power loss**
TUESDAY	AC Level 1 charging	10 A	2.3 kw	~83%	12.92 kWh	5.61 hr	3.03 kWh
		16A	3.68 kw			3.51 hr	3.03 kWh
	AC Level 2 charging	16 A	7 kw	~80-85%	12.92 kWh	1.84 hr	2.72 kWh
		32 A	11 kw	~81-86%		1.17 hr	2.53 kWh
		32 A	22 kw	~81-88%		0.58 hr	2.28 kWh
	Wireless Charging		7 kW	~83-87%%	12.92 kWh	1.84 hr	2.31 kWh
THURSDAY	AC Level 1 charging	10 A	2.3 kw	~83%	9.5 kWh	4.13 hr	2.22 kWh
		16A	3.68 kw			2.58 hr	2.22 kWh
	AC Level 2 charging	16 A	7 kw	~80-85%	9.5 kWh	1.35 hr	2.11 kWh
		32 A	11 kw	~81-86%		0.86 hr	1.97 kWh
		32 A	22 kw	~81-88%		0.43 hr	1.81 kWh
	Wireless Charging		7 kW	~83-87%%	9.5 kWh	1.35 hr	1.84 kWh
FRIDAY	AC Level 1 charging	10 A	2.3 kw	~83%	9.88 kWh	4.29 hr	2.32 kWh
		16A	3.68 kw			2.68 hr	2.32 kWh
	AC Level 2 charging	16 A	7 kw	~80-85%	9.88 kWh	1.411 hr	2.18 kWh
		32 A	11 kw	~81-86%		0.89 hr	2.03 kWh
		32 A	22 kw	~81-88%		0.449 hr	1.86 kWh
	Wireless Charging		7 kW	~83-87%%	9.88 kWh	1.411 hr	1.76 kWh

Additional Daily urban trip

As we have seen in the previous section for a larger battery pack, adding an additional daily trip was leading to an additional daily drop of 4% in the state of charge during the week. Therefore, for that it would be interesting to see the effect of an additional trip for a smaller larger pack and how it would affect the need of additional charging for the vehicle.

The total energy consumption of this trip, of 7 kilometers is 1.03 kWh, which represents a consumption of 14.7 kWh/100km, which is suitable for urban trips for a Nissan leaf, the SOC% varied from 63% leaving home, and arriving to the gym at 60.2%. Then the same consumption will be consumed by getting back home, whereas the state of charge will vary from 60.2% leaving the gym and then the user will finally arrive at home with a 57.4% state of charge.

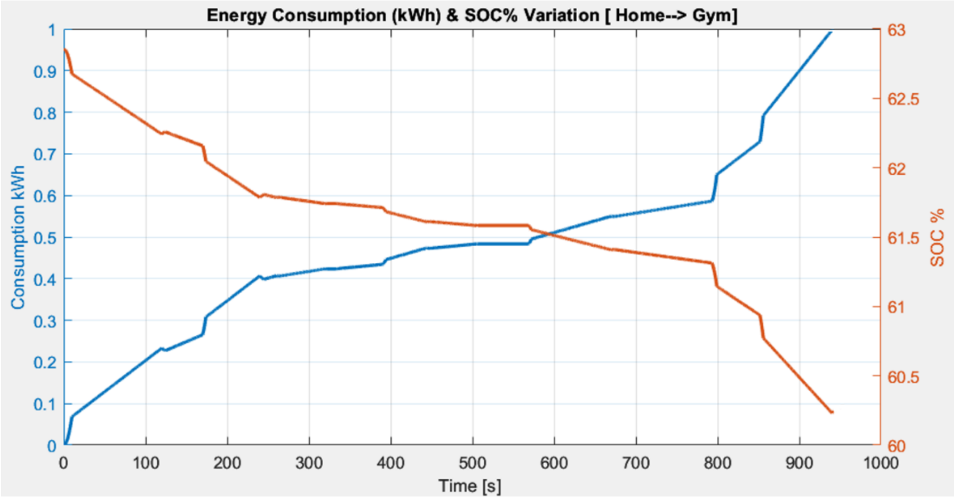


Figure 77: Energy consumption and SOC% variation from Home to Gym for 40kWh Leaf

After obtaining the energy consumption and state of charge variation for a smaller battery pack going to gym, we will immeadtly simulate the variation of SOC during the week with an additional trip by using the best charging strategy concluded.

The table below (Table 33) shows the variation of state of charge during the week with implementing the best charging strategy. The vehicle was recharged the first time on Tuesday at work, charging the vehicle from 49.4% state of charge, and the second time was on Wednesday night, charging the vehicle from 42.8% starting SOC% and the third time was at the end of the week on Friday charging it from 34.8%.

What is also interesting is that for a smaller battery pack, an additional trip did not increase the number of times to charge the vehicle, as it also needed to be charged three times per week.

Table 33: SOC% variation over the week at different locations (Home, Work, Gym)

Day of the week	**SOC % Home Morning**	**SOC% Work**	**SOC% Leaving work**	**SOC% Home At night**	**SOC% Gym**
Monday	80%	72%	72%	63%	60.2%
Tuesday	57.4%	49.4%	80%	71%	68.2%
Wednesday	65.4%	57.4%	57.4%	48.4%	45.6%
Thursday	42.8% → 80%	72%	72%	63%	60.2%
Friday	57.4%	49.4%	49.4%	40.4%	37.6%
Friday Night	34.8% → 80%				

The following table (Table 34) will show the calculations for different types of chargers for charging three times per week the 40 kWh Nissan leaf starting at 49.4% and 42.8% and 34.8% as starting SOC and 80% as desired state of charge.

Table 34: Charging Losses and Charging Time for different Charging types with an additional trip and using the best charging strategy

Charging Day	Charging Type		**Charging Power**	**Charger efficiency**	**Required kWh**	**Charging time**	**Power loss**
TUESDAY	AC Level 1 charging	10 A	2.3 kw	~83%	11.59 kWh	5.03 h	2.72 kWh
		16A	3.68 kw			3.14 h	2.72 kWh
	AC Level 2 charging	16 A	7 kw	~80-85%	11.59 kWh	1.66 h	2.49 kWh
		32 A	11 kw	~81-86%		1.05 h	2.32 kWh
		32 A	22 kw	~81-88%		0.52 h	2.10 kWh
	Wireless Charging		7 kW	~83-87%%	11.59 kWh	1.66 h	2.16 kWh
THURSDAY	AC Level 1 charging	10 A	2.3 kw	~83%	14.136 kWh	6.14 h	3.31 kWh
		16A	3.68 kw			3.84 h	3.31 kWh
	AC Level 2 charging	16 A	7 kw	~80-85%	14.136 kWh	2.01 h	2.93 kWh
		32 A	11 kw	~81-86%		1.28 h	2.73 kWh
		32 A	22 kw	~81-88%		0.64 h	2.44 kWh
	Wireless Charging		7 kW	~83-87%%	14.136 kWh	2.01	2.56kWh
FRIDAY	AC Level 1 charging	10 A	2.3 kw	~83%	17.17 kWh	7.46 h	4.02 kWh
		16A	3.68 kw			4.66 h	4.02 kWh
	AC Level 2 charging	16 A	7 kw	~80-85%	17.17 kWh	2.45 h	3.47 kWh
		32 A	11 kw	~81-86%		1.56 h	3.22 kWh
		32 A	22 kw	~81-88%		0.78 h	2.86 kWh
	Wireless Charging		7 kW	~83-87%%	17.17 kWh	2.45 h	3.07 kWh

9 DISCUSSION AND ANALYSIS

This thesis carried out two major case studies of an EV user possible scenarios, a long trip and an everyday work commute. After obtaining different types of results with many charging scenarios, charger types, battery sizes and driving routines, this section will show and compare all these important aspects related to electric vehicles charging.

When discussing charging losses in general, both energy loss and power loss provide us with valuable insights on different aspects of the charging process. Comparison of energy losses (kWh) between chargers allows us to understand which charger is more efficient during the overall charging process, in addition to the total power lost from the grid where the user is paying for it while charging his EV. Therefore, when we are concerned about the total energy wastage, the overall efficiency of the charger and the operational costs, energy loss is a major variable to look into during the comparisons.

In the other hand, power loss (kW) provides us an instantaneous measure of how energy is being wasted at any given moment during charging, and this variable can give better understanding of potential issues with the grid supply or charger's hardware. Therefore, if we are concerned in examining the peak demand on the electrical grid or heat generation issues, power loss become an interesting measure to quantify.

9.1 Charger types AC/DC

For the first analysis, we will compare for the same battery pack the use of different fast chargers. In this case we will take the first case scenario of a long trip, comparing the total energy loss and power loss between DC Level 1 50 kW charger vs DC Level 2 100 kW fast charger for charging a 62 kWh Nissan leaf doing the same trip, as this model supports higher charging power than the other one. We assume that the DC Level 1 and Level 2 chargers were used at the charging station going to the destination, at the destination and at the charging station while going back home.

Table 35 shows the energy lost while charging the same vehicle with two different types of chargers on different charging locations. The total energy lost from the grid while charging the vehicle using a 50 kW charger was 19.34 kWh while the total loss when using a 100 kW charger was 16.81 kWh, where we have around 13% more loss by the grid while using the lower power charger.

The power loss when we were DC Level 1 fast charging the vehicle from a 37% state of charge was rated at about 10 kW, and it was about 9.5 kW when we were charging the vehicle from a 27% SOC noting that the charging curve peaked at around 47 kW of delivered power for this charger. Whereas for the DC Level 2 fast charger, the power loss was around 10.77 kW when we were charging from a 37% starting state of charge; whereas when the starting state of charge was 27% we had around 10.2 Kw of power loss, noting that the peak power for this charger was 69 kW. The total charging time needed using a 50 kW charger during this trip was 2 hours while it took 98 minutes or 1.6 hours to charge the vehicle using a 100 kW charger for the same exact trip. Putting all that together, one can conclude that during a long trip, if the vehicle with a big battery pack size is accessible to a high charging power, all the aspects of power and energy losses, charging time and efficiency aligns that a 100 kW charger would be the better option in such scenario.

Table 35: DC Fast chargers comparison for charging a 62 kWh Nissan Leaf for the same trip

Charging Location	DC Level 1 Fast Charging (50 kW)	DC Level 2 Fast Charging (100 kW)
Charging Station going to destination	5.76 kWh	5.03 kWh
Charging at Destination	6.87 kWh	5.96 kWh
Charging station on way back	6.71 kWh	5.82 kWh
TOTAL	19.34 kWh	16.81 kWh

After analyzing different types of DC chargers, it would also be crucial to compare the different types of AC chargers as well. In this case we will take the second case scenario of the short trip, comparing the total energy loss and power loss between AC Level 1 3.68 kW charger and AC Level 2 (7 kW, 11 kW and 22 kW) chargers for charging a 62 kWh Nissan leaf during the week. The results were obtained using the best charging strategy by charging the vehicle within the 40-60% range of state of charge.

Results in Table 36 shows the energy lost while charging the same vehicle within the same weekly trip comparing four different AC chargers. The total energy lost from the grid while charging the vehicle using a 3.68 kW charger was 8.07 kWh while the total loss when using a 7 kW charger was 7.44 kWh, as charging power was increasing, the total energy loss was decreasing. Comparing the AC Level 2 11 kW and 22 kW chargers, we see that the 22 kW charger had the least amount of losses having 6.23 kWh, while the 11 kW charger had 6.93 kWh of total energy loss.

When charging the vehicle from a state of charge of 44%, the power loss using a Level 1 charger was 0.85 kW, while for the AC Level 2 chargers of 7 kW, 11 kW and 22 kW, the power loss were 1.45 kW, 2.17 kW and 3.8 kW respectively. The 22 kW charger has shown that it was the most efficient charger between them all with the least amount of energy loss from the grid. Whereas the AC Level 1 charger was the worst type of charger to use and the least efficient.

In regards of charging times, using an AC Level 1 charger it needed 9.38 hrs to charge the vehicle during this exact scenario, whereas as for the Level 2 chargers, it took 4.94 hrs, 3.1 hrs and 1.57 hrs respectively. Therefore, by comparing the AC Level 1 charger with the AC Level 2 22 kW charger, as best vs worst, it took 7.8 hours less to charge the vehicle with the same purpose using the Level 2 charger, in addition to that, the AC Level 1 charger has shown a 23% more total energy loss from the grid compared to the 22 kW.

Which leads us to the conclusion by having the availability of the 22 kW AC Level 2 charger; it might be the best option to consider compared to the other types. One has to note that, the typical chargers available at home are 7 kW chargers, because higher power chargers cannot function on a single-phase supply, so in order to install a 22 kW charger at home, you must have a 3-phase electricity supply installed.

Table 36: AC chargers comparison for charging a 62 kWh Nissan Leaf for the same roundtrip over the week

Charging day	AC Level 1 3.68 kW	AC Level 2, 7 kW	AC Level 2, 11 kW	AC Level 2, 22 kW
Tuesday	3.23 kWh	3.13 kWh	2.92 kWh	2.69 kWh
Friday	4.84 kWh	4.31 kWh	4.01 kWh	3.6 kWh
TOTAL	8.07 kWh	7.44 kWh	6.93 kWh	6.23 kWh

9.2 Battery packs

Knowing range anxiety has been a main issue in the EV world, and even if the number electric vehicle charging stations are increasing with time, there is still a limited number of stations distributed in cities and highways. For that issue, automotive companies started implementing bigger battery packs in order to fulfill their clients' needs and try to reduce this anxiety. However, larger batteries means more cost per vehicle as batteries represents around 30% of an EV cost, larger batteries also means more mass on the vehicle, longer charging time will be needed to fill, and more technical challenges for the vehicle.

Therefore, one of the main goal of this thesis is to compare the charging aspects of two different battery packs for the same vehicle model for different driving scenarios in order to evaluate if it is worth it to keep on upgrading the battery size for the next models of electric vehicles.

We will first of all compare for our long trip, the 62 kWh vs 40 kWh battery sizes of the Nissan Leaf from the charging losses point of view and charging times. For this case, it was assumed for both battery packs that the user while going to the destination, he charges his vehicle using a DC Level 1 50 kW charger, then when he reaches the destination (Paris), we assume that the user charges his vehicle there using an AC Level 2 22 kW charger, afterwards, on his way back home he also charges his vehicle using a DC Level 50 kW charger.

DC Level 1 charger was chosen because it is the common fast charger between both vehicles, knowing that the 40 kWh Nissan Leaf is not supported with a charging power more than 50 kW, in addition, the 40 kWh Leaf makes two stops for charging while going to the destination and on its way back.

The table below (Table 37) summarizes these results, where we can see that the total energy lost by the grid in order to charge the 62 kWh Leaf for this long roundtrip was 17.44 kWh, while the 40 kWh Leaf had 20.98 kWh of total energy loss. These results shows that the smaller battery Leaf has led to 17% more energy loss for charging it during a long trip compared to the larger pack. In addition, the 40 kWh leaf needed two stops to charge the vehicle on each way with a total charging time of 2.96 hours while the 62 kWh Leaf needed only one stop on each way but with a close total charging time of 2.64 hours. We also need to note that the 62 kWh leaf arrives back home with an 18% state of charge while the 40 kWh arrives at 28% which highlights the fact that the vehicle will also need recharging when it arrives home that might change the overall energy loss for a complete trip, this will be identified later by creating a bigger simulation for this roundtrip.

But in regards of the charging time, both needed approximately the same amount of time but with different number of stops, this is a good result to see to understand the importance of investing in charging infrastructure and increasing charging points.

Table 37: Long trip total energy losses for a 62 kWh vs 40 kWh Nissan Leaf

Charging Location	62 kWh Nissan Leaf	40 kWh Nissan Leaf
Charging Station going to destination	5.76 kWh	3.3 kWh + 5.08 kWh
Charging at Destination	4.97 kWh	3.19 kWh
Charging station on way back	6.71 kWh	4.33 kWh + 5.08 kWh
TOTAL	17.44 kWh	20.98 kWh

For the battery packs comparison, we have first saw the case of charging while going on a long trip, now we will do the same comparison between both vehicles, but for the second case scenario of an urban daily routine.

For this case, we have assumed that the user uses a 7 kW charger to charge both vehicles during his working week, the best charging strategies were used for this comparison. As we have seen before, the 62 kWh Leaf needed two times to be charged during the week, while the 40 kWh Leaf needed three-time charging per week.

During the long trip, we have seen that the smaller battery pack needed an additional charging stop on the highway even though the charging time was nearly the same, which might be a little bit frustrating to the user specially if there are not many charging points available on his way to the destination. In contrary, for urban trips, one more charging time per week might not be annoying for the user and will not give a larger battery pack an advantage over the smaller one, because the assumption stands on having the user to charge his EV overnight at home or at work. Therefore, an additional charging time per week will not affect the users rush for charging and immediate need for refilling his battery.

The table below (Table 38) sums up the energy loss for charging the EV during the working week, where the total energy loss for a 62 kWh Leaf was 7.44 kWh, assuming we are starting the week with an 80% SOC, completing the roundtrips to work, and then coming back home on Friday with an 80% SOC for both cases. Whereas, for a smaller battery pack we can see smaller energy losses during the week with having 7.01 kWh total energy lost by the grid, which represents a 5.7% less loss for the smaller battery pack.

Table 38: Short trip total energy losses for a 62 kWh vs 40 kWh Nissan Leaf

Charging Time	62 kWh Nissan Leaf	40 kWh Nissan Leaf
First Time Charging	3.13	2.72
Second Time Charging	4.31	2.11
Third Time Charging	0	2.18
TOTAL	7.44 kWh	7.01 kWh

9.3 Wireless Charging

Wireless charging is expected to be the future of EV charging, and implementing this technology for the future would solve many major problems concerning range anxiety and battery sizes. However, it is still a challenging technology due to many infrastructure challenges and alignment problems. Nowadays, there exists several types of wireless chargers offering wide ranges of powers, but due to lack of literature for wireless charging, we were only able to find some characteristics for charger efficiencies for a 7 kW and 50 kW wireless chargers. However, having included the calculations of charging losses for the same types of conductive chargers powers, this would give us a good opportunity to compare the overall charging efficiency of conductive vs inductive charging.

For the 50 kW chargers, we will take the results of charging the 62 kWh Leaf during the long trip. The results are summarized in Table 39, we can see that the total energy lost by the grid while charging the vehicle using conductive charging is 19.34 kWh, while it was 16.3 kWh using a wireless charger showing a 15% more charging loss while conductive fast charging the vehicle.

Whereas for the 7 kW charger we will take the results of charging the 62 kWh Leaf during the week for short trip assuming the best charging strategy concluded. The results are summarized in Table 4, we can see that the total energy lost while wireless charging the vehicle is 6.13 kWh which was 17% less than the total energy lost while conductive charging being 7.44 kWh under same conditions.

With these results, we can see that wireless charging showed better overall charging efficiency for both 7 kW and 50 kW chargers. However, we would like to note an important factor with these calculations, the efficiency of the wireless chargers were obtained assuming an optimal air gap and with having no misalignments between the EV and the charger pads, and as we have seen in chapter 6, those two variables are the most influencing factors in inefficiencies for inductive power transfer. Therefore, this comparison stands under the best conditions for wireless charging the vehicle, until today companies and research continue to improve the efficiency of wireless charging systems against air gaps and misalignments. Companies are implementing now automated parking assistance systems for EVs in order to ensure nearly perfect alignment every time, and advanced systems have been developed with a certain tolerance to misalignment, meaning even if the vehicle is not perfectly aligned, it will still charge, but of course with less efficiency.

Table 39: 50 kW DC Fast chargers (Conductive vs Inductive) comparison for charging a 62 kWh Nissan Leaf for the same trip

Charging Location	50 kW Conductive Charger	50 kW Wireless Charger
Charging Station going to destination	5.76 kWh	4.7 kWh
Charging at Destination	6.87 kWh	5.85 kWh
Charging station on way back	6.71 kWh	5.74 kWh
TOTAL	19.34 kWh	16.3 kWh

Table 40: 7 kW AC chargers comparison (Conductive vs Inductive) for charging a 62 kWh Nissan Leaf for the same roundtrip over the week

Charging day	7 kW Wireless Charger	7 kW Conductive Charger
Tuesday	2.448 kWh	3.13 kWh
Friday	3.69 kWh	4.31 kWh
TOTAL	6.13 kWh	7.44 kWh

9.4 Additional Trip

As we know that each person have his own daily routine, the addition of a daily trip is an interesting factor to compare for a daily lifestyle of a human. This addition will let us understand the effect of extra daily use of an EV, and would hopefully highlight some ideas that a user might consider when owning an electric vehicle.

In this section, we will identify the effect of increasing your daily driving range (in this case 14 km were added to the daily range), for both 40 kWh and 62 kWh Leaf. The results are obtained by using the best charging strategy during the week for a person going to work and the gym every single day of the week. The results were taken from the assumption that the user uses a 7 kW charger to charge his EV during the week, and as we have seen, the same amount of charging times remained the same for both battery packs with and without the additional trip.

We have also seen that for a 62 kWh Leaf, an additional trip has led to an extra daily 4% drop in the state of charge, whereas for a 40 kWh Leaf, it led to an extra 5.8% daily drop.

The table below (Table 41) sums up these results showing that a daily additional trip leads to around 21% more energy losses for both battery packs, which is a significant amount that could be effective on the long run. In Addition, as for charging time, the total charging time for a 62 kWh leaf without an additional trip was 5 hours, and the additional trip increased the total charging time by 1.4 extra hours. Same goes for the 40 kWh Leaf which needed 4.6 hours of weekly charging, where an additional trip increased the total charging time by 1.5 hours. Knowing that most workers prefer going to work by car, the additional daily trip is usually within the city, hopefully this comparison would encourage EV users to use public transports or carpooling or any other alternative that could reduce their vehicle usage on a daily basis for close range needs.

Table 41: Short trip with additional trip total energy losses for a 62 kWh vs 40 kWh Nissan Leaf

Charging Time	62 kWh Nissan Leaf		40 kWh Nissan Leaf	
	Without Additional	With Additional	Without Additional	With Additional
First Time Charging	3.13 kWh	4.48 kWh	2.72 kWh	2.49 kWh
Second Time Charging	4.31 kWh	4.97 kWh	2.11 kWh	2.93 kWh
Third Time Charging	0	0	2.18 kWh	3.47 kWh
TOTAL	7.44 kWh	9.45 kWh	7.01 kWh	8.89 kWh

9.5 Overall Simulation

After having a better understanding on each type of charger, battery size, range effect, energy losses and best charging strategy, we will now create an overall simulation that adds up the different aspects understood so far. This simulation will sum up the different ideas covered by this thesis. We will create a scenario where the user goes every day to work and to the gym, combining the additional trip with the daily work trip.

We will assume that the user uses a 7 kW AC Level 2 charger at home to charge his EV, and the availability of an AC Level 2 22 kW charger at work. After completing this Monday to Friday daily simulation, we will assume that on Friday, the user gets back from the gym and arrives at home with his final state of charge. Afterwards, the user will use his 7 kW charger to charge his EV overnight to a 100% state of charge, knowing that on Saturday he is going to Paris.

On Saturday morning, the user leaves home with a full capacity battery, and on his way to Paris, for a 62 kWh Leaf the user will charge his vehicle using a 100 kW DC Fast charger because his model is accessible for it, whereas for a 40 kWh, the user will use a 50 kW DC Fast charger to charge his EV. When the user arrives to the destination, he will use an 11 kW AC Level 2 charger to charge his vehicle there, and after finishing his purpose at the destination, he then goes back home and similarly to the first way, he DC Fast charges his vehicle on his way back.

When the user finally gets back home on a Saturday night, he will charge back his vehicle back to 80% overnight using his 7 kW home charger, and rests on Sunday where there will be no use of the vehicle on that day. The results of this simulation are shown in Table 42.

Table 42: Overall simulation total energy losses for a 62 kWh vs 40 kWh Nissan Leaf

		62 kWh Nissan Leaf	40 kWh Nissan Leaf
Weekdays (Monday-Friday)	*First Time Charging (At work **22 kW**)*	3.73 kWh – 1 hr	2.1 kWh – 0.52 hr
	Second Time Charging *(At Home **7 kW**)*	Charge until 100%: 7.5 kWh – 5.1 hr	2.93 kWh – 2 hr
	Third Time Charging *(At Home **7 kW**)*		Charge until 100%: 5.34 kWh – 3.5 hr
Weekend (Saturday)	*Charging Station going to destination* *(**100 kW** DC vs **50 kW** DC)*	5.03kWh – 28 min	3.3 kWh-22 min + 5.08 kWh-36 min
	*Charging at Destination (AC Level 2 **11 kW**)*	5.96 kWh- 2.8 hr	3.81 kWh – 1.8 hr
	Charging station on way back *(**100 kW** DC vs **50 kW** DC)*	5.82kWh – 35 min	4.33 kWh-33min + 5.08 kWh- 37 min
Saturday Night	*Refill to 80% On Saturday* *(At home **7 kW** AC Level 2)*	From 17.8%: 7.58 kWh – 5.1 hr	From 34.8%: 4.4 kWh- 3 hrs
TOTAL		35.62 kWh – 15 hr	36.37 kWh – 13 hr

This overall simulation was created to reflect what a week for an EV user might look like and how would his charging habits be. This simulation was crucial for this study because it combined all the different charging aspects that were discussed in the previous chapters, taking into account daily charging patterns, having a mix of home charging and workplace charging in addition to charging at charging stations. A variety of charger types and power levels were used including a 7 kW, 11 kW, 22 kW AC chargers as well as 50 kW and 100 kW DC fast chargers. Special weekend trip, simulating the necessity for DC fast charging, and most importantly, a comparison of two different battery packs, highlighting the differences for owning a large or small battery size EV.

Total energy loss by charging both vehicles for the exact same case scenarios were calculated as well as the total charging time for the different battery sizes. Comparing both results found in Table 42 , we have found out that the total energy loss for charging a 62 kWh Leaf for a complete one week driving habit was 35.62 kWh which was very close to the total energy loss for charging a 40 kWh Leaf being 36.37 kWh. These results shows a significantly small difference of 2% of total energy lost from the grid for charging each vehicle, noting that the 62 kWh Leaf was using a more efficient DC fast charger for charging during the long trip, which didn’t affect the total overall difference.

Another point of discussion will be the total charging time and stops, where we have seen that for a 40 kWh Leaf, during the long trip it needed an additional stop at a charging station, in addition it needed to be charged one more time per week during the daily commute to work . However, this additional charging per week and charging stop did not increase the total charging time, where it was interesting to see that the smaller battery pack needed at total of 13 hours of charging while the bigger one needed 15 hours charging per week, however, the difference is not so big compared to the difference in their capacities.

As we have seen in previous chapters, charging frequency could lead to reduced wear on the battery over time since batteries have a limited number of charge cycles before their capacity starts to degrade. Hence, here comes the importance of the user driving habits in regards of this issue, if most of the driving habits of the user are mainly in-city urban transportations, an additional charging time per week using an AC charger won’t largely affect the overall battery health. Whereas this situation of battery wear depends on the frequency of long trips, where DC fast charging is mostly needed, because as we have seen, the smaller battery pack needed an additional stop at the charging station on the way to the destination.

As a result, if such long trips are normally needed by the user, around one or two times per month, it will not largely make a difference, because the larger battery pack is also using DC fast charging as well. Nevertheless, for more needs of long trips depending on the user driving routines, we will notice more drop in the battery state of health after a period of time between the two packs.

If we go back to section 7.1, for a 62 kWh Leaf going on a long trip, the only two types of charger that we could have logically used were 50 kW and 100 kW DC fast chargers, lower charging powers would lead to a huge difference in charging time for such big battery size. In contrast, in section 7.2, for a 40 kWh Leaf going on a long trip, we have suggested two types of chargers to use, a 50 kw DC fast charger (the 100 kW is not compatible for this model) and a 22 kW AC Level 2 charger, which was reasonable to use for a smaller battery pack not having extremely huge differences in charging times, plus it had better charging efficiency. For instance, by having a smaller battery pack, we could potentially reduce the use of DC fast charging for this exact same trip. If we revisit the long trip scenario, the user using a 62 kWh Leaf going to Paris has no option other than DC fast charging his vehicle for time efficiency, which concludes a total of two uses of fast charging for a round trip. In contrast, if the user is using a 40 kWh Leaf, where we know that two stops are needed on each way, by having now a clearer vision and understanding on the charging effects, the user can optimize his round trip. The user can optimize by using a 22 kW AC charger at the first charging station and use DC fast charging at the second charging station, which adds a little bit more of charging time which is acceptable, but eliminates the advantage of the bigger larger pack on it letting both vehicles use the same amount of fast charging for the same trip.

Therefore, from an overall efficiency point of view from the results in the last simulation, having the same amount of energy loss by the grid for charging both packs during the week, we can conclude that even if there was more charging frequency for a smaller battery, there was no difference in the overall charging efficiency for a small battery size compared to a larger one.

However, the decision in investing in larger battery for electric vehicles should not be only based on these points, other factors also plays in role. One major factor is cost, as batteries represent around 30% of an EV cost, larger battery packs vehicles cost much more than smaller battery one, to show some numbers for the selected models, a 40 kWh Nissan Leaf costs around 29.000 euros while a 62 kWh Leaf costs around 34.500 euros (57). Another factor would be weight, as bigger batteries are heavier, in our case of the Leaf, the larger battery model was around 170 kg heavier, which can influence the vehicle performance and consumption on long runs. Moreover, as the main purpose of implementing EV technology is mainly for its environmental advantages, the production of larger batteries can have a greater environmental impact than producing smaller battery packs. As we have seen in chapter 4 how crucial BMS and battery thermal management are and their major effects on charging losses and efficiencies, larger batteries would require more cooling challenges requiring more complex cooling systems, thus, more advanced technologies would be required.

Larger batteries were introduced by automotive companies mainly to solve range anxiety, as they will certainly increase the range of an EV; the purpose of our simulations during an entire week helped us visualize the variation of state of charges. If the EV user have a good understanding of his EV consumption and how his SOC would vary for various types of trips as it was analyzed in this research, this range anxiety could be reduced. As for the long trip, we were able to pre-locate charging stations before starting the journeys, insuring that the user would reach each charging station within the 20-80% range. Whereas, for daily work commute, even though the availability of chargers at work or public spaces helped in using the best charging strategy, we were able to create a perfect charging scenario letting the user fulfil his daily driving routines and not letting him drop under the 40-60% range of SOC, insuring three major aspects: Preventing battery degradation, reducing range anxiety and reducing charging losses. This highlights one major thing to understand, and it is the importance of charging infrastructure and having multiple charging points.

Some strategies that are being investigated in order to reduce the effect of DC fast charging on the battery health are: improved battery management systems, better thermal management, improved Anode/Cathode materials, and one major strategy is the development of new electrolyte chemistries that can improve ion transport rates. In electric vehicle technology, there is a big need in innovating batteries that can offer the use of fast charging with a longer battery life, so researchers in this field have created a new Li-ion battery design that allows for a better flow of electrons though its anode which is a step forward regarding this issue and are continuously working on improving this aspect (62) .

Summing up these points of comparisons and factors comes the main topic of this thesis of where to invest. Many initially believed that bigger batteries would solve range anxiety and make EVs more practical, however in this research it was found out to be not the best solution. Researchers in this field are currently investigating in reducing the degradation effects of fast charging on batteries, which is already a great progress and a step forward in order to take more advantage of high power charging without penalties. Governments around the world are investing in promoting the expansion of electric vehicle charging infrastructure as part of fulfilling their environmental goals, so more charging points increase the ease of finding a place to charge your vehicle reducing range anxiety.

As wireless charging for EVs is evolving, investing in this technology is challenging but extremely beneficial, the implementation of wireless charging infrastructure ideally should be integrated into areas where vehicles tend to park for extended periods. To implement this technology with maximizing its advantages, opportunistic wireless charging scenarios such as traffic lights and drive-thru services would be a great and interesting idea to have, though this would require more rapid charging technology. Finally, Dynamic Wireless Charging would be the game changer, this would revolutionize the electric vehicle industry, it would support continuous charging while driving on the road, and this would reduce the need for large battery packs and would solve most of the challenges faced in this field. Such system would definitely require significant infrastructure changes, including the installation of transmitter pads and power supply segments along specific routes with extremely high installation and maintenance costs, but once fully realized, this technology could completely transform our approach to EV charging and usage.

From this, as larger battery packs offer more range, balancing the battery size with other factors and taking the entire ecosystem including user needs, charging losses, battery technology and vehicle design, it is not ideal to simply select bigger battery sizes. Therefore investing in more important solutions like advanced charging infrastructures and more charging points, wireless technologies and battery enhancement can create a more sustainable EV ecosystem.

10 CONCLUSION

The objectives of this master's thesis covered theoretical and practical aspects regarding different charging strategies and types for charging an EV. The final goal was to quantify the charging losses and charging times and stops needed for different battery packs in order to understand if larger battery size would be the best solution to solve range anxiety. In order to reach this goal, the first thing needed to done was identifying the different types of chargers and charging powers, such as AC Level 1&2 which are the common chargers types found in homes and DC Level 1&2 fast chargers mostly available in charging stations. It was also important to identify the different charging methods commonly used, where conductive and wireless charging were the main methods covered in this thesis, after finding out that Battery Swapping Stations is not an ideal charging method and have several drawbacks.

Many factors that affect the battery were important to understand as their influence on the battery affect the charging efficiency and lead to an increase in charging losses such as capacity, lithium plating, open-circuit voltage, cell and ambient temperature, internal resistance and battery management systems, therefore, battery thermal management is crucial. There are three main sources of power loss during conductive charging, the first one is converter inefficiencies where around half of the charging losses are due to converter losses. The first approach of this work was to theoretically calculate these losses for different charging powers, but due to lack of literature, experimental data were used to quantify the overall charging losses. Other factors contributing in charging losses are connector and cable losses and battery internal resistance, the effect of changing cable material, length and thickness and ambient temperature were studied, as well as the effect of the state of the battery (SOC and SOH).

Similar to conductive charging, inductive charging had common factors that led to power losses while charging, and its own losses due to the difference in technologies. The main sources of losses in such systems are mainly influenced from three different factors being Misalignments and air gap between the charger and EV, coil and ferrite losses and resonant circuit loses.

The health of the battery, known as State of Health, is a significant determinant in the efficiency of conductive charging for electric vehicles. Results showed many important factors influencing the battery state of health the most, these factors were carried taken into consideration throughout this research in order to optimize the best charging strategies. The most important one was understanding the effect of DC fast charging on battery degradation. If the user never uses DC fast chargers, the approximate battery SOH after two years will be around 90%, while if the user uses DC fast charging over 3 times per month, the battery SOH drops to 80% after two years, which is a huge difference that leads to an increase in power losses for the overall system.

Two case scenarios were identified during this research representing general and possible driving routines for an EV user, the first case scenario held in this thesis simulated a real-life long trip, assuming one of the frequently traveled routes in Europe (>300km). The second case scenario simulated an everyday routine short trips (<80km) for a usual vehicle owner going to work and other places as well. Charging times and losses in addition to the variation of state of charge were obtained having both journeys initiated in a Nissan Leaf, offering varying battery capacities of 40kWh, or 62kWh.

A very interesting goal was covered while simulating the weekly routine, which was identifying the best charging strategy to charge your EV. By simulating different strategies such as charging from low, mid and high state of charges led us to the conclusion that charging the vehicle when the initial state of charge is between 40-60% is the best strategy that could be used. The main reasons behind this conclusion was the decrease in the energy loss from the grid where the charger shows great efficiencies between these SOC, and for battery health as it is an optimal state of charge to stay between and decrease the chances of battery degradation. Choosing this ideal strategy, by comparing it by the worst one, it was concluded that charging the vehicle at high state of charges (~70%) to 80% will lead to an increase of 25% in the total energy lost compared to the best charging strategy. This charging strategy was then implemented in later simulations.

Another conclusion drawn by these simulations was from comparing DC Level 1 50 kW and DC Level 2 100 kW chargers efficiencies. If the vehicle is accessible for a higher charging power, all the aspects of power and energy losses, charging time and efficiency aligns that a 100 kW charger would be the better option. AC chargers were also compared from the short trip scenario. It was concluded that the AC Level 2 22 kW charger had the best efficiency compared to the other AC chargers. Comparing the AC Level 1 charger with the AC Level 2 22 kW charger, as best vs worst, it took 7.8 hours less to charge the vehicle than for using the Level 2 charger, in addition to that, the 7 kW charger has shown a 23% more total energy loss from the grid compared to the 22 kW.

It was also shown that wireless charging showed better overall charging efficiency for both 7 kW and 50 kW chargers, but is was noted that the efficiencies of the wireless chargers were obtained assuming an optimal air gap and with no misalignments between the EV and the charger pads. Other interesting obtained results showed that a daily additional trip (~14 km) leads to around 21% more energy losses for both battery packs, which is a significant amount that could be effective on the long run.

Finally, an overall simulation was created in order to combine all the different aspects covered in this thesis, simulating an entire week combined long-short trips for an EV user. The results have shown that the total energy loss for charging a 62 kWh Leaf was 35.62 kWh, which was very close to the total energy loss for charging a 40 kWh Leaf being 36.37 kWh. The smaller battery pack needed an additional stop on the highway going to the destination and an additional time for charging during the week for daily commute. However, it was interesting to see that the smaller battery pack needed at total of 13 hours of charging while the bigger one needed 15 hours charging per week. From this simulation, it was evident that while smaller batteries required more frequent charging than the larger one, the overall charging efficiency for both sizes remained the same. However, it was found out that if the user have a good understanding of his EV consumption and charging strategies, he could optimize his round trip and reduce the number of Fast charging usage by using high power AC chargers for charging vehicle having a small battery pack.

However, the decision in investing in larger battery did not only rely on these points, larger batteries cost more, add weight to vehicles, require more advanced technologies and pose greater environmental production challenges. Therefore, as governments are currently working on increasing charging points and enhancing charging infrastructure and researchers in this field have started to find solutions regarding battery degradation and are focusing on implementing wireless charging for the future, it becomes increasingly evident that the path forward is not necessarily through larger battery packs. These considerations open the door for future investigations, and set the stage for further studies and developments in Electric Vehicles Charging technologies.

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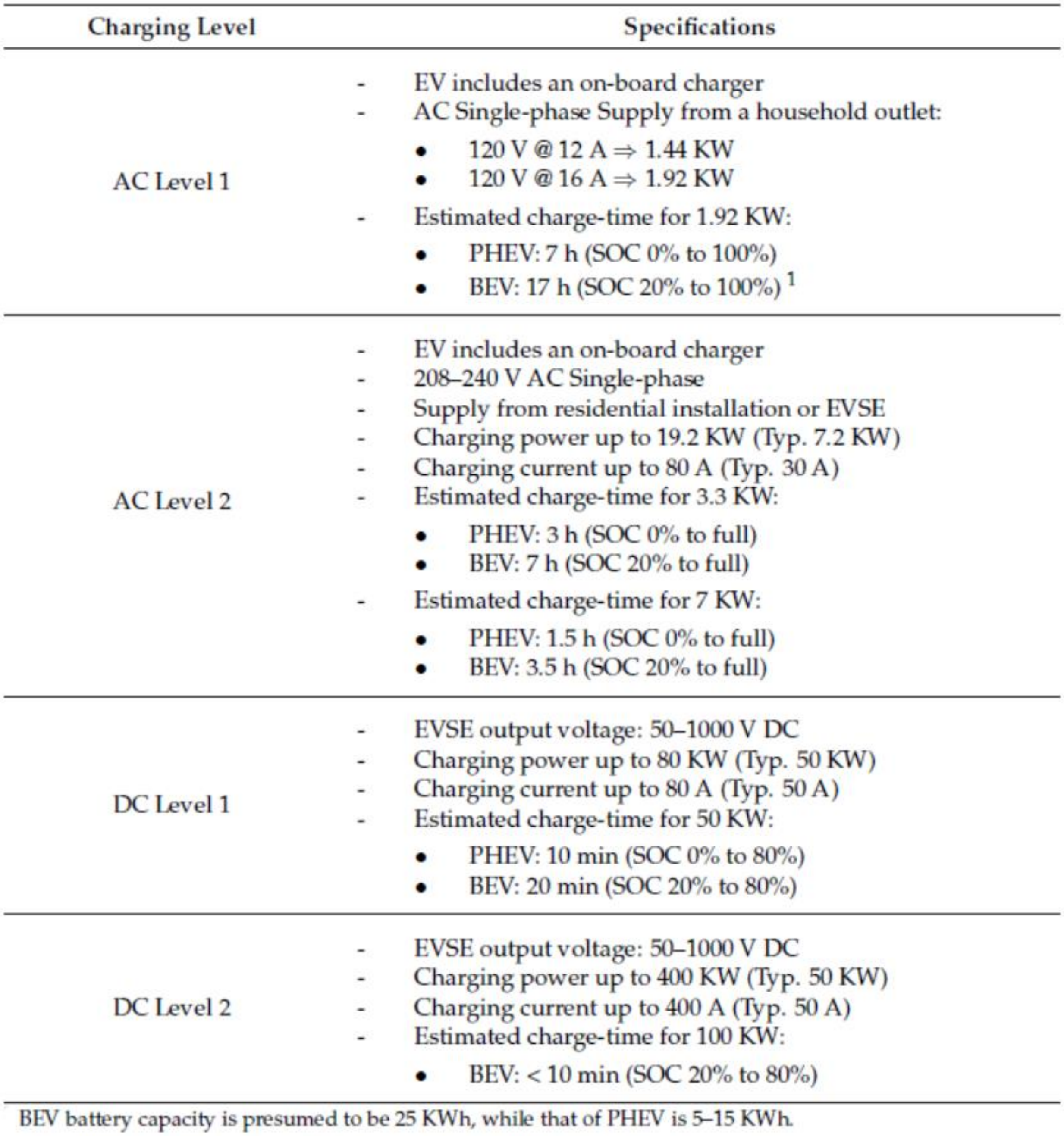
APPENDIX A: CHARGING SPECIFICATIONS

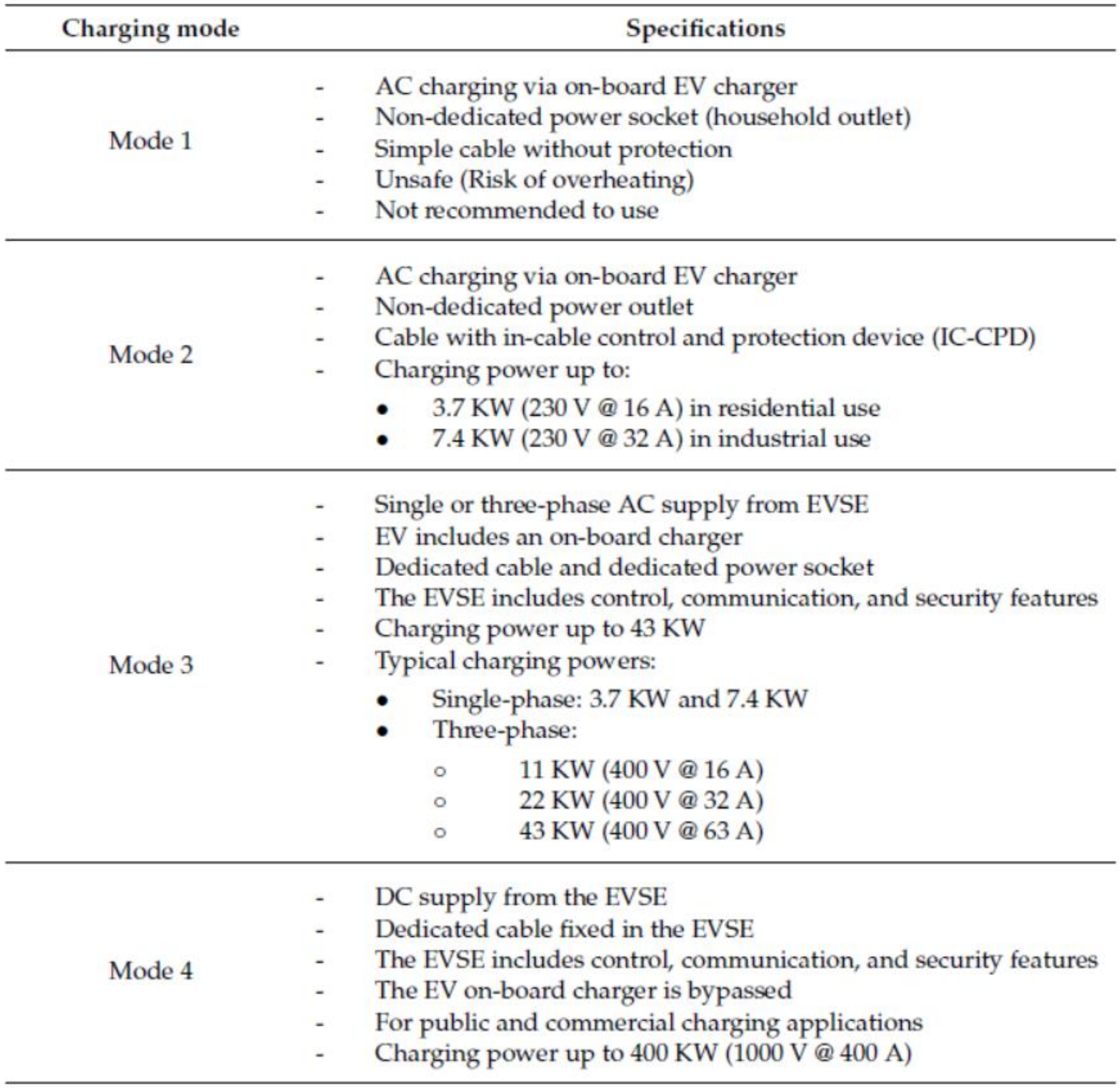
Table 43 Charging Levels and Specifications for SAE J1772 standard (36)



Charging Level	Specifications
AC Level 1	- EV includes an on-board charger - AC Single-phase Supply from a household outlet: • 120 V @ 12 A ⇒ 1.44 KW • 120 V @ 16 A ⇒ 1.92 KW - Estimated charge-time for 1.92 KW: • PHEV: 7 h (SOC 0% to 100%) • BEV: 17 h (SOC 20% to 100%) [1]
AC Level 2	- EV includes an on-board charger - 208–240 V AC Single-phase - Supply from residential installation or EVSE - Charging power up to 19.2 KW (Typ. 7.2 KW) - Charging current up to 80 A (Typ. 30 A) - Estimated charge-time for 3.3 KW: • PHEV: 3 h (SOC 0% to full) • BEV: 7 h (SOC 20% to full) - Estimated charge-time for 7 KW: • PHEV: 1.5 h (SOC 0% to full) • BEV: 3.5 h (SOC 20% to full)
DC Level 1	- EVSE output voltage: 50–1000 V DC - Charging power up to 80 KW (Typ. 50 KW) - Charging current up to 80 A (Typ. 50 A) - Estimated charge-time for 50 KW: • PHEV: 10 min (SOC 0% to 80%) • BEV: 20 min (SOC 20% to 80%)
DC Level 2	- EVSE output voltage: 50–1000 V DC - Charging power up to 400 KW (Typ. 50 KW) - Charging current up to 400 A (Typ. 50 A) - Estimated charge-time for 100 KW: • BEV: < 10 min (SOC 20% to 80%)

BEV battery capacity is presumed to be 25 KWh, while that of PHEV is 5–15 KWh.

Table 44 Charging Modes and Specifications for IEC 61851 standards (36)



Charging mode	**Specifications**
Mode 1	- AC charging via on-board EV charger - Non-dedicated power socket (household outlet) - Simple cable without protection - Unsafe (Risk of overheating) - Not recommended to use
Mode 2	- AC charging via on-board EV charger - Non-dedicated power outlet - Cable with in-cable control and protection device (IC-CPD) - Charging power up to: • 3.7 KW (230 V @ 16 A) in residential use • 7.4 KW (230 V @ 32 A) in industrial use
Mode 3	- Single or three-phase AC supply from EVSE - EV includes an on-board charger - Dedicated cable and dedicated power socket - The EVSE includes control, communication, and security features - Charging power up to 43 KW - Typical charging powers: • Single-phase: 3.7 KW and 7.4 KW • Three-phase: ○ 11 KW (400 V @ 16 A) ○ 22 KW (400 V @ 32 A) ○ 43 KW (400 V @ 63 A)
Mode 4	- DC supply from the EVSE - Dedicated cable fixed in the EVSE - The EVSE includes control, communication, and security features - The EV on-board charger is bypassed - For public and commercial charging applications - Charging power up to 400 KW (1000 V @ 400 A)

Table 45: Wireless charging Standards Definition and Description (25)

Organisation/Society	Relevant Standard/s	Standard Definition/Description
Society for Automobile Engineers (SAE)	J2954	Wireless Power Transfer for Light-Duty Plug-In EVs and Alignment Methodology
	J1772	EV/PHEV Conductive Charge Coupler (CCC)
	J2847/6	Communication Between Wireless Charged Vehicles and Wireless EV Chargers
	J1773	EV Inductively Coupled Charging
	J2836/6	Use Cases for Wireless Charging Communication for PEV
Institute of Electrical and Electronic Engineers (IEEE)	P2100.1	Wireless Power and Charging Systems
	C95.1	Respect to Human Exposure to Radio Frequency (3 kHz – 300 GHz) Electromagnetic Fields
Underwriters Laboratories Inc.(UL)	Subject 2750	Outline of Investigation, for WEVCS
International Organization for Standardization (ISO)	19,363	Electrically Propelled Road Vehicles – Magnetic Field WPT – Safety and Interoperability Requirements
International Electro-mechanical Commission (IEC)	61980-1 Cor.1 Ed.1.0	EV WPT Systems Part -1: General Requirements
	62827-2 Ed.1.0	WPT-Management: Part 2: Multiple Device Control Management (MDCM)
	63,028 Ed.1.0	WPT-Air Fuel Alliance Resonant Baseline System Specification (BSS)
	15149-2 (ISO-IEC)	Information Technology – Telecommunications and Information Exchange Between Systems – Magnetic Field Area Network (MFAN) – Part 2: In-band Control Protocol for WPT
Japan Electric Vehicle Association (JEVS)	G106	Inductive Charging System for EVs-General Requirements
	G107	Inductive Charging System for EVs-Manual Connection
	G108	Inductive Charging System for EVs-Software Interface
	G109	Inductive Charging System for EVs-General Requirements

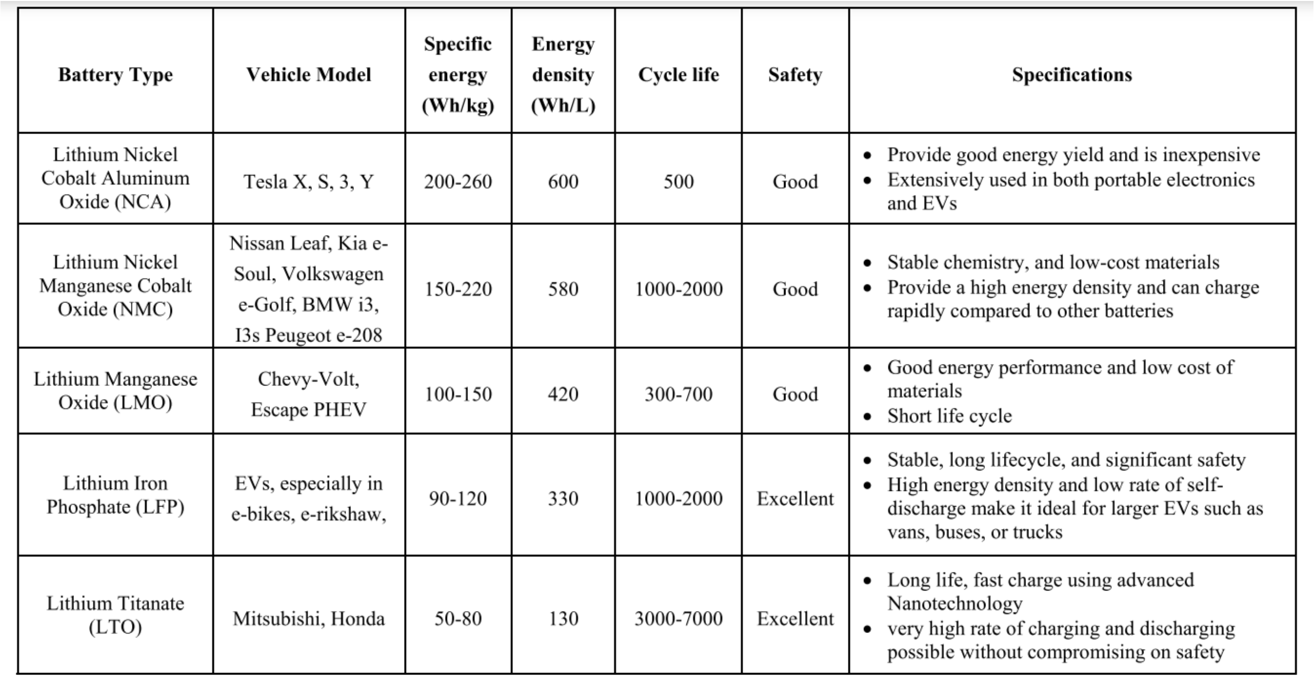
Table 46 Specifications of different AC charging connectors (63)

Specifications	**Japan**	**USA**	**Europe**		**China**		**ALL Markets**	
Charger type								
	Type 1 (SAE J1772)		Type 2 (Mennekes)		Type 2 (GB/T)		Tesla	
	Level 1	Level 2	Mode 1	Mode 2-3	Mode 2	Mode 3	Mobile connection	Wall connection
Maximum Capacity	1.9 kW	19.2 kW	4 kW	22 kW	7 kW	27.7 kW	7.7 kW	11.5 kW
Input voltage	120 V Single phase	240 V Split phase	250 V Single phase	480 V Three phase	250 V Single phase	400 V Three phase	120/240 V Single phase	208/250V single phase
Current rating	16 A	80 A	16 A	32 A	16 A	32 A	16/32 A	48 A
Standards	SAE J1772-2017 IEC 62196-2, IEC 61851-22/23		IEC 62196-2 IEC 61851-22/23		GB/T 20234-2 IEC 62196-2		IEC 62196-2	

Table 47 Specifications of different DC charging connectors (63)

Specifications	Japan	USA	Europe	China	ALL Markets	
Charger type	CHAdeMO	CCS - Combo 1	CCS - Combo 2	GB/T	Tesla Supercharger	CHAdeMO
Capacity	50 - 400 kW	150 - 350 kW	350 kW	60 - 237 kW	250 - 350 kW	50 - 400 kW
Input voltage	50 - 1000 V	200 - 1000 V	200 - 1000 V	250 – 950 V	300 - 480 V	50 - 1000 V
Maximum Current	400 A	500 A	500 A	250 – 400 A	800 A	400 A
Standards	IEC 61851-23/4 IEC 62196-3 JEVS G105	SAE J1772 IEC 61851-23/24 IEC 62196-3	IEC 61851-23/24 IEC 62196-3 DIN EN 62196-3	GB/T 20234-3 IEC 62196-3	IEC 62196-3	IEC 61851-23/4 IEC 62196-3 JEVS G105

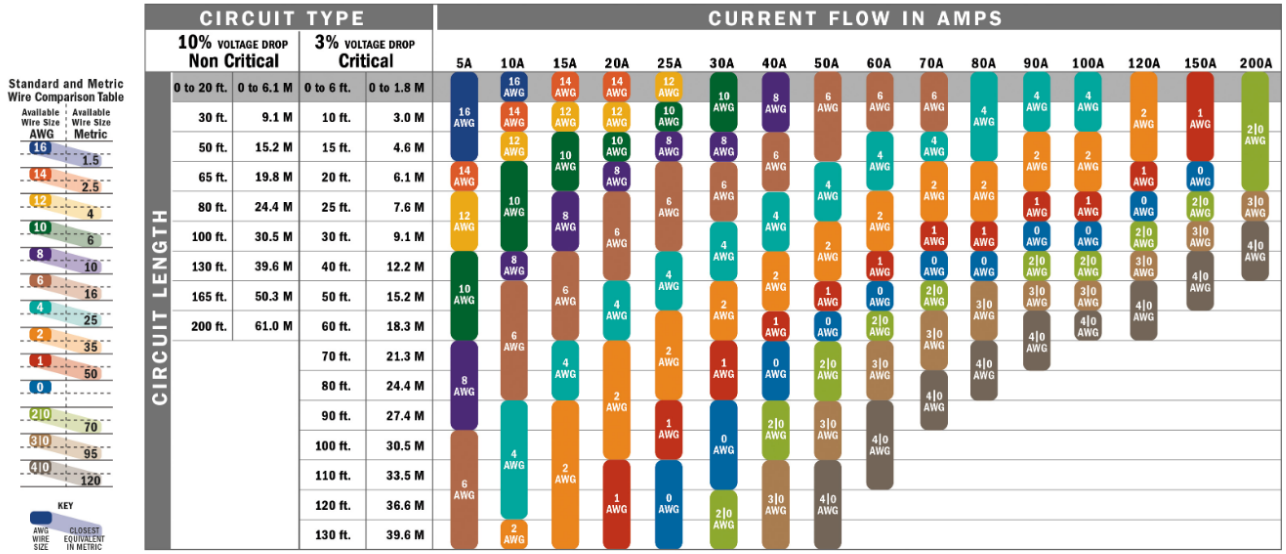
Table 48 EV batteries specifications (63)



Battery Type	Vehicle Model	Specific energy (Wh/kg)	Energy density (Wh/L)	Cycle life	Safety	Specifications
Lithium Nickel Cobalt Aluminum Oxide (NCA)	Tesla X, S, 3, Y	200-260	600	500	Good	• Provide good energy yield and is inexpensive • Extensively used in both portable electronics and EVs
Lithium Nickel Manganese Cobalt Oxide (NMC)	Nissan Leaf, Kia e-Soul, Volkswagen e-Golf, BMW i3, I3s Peugeot e-208	150-220	580	1000-2000	Good	• Stable chemistry, and low-cost materials • Provide a high energy density and can charge rapidly compared to other batteries
Lithium Manganese Oxide (LMO)	Chevy-Volt, Escape PHEV	100-150	420	300-700	Good	• Good energy performance and low cost of materials • Short life cycle
Lithium Iron Phosphate (LFP)	EVs, especially in e-bikes, e-rikshaw,	90-120	330	1000-2000	Excellent	• Stable, long lifecycle, and significant safety • High energy density and low rate of self-discharge make it ideal for larger EVs such as vans, buses, or trucks
Lithium Titanate (LTO)	Mitsubishi, Honda	50-80	130	3000-7000	Excellent	• Long life, fast charge using advanced Nanotechnology • very high rate of charging and discharging possible without compromising on safety

APPENDIX B: AWG- AMERICAN WIRE GAUGE CURRENT RATINGS

Table 49: Choosing the correct Wire size (AWG) (64)



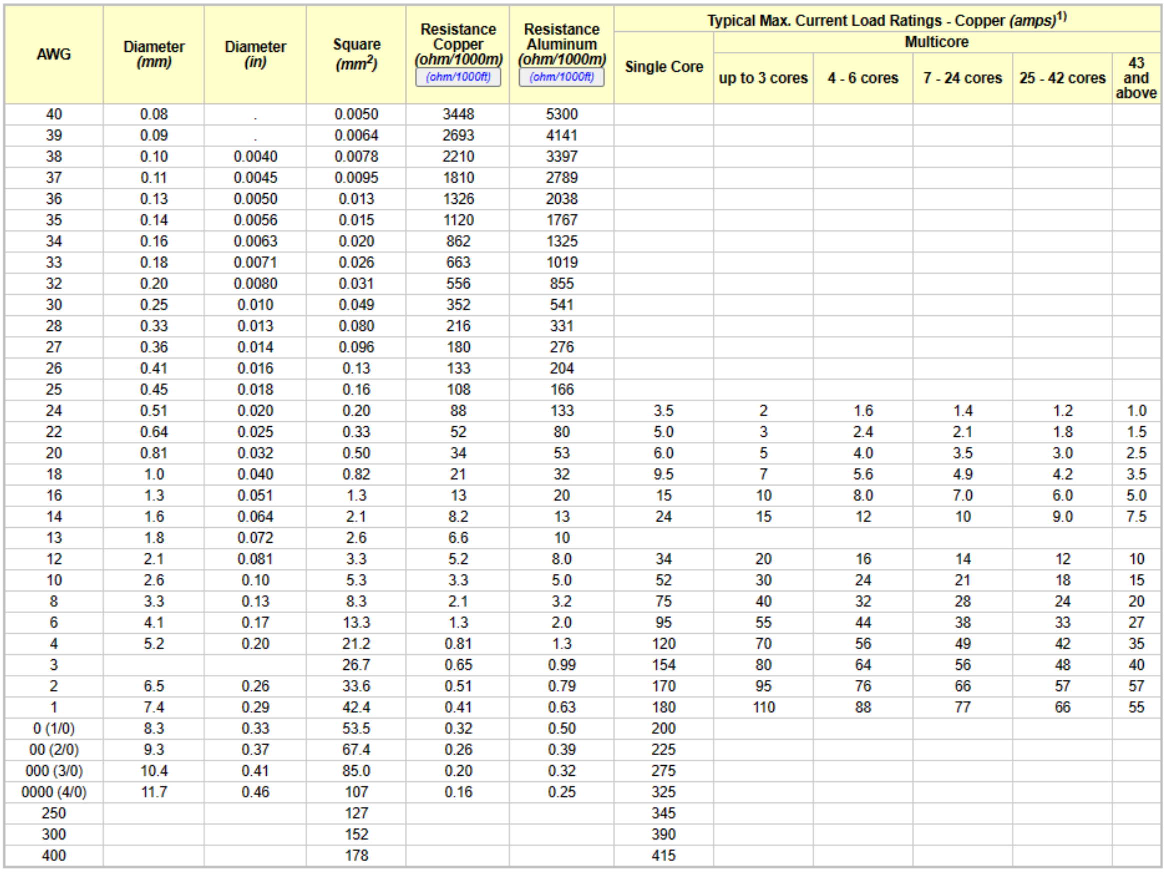
Standard and Metric Wire Comparison Table

Available Wire Size AWG	Available Wire Size Metric
16	1.5
14	2.5
12	4
10	6
8	10
6	16
4	25
2	35
1	50
0	
2|0	70
3|0	95
4|0	120

KEY
AWG WIRE SIZE
CLOSEST EQUIVALENT IN METRIC

	CIRCUIT TYPE				CURRENT FLOW IN AMPS															
	10% VOLTAGE DROP Non Critical		3% VOLTAGE DROP Critical		5A	10A	15A	20A	25A	30A	40A	50A	60A	70A	80A	90A	100A	120A	150A	200A
CIRCUIT LENGTH	0 to 20 ft.	0 to 6.1 M	0 to 6 ft.	0 to 1.8 M	16 AWG	16 AWG	14 AWG	14 AWG	12 AWG	10 AWG	8 AWG	6 AWG	6 AWG	6 AWG	4 AWG	4 AWG	4 AWG	2 AWG	1 AWG	2|0 AWG
	30 ft.	9.1 M	10 ft.	3.0 M		14 AWG	12 AWG	12 AWG	10 AWG											
	50 ft.	15.2 M	15 ft.	4.6 M		12 AWG	10 AWG	10 AWG	8 AWG	8 AWG	6 AWG		4 AWG	4 AWG		2 AWG	2 AWG			
	65 ft.	19.8 M	20 ft.	6.1 M	14 AWG	10 AWG		8 AWG	6 AWG	6 AWG		4 AWG		2 AWG	2 AWG			1 AWG	0 AWG	
	80 ft.	24.4 M	25 ft.	7.6 M	12 AWG		8 AWG	6 AWG			4 AWG		2 AWG			1 AWG	1 AWG	0 AWG	2|0 AWG	3|0 AWG
	100 ft.	30.5 M	30 ft.	9.1 M						4 AWG		2 AWG		1 AWG	1 AWG	0 AWG	0 AWG	2|0 AWG	3|0 AWG	4|0 AWG
	130 ft.	39.6 M	40 ft.	12.2 M	10 AWG	8 AWG	6 AWG		4 AWG		2 AWG		1 AWG	0 AWG	0 AWG	2|0 AWG	2|0 AWG	3|0 AWG	4|0 AWG	
	165 ft.	50.3 M	50 ft.	15.2 M		6 AWG		4 AWG		2 AWG		1 AWG	0 AWG	2|0 AWG	3|0 AWG	3|0 AWG	3|0 AWG	4|0 AWG		
	200 ft.	61.0 M	60 ft.	18.3 M					2 AWG		1 AWG	0 AWG	2|0 AWG	3|0 AWG		4|0 AWG	4|0 AWG			
			70 ft.	21.3 M	8 AWG		4 AWG	2 AWG		1 AWG	0 AWG	2|0 AWG	3|0 AWG		4|0 AWG					
			80 ft.	24.4 M										4|0 AWG						
			90 ft.	27.4 M		4 AWG	2 AWG		1 AWG	0 AWG	2|0 AWG	3|0 AWG	4|0 AWG							
			100 ft.	30.5 M	6 AWG															
			110 ft.	33.5 M				1 AWG	0 AWG		3|0 AWG	4|0 AWG								
			120 ft.	36.6 M						2|0 AWG										
			130 ft.	39.6 M		2 AWG														

Table 50: AWG - American Wire Gauge Current Ratings (65)



AWG	Diameter *(mm)*	Diameter *(in)*	Square (mm^2)	Resistance Copper *(ohm/1000m)* *(ohm/1000ft)*	Resistance Aluminum *(ohm/1000m)* *(ohm/1000ft)*	Typical Max. Current Load Ratings - Copper *(amps)*$^{1)}$					
						Single Core	Multicore				
							up to 3 cores	4 - 6 cores	7 - 24 cores	25 - 42 cores	43 and above
40	0.08	.	0.0050	3448	5300						
39	0.09	.	0.0064	2693	4141						
38	0.10	0.0040	0.0078	2210	3397						
37	0.11	0.0045	0.0095	1810	2789						
36	0.13	0.0050	0.013	1326	2038						
35	0.14	0.0056	0.015	1120	1767						
34	0.16	0.0063	0.020	862	1325						
33	0.18	0.0071	0.026	663	1019						
32	0.20	0.0080	0.031	556	855						
30	0.25	0.010	0.049	352	541						
28	0.33	0.013	0.080	216	331						
27	0.36	0.014	0.096	180	276						
26	0.41	0.016	0.13	133	204						
25	0.45	0.018	0.16	108	166						
24	0.51	0.020	0.20	88	133	3.5	2	1.6	1.4	1.2	1.0
22	0.64	0.025	0.33	52	80	5.0	3	2.4	2.1	1.8	1.5
20	0.81	0.032	0.50	34	53	6.0	5	4.0	3.5	3.0	2.5
18	1.0	0.040	0.82	21	32	9.5	7	5.6	4.9	4.2	3.5
16	1.3	0.051	1.3	13	20	15	10	8.0	7.0	6.0	5.0
14	1.6	0.064	2.1	8.2	13	24	15	12	10	9.0	7.5
13	1.8	0.072	2.6	6.6	10						
12	2.1	0.081	3.3	5.2	8.0	34	20	16	14	12	10
10	2.6	0.10	5.3	3.3	5.0	52	30	24	21	18	15
8	3.3	0.13	8.3	2.1	3.2	75	40	32	28	24	20
6	4.1	0.17	13.3	1.3	2.0	95	55	44	38	33	27
4	5.2	0.20	21.2	0.81	1.3	120	70	56	49	42	35
3			26.7	0.65	0.99	154	80	64	56	48	40
2	6.5	0.26	33.6	0.51	0.79	170	95	76	66	57	57
1	7.4	0.29	42.4	0.41	0.63	180	110	88	77	66	55
0 (1/0)	8.3	0.33	53.5	0.32	0.50	200					
00 (2/0)	9.3	0.37	67.4	0.26	0.39	225					
000 (3/0)	10.4	0.41	85.0	0.20	0.32	275					
0000 (4/0)	11.7	0.46	107	0.16	0.25	325					
250			127			345					
300			152			390					
400			178			415					