Load Balancing Potential of Wireless On-Road EV Charging

WDPT EV charging grid and environmental impact compared to plug-in charging considering the EU, 2050

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SUMMARY

In order to mitigate climate change, Europe has addressed the most carbon intensive sectors, investigating decarbonisation strategies. The transport sector, with 22% share of greenhouse gas emissions calls for urgent and significant changes. Amongst numerous alternative transportation methods, electric vehicles (EVs) seem to be the most popular choice, especially in Europe, where EV deployment is the second greatest after China. The 2.6% EV share is expected to grow exponentially. In Roadmap 2050, the European commission is preparing for the possibility of 80% EV share by 2050.

EV deployment, however, does not come without challenges. Consumer choices in lithium-ion battery size and charging methods show concerning tendencies. Lithium is a scarce material, especially in Europe, where lithium mines are not widely available. Also, the production of lithium-ion batteries accounts for significant emissions. One could argue that battery demand will go down, when EV chargers will be faster and widely available. However, publicly available chargers cannot compete with the convenience and low price of home charging. In the future, 70%-80% of charging still expected to happen from home. This charging behaviour can significantly increase the already problematic evening peak demand, causing a 2TWh electricity deficit daily in Europe, which is approximately 20% of future daily electricity demand. Consequently, increasing public charger availability could not solve the evening peak alone. HDVs face the greatest barriers in vehicle electrification. The batteries for trucks and lorries to become electric would cost around the same as the truck itself. Also, the heavy battery on board can increase vehicle consumption. Therefore, different EV charging methods should be considered, that could compete with the convenience of home charging, and create trust for EV owners in public charging to let go of range anxiety and the need of large batteries.

A novel EV charging technology called Wireless Dynamic Power Transfer (WDPT) allows charging on the road wirelessly, whilst driving. The convenience of charging on the way could decrease battery demand, as well as distribute the evening peak throughout the day, in relation to traffic patterns.

In this research, an energy model has been created in MATLAB to assess the impacts of different charging technologies and behaviours in relation to electricity generation in the future (2050), considering high renewable energy share in Europe. The daily electricity supply-demand deficit, battery downsizing potential and the overall environmental impacts are the main scope.

The model revealed that 100% EV share on the road, with conventional plug-in charging could damage the daily grid balance by 22%, creating a 2TWh daily deficit in Europe. Using wireless road charging could decrease the daily deficit to only 0.7TWh. In this case, there would be no damage, nor improvement on the daily grid balance by EVs. Improvement only could be achieved on the grid balance, by the optimisation of a hybrid scenario of smart (controlled) plug-in charging and wireless chargers on motorways.

Wireless charging would allow commercial vehicles, that cannot afford to stop for long charging to use EVs including medium and heavy-duty vehicles, without the need of large batteries. Battery needs of a heavy duty-vehicle could decrease by 92%, in case of wireless road charging availability on motorways and major roads. This could enable the feasibility of electric lorries and trucks.

Research has revealed that the best option for the future would be a hybrid scenario, where wireless on-road charging and smart plug-in charging at home would be combined. This could decrease environmental impacts significantly and it could improve grid balance as well in Europe.

LIST OF ABBREVIATIONS

CF	Capacity factor
EFTA	European free trade association
EU	European Union
EV	Electric vehicle
GHG	Greenhouse gas
GWI	Global warming impact
H100%	100% home plug-in charging
H40%-W30%-O30%	40% home charging, 30% workplace and 30% other plug-in charging
H60%-W40%	60% home charging, 40% workplace plug-in charging
HDV	Heavy-duty vehicle
ICE	Internal combustion engine
LCA	Life cycle analysis
LDV	Light-duty vehicle
Max.WDPT	Maximum coverage (all roads are covered)
MCA	Multi-criteria analysis
MDV	Medium-duty vehicle
Min.WDPT	Minimum required coverage for WDPT (100% motorway, 30% major road)
Mod.WDPT	Moderate (realistic) WDPT charging scenario (100% motorway and major road)
NEDC	New European Driving Cycle
R&D	Research and Development
RE	Renewable Energy
RES	Renewable energy system
S100%	100% smart home chargers
UK	United Kingdom
WDPT	Wireless dynamic power transfer
WLTP	Worldwide Harmonized Light Vehicle Test Procedure

1. INTRODUCTION

In this chapter an introduction to the topic of this research will be presented, including the exploration of relevance and significance in the collective academic knowledge. Afterwards, the aim and scope will be determined, enabling the formation of research questions, necessary assumptions and methodology, which will all be described throughout this chapter.

1.1. Background

Reducing greenhouse gas emissions is one of the most important targets of Climate Action, by the EU. In order to diminish climate change, serious steps must be taken. In Europe, 25% of CO_2 emission derives from transportation (EEA, 2017a). Fossil fuel combustion by conventional vehicles is responsible for this extreme emission share. Therefore, reforming the transportation sector is inevitable in order to reach the CO_2 emission reduction highlighted by the Paris Agreement[1]. Electric vehicles (EVs) fuelled by renewable energy sources could be a solution to mitigate the major environmental impact by road transport and so far, it appears to be the most popular choice for future road transport in Europe (Ahmad et al., 2017).

EV deployment has taken rapid measures in the last decade, leaving other sustainable transport technologies, such as hydrogen far behind. In Europe, the electrification of mobility has already taken the first steps with 2.6 % market share of new electric cars in 2018, which is a 31% increase compared to 2016. (IEA, 2019) The growth rate in Europe is expected to experience exponential increase, as several European countries are planning to ban ICE (Internal Combustion Engine) sales as soon as 2030, such as Norway, the Netherlands, Denmark, Iceland, Ireland and Slovenia. Many countries are following the trend and joining in 2040. The EV30@30 predicts a 30% share by 2030 (IEA, 2019). Furthermore, EU incentives are targeting for an 80% EV stock in the EU by 2050. Assuming the rapid EV growth expected, charging infrastructure and additional electricity demand must be taken into account. In case of 80% share of EVs, their electricity consumption can reach a 10% of the overall electricity demand in Europe, which can place considerable stress on the already challenging renewable energy (RE) transition (EEA, 2017). The increasing electricity demand from this new rising electricity consumer category can be an additional risk to electricity grid balance.

RE integration is a crucial component of energy transition. The EU Roadmap 2050 long term strategy has stated the critical need of decarbonizing the energy sector by 80%. To achieve that, the study has identified several pathways that includes the future demand by electric vehicles (EC, 2011). However, harmonizing the transition in both sectors will be highly challenging (Masuta et al., 2014). The infrastructure of this new rising electricity consumer category has to be carefully integrated to the transitioning RE infrastructure to provide energy security and a reliable electricity grid (Bellekom et al., 2012). In order to achieve that, charging of EVs should occur when power is being produced. Since the time of charging is free consumer choice, controlling demand curve is highly challenging IRENA (2019). points out in its report, that operational automation of domestic and industrial electronic devices is a crucial component of RE transition, since consumer behaviour has not proved to take power generation into account in their daily routine. This applies to EV charging also, time-of-use tariffs will not be able to eliminate peak usage on their own. Increasing charger availability could help consumers to spread out their EV charging throughout the day; however, the development of charging infrastructure is lagging behind EV deployment and availability of public chargers do not prove to fulfil consumer requirements (Onar et al., 2013).

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[1] The Paris Agreement is an agreement within the United Nations Framework Convention on Climate Change, on dealing with greenhouse-gas-emissions and temperature rise , signed in 2016 (more: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement)

The European Union Alternative Fuels Infrastructure Directive recommends a minimum of 1 public charger per 10 EVs, however this number is only reached in Denmark and the Netherlands with 1 charger to about 8 EVs. The charging infrastructures of Norway and Germany are struggling to keep up with the rapid growth of EV deployment, as a result, 20 EVs have to share one public charger as of 2018. Other European countries are failing to come even close to this target. However, domestic private chargers have been highly dominant (Figure 1.) and expected to exponentially increase in the near future (IEA, 2019).

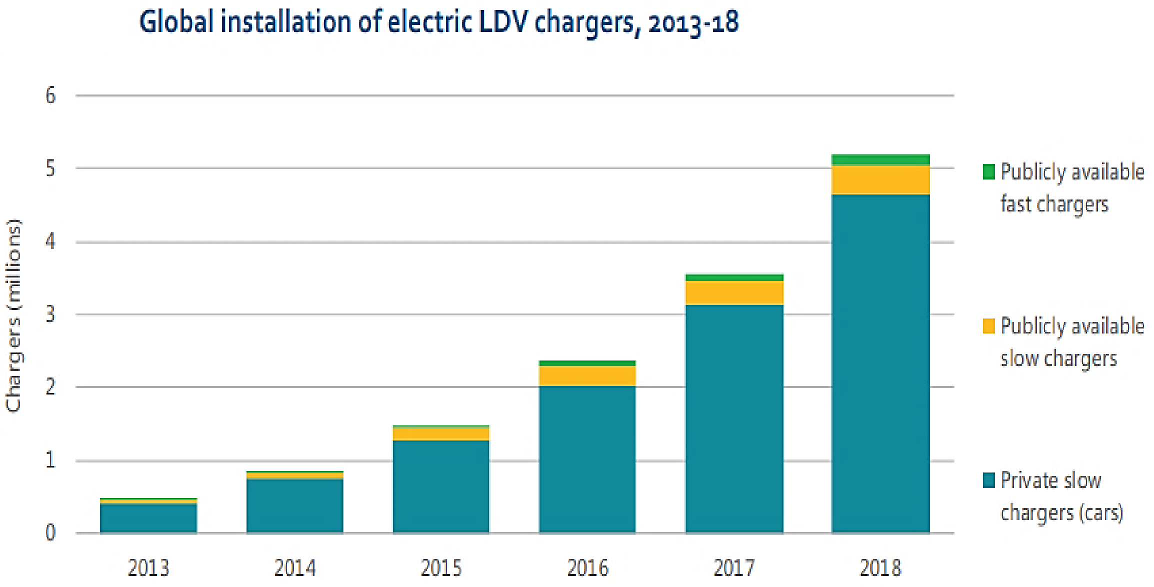

Figure 1. Electric Light Duty Vehicles Charger installation (Source: IEA, 2019)

The dominance of home charging is decelerating public charging infrastructure development, as well as placing major pressure on the electricity grid (Tan et al., 2016). Since most EV owners take the liberty to plug in their car comfortably at home, when they arrive in the evening, a significant peak is being created. Peak power demand is one of the most important factors in designing an electricity infrastructure (Chavarría et al., 2013). High daily or seasonal peaks place extreme pressure on grid operators, as they are financially and technically challenging. (Arias & Bae, 2016; Rassaei et al., 2015).

According to Verzijlbergh et al. (2012), reinforcement of the grid to support the uncontrolled EV charging peaks would increase the costs by 30%. This mainly derives from reinforcing medium voltage cables and transformers. Also, with increased load, transmission losses also increase, resulting in lower efficiency and further financial losses. Furthermore, dominant home charging results in significant stress on residential load and therefore requires higher reinforcement investments in that area (Qian et al., 2011). As well as increased peak demand, extensive storage capacity requirements are also a crucial problem by mismatch between supply and demand. Storing electricity results in significant energy losses and additional investments (Theodoropoulos et al., 2014). Therefore, uncontrolled EV charging by consumers would require reinforcement of grid, additional grid storage capacity and significant losses throughout the transmission line and during storage. Consequently, future EV charging behaviours, considering time of charging, plays key role in the future of power load cost and efficiency (Rassaei et al., 2015). Figure 2 is showing the considerable difference between daily supply-demand caused by private charging, in case of 100% EV share.

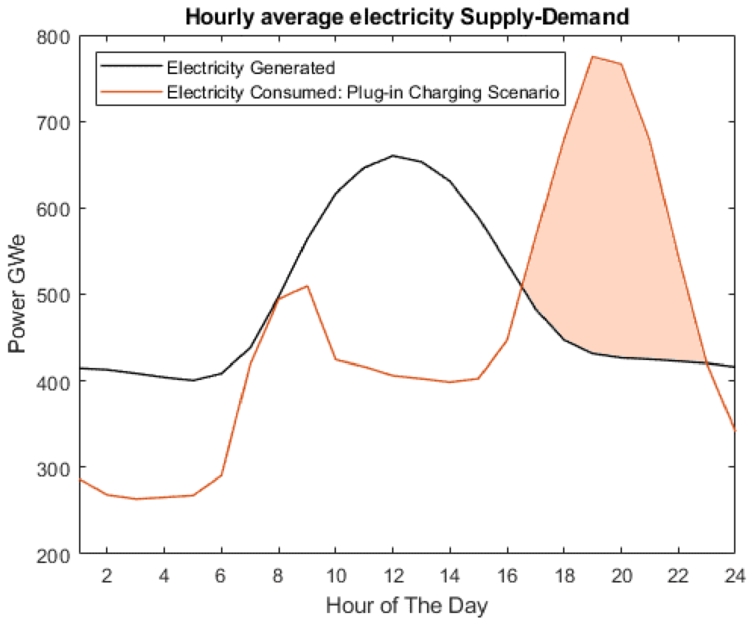

Figure 2.- Difference between electricity supply demand with 100% EV share

There are several different ways to control load by EVs. Nevertheless, as a first step, significant changes in currently available EV charging systems has to be made. With increasing number of EVs, and home charging, critical peaks can be expected in power demand (Masuta et al., 2014). In light of these challenges, different EV charging approaches should be considered. Popularisation of public chargers would be a key factor to smoothen the demand curve, as well as to make chargers on road more broadly available and mitigate range anxiety (Choi et al., 2015).

EV owners do not feel safe with the range available with one charge (range anxiety). That is the reason why the demand for greater range is rapidly increasing. (Rubino et al., 2017) That means an increasing demand for lithium-ion batteries by EVs, questioning the sustainability of the new technology, since lithium resources are limited, and battery production has a significant impact on the environment (Tan et al., 2016). From a European perspective, large lithium demand is highly challenging, since Europe does not have significant lithium reserves, which means critical international dependence (Miedema & Moll, 2013). Therefore, future EV infrastructure will have to eliminate the demand for large batteries (Choi et al., 2015). Furthermore, lithium-ion batteries have remained the most expensive and most carbon intensive part of the entire lifecycle of an EV. Producing an average sized 25-30 kWh battery can be responsible for 3 tons of CO_2eq respectively. As a result, producing an EV has 30% higher GHG emission, than ICE vehicle production. (Hao et al., 2017) Even though, the entire EV life cycle emission is significantly lower than ICE, lithium-ion batteries remain a great cause of environmental damage (Girardi et al., 2015). Ahmadi et al., (2017) states that, even with improving future recycling, production of lithium ion batteries will still have the highest environmental impact in EVs. Therefore, it is crucial to reduce lithium-ion battery use in the future (Zackrisson et al., 2016).

The engagement of heavy-duty vehicles (HDV) in the electrification of the transport sector remains greatly challenging (Çabukoglu et al., 2018). The average range necessary by trucks or buses daily would require around 250-300kWh battery capacity, which means several tons of extra weight, as well as approximately double the price of a conventional ICE truck (Bi et al., 2019; Sen et al., 2017). In case HDVs are also desired to be electrified, batteries must be downsized.

As mentioned earlier, a comprehensive public charging infrastructure is needed to overcome challenges of grid balance. It also could mitigate the need for large batteries on board. If charging was widely available and more convenient whilst traveling, EV owners would be more comfortable with smaller batteries. This would mean decrease in lithium demand, as well as energy consumption, since the vehicle would reduce in weight. (Onar et al., 2013) Plug-in charging has its limitations in terms of controlling charging patterns. ICE vehicles run on diesel or petrol and fuel can be only collected from gas stations, the fuel for EVs on the other hand is electricity, which can be found in consumers home and workplace. Charging at these locations is the cheapest and most convenient for EV owners, therefore, public charging is less probable to gain dominance (Neubauer & Wood, 2014). Taking these limitations into account, it is reasonable to consider different, potentially more convenient charging methods, that would shift the charging peaks and distribute them throughout the day.

There are several different EV charging approaches that could potentially serve as a solution for range anxiety and for extreme peak demand. Possible solutions include battery swapping, where at designated battery stations, discharged batteries are being replaced, with a fully charged one (Zheng et al., 2014). In this case, charging of batteries could be more controlled and distributed throughout the day. However, battery and therefore lithium demand in this method would drastically increase, thus it would mean solving one problem by creating another. Improving grid balance, as well as reducing battery requirements could potentially be achieved by dynamic charging, where power can be transferred to EVs while traveling on road. This technology has been popular since the 19th century. Trolleybuses powered by transmission lines hanging above the road have been widely used all around the world (Brunton, 1992). Overhead wires for EVs, however, would be problematic for several reasons. Physically connecting and disconnecting the vehicles would require complicated processes. Also, the visual pollution of the wire network is debatable. (Sevcik & Prikryl, 2019) A more approachable method of dynamic, on-road charging is when transmission line is installed in road and connection occurs from the bottom of the car. In this way, wires are not causing visual pollution, and the distance that power has to travel from primary transmission to EV is also reduced. There are two types of transmissions available for this purpose: inductive and conductive power transfer. In case of inductive power transfer, coupling two inductive coils is charging the power wirelessly. The primary, transmitting coil is creating an electromagnetic field that induces voltage in the receiving coil (on vehicle). (Bi et al., 2019; Patil, McDonough et al., 2017) With conductive charging, a conductive rod is connecting physically to the transmission wires using conventional conductive transmission. Reaching connection with conductive charging can be more complex, especially at high velocities on motorways. (Khaligh & Dusmez, 2012; Villa et al., 2012) Wireless charging however does not require physical connection, EV owners could charge without difficult action required for charging. Wireless dynamic power transfer (WDPT) has been chosen to challenge plug-in charging in this study, as user convenience could potentially compete with home plug-in charging, peak demand would be distributed throughout the day and battery could be significantly downsized as charging is broadly available whilst travelling. Therefore, this technology could potentially solve three of the major challenges that sustainable EV integration needs to face.

1.2. EV Charging Systems

In this chapter a more detailed exploration of the two EV charging methods will be offered, including technical specifications, state of development and possible advantages and disadvantages.

Plug-in charging is the most common charging method presently. There are 5.2 million EV chargers installed globally, 4.7 million of which are private chargers (home chargers mainly). The EV Outlook (2018), by the International Energy Agency predicts a 200TWh annual EV energy demand by 2030 in Europe, 145TWh of which is expected to be charged by private slow chargers. This means that even in a 2030 scenario 72% of the charging is expected to happen at home. (IEA, 2019)

There are different chargers available on the market and standardisation of sockets have been initiated in Europe (Habib et al., 2018). As not all chargers are compatible with all EVs at the moment, greater amounts of chargers have to be installed to ensure availability to all EVs. The most commonly used chargers can be divided in four categories. The most basic charger is the single-phase AC charger that can be easily applied for domestic use; with power output of about 4-10 kW. To achieve slightly higher power output of 4-22 kW, 3-phase connection is recommended, that can be slightly more difficult to install for domestic purposes; however, numerous residential buildings have the capabilities. This upgrade can reduce charging time from 4-10 hours to 2-6. For high power output chargers, mainly applied for public charging, 3-phase AC connection, or DC connection is used. Currently, 3 phase AC fast chargers are about 50-100 kW and DC chargers are 100-240 kW. With fast charging, battery can be charged under half an hour, some cases under 10 minutes. (Falvo et al., 2014; Habib et al., 2018; IEA, 2019) As mentioned earlier, EV owners are expected to charge their vehicle predominantly at home, around evening arrival. Considering the home chargers with around 4-10 hours, evening peak of home charging can be expected from about 17:00 to 23:00 (Babrowski, 2014). Presently, public chargers can vary by transmission (1 phase AC, 3 phase AC or DC) or connectors and sockets as well. As a result, not every EV owner can use the same stations. However, the European Automotive Industry is furthering a combined charging system with the so-called Combo connector, which features a single inlet for AC and DC charging on the side of the EV and can deliver from 5-100 kW power. This connector is currently under development by IEC standardisation process (Falvo et al., 2014). With standards, flexibility and wide availability of chargers in the future, plug-in charging could potentially become feasible (Habib et al., 2018). However, with dominant home charging and the premature public charging infrastructure without standardisation, EV charging remains highly problematic.

In terms of Wireless Dynamic Power Transfer (WDPT), charging is possible whilst driving, which can be highly convenient for consumers (Bludszuweit, 2018). This charging method does not need physical connection for power transfer, since electrons are transmitted via induction instead of conduction (Mi et al., 2016). Two coils – one on the car and one on road – are electromagnetically coupling and therefore, the primary road coil can transmit electricity to the receiving coil. The efficiency of current inductive chargers varies from 80% to 92% (Patil et al., 2017a; Rubino et al., 2017), with a theoretical efficiency of 96% (Ahmad et al., 2017). The gap between the coupling coils is an important factor. These high efficiencies are achieved with 100-300 mm gap between the coupling coils (Journé et al., 2014; Patil et al., 2017). Figure 3 shows the basic working principle of WDPT.

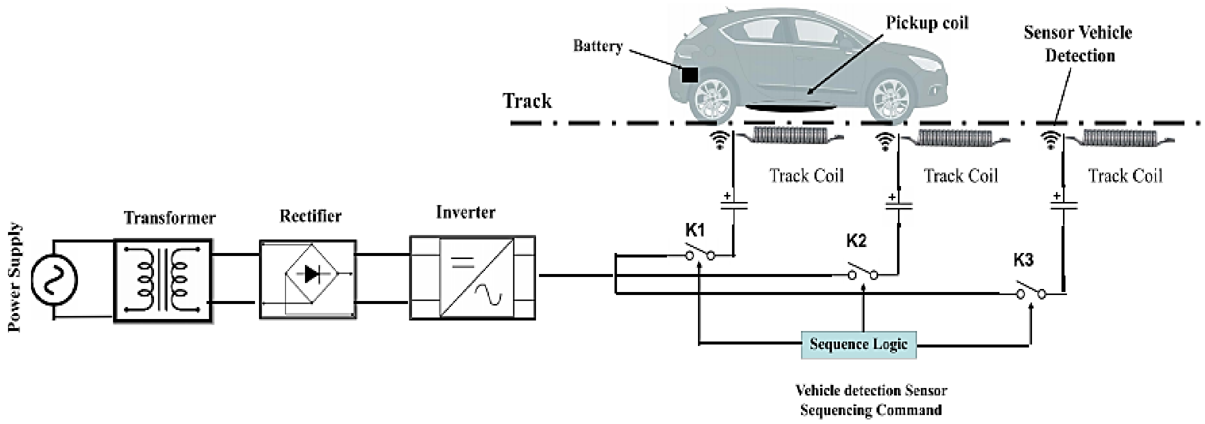

Figure 3 - Working principle of road WDPT (source: Ahmad et al., 2017)

This technology, however, contains technical complexities that EV owners would have to get used to. For efficient power transfer, the 2 coils must have sufficient alignment. The necessary alignment for power transfer differs between models. The best coils can achieve acceptable power transfer with only around 60% alignment of the coils. The majority of the pilots, however, need an alignment of 70%-80% for the electromagnetic field to be created. Therefore, driving accurately above the primary coils is crucial for this technology to work. That means drivers have to pay extra attention on road. However, there are software being developed that warns drivers, when they are misaligning. Other software can micro-control the vehicle and keeping it exactly aligned for the comfort of consumers.

There are several pilots available around the globe with power ratings from 3.6 kW to 100 kW (Rubino et al., 2017). In Europe there are test sites in Sweden, Spain and Italy among others. Also, there are working pilots of WDPT charging, for example buses in the UK at bus stops and on-road charging trails for buses in Seoul, South Korea as well (Ahmad et al., 2017).

Wireless dynamic charging can be a tool to integrate EVs to the electricity infrastructure effectively, as it could potentially shift the evening peak demand and distribute it throughout the day (Bludszuweit, 2018, Choi et al., 2014). EVs would not have to carry the charge they need for the entire journey as vehicles would be constantly recharging on the road (Onar et al., 2013). Charging whilst driving, therefore will reduce the need of large storage capacities, and consumers will most likely be more comfortable with smaller battery packs onboard. (Ahmad et al., 2017; Onar et al., 2013; Patil et al., 2017)

This technology would have key importance on the main logistic routes around Europe, where long distance travelling is more typical. With on-road charging, the electrification of HDVs would be more feasible as storage capacity onboard and charging breaks can be reduced (Journé et al., 2014). WDPT technology could also serve as the foundation of future autonomous vehicles on-road (Ahmad et al., 2017).

Both technologies carry some advantages and disadvantages. In terms of plug-in charging, extensive evening peaks can be expected, especially in terms of LDVs . This also means large battery capacity requirements, as consumers demand batteries of 5-20 kWh that can provide them all day, until they get home. On the other hand, plug-in charging appears to be the simplest and cheapest charging technology to be adapted for the rapid growth of EVs. WDPT charging is more expensive per kWh installed. Moreover, WDPT is only effective with wide availability on roads; therefore, the early stages of implementation would not support demand as well as plug-in charging. However, with sufficient road coverage and mature infrastructure, WDPT can potentially reduce battery requirements, as well as distribute the peak demands throughout the day corresponding to traffic patterns. In this study, the focus is on exploring if WDPT charging is in fact more beneficial long term, regarding distribution of peak, battery downsizing and environmental impact.

1.3. Gaps in Knowledge

There are studies available on the technical and infrastructural feasibility and optimisation of WDPT and plug-in charging as well (Choi et al., 2015; Onar et al., 2013; Patil et al., 2017, Bludszuweit et al., 2018). Research and development on WDPT have been carried out in the past 10 years all around the globe. Developments include the FABRIC project (Amditis et al., 2015), the UNPLUGGED project (Sanz et al., 2014), the South Korean KAIST – OLEV project (Huh & Rim, 2011) and Qualcomm HALO project (Qualcomm, 2018), with several test sites in Europe, South Korea and New Zealand as well. However, in terms of WDPT charging, there is not much attention on the large scale environmental and energy system impacts. Although WDPT charging impact on the grid balance has been neglected, several studies have been carried out on the load shifting nature of plug-in charging in the future (Babrowski et al., 2014; Bellekom et al., 2012). These studies, however, retain different aim and scope and comparison of different charging technologies does not occur either. Some LCAs have also been found on plug-in charging and WDPT as well (Bi et al., 2019; Bi et al., 2015). These studies are assessing charging for smaller scale systems, such as one bus route. However, studying these charging systems for the entirety of Europe, considering effects on grid balance and environment would be a new perspective, that could show insights of large scale EV deployment, taking all supply-demand imbalance, large material exploitations and system emissions into account. The EU is investigating the most suitable pathways for charging infrastructure planning (EEA, 2017). Assessing patterns of two charging technologies for Europe can be a great addition to the collective knowledgebase on electric vehicles.

1.4. Research Aim and Scope

The aim of this research is to model electricity supply-demand patterns in 2050, and add future EV charging scenarios to analyse its impact on the grid balance in case of WDPT and Plug-in charging. Additionally, the battery downsizing potential and consequently the environmental impact of the charging scenarios will be assessed. The system is going to be large scale, for European road transport and electricity sectors, to see if these technologies could help EU energy targets in the future. The scope is limited to a future static scenario in 2050, rather than a dynamic from today to 2050. This method enables the study to consider the maturity stage of both sustainable electricity and transport sectors. This means analysis can be carried out on significant share of EVs and significant share of renewable energy, allocating future impact factors more effective way.

By implementing a comprehensive charging infrastructure in Europe, EV charging industry would substantially increase, using more materials and energy. The environmental impact of this new rising industry cannot be ignored. Environmental impacts deriving from battery production can be reduced by increasing charger availability; however, this only result in overall progress, if charger production does not involve large environmental impact on the other hand. Therefore, the main scope is to compare two important environmental impact factors involved in the charging system: impact of batteries and of chargers. Cost estimations are excluded from the main scope; however, simple preliminary cost calculations will be attempted for further analysis.

In order to ensure achievability of the project, modelling future electricity supply-demand must be simplified and more focus to be directed towards EV charging patterns. The complexity of supply-demand scenarios must be reduced to one standard future system. Intermittent renewable energy generation, and equally intermittent consumer behaviour must be generalised in some ways for this project. At the end of this research, a better understanding of the impacts of EV charging on grid balance and environment to be gained, as well as analysis of change in these impact categories in terms of different charging technologies and charging habits.

1.5. Research Question

The following research questions have derived from the problem statement, gaps in knowledge and the aims and scope above. In order to assess the impacts of different EV charging methods, the following main research question has been formulated:

How does Wireless Dynamic Power Transfer (WDPT) effect future EV charging patterns and sustainability in the European energy and transport sectors as oppose to conventional plug-in charging in 2050?

With sub-questions as follows:

1. What are the driving and consumption patterns in 2050?
2. What are the traffic patterns in Europe, 2050?
3. What sort of WDPT system is required for future EVs?

4. What sort of Plug-in system is required for future EVs?
5. What is the future of electricity demand-supply without EVs
6. How does future electricity supply-demand change with EVs?
7. How will the demand curve behave with WDPT or Plug-in charging in Europe 2050?
8. What factors do WDPT and Plug-in strongly depend on and how?
9. How does WDPT charging changes the battery requirements on board of the vehicle?
10. What are the environmental impacts of WDPT compared to conventional plug-in charging?
11. Are there important factors, other than supply-demand balance and environmental impact to focus on?

1.6. System Boundaries and Assumptions

The main assumption of the study is that Europe has high, more than 80% renewable energy (RE) share and 100% share of electric vehicles (EVs) by 2050. 100% EVs include all road transport vehicles, even trucks and buses. Future electricity mix scenario and demand curves are represented by Energy Roadmap 2050 scenarios (EC, 2011) and both the generation and demand is based on European averages. Assessing the potential of European countries separately is outside of the system boundaries. Europe is considered as one interconnected energy and road transport infrastructure. Also, seasonal and other periodical variations of electricity generation and demand had to be excluded, as a result of the high complexity. EV charging behaviour is more related to daily patterns, the main impact is expected to show in daily peaks. As a result, this research is focusing on the daily patterns only, assuming charging of all vehicle types happens daily. As a result, electricity supply-demand patterns have also been designed to focus on daily periodicity. For this, only the most average and more frequently occurring daily pattern have been chosen throughout the entire year from all historical data used (electricity generation, demand, charging and traffic patterns).

Another important system specification is that batteries on board of electric vehicles only serve the EV owners in this model. Vehicle to grid (V2G) is not considered in this study.

The system boundaries are placed around three vehicle types: light-duty vehicle or LDV (represents mainly privately-owned passenger cars), medium-duty vehicles or MDV (representing everyday delivery commercial vehicles) and heavy-duty vehicles or HDV (representing lorries, trucks and buses). The vehicles are considered fully electric with advanced lithium-ion batteries on board. The driving patterns of the three vehicle types will be assessed on motorways, major roads (larger urban roads and main roads) and minor roads (small urban roads with 50km/h or smaller speed limit). Also, the study is assuming 3 main types of plug-in, stationary charging: charging at home, at work and other (including charging at random parking lots, at shopping are by charging stations on motorways).

Driving habits in this research are based on maximum road capacity and the state of saturation depending in the hour of the day. Extreme circumstances, such as severe road congestions, or drivers ignoring law (going over speed limit, or violating breaking distance) are not included in the system boundaries. The system includes weekend and weekday hourly traffic variations; however, holidays are not included.

In terms of technical specifications of the charging methods, alignment differences cannot be incorporated in this research, since predicting how well people can align whilst driving is far from scientific knowledge, partly as WDPT is not available for passenger cars yet (only experienced bus drivers and test drivers). However, studies show that, there are communication systems being tested between road and vehicle to help staying aligned (Qualcomm, 2018). Also, by 2050, vehicles are expected to become partly autonomous, with advanced control features that keeps drivers on lane and controls speed (Tettamanti et al., 2016). As a result, misalignment during driving will not be considered in the model.

System boundaries will be present more detailed for the environmental impact, in the model description section.

1.7. Methodology

To assess the impacts of different charging behaviours effectively, future electricity supply-demand and driving patterns need to be accurately simulated, taking technological advancements also into account. To achieve that, an energy model has been created in MATLAB[2]. This model is modular with highly distinguishable submodules to model the main impact factors individually. Figure 4 summarises the main stages starting with some input data, modelling the submodules and integrating them passing through the different charging scenarios designed.

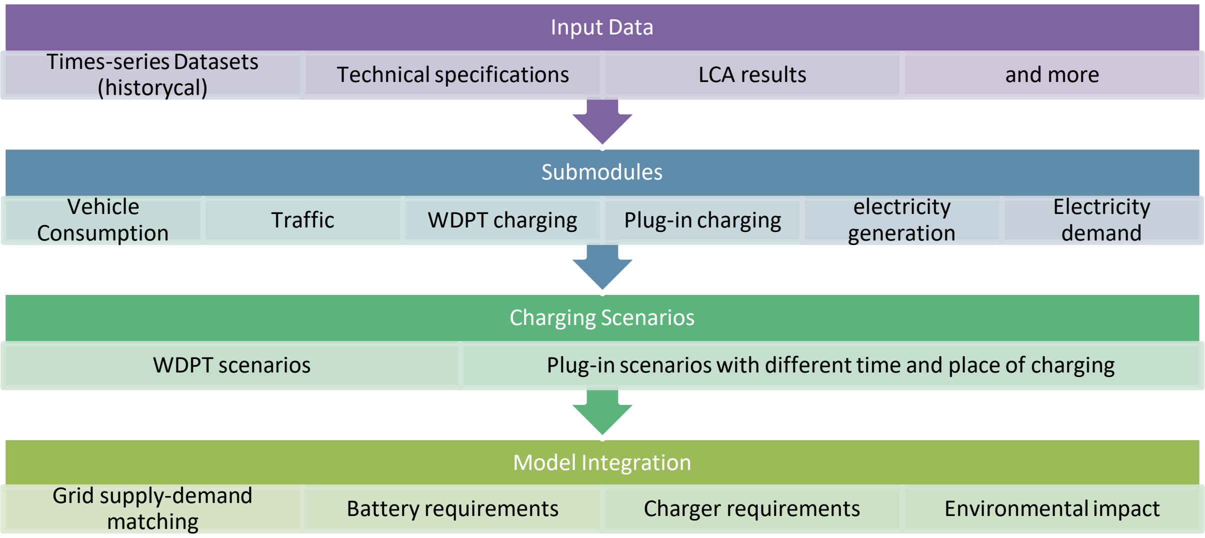

Figure 4- Model methodology

In MATLAB, submodules are functions, that can be called into the script and further operations can be carried out. For the input data, a data sheet has been created with all the necessary input variables, that can also be called into the script. Similarly, the various charging scenarios have all been modelled separately, consisting commands about which charging methods to be considered (e.g. consider only home charging). These scenarios can also be called into the script. To connect all these components, the main script in MATLAB serves as the integration platform, where the input datasheet, all the functions (submodules) and the scenario restrictions can be combined, and with further computation the final results can be created.

The submodules can function separately and interconnected as well. All the submodules require extensive literature research, carefully chosen input data and model validation. The input values for the data include historical, recorded datasets of traffic densities, electricity consumption and electricity generation of capacity factors (APARICIO et al., 2016; DFT, 2017.; EC, 2011, 2014, Bobmann & Staffell, 2015 etc). Datapoints are hourly, and several years mostly from 2013-2017 have been analysed. Other input values, such as technical specifications of vehicles and chargers come from review articles and reports (Delorme et al., 2009; IEA, 2019; Patil et al., 2017; UNECE, 2018 etc.); and most importantly, input data, such as environmental impacts of different components have been taken

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[2] MATLAB is a numerical computing interface and programming language developed by MathWorks. MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms. More: https://www.mathworks.com/products/matlab.html

from the results of LCA research papers (Bi et al., 2015; Emilsson & Dahllöf, 2019; Girardi et al., 2015 etc.) Detailed input data and reference list can be seen in Appendix VI.

Input data is mainly run through the submodules first and combined at the module integration stage. Before the submodules are being connected to compute final results, they are combined with different charging scenarios. These scenarios vary between technologies: plug-in or WDPT; and charging behaviour as well: time and place of charging. The submodules are constant, only the charging scenarios are changing, producing different final results accordingly.

Some of the sub questions of the research can be answered by the submodules separately, without the need of scenarios or integration. These are the first 2 questions on vehicle consumption and traffic patterns, that can be answered by the related submodules separately. For question 3 and 4 on WDPT and Plug-in requirements, the different charging scenarios also have to be involved to identify the number and type of chargers required to fulfil the charging patterns. For the questions regarding electricity supply-demand patterns (question 5,6 and 7) require the integration of almost all submodules including electricity supply, demand, traffic and consumption patterns and also, the varying charging scenarios, especially for question 7. Similarly, questions on battery requirements and environmental impact can only be answered by complex integration of several submodules and running them through all the different charging scenarios. Most important submodules in this case are consumption and traffic patterns. For environmental impact an additional life cycle analysis (LCA) is carried out with input data from other parts of the model (battery and charger requirements especially).

In order to answer question 10, a comprehensive sensitivity analysis of the model will be carried out, to identify the most impactful variables of the charging systems.

Finally question 11 can be answered by a comprehensive multi-criteria analysis (MCA), bringing in additional impact factors and comparing them with results of the MATLAB energy model.

More detailed description of the model is provided in chapter below, explaining the architecture of the submodules and the integrations for different purposes as well.

2. MODEL DISCRIPTION

The MATLAB model described above is going to be further explained in this section. The interconnectivity of the model can be seen on Figure 5 with the interactions of input data, subfunctions and model integrations. Graph is horizontally split into the model stages from input data to result analysis. Also, the top half consist a vertical division of electricity supply model on the left and demand model on the right. The most important results are present in rhombus and the various charging scenarios are shown in an ellipse.

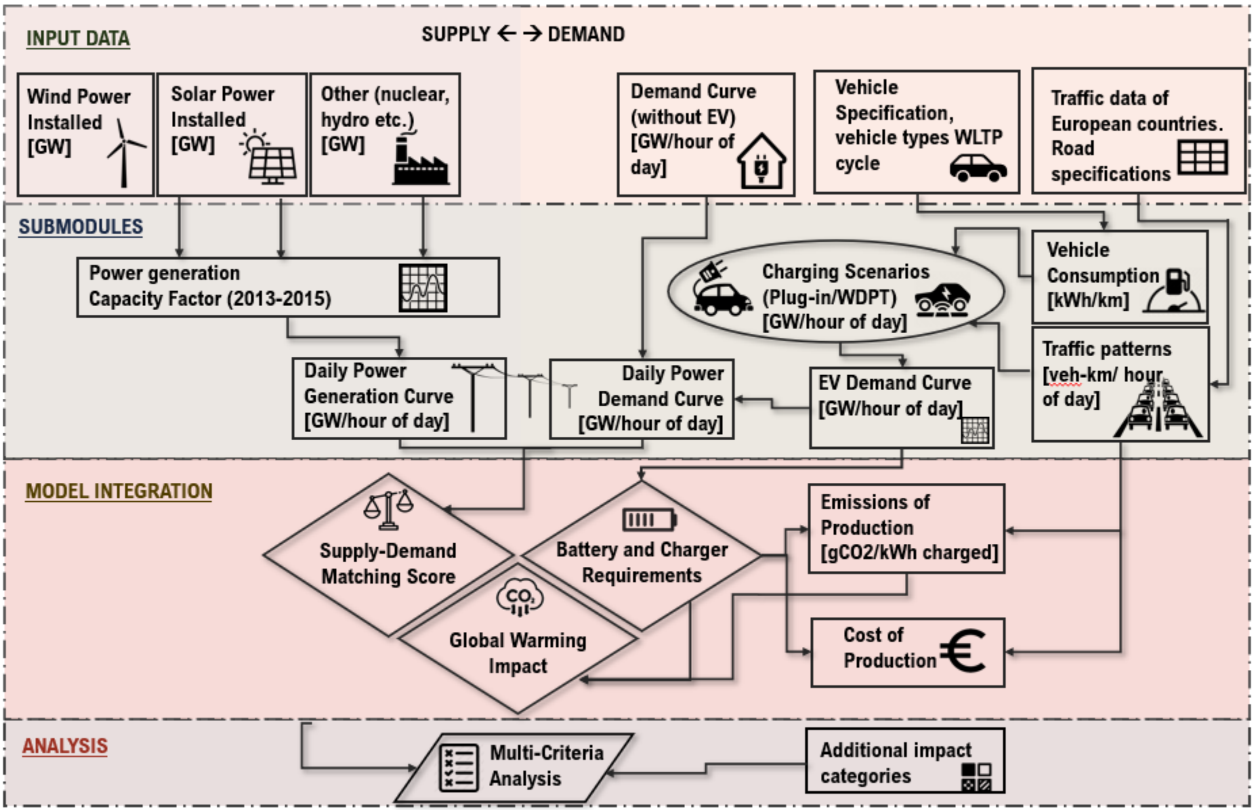

Figure 5 - Energy model overview of major flows

It can be seen that the supply side of the model is much simpler, than the demand side. The reason for that is mainly the scope. As traffic and charging behaviours are the main interest of this study, electricity generation is kept simple and constant. Charging scenarios in the ellipse produce the hourly EV charging demand curve per day. This can be added on top of the demand curve from other sectors (without EV) to produce the overall demand curve in Europe. This allows comparison with the electricity generation that has been computed to the same unit. The other important calculation deriving from the charging scenarios is the battery capacity and number of chargers required. These are important result on its own; however, combining them with emissions and scarce material exploitations associated with charger and battery production will also reveal the environmental impact. Finally, all of the results combined with additional impact categories can be assessed in an MCA.

There are two main components to this model, in order to determine charging and energy storage requirements:

1. EV charging patterns, with emphasis on energy consumed by vehicles throughout the day
2. Electricity system, where demand is calculated without road transport

In the followings the methodology behind the components of the model will be explored.

2.1. Modelling EV Charging Patterns

Charging patterns are modelled by consumption of the different vehicles, traffic distribution and charging behaviour. The last component on charging pattern is the one that will be manipulated by the different charging scenarios. Consumption and traffic patterns are the foundation that these charging patterns are built on. In this chapter, the approach behind EV consumption modelling, traffic modelling, and charging modelling will be described.

2.1.1. Consumption per Vehicle

EV consumption is based on the sum of general forces acting on a vehicle combined with battery to wheel efficiency and regenerative breaking capabilities.

The forces acting on the vehicle can be determined by the equation below (Juan Luis Villa, 2018)
Unit: Newton[N]:

$$\mathrm{F_{total}} = \mathrm{F_{friction}} + \mathrm{F_{aerodynamics}} + \mathrm{F_{linear\ acceleration}} + \mathrm{F_{angular\ acceleration}}$$

$$\mathrm{F_{total_t}} = \mathrm{C_r mg} + 0.5\rho\mathrm{AC_d v_t^2} + \mathrm{ma_t} + 0.05\mathrm{ma_t}$$

Power required by vehicle, including regenerative breaking in P [W]:

$$\text{for } \mathrm{F_{total}} \geq 0; \rightarrow \quad \mathrm{P_t\,[W]} = \mathrm{F_{total_t}} * \mathrm{v_t}/\eta_{\mathrm{tank-to-wheel}}$$
$$\text{for } \mathrm{F_{total}} < 0\ ; \rightarrow \quad \mathrm{P_t[W]} = \mathrm{F_{total_t}} * \Delta\mathrm{v}/\eta_{\mathrm{tank-to-wheel}} - \Delta\mathrm{F_{total}} * \Delta\mathrm{v} * \eta_{\mathrm{regenerative}}$$

Consumption in kWh can be expressed as the sum of hourly average power demand, deriving from total forces multiplied by average velocity.

The variables that will determine the characteristics of different vehicle types:

$\mathrm{C_r}$ – Friction coefficient
m – Mass of the vehicle [kg]
A – Frontal area of the vehicle $[\mathrm{m^2}]$
$\mathrm{C_d}$ – Aerodynamic coefficient
v – velocity of vehicle [m/s]
a – Acceleration of vehicle $[\mathrm{m/s^2}]$

$\eta_{\mathrm{tank-to-wheel}}$ – Tank to wheel efficiency
$\eta_{\mathrm{regenerative}}$ – regeneration efficiency by breaking or deceleration

ρ – air density and g – gravitational acceleration are constant)

The coefficients and efficiencies have been taken directly from literature, the mass and frontal area is an average of different vehicles. The typical velocity and acceleration of the vehicle categories are provided by the WLTP driving cycle. WLTP or Worldwide Harmonised Light Vehicle Test[3] is the internationally accepted standard driving cycle with velocity and acceleration per second for different vehicle and road types, developed by the UN. *(UNECE, 2015)* WLTP driving cycles can be visited in Appendix I.

In Appendix II, the specifications of the 3 vehicle types: light-duty (LDV), medium-duty (MDV) and heavy-duty (HDV) can be found. These served as input data for the EV consumption function described in Appendix II. The output value is calculated in kWh/km. The EV consumption model does not include

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[3] See more on WLTP driving cycle: https://wltpfacts.eu/

wind caused air resistance, nor road tilt. It is considered that on a large, European scale, these factors balance out. Also, technological improvements are not assumed in case of aerodynamics or friction coefficient by 2050.

The battery to wheel efficiency assumes technological advancement of EVs by 2050, raising the average battery-to-wheel efficiency from 75% in 2010 to 90% in 2050 (*Hofman & Dai, 2010)*. It is more challenging to expect significant regenerative breaking efficiency improvements, since the mechanical and heat losses are difficult to avoid *(Apter & Präthaler, 2002)*. However, 10% of efficiency increase will be taken into account considering regeneration, assuming advancements on motor to battery transmission. The consumption model assumes that all EVs have energy saving mode, where electric motor stops when velocity equals 0 for longer than 5 seconds.

The output of this submodule is EV consumption in kWh/km. Depending on the input data, the submodule was able to produce LDV, MDV and HDV consumption on the three different road types: motorway, major roads and minor roads.

2.1.2. Traffic Patterns

In order to create a generally applicable traffic model, first the maximum vehicle capacity of a road has been determined. Maximum road capacity is considered equal to peak traffic. Therefore, this value is used as peak traffic and an hourly distribution throughout the day has been extracted from DFT, 2019 and Babrowski et al, 2014 by normalising vehicles per hour data.

To set the maximum capacity of certain road types, the legal requirement of breaking distance has been applied. The breaking distance is determined by the 2 second reaction time rule that drivers have to take into account. Considering the 2 second reaction time, and the average velocity of the vehicle, the minimum distance required between 2 vehicles can be calculated. Average velocity on different roads is calculated using the WLTP driving cycle. Adding this distance to the average vehicle length will determine the maximum vehicle capacity of a specific road at given average velocity. (Bludszuweit et al., 2018). Calculations for maximum road capacity:

$$RC_{max} = \frac{RL}{BD + VL}$$

Where:

RC_{max} is the maximum road capacity, or maximum amount of vehicles on road

RL is the length of the sample road to be assessed in meters including multiple lanes

VL is the average length of vehicle (4m for light duty)

BD is the breaking distance deriving from the 2s distance multiplied by the average velocity.

Road lengths in Europe have been categorized to motorways, major roads and minor roads to follow the categories of the WLTP driving cycle. Road lengths, identified for the entirety of Europe are 78,654km of motorways, 903,613km of major roads and 3,537,016km of minor roads. Motorways are considered to consist 2 lanes in average, and major roads are 1.5 lanes. Therefore, for calculations that must entail lanes, the road length is multiplied by the associated lane count. (UNECE, 2018)

The daily traffic distribution curve is almost identical in most European countries; peak hours are approximately the same, only the magnitude of the peak differs marginally. (Babrowski et al., 2014) Therefore, an average of the traffic patterns of different European countries can be a suitable modelling approach. (DFT, 2019; Babrowski et al, 2014)

Data has shown two distinguishable groups with high correlation within: weekend and weekly traffic distribution. Therefore, weekdays and weekends have been averaged separately.

Figure 6 below shows the European weekday and weekend traffic distribution averages. The sum of the normalised traffic distributions add up to 1.

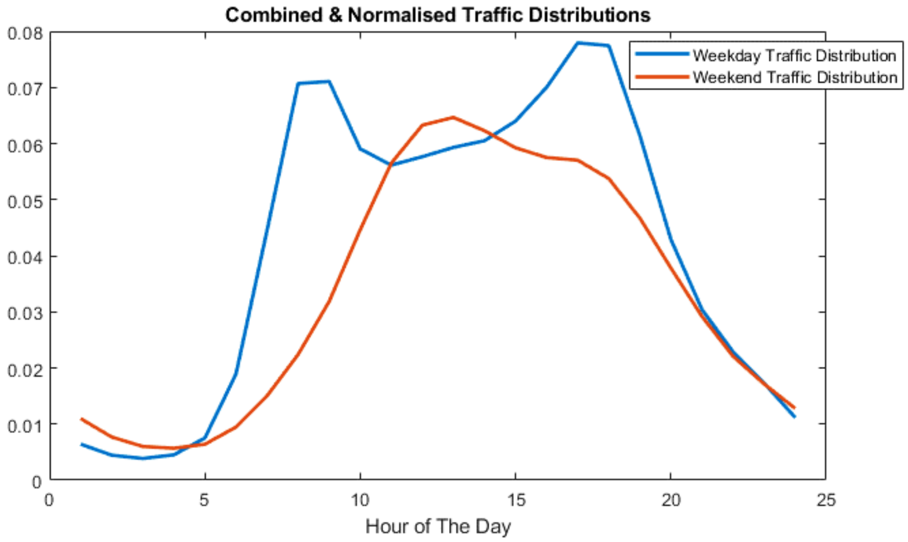

Figure 6 – Combined and normalized traffic distribution weekday and weekend

Traffic on the weekend is considered 80% of the weekday traffic. Different road types are further categorized on the annual average vehicle proportions present on the road.

In terms of distance travelled by a single vehicle, further calculations have to be applied. The 2 second break time only shows the number of vehicles on the road in vehicle-kilometre in certain hour; however, it does not define the exact number of vehicles over the day. Therefore, vehicles also have to be defined by the number of hours they stay on road. Distance travelled by vehicles is treated as a positively skewed normal distribution[4], with mode and standard deviation taken from literature (GOV.UK, 2019; Qian et al., 2011). Table 1 shows the most common daily distance travelled.

Table 1 – Most common distance travelled by vehicle types[5]

Vehicle type	Mode (km/day)	Standard Deviation (km/day)
LDV	36	14.4
MDV	200	180
HDV	400	160

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[4] In probability theory and statistics, normal distribution is the even distribution of the probability of the values to occur around the mean. Skewness is a measure of the asymmetry of the probability distribution of a real-valued random variable about its mean. (more: https://www.statisticshowto.datasciencecentral.com/probability-and-statistics/normal-distributions/)

[5] References for Table2: Light-Duty/Passenger (Qian et al., 2011), medium and light duty (GOV.UK, 2019)

Commercial MDVs have a significantly larger standard deviation as a result of large variation of purposes. These distances travelled are also used to convert vehicle-kilometers per road into number of vehicles per road.

Further information on the input data and calculations in traffic submodule can be found in Appendix II.

2.1.3. WDPT Charging

The energy transmission by WDPT charging is assuming continuous charging on a road length, specified by the charging scenario. Calculations can be visited in Appendix II.

In the base scenario, efficiency is considered 90% (Rubino et al., 2017), charging output is 60kW (Amditis et al., 2015) and velocity is given by the WLTP driving cycle described at EV Consumption section. Computing these variables will result in charging capabilities of different road types in kWh/km. LDVs consist 1 coil, as the average vehicle length could not hold more than that. However, MDVs can be fitted with 2 of the standard 4m coils; and HDVs with 4 coils. Therefore, MDVs and HDVs can charge 2 and 4 times more energy, than LDV.

Additionally, the charging capabilities can be compared to consumption patterns to see if charging availability can fulfil EV consumption, in order to eliminate the need of plug-in charging in the system. Calculations by this model can be viewed in Appendix II.

As well as defining energy transmitting capabilities, finding the number of coils required for the transmission has significant importance. The number of coils installed on the road will determine the material requirements and therefore, the environmental impact of this charging method. The number of coils required on road highly depends on the distance necessary between two installed road coils. As the vehicle coil only can couple with one road coil at the time, the length on which two coils are in contact will determine the space required between two road coils. This contact range depends on the alignment requirements of coupling coils. Alignment requirement means the percentage that two coils must overlap in order to create a shared, resonant electromagnetic field (Ahmad et al., 2017). In this study, a typical 70% of alignment requirement has been assumed. This means transmission between the coupled coils from 70% of alignment when entering the road coil, until 70% alignment when leaving the road coil as Figure 7 shows.

Figure 7 – Contact length of coils with alignment

Therefore, if minimum alignment for energy transfer is 70%, then the contact range is 60% (2x100-70) of the coil length, which means one 4m coil can charge the vehicle for 2.4m. From this, the spacing required between two road coils can also be calculated, which can determine the number of coils installed per km.

This submodule uses the output results of consumption submodule (kWh/km consumed) and traffic submodule (hourly distribution of veh-km travelled) to identify the total energy demand by EVs, as well as the charging pattern. For wireless charging, the daily charging distribution is identical to the traffic distribution, since EVs are charging whilst driving. Therefore, identifying hourly traffic distribution was crucial for WDPT. The consumption, traffic distribution and charging efficiency together created the WDPT hourly charging curve.

Additionally, the number of coils required on road considering alignment requirements is also an important output of this submodule for charger requirement calculations later.

2.1.4. Plug-In Charging

In order to fit plug-in charging patterns into the daily demand curve, the assumption had to be made that drivers are charging back what has been used every day. This will not have a large effect on the accuracy of the results, since the model considers an average daily pattern in every case. The time of the day, when charging is happening will be defined by the formulated scenarios. The equations behind the plug-in charging model can be seen in Appendix II.

In terms of stationary plug-in charging, the grid consumption of the vehicle largely depends on the time of charging and efficiency of charging. Home chargers are considered to range between 4kW and 22kW. Defining the exact charging power is unnecessary, since charging time and power averages out on a large scale. Therefore 12 kW charges have been used for private plug-in charging calculations. Considering power output was important in these cases, since home and work related charging create peaks (Babrowski et al., 2014). These peaks are considered a normal distribution, where the power output of the charger plays important role in defining the length of charging and therefore, the distribution of charging around the peak. Public charging, however, does not have significant peaks, it is more evenly distributed throughout the day. Therefore, power output in this case does not play a role. The grid to wheel efficiency is considered to be 95%, with 5% efficiency increase considered.

At the end, the plug-in charging submodule creates a daily overall power demand curve by Plug-in charging. The total electricity demand of EVs calculated by the consumption submodule is distributed throughout the day, using the distribution curve created by different combinations of the daily private charging (normal distribution peaks) and public charging (evenly distributed), resulting in an hourly power demand curve.

2.2. Modelling European Energy System

As well as modelling traffic and consumption of EVs, the involvement of RE electricity generation patterns is crucial to identify potential deficits between EV charging and electricity generation. Electricity demand, without EVs is also important, since the electricity demand and EV charging together will create the total demand.

In this section, submodules of electricity generation curve and demand curve will be explained.

2.2.1. Electricity Generation

The daily electricity generation patterns will focus on the intermittent energy sources of future electricity generation: wind and solar. Other energy sources in the electricity mix, such as nuclear or hydro will be considered constant throughout an average day.

There are two main impact categories involved in the energy generation model: hourly generation patterns, represented by hourly capacity factors and the installed capacity of different RE sources in 2050.

Hourly generation patterns of solar and wind energy in Europe have been created by EMHIRES capacity factor datasets by APARICIO et al., (2016) (Appendix III). In the model, hourly capacity factors from 2013 to 2016 have been processed into averaged daily patterns. Prior to that, ANOVA testing (Cuevas, Febrero, & Fraiman, 2004) has shown significant correlation between countries and daily frequency as well for solar capacity factor data. However, wind capacity factors show no correlation in daily variation, nor between countries and it is not normally distributed. Therefore, an average of solar capacity factor can be directly used in the model, however, averaging wind energy data has significant limitations, therefore, testing the model with randomly selected days of the dataset has taken place.

In order to compose European electricity generation of 2050, the assumption has been made that the contribution of different countries have the same proportion as of today (Watson, 2018)

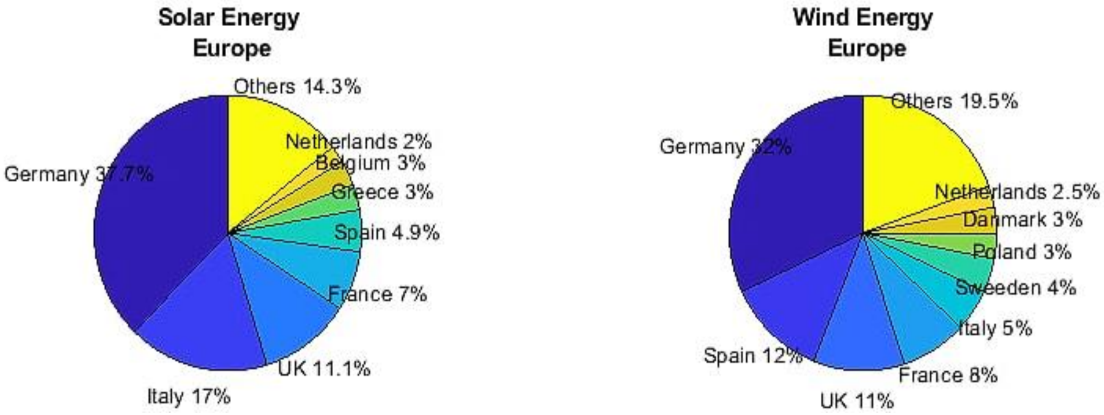

Figure 8 Solar and Wind Energy in Europe by Countries

According to Kreith & Yogi Goswami, 2007, increase in capacity factor can be expected in the upcoming decades, as a result of technological improvements and more deliberate solar and wind farm installation. Therefore, 10% of capacity factor improvement will be considered for 2050.

The hourly capacity factors multiplied by the installed capacity will determine the power generation. To determine installed capacity, the Energy Roadmap 2050 by the European Commission (EC, 2011) has been applied.

There are six 2050 low carbon electricity mix scenarios by EU Roadmap 2050 (Appendix III). They were all designed to meet decarbonisation goals of 80% compared to 1990 and to achieve renewable energy targets (EC, 2011). The high RE scenario has been chosen for this study to demonstrate a more intermittent daily power curve. High RE scenario from the report includes 603 GW installed photovoltaics, 373 GW off-shore wind, 612 GW on-shore wind, 131 GW hydro, 41 GW nuclear and 30 GW backup natural gas and some fossil fuel generation (EC, 2011).

In this model, the variation of solar (photovoltaic), on-shore and off-shore wind has been modelled with hourly capacity factor, the rest has been kept constant. The model has the restriction that electricity generation must be 110% of the demand, where all the daily wind and solar has to be used, and the rest, to make up to the 110% comes from the 'other' category, that includes the backup nuclear and natural gas power plants.

Setting the supply 10% higher, than demand was important for the MATLAB model, to avoid errors, where supply becomes smaller, than demand as a result of fine tuning or sensitivity analysis. Also, 10% additional generation could be justified to allow energy losses, or uncertainties in the system.

The output of this submodule is the hourly power output curve throughout the day in GW per hour of the day.

2.2.2. Electricity Demand Model

In order to model hourly electricity demand, data has been taken from literature combining (Bobmann & Staffell, 2015) , (Ferraro et al., 2016) and (EC, 2011)

From Ferraro et al. (2016), the avarage of the hourly power demand of eight European countries have been adapted. The contries analysed in this study are: Belgium, France, Germany, Ireland, Italy, United Kingdom, Spain and Denmark. The assumption is that the avarage of these eight countries is generally applicable to every European country.

The dataset described above is resembling electricity demand in 2016. However, some changes in the European electricity demand can be expected by 2050. Therefore, data has been altered according to the 2050 changes highlighted by Bobmann & Staffell (2015), since this study is focusing on changes in the demand curve precisely by 2050. It takes into account future demand response and new appliances, such as electrification of residential heating and industry, and future increase in EV deployment as well. EV electricity demand was subtracted from their demand curev, creating one without electric transport. The paper offers a possible future demand curve for 2050 modelled by eLoad and DESSTinEE.

The daily demand curve from the average of the eight countries and the 2050 model have been normalised, thus the total energy demand can be distributed to hourly demand.

The annual European energy demand has also been taken from the EU Roadmap 2050 energy demand scenario with high RE, where the total annual electricity demand is estimated at 3619TWh. The transport sector accounts for 675TWh in this model with 80% EV fleet on the roads. Therefore, the electricity demand without transport is considered 2944TWh. (EC, 2011)

The output of this submodule is GW power demand per hour of the day, that can be combined with GW power demand of EVs per hour of the day.

2.3. Model Integration

This part of the MATLAB model is producing the final results desired by research question and scope, including differences in power supply-demand, battery requirements, charger requirements, global warming impact of the charging system and copper and lithium exploitation. These results are computed by various combinations of the above described submodules, as well as introducing additional input data to the model, such as emissions of different parts of the charging system and battery specifications. Further integrated model descriptions are below.

2.3.1. Supply-demand Matching Score

In order to model load balance, electricity generation and demand needs to be compared. The total demand is determined by the sum of electricity demand (without EVs) and the EV charging model outputs. The aim of this model is to determine whether there is large shortage of generation at any point during the day. Therefore, the model focuses on the differences only when demand exceeds generation. Overproduction does not count towards the imbalance of the grid in this model, since electricity generation and demand are linked. The model is assuming 10% higher electricity generation, than demand to ensure safety.

The supply-demand matching score is using two main measures to evaluate the impact of the deficit between consumption and generation:

1. Total daily deficit that calculates the area enclosed between demand and supply when demand is greater than supply
2. Peak Deficit calculates the maximum difference between supply and demand, when demand is greater than supply

Figure 9 summarises the integrated model and the main expected outputs.

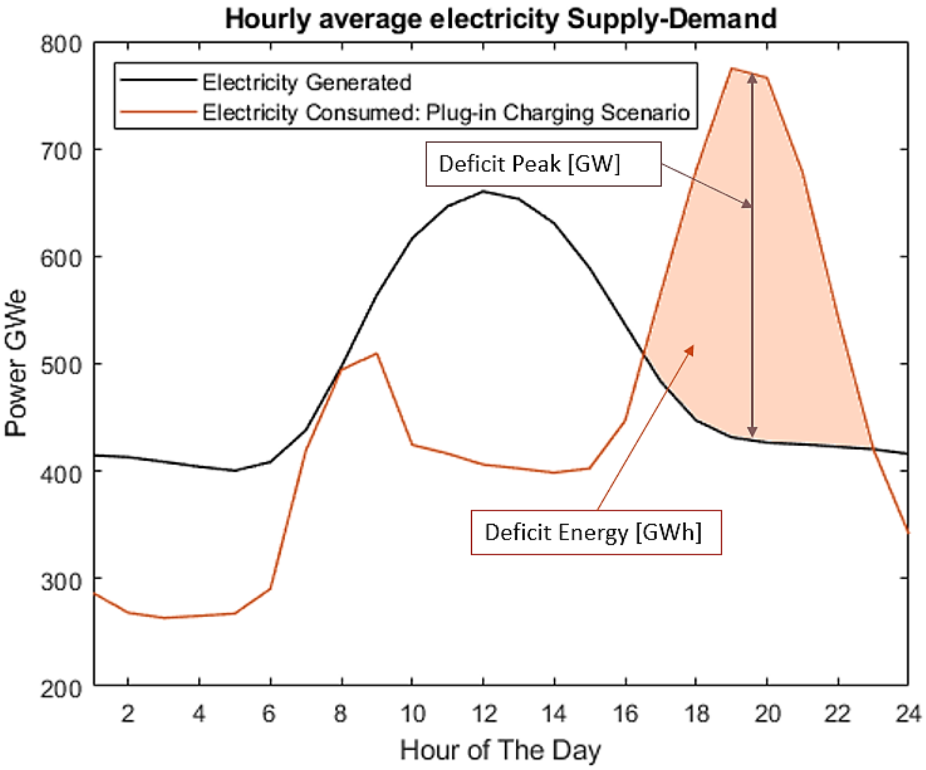

Figure 9-Method of calculating Supply-demand matching score

These measures are combined to an electricity supply-demand matching score from 0-1, where 1 is the perfect alignment between demand and supply curve and 0 is the absolute misalignment, where generation equals 0. The supply demand matching score is calculated as follows:

$$Matching\_score = 1 - \left(0.5\frac{total(deficit)}{total(demand)} + 0.5\frac{\mathrm{peak}(deficit)}{\mathrm{peak}(demand)}\right)$$

Weighting has been considered, however, it has been determined that the large peaks and large electricity shortage has equal importance, since large increase in peak requires significant grid reinforcements and electricity shortage requires electricity storage (Arias & Bae, 2016; Rassaei et al., 2015, Verzijlbergh et al., 2012). Detailed equations of the supply-demand matching score can be viewed in Appendix IV.

The output of this model is peak deficit in GW, total deficit in GWh and the combined supply-demand matching score allocated between 0 and 1.

2.3.2. Minimum Battery Requirements

In order to establish the minimum battery requirements, the energy consumed between two charging availability needs to be calculated. That will be specific to each scenario established. In case of plug-in charging, the battery requirement will be established by consumption between major stops, such as work to home, or home to home. This will reveal the distance taken between two charging points, and therefore, the energy requirements on that distance, that needs to be stored in battery. For WDPT charging, battery requirements will be addressed by calculating the consumption on roads without charging capabilities. The battery on board of the EV in this case will need to be able to store energy for the roads, that are not installed with charging coils. That will also be specific to different scenarios.

The consumption between charging cannot define battery requirements alone, since absolute discharge needs to be avoided in lithium-ion batteries. Therefore, the battery capacity must be somewhat larger, than the general consumption of the vehicle. The maximum recommended depth of discharge (DoD) is 50% according to (Persio & Ruiz, 2018). Although the DoD will most certainly improve by 2050, the extra battery capacity of 50% will be kept, ensuring 50% longer journeys, than the average, with the same charging pattern.

Therefore, minimum battery requirement will be determined by the following equation:

$$Battery_{minimum}\ [kWh] = \frac{1.5 * Consumption_{charger-charger}[kWh]}{Efficiency_{Battery-Wheel}}$$

Charging to wheel efficiency is 95% considering 5% future efficiency improvement by 2050. Charger to charger consumption is taken from above described consumption model, therefore, it includes regenerative breaking.

Calculating the battery capacity, allows the computation of battery mass as well. In order to do that, the energy density in kWh/kg needed to be determined. As energy density of batteries have been improving in the last decade continuously, 0.5kWh/kg has been identified as a realistic energy density in 2050 (Sarlioglu, 2017). Therefore, the required battery capacity divided by the energy density will result approximately in the mass of the battery (excluding some additional weight such as coating/cabling). Battery mass is important to examine the effects of battery mass on vehicle consumption. The new vehicle mass with the battery weight added can be run through the model again to reveal the updated consumption, and therefore, the updated battery size. This cycle is repeated until the consumption stabilizes on the nearest 3 decimal places (3-4 cycles). Loop has been designed as figure 10 shows.

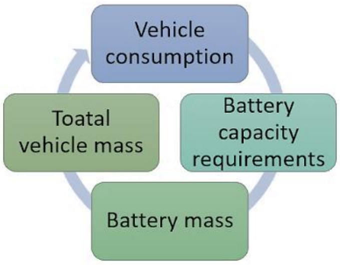

Figure 10 – Battery mass on consumption

The outputs of this model are battery capacity required on board of LDVs , MDVs and heavy-duty vehicles, and the mass of these batteries. Also, the percentage impact on consumption is being calculated in this model.

2.3.3. Charger Requirements

For environmental impact, identifying the number of chargers required is key. For plug-in charging, the number of chargers required is linked to vehicle count. For public charging, there is 1 charger accounted for every 5 vehicles. Additionally, for privately owned chargers, there is one accounted for each vehicle. Finally, in case work charging is also taken into account, an additional charger is assumed per vehicle. Therefore, all of these chargers will account for 2.2 chargers per vehicle. Nonetheless, not all scenarios will include all these charging availabilities, therefore, number of chargers per vehicles vary throughout the scenarios.

For WDPT charging, the number of on-board (vehicle) coil is also linked to the number of vehicles. The coils are considered a standard 4 meters long. There is one installed on LDVs , 2 on MDVs and 4 on heavy-duty vehicles. Therefore, the product of the number of vehicles and the number of coils per vehicle will result in the number of on-board charging coils required. For WDPT charging, numerous transmission coils also have to be installed on the roads assumed in scenarios. That however is linked to the length of the road, rather than the number of vehicles. The number of coils necessary per kilometre has already been calculated at this point by the WDPT charging submodule. Therefore, multiplying road coils per kilometre with the road length, desired to be installed with charging capability will result in the number of coils required on road.

For plug-in charging, only the charging station is considered. Components required on vehicle, such as sockets are ignored, since these parts in material requirements are negligible. However, for WDPT charging, the total number of chargers will be calculated by adding all vehicle chargers and road chargers together, as the on-vehicle component in this case is highly similar in size and complexity to the road component. All the calculations for this model can be seen in Appendix V.

2.3.4. Environmental Impact

Knowing the power consumption, the battery size and the number of chargers required at this point allows the study to compute environmental impact. It will be executed by determining the global warming impact and raw material exploitation.

2.3.4.1. Global Warming Impact

For GWI (global warming impact) the production of necessary chargers, production of EV battery and the production of power consumed by the EV throughout the lifecycle, which is set at 12 years.

The functional unit used for this analysis is gCO_2eq/kWh charged. And the only considered life cycle stage is production. In terms of EVs, there is no emissions in user phase; therefore, only maintenance emissions could be considered. EV production has the same impact, regardless of the charging method, therefore it is not considered in the system boundaries. Disposal phase has been excluded, as a result of significant uncertainties in this area. Highly important materials, in terms of disposal are the copper and ferrite in terms of WDPT charger, copper and polycarbonate materials for plug-in charger and the Li-ion battery. The recycling methods of all of these materials are expected to change significantly in the next decades. Recycling copper has been a popular and cost-effective choice worldwide, predominantly since the 1960s. Copper can be fully recovered most of the time and methods to extract copper from waste devices and cables are improving radically (ECI, 2018). Significant changes are taking place in terms of battery recycling as well (Miedema & Moll, 2013). Up until a few years ago recycling of ferrites was close to non-existent, therefore ferrite is associated with high global warming impact in most LCA studies. However, recent innovative researches, such as K. S. Lin et al., 2018 show that ferrite production could even be a tool for CO_2 capture (K. S. Lin et al., 2018). Considering that the recycling methods and magnitudes of all of these materials are in a high R&D, innovative phase; extreme assumptions would be required for their 2050 state, which would jeopardize the accountability of results. As a result, the considered stages of this assessment are limited to production of battery, chargers and electricity.

The global warming impact of battery production highly varies from study to study. Latest studies suggest lithium-ion battery production from 61-282 (Bi et al., 2015; Emilsson & Dahllöf, 2019; Gaines, 2014; Hao et al., 2017b). For this analysis, a recent study from (Emilsson & Dahllöf, 2019) has been chosen with 106kg CO2-eq/kWh battery capacity estimated. The choice has been made as this study is considering high renewable energy presence and new European regulations concerning sustainable material resourcing for the battery production. Therefore, this value represents a 2050 European production emission the most precisely.

In terms of charger production emissions, a study by Bi et al., 2015 has been considered, where Simapro8 LCA has been carried out to model 6kW WDPT and plug-in charging system for electric buses. The architecture of the two different charger types have been adapted from the study and generalized to all vehicle types. Figure 11 shows the components included in the study. Detailed inventory can be seen in Appendix VI.

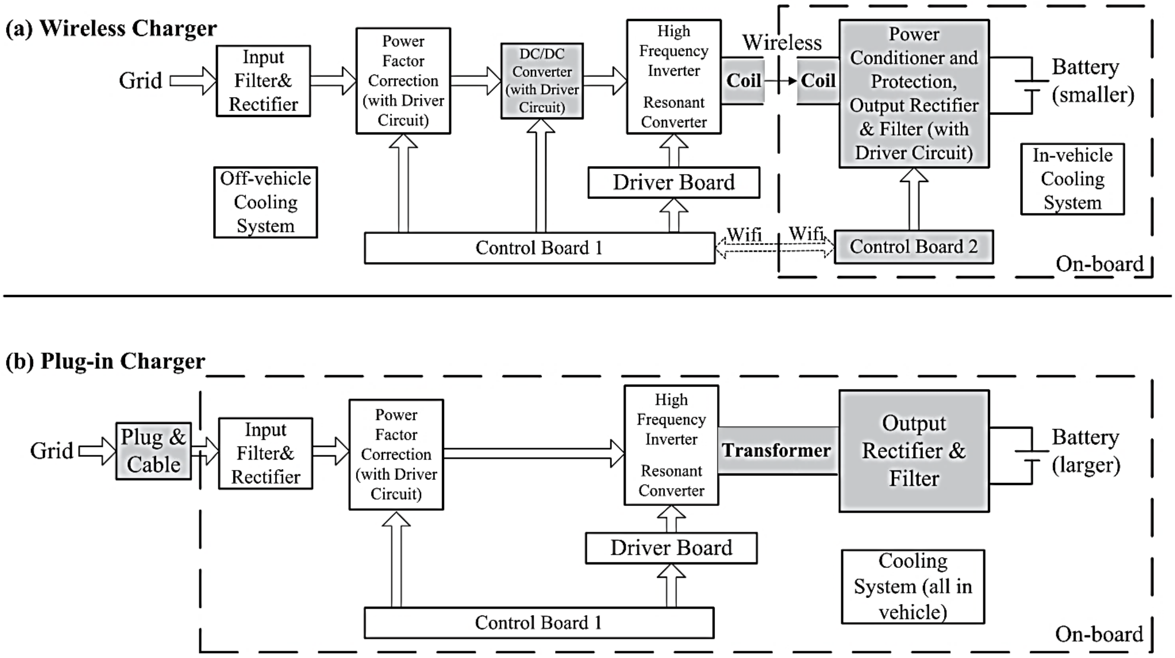

Figure 11 – Charger system boundaries by (Bi et al., 2015) – components that are different marked grey, dashed line representing on-board equipment

Note that battery global warming impact has not been taken from this study. All other components have been adapted. However, the study is considering US electricity and energy mix from 2015, which is has 7.5 times higher CO_2eq emission, than 2050 European electricity mix assumed in this study. Therefore, emissions deriving from energy use in this study have been replaced by 2050 European electricity mix emissions. Also, this research is considering higher power output coils of 60kW, which requires significantly more turns in the coil, and therefore, more copper. Therefore, emissions related to copper in WDPT charging have been increased by 25%. At the end of the adjustments to a 2050 European setting, one plug-in charger results in 847 kgCO_2eq/charger, one WDPT road charging coil emits 841.25 kgCO_2eq/charger and the on-board, secondary charging coil is responsible for 192.25 kgCO_2eq/charger. (Bi et al., 2015; EEA, 2017a)

The global warming impact of the electricity consumed by EVs have also been taken from literature. Decarbonization targets by European Commission Climate Action Framework aiming for 80% emission reduction compared to 1990 by 2050. Therefore, 20% of the 1990 electricity mix emissions have been set, as electricity generation emission for this analysis: 105 gCO_2 eq/kWh (EEA, 2017a). The European Commission Energy Roadmap 2050 predicts similar figure with about 121 gCO_2eq/kWh (EC, 2011).

All the GWI data collected from different studies have been modified to be closer to European production emissions in 2050. It has been achieved by taking European future energy emissions into account to replace the energy related emissions associated with production in the considered studies. The exact calculations of the model can be viewed in Appendix VII.

The output results of this model are the global warming impact in gCO_2eq/kWh charged of battery production, charger production and electricity production that is charged throughout the lifetime.

2.3.4.2. Scarce material exploitation

The analysis of scarce material exploitation only focuses on lithium and copper in this study. In order to determine the total amount of lithium and copper use, the unprocessed lithium required by kWh of battery production and copper required by charger production. The copper requirements per charger have been identified by (Bi et al., 2015), allocating approximately 1kg copper required for plug-in chargers, mainly for cabling and 2.4 kg copper for a charging coil. Both, vehicle and road coil have the same amount of copper. In terms of a conventional lithium-ion battery, about 780g/kWh raw lithium is to be mined (Hao et al., 2017; Zackrisson et al., 2016). Results from battery requirements and charger requirements models can be multiplied with the raw material requirements to reveal the total amount of copper and lithium exploitation for the European EV charging systems, measured in metric tons.

In order to place this raw material exploitation in context, the amount of copper and lithium needed has been compared to the global reserves available. For copper, the global reserves are around 830 million metric tons (CopperAlliance, 2018), while for lithium the global reserves are about 14 million metric tons (Narins, 2017). These comparisons will determine the degree of feasibility in terms of availability of key materials. However, it is important to mention that the possibility of recycling is excluded from the calculations, whereas recycling of copper is highly common in Europe and recycling of lithium can be expected to take rapid measures in the future. (Ciacci et al., 2017; Gaines, 2014)

3. SCENARIO DESCRIPTION

Combining different charging behaviours and energy generation patterns are the fundamental scope of this study. Therefore, cross-examining electricity mixes with various plug-in and WDPT charging scenarios is critical. 2050 base scenarios have been adapted from literature, as described in the followings.

3.1. Plug-in Charging

Plug-in charging scenarios have been designed by gradually introducing different charging availabilities. In the first scenario, there is only one private charger is available for average daily charging. After, charging at work is also being taken into consideration, followed by largely available public charging also integrated. Note that, even only home charging has public chargers included (1 charger for 5 EVs) to support longer journeys, that only happen 15.86% of the time (according to normal distribution). All of the scenarios include these public chargers for occasional irregular long distance travelled.

Babrowski et al., 2014 suggests three base scenarios for future EV charging with distinct patterns:

- **H100%:** Home100% stands for 100% of the EV owners charging their vehicles at home
- **H60%-W40%**: Home60% and Work40% means 60% home charging at evening arrival and 40% at work on morning arrival
- **H40%-W30%-O30%** is 40% at home, 30% at work and the remaining 30% is throughout the day while running errands

Additionally, a smart plug-in scenario has also been designed, adapted after controlled charging designed by Bellekom et al, 2012.

- **S100%**: Smart100% is a highly advantageous future scenario for home charging that EV chargers have load control capabilities that will charge EVs distributed out between 11pm and 7 am,

The peak of home charging is set at 19:30, the peak of work charging is 08:30 and other public charging is 80% at daytime and 20% at night-time (23:00-06:00) distributed out equally (Arias & Bae, 2017).

Charging of MDVs is considered distributed throughout the day, with a 20% increase around the end of working days (18:00-22:00).

Unlike MDVs and LDVs, charging of battery electric HDV is not common currently (Katrašnik, 2013). Therefore, the assumption had to be made that charging of HDVs is distributed throughout the day, with 1.5 times more charging at night with buses stopping and lorry drivers sleeping.

The hourly distribution of the 4 Plug-in scenarios can be seen on Figure 12 with close MDV and HDV scenarios included in all cases.

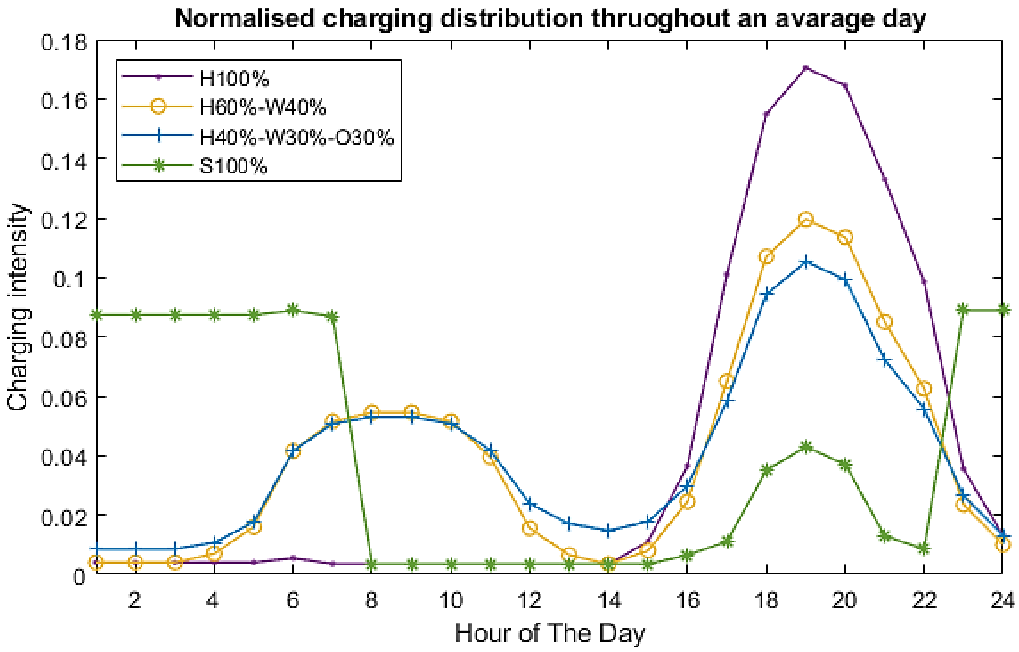

Figure 12 – Plug-in charging scenarios

As figure shows, scenarios have been kept simple, with peaks for private charging (home and work) in the smart charging scenario, the small evening peak derives from commercial MDV arriving back to their garage. Different combinations also have been tested, showing little difference from these base scenarios in final results. As a result, scenarios have been kept clean and consistent.

3.2. WDPT Charging

The WDPT charging model allows to change the percentage of installation on the road as well as pick the roads that will be installed with a given percentage. As an example, the model can be run by assuming 70% WDPT coverage on motorways and 50% coverage on highways, in order to evaluate all the scenarios possible.

Similarly to plug-in charging, here also the charger availability is the changing variable. First, a scenario has been designed with just enough coverage that plug-in charging can be eliminated. After a higher level of coverage has also been created to increase reliability and finally a full coverage scenario has been considered to play with the idea of eliminating battery requirements.

Final WDPT scenarios as follows:

- **Min.WDPT**: 100% motorway and 30% major road coverage
- **Mod.WDPT**: moderate WDPT 100% Motorway and 100% Major road coverage
- **Max.WDPT**: charging on all roads to eliminate battery requirements

Computing all the scenarios made it clear that, combining the two charging methods could show more beneficial results, than keeping them separately. Therefore, after trying numerous combinations thorough an optimisation process, the best possible combination has been designed. The final hybrid scenario:

- **Opt.hybrid**: optimum hybrid with 100% motorway WDPT coverage, combined with smart home charging to make up for difference

A summary of all considered scenarios can be seen on Table 2.

Table 2 – Summary of Scenarios computed

Scenarios	Name	Description
1	H100%	Plug-in: 100% home charging
2	H60%-W40%	Plug-in: 60% home, 40% work charging
3	H40%-W30%-O30%	Plug-in: 40% home, 30% work, 30% other
4	S100%	Plug-in: 100% smart charging (home) 23:00-07:00
5	Min. WDPT	WDPT: Minimum coverage required for WDPT
6	Mod. WDPT	WDPT: Motorway and major road coverage
7	Max. WDPT	WDPT: All-roads coverage
8	Opt. Hybrid	Optimum hybrid: WDPT: Motorway, Plug-in: Smart

In order to place these scenarios in context, two reference scenarios will be added. One for the supply-demand matching score, and one for the environmental impact, both have been designed to resemble a 'Business as usual' case that best highlights the impacts of the scenarios.

For the supply-demand matching score, the reference scenario is the supply-demand matching of the electricity system without any EVs integrated. This scenario is called a No EV scenario. It takes into account the same 2050 high renewable energy setting, without the presence of EVs. This will show the potential improvement or damage on supply-demand matching by the different scenarios.

For environmental impact, however, this reference scenario would not make sense, since no EVs would mean zero emission of EV battery or charger production. For this impact category, the reference scenario shows the environmental impact of batteries used today. Therefore, range of an average light-duty EV is set to 300km to reveal the impact of following today's trend of large batteries and compare them to reduced (minimum) battery requirements by scenarios. Calculating with minimum battery requirements in this study is crucial to fairly compare plug-in charging to WDPT charging. In case the study would take the smallest battery needed for WDPT charging, as it is a hypothetical system, and today's large batteries for plug in charging, the results would become biased. As a result, comparison of scenarios is carried out, considering minimum battery requirements; however, they are all compared to the reference scenario, that considers the demands and trends of today for 300 km range on average. This reference scenario simply called '300km Range'. This will represent the environmental impacts of continuing as of today.

To summarise the reference scenarios:

- **No EV**: 2050 Demand and Supply, without the presence of EVs
- **300km Range**: designed after today's trends, 300km range batteries paired with dominant home charging

4. RESULTS

The results will be presented in this chapter in three parts. First the most important preliminary results will be summarised, such as consumption, traffic and electricity generation patterns. Afterwards, these results will be combined with the eight charging scenarios. By analysing the results, the 3 most advantageous will be chosen for further conclusions and a multicriteria analysis to consider further impact categories for the best scenarios.

4.1. Preliminary Results

Computing the three different vehicle types on the three different road types has brought the following results shown on table 3.

Table 3 – consumption per km on different roads

Unit: kWh/km	**LDV**	**MDV**	**HDV**
Minor Roads	0.13	0.56	1.08
Major Roads	0.16	0.64	1.12
Motorways	0.26	1.16	1.46

Note that these consumptions do not include the impact of battery weight on consumption. Consumption including battery weight will be shown after battery calculations. The significant difference in consumption of different vehicle types mainly derives from the difference in mass, and frontal area that increases air resistance. The difference between consumption on different roads derives from the difference in velocity and acceleration patterns. Minor and major roads have lower average velocity, which reduces consumption. Also, lower velocity means longer time spent on road, which is beneficial for WDPT charging.

European consumption patterns are the product of consumption per kilometre summarized above and traffic patterns in vehicle-kilometres in Europe. The model output for traffic patterns on an average day can be seen on Figure 13.

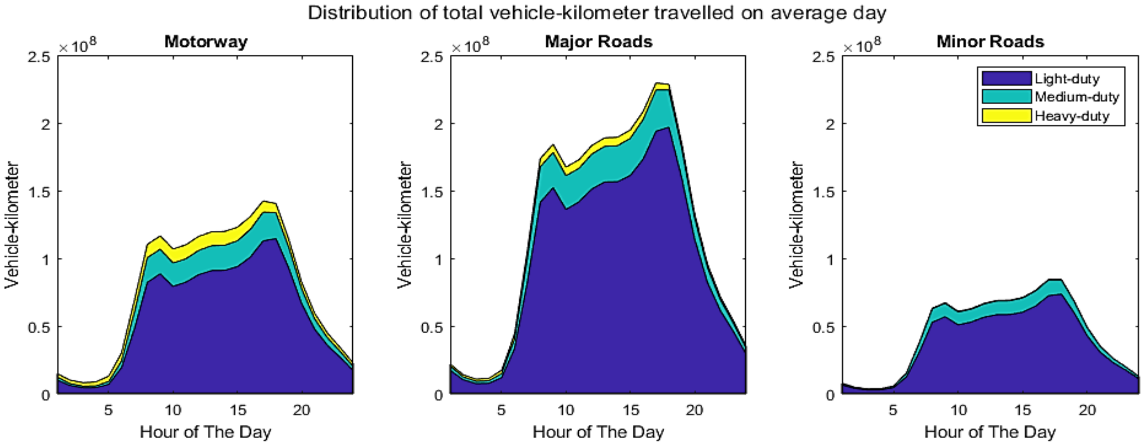

Figure 13 – distribution of total vehicle-kilometres throughout an average day

Figure 13 shows that major roads have the highest vehicle-kilometre travelled on an average day. Approximately 50% of total vehicle-kilometre travelled happens on major roads, 30% on motorways and approximately 20% on minor roads. With around 7 million vehicle-kilometre , HDV. on minor roads are insignificant, it barely shows on the graph, with only 2% share on minor roads. LDVs are highly dominant on all road types. However, final consumption also depends on velocity, acceleration and other vehicle specifications. Therefore, final daily consumption shows different profile. Total consumption of all vehicle types on the different European road types can be seen on Figure 14.

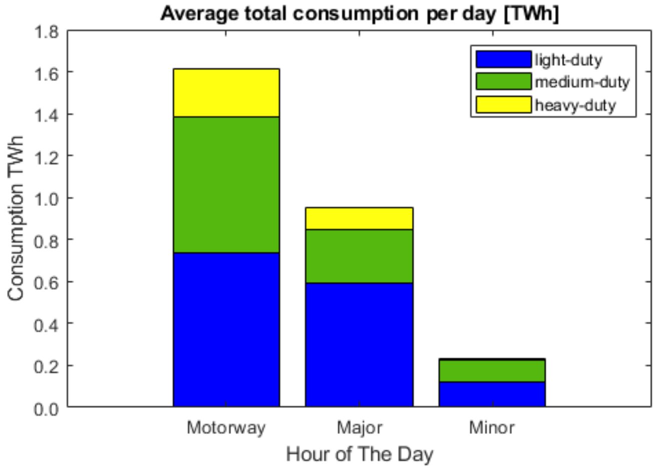

Figure 14 – Daily consumption in [TWh/day]

Figure 14 reveals that vehicles on motorways have greater consumption, even though there is more vehicle-kilometre travelled on major roads. The reason for that is the higher average velocity and acceleration. MDVs and HDVs have the most significant increase in consumption, when driving on motorway, since high velocities are paired with large vehicle masses in these cases.

After identifying electricity consumption deriving from EV traffic, electricity consumption of the other sectors together has been calculated. Demand curve computed in the model have resulted on the average daily load curve shown Figure 15.

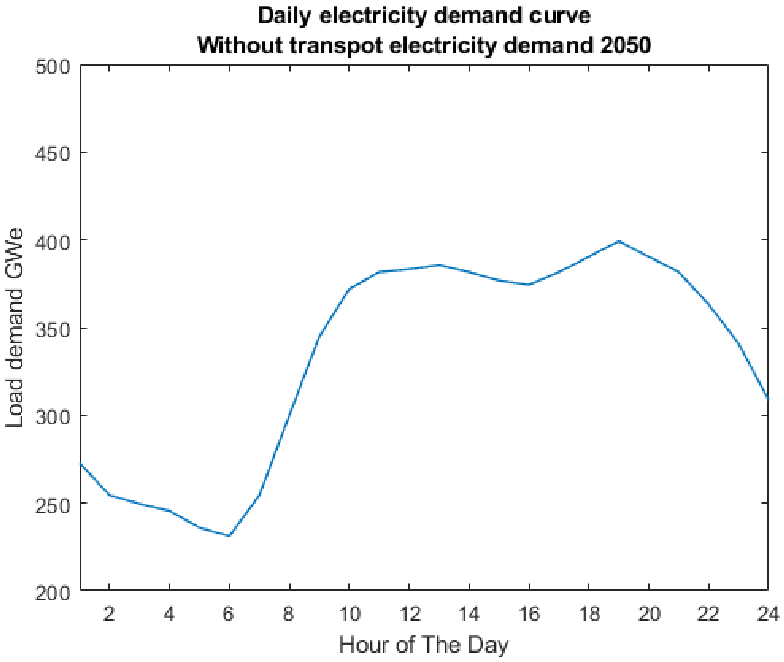

Figure 15 – Average Daily demand curve

Figure 15 reveals that demand curve without the consideration of EVs show high variation throughout the day. In order to flatten the daily demand curve, the best option would be to shift EV charging between 11pm and 6am, which is exactly what smart charging represents in the scenarios. However, in terms of intermittent renewable energy, flattening the curve is not the only factor that needs to be considered, since electricity generation is not flat in this case. Therefore, matching the demand curve to generation is crucial. For, this an average daily renewable electricity generation curve has been created for 2050, Europe.

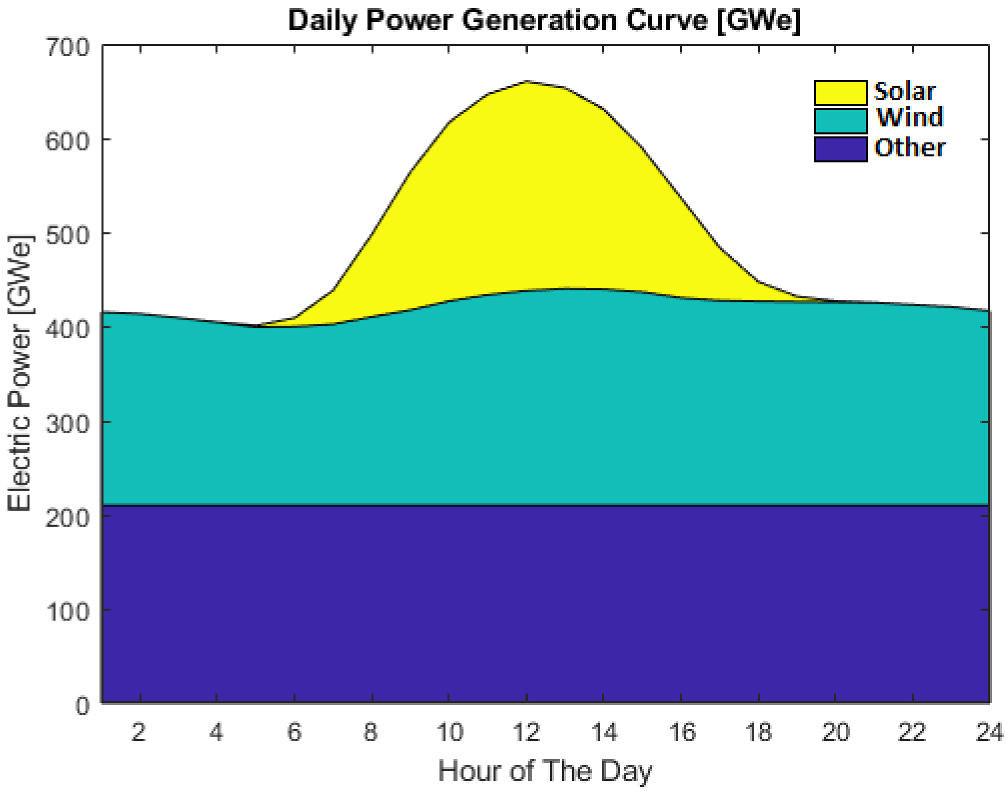

Figure 16 - Installed Power by Roadmap 2050 Scenario 4 High RES

Figure 16 shows that the irregular alternations of wind generation is significantly smoothened out through averaging. However, intermittency can only be considered to a certain level, as the model is trying to focus on average daily patterns. ‘Other’ generation includes nuclear, hydro and natural gas; and it is kept constant, representing base load.

4.2. Model Integration

Energy consumption and traffic patterns combined with the charging scenarios and added to base demand have revealed the overall hourly load demand of each scenario. This demand curve then can be compared to the generation curve.

The average daily charging patterns different scenarios and their behaviour compared to electricity supply can be seen on figure 17. Note that there is only one WDPT scenario present on the daily pattern graph, since WDPT scenarios do not influence when people charge, only where.

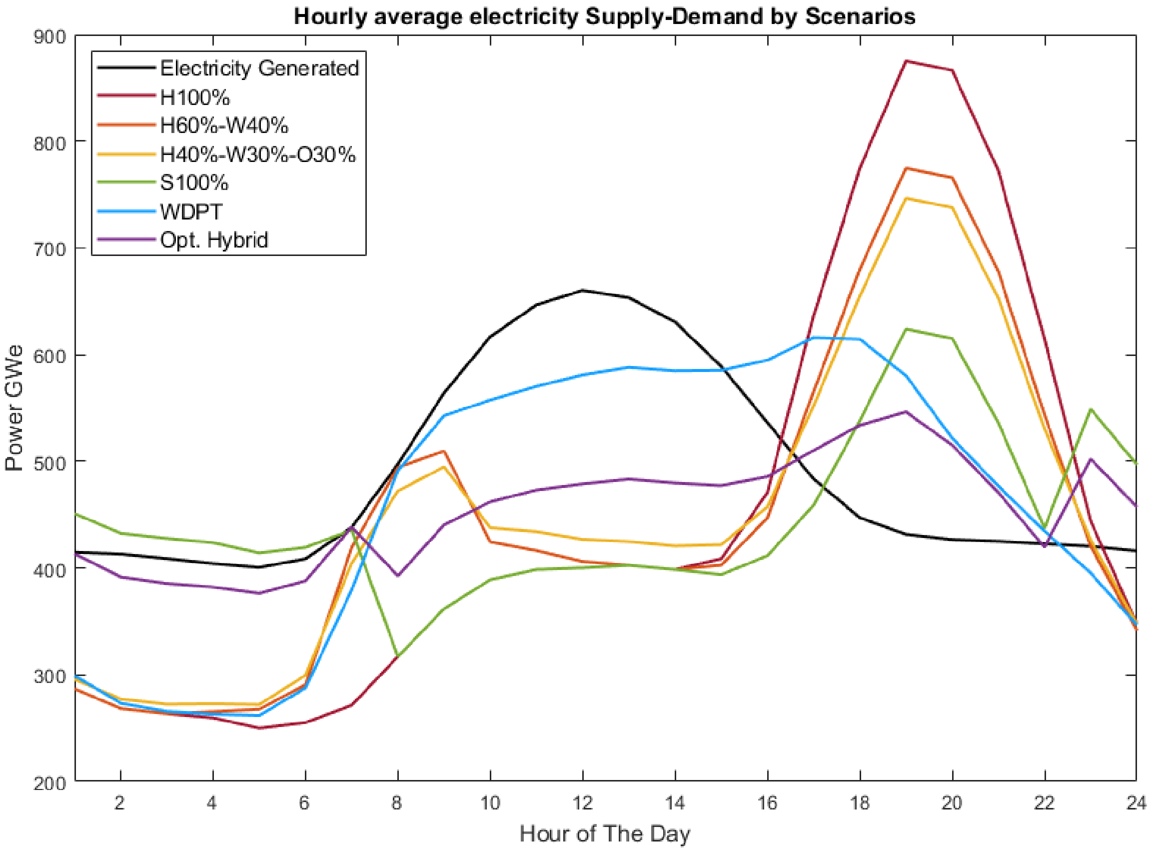

Figure 17 – Charging distribution of different scenarios throughout the day

It can be seen that 100% home charging differ the most from the supply curve, followed by the other two uncontrolled plug-in charging scenarios. It is already visible that smart charging, WDPT and Hybrid scenarios are the most comparable to the electricity load curve.

To quantify these results, the matching score has been calculated by the method described in the model description section.

The matching score of charging scenarios, where 1 is perfect match of electricity generation and consumption throughout the day and 0 is when generation is 0, representing the perfect mismatch.

EV charging could potentially improve the match of supply-demand curves. In order to study this possibility, the demand curve without EV has been computed as well, to see if any of the scenarios mean improvement compared to that. Results are present on figure 18.

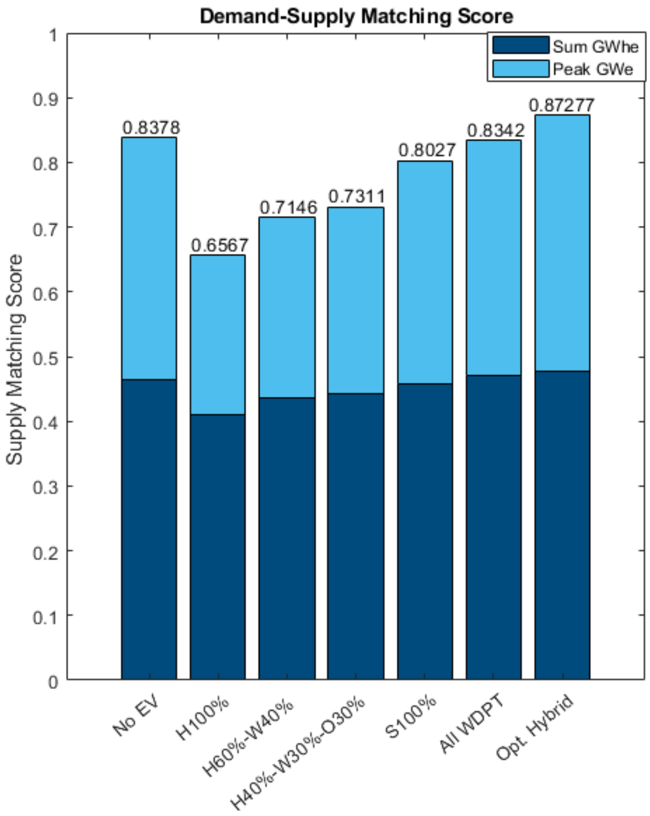

Figure 18 Supply demand Matching Score

It can be seen that only the Optimum Hybrid scenario means improvement (4%) compared to a no EV scenario with 87.3% match in supply-demand, compared to the 83.8% in the No EV scenario. The 100% Home charging scenario has received the lowest matching score with approximately 20% deficit in daily electricity and more than double of the peak compared to supply. This scenario means 22% decline compared to the no EV scenario. The last three scenarios: smart charging, WDPT charging and the hybrid are all in the +/-5% change compared to No-EV. That means none of the EV scenarios mean significant improvement, however, the last three scenarios are not damaging the grid balance considerably either.

The electricity supply side also has a large impact on the matching score; therefore, the matching score has been computed with:

a) 25% increase in solar installation (wind installation reduced accordingly to keep the same total generation)

b) 25% increase in wind installation (solar installation reduced accordingly to keep the same total generation)

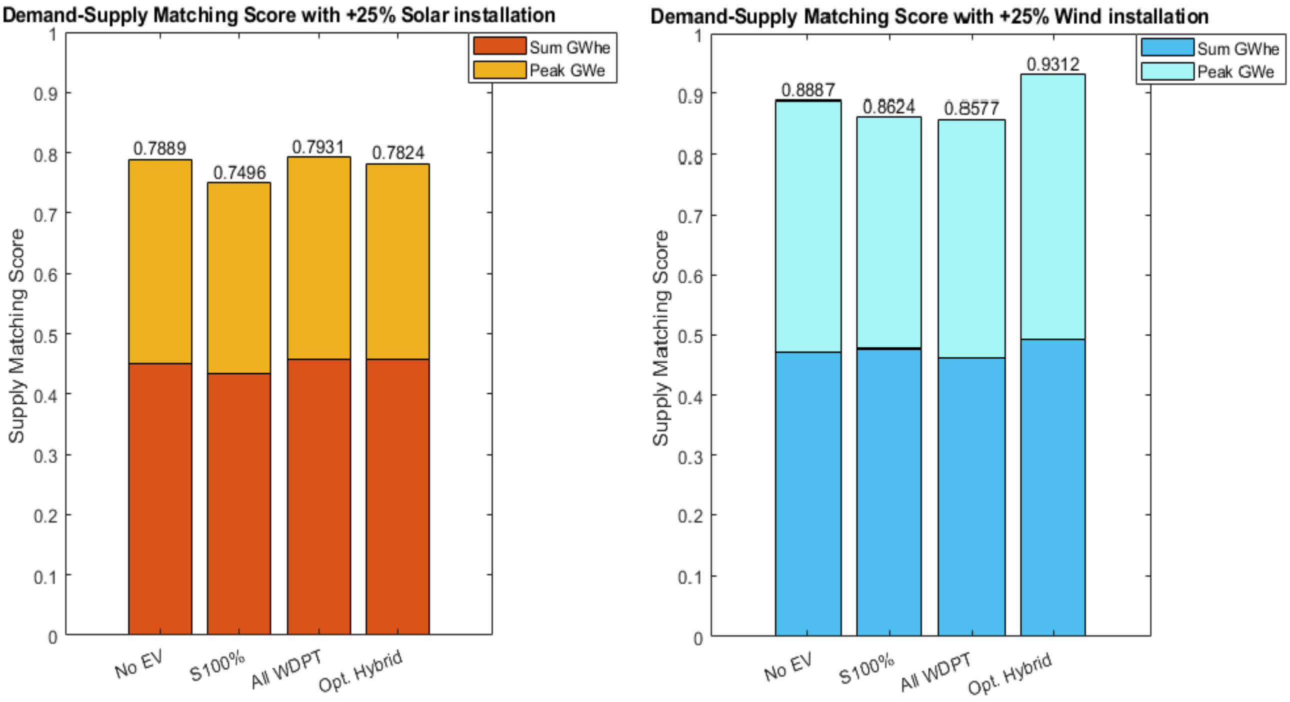

Figure 19 – solar and wind dominant electricity supply matching scores

The supply-demand matching score has been computed for the three most advantageous scenarios to find which one would fit a more solar dominant or a wind dominant electricity mix. Results on figure 19.

For a solar dominant scenario all matching scores are significantly lower as a result uneven electricity supply of solar throughout a day. However, the best match for solar dominant generation seems to be the WDPT charging scenario with 79.3. This scenario also means a match improvement of 0.5% compared to the No-EV scenario. Wind dominated generation scenario on the other hand shows significant advantages in terms of the Optimum Hybrid scenario with 93.12%

The best matches are present on Figure 20.

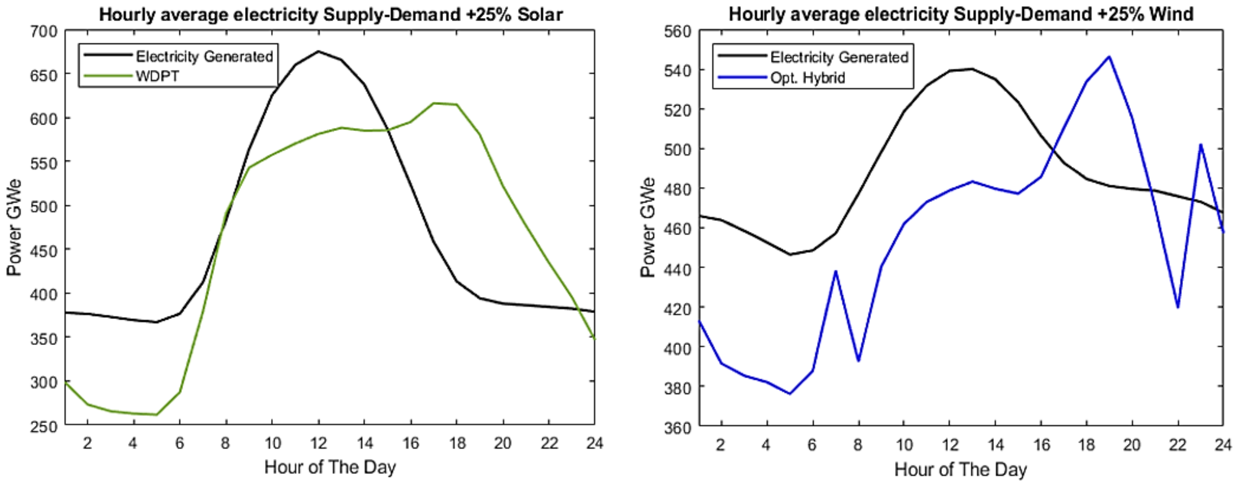

Figure 20 – Best match in Solar and Wind dominant electricity scenarios

Consequently, the best match for the base Roadmap 2050 High RES scenario was the Opt.Hybrid, in which case, only 0.48TWh electricity needs to be stored for average daily use. In terms of the solar dominant electricity supply scenario, WDPT charging proved to be the most advantageous.

After identifying the impacts on grid balance, the batteries and chargers required to facilitate the different scenarios have been calculated. Number of chargers and batteries requires will serve as the foundation for all global warming impact, storage requirements and brief cost calculations.

4.3. Equipment requirements

The minimum battery requirement of each scenario is present on Table 4, with an average maximum DoD of 50%. Note that the Medium and heavy-duty battery requirements in plug-in scenarios do not vary, as their charging behaviours are considered constant.

Table 4 – Minimum battery requirement on board in kg

		Minimum EV battery by scenarios in kg			**Number of Chargers**
	Scenarios	**LDV**	**MDV**	**HDV**	**All chargers[6]**
0	300km Range	171.26	492.15	1491.80	2.53x10^8
1	H100%	20.55	492.15	1491.80	2.53x10^8
2	H60%-W40%	12.33	492.15	1491.80	4.21x10^8
3	H40%-W30%-O30%	8.22	492.15	1491.80	4.63x10^8
4	S100%	20.55	492.15	1491.80	2.53x10^8
5	Min-WDPT	8.98	213.49	726.03	4.20x10^8
6	Mod-WDPT	2.99	81.82	132.07	7.22x10^8
7	Max-WDPT	0.00	0.00	0.00	19.01x10^8
8	Opt.Hybrid	5.96	139.17	476.76	5.23x10^8

Table 5 reveals that 300km range battery is over 8 times larger, than the minimum required for daily commute. The last column in Table 5 shows the number of chargers required per scenario. The lower the battery requirement is, the more chargers are required in most scenarios. WDPT chargers include the sum of onboard and on-road chargers together. The all-road coverage WDPT scenario does not need battery theoretically, however, it would need significantly more chargers than the other scenarios. Largest batteries are required in case of home charging and smart charging, on the other hand, charger requirements are approximately 50% less in these cases, than the other scenarios. In terms of equipment requirements, the best scenario is WDPT motorway and major coverage with the lowest battery requirements (after 0) and moderate charger requirements.

After computing the battery mass necessary onboard, the impact of the extra weight on consumption can be also identified. The increase in consumption is shown in percentage compared to the base consumption. Increase in consumption by battery mass can be seen on table 6. Note that only the mass of battery is taken into account. Other mass increasing factors such as the reinforcement of chassis or additional equipment are outside the system boundaries.

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[6] All chargers include the sum of vehicle and road coils, in terms of WDPT. For the hybrid scenario, the total of plug-in chargers, road coils and vehicle coils have been added up.

Table 5 – Change in consumption through battery weight

	Scenarios	LDV	MDV	HDV
0	300km Range	9.7%	2.5%	3.2%
1	H100%	0.5%	2.5%	3.2%
2	H60%-W40%	0.3%	2.5%	3.2%
3	H40%-W30%-O30%	0.2%	2.5%	3.2%
4	S100%	0.5%	2.5%	3.2%
5	Min-WDPT	0.2%	1.1%	1.6%
6	Mod-WDPT	0.1%	0.4%	0.3%
7	Max-WDPT	0.0%	0.0%	0.0%
8	Opt.Hybrid	0.2%	0.7%	1.0%

According to table 6, significant change in consumption has been experienced in terms of 300km Range for LDVs and all HDVs. The greatest increase was 9.7% in terms of LDV reference large range scenario. HDV and MDV vehicle require larger batteries; however, the increase in consumption also depends on the ratio between vehicle mass and battery, as well as acceleration and velocity patterns. Therefore, the lower initial mass of LDVs and the greater amplitude of acceleration and velocity patterns mean significantly higher jump in consumption. The second highest increase was 3.2% for HDVs, with plug-in charging. In this case, range is decreased by 3%.

Now that the battery requirements and the supply demand matching have both been identified, the total battery demand and storage requirement for daily deficit storage can be calculated for each scenario (see Figure 21).

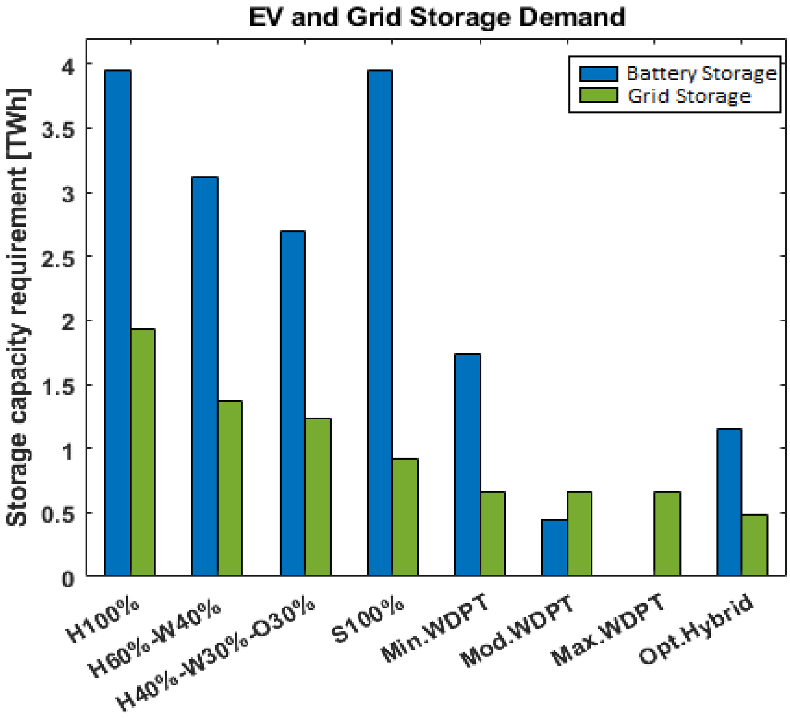


Figure 21 – Total grid and EV storage requirements

Note that the three WDPT scenarios have the same grid storage requirements, as their supply-demand matching score is identical.

Results show that total EV battery demand and grid storage are changing in a similar fashion, apart from smart plug-in charging and maximum WDPT coverage charging scenarios. For the smart charging scenario, battery requirements are the same as home charging, while the grid deficit is reduced. Also, in every case, daily deficit storage requirements are less than half of the battery demand, which indicates that EV battery demand in the future is more concerning than supply-demand storage.

In the following, different impacts of the battery and charging systems will be presented, namely global warming impact and scarce material exploitation.

4.4. Environmental Impact

As mentioned in previous chapters, battery capacity demand greatly exceeds daily grid storage demand. Batteries are challenging for their significant weight and for their large global warming impact, with high emissions involved in production. Therefore, downsizing batteries is important to improve high production emissions. However, batteries can be reduced by increasing charger availability and therefore more intensive charger production. The impact of both components must be taken into consideration, to reveal the total global warming impact of the charging system. Moreover, the scenarios with minimum battery demand taken into account can be compared to the 300km Range scenario to identify the difference between them and to see if the reference 300km Range scenario would even be feasible.

Additionally, highlighting the most significant materials of both components: lithium for batteries and copper for chargers, the total amount of raw material required to produce the European system has also been calculated.

4.4.1. Global Warming Impact

The global warming impact (GWI) measured in gCO_2eq/kWh charged includes the production of chargers and batteries and production of electricity consumed by vehicles, considering 12 years lifespan for the chargers and batteries in 2050. The entire inventory and all the assumptions with sources for the global warming impact assessment can be seen in Appendix VI. The global warming impact of different scenarios can be seen on figure 22.

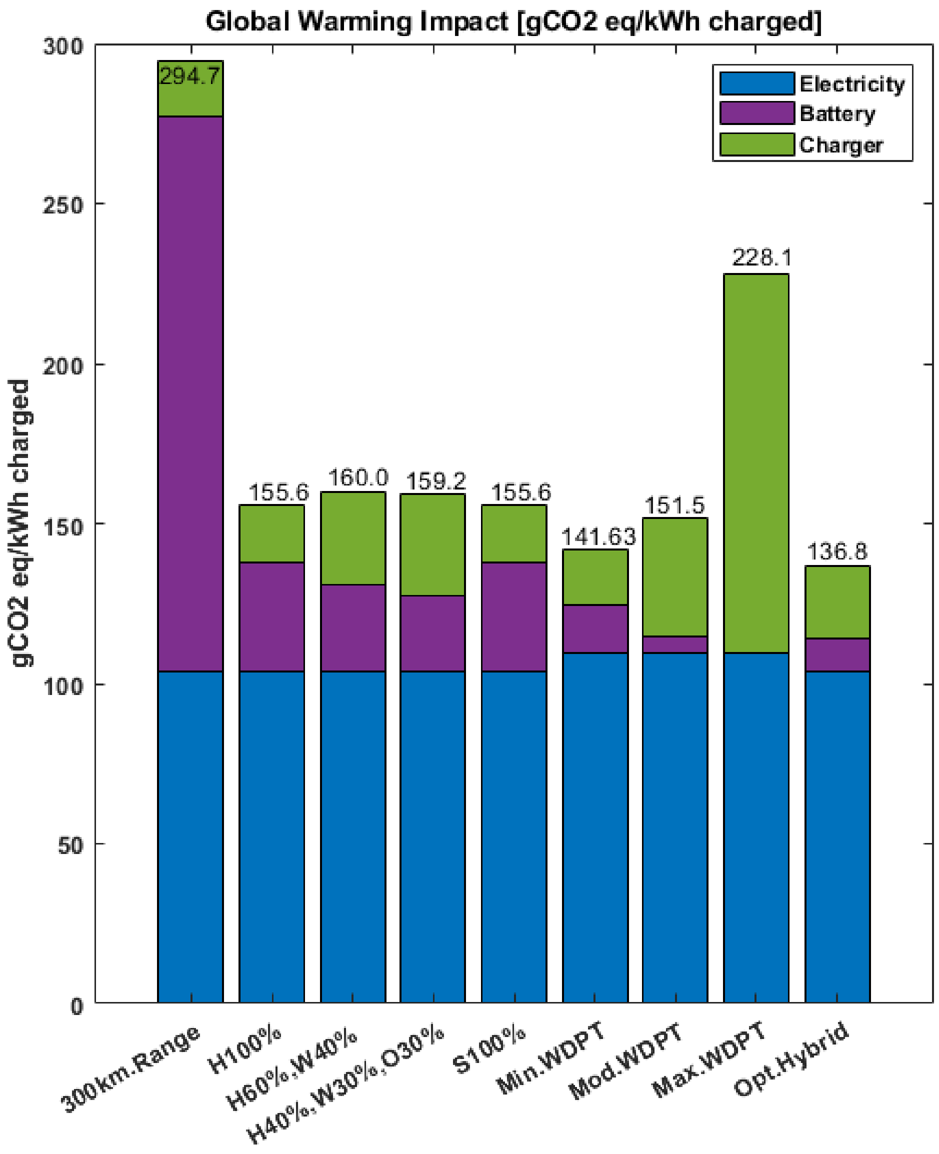


Figure 22 – Global warming impact of charging scenarios

Figure 22 reveals the substantial impact of a 'business as usual' battery capacity (for 300km range), with more than half of the GWI caused by batteries alone. Even the maximum coverage WDPT (Max.WDPT) is 22% lower, than the reference scenario. GWI revealed that batteries desired today are 4 times higher, than the necessary and the reduction of batteries to the everyday commute requirements could halve the GWI.

The global warming impact assessment has shown no significant difference in terms of plug-in charging between the scenarios, with only about 3% increase with scenarios, where charging is available other than home (work, supermarket etc.). It means that battery downsizing by more charging on road and running errands would not decrease the overall GWI, as the number of chargers required increases emissions. WDPT charging on the other hand could somewhat reduce the overall GWI. The first two scenarios of WDPT charging show 6-8% reduction in GWI, as a result of significant reduction of battery sizes in these cases. However, the maximum coverage scenario would require large number of coils installed to eliminate the need for batteries, the overall emissions would be 60% higher. The most important observation of the GWI assessment is the fact that applying more chargers to reduce battery size did not reduce the overall emissions neither with plug-in charging, nor WDPT. The only occasion where GWI could be reduced in both battery and charger emission was the optimised hybrid scenario, in which case an approximately 10% GWI improvement could be achieved.

Since increased charger availability did not show improvement in the overall emissions, the results of the lithium and copper impacts becomes highly important. If lithium savings do not prove to worth all the charging installations and copper investments in this case, it would mean that charging infrastructure is not solving any of the problems stated above.

4.4.2. Scarce Resource Impact

As mentioned earlier, one of the greatest issues considering an electric road transport future is the lithium demand. WDPT charging could decrease the need for lithium, however it raises another issue of extreme copper requirement for the induction coils. The question here is, if it is worth using large amount of coppers to decrease lithium demand. Figure 23 shows the total resource exploitation in metric tons of lithium and copper in each scenario for comparison.

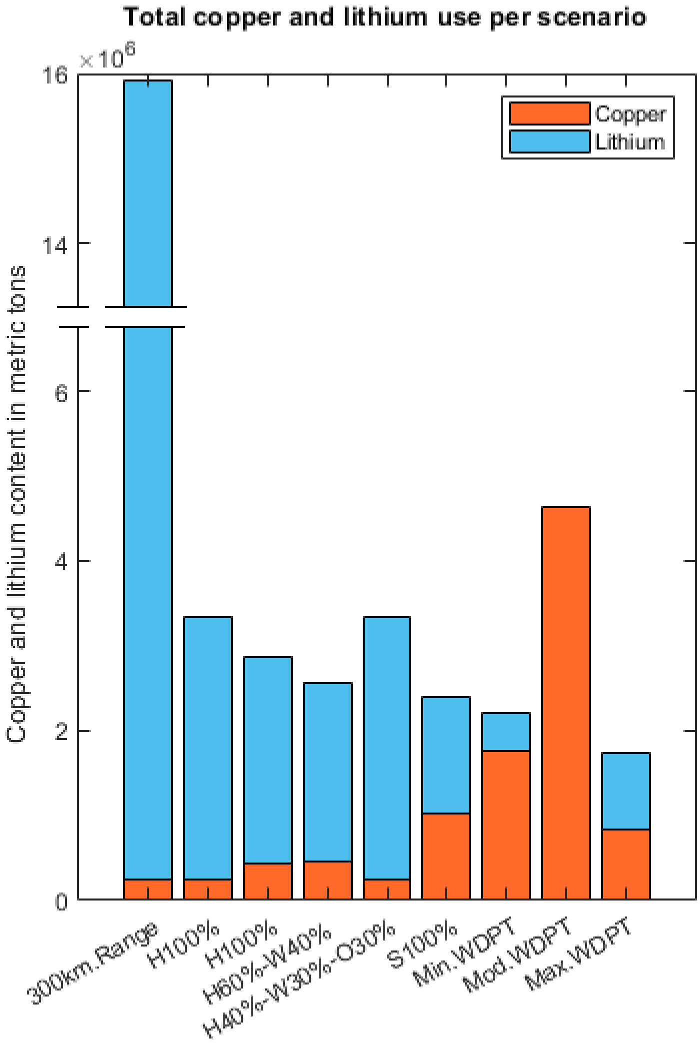


Figure 23 – Copper vs Lithium requirements by scenario (in tons)

As figure 23 shows, the reference scenario with 300km range implies excessive lithium requirements, with 6 times more lithium required, than the minimum demand for everyday commute.

Copper required by WDPT scenarios only exceeds the lithium requirements of plug-in scenarios in case of maximum WDPT coverage. The difference between minimum, moderate and maximum WDPT coverage shows the significant amount of copper required to cover major roads and minor roads. Charging coils on major and minor roads would require 5 times more copper, than for motorways. Therefore, optimum scenario, where only motorways are equipped with charging capabilities can save substantial amount of copper. Lithium exploitation can be reduced by 80-87% by replacing Plug-in charging with WDPT (Max.WDPT excluded). Minimum and moderate coverage WDPT charging could somewhat decrease overall scarce material demand; optimum scenario could halve the overall scarce material exploitation, compared to home plug-in charging scenarios.

To put these amounts in context, they were compared to the overall global reserves available. (copper: 830 million metric tons (CopperAlliance, 2018), lithium: 14 million metric tons (Narins, 2017)) can be seen on Table 7.

Table 6 – Percentage of raw material requirements compared to global reserves

Scenarios	**Description**	**Lithium**	**Copper**
0	300km Range	112.86%	0.03%
1	H100%	22.03%	0.03%
2	H60%-W40%	17.35%	0.05%
3	H40%-W30%-O30%	15.00%	0.06%
4	S100%	22.03%	0.03%
5	Min-WDPT	9.74%	0.12%
6	Mod-WDPT	3.20%	0.21%
7	Max-WDPT	0.00%	0.56%
8	Opt.Hybrid	6.42%	0.10%

Table 7 reveals that batteries fulfilling 300km range would require almost 13% more lithium, than available. This makes 100% EV share with batteries of today unfeasible, according to these results. This means that battery reduction is inevitable for EV deployment.

Plug-in scenarios would require 15%-22% of the global reserves, which could also be considered unfeasible. Nonetheless, there is no recycling of lithium considered. In terms of copper requirements, WDPT scenarios would exploit about 0.12%-0.56% of the reserves. Furthermore, copper recycling is highly efficient in Europe. According to the European Copper Institute, the recycled copper used in industry has exceeded 50% in 2014 (ECA, 2015). However, recycling has not been considered in this assessment.

4.5. Multi-criteria Analysis

For multicriteria analysis, the results of model and some additional impact categories have been assessed to produce a final, conclusive result. For multicriteria analysis, only one scenario from plug-in, one from WDPT and the hybrid scenario have been considered. From WDPT and Plug-in the best performing scenarios throughout the different assessments have been picked, namely the smart plug-in and the moderate WDPT scenarios. Additional impact categories are cost and difficulty of implementation, infrastructural complexity, social acceptance and adaptability. The scores allocated are +1, 0 and -1 given to best, medium and worst scenario respectively. The last 4 additional impact categories are qualitative, rather than quantitative measures, simply by ranking the scenarios. For cost, a simplified calculation has been carried out, placing an approximate price tag on the scenarios. Weighting has been allocated according to the magnitude of their impact or influence on a future charging scenario. Impact factors are further explained below.

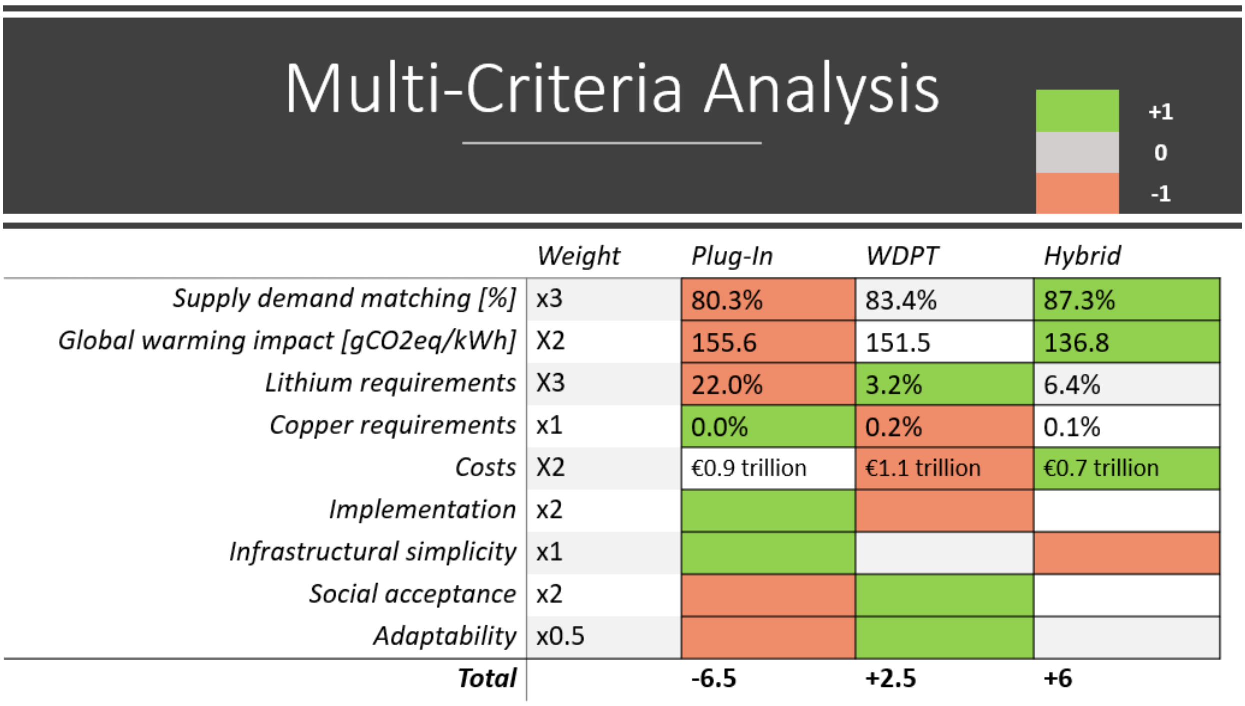
Behind the score allocations:

- **Supply demand improvements:** The score has been determined by the improvements in grid balance, compared to the no EV scenario. In other words, the score is measuring if the presence of EVs in the electricity system improves or damages the grid balance. The high weight of this category (3) is the result of the high impact of electricity shortage in the system, resulting need of energy storage and complex grid control and management systems.
- **Global warming impact:** The scores are measured by the improvement compared to a No-EV, fossil-fuel dominated road transport scenario. In this study, comprehensive global warming impact of combustion engine fuel supply has not been carried out. However, just to compare, only the exhaust CO_2 emission of combustion engine vehicles would be about 180-200gCO_2/km (LDV, MDV and HDV weighted average)(E&T, 2018) and this emission does not include mining and production of the fuel or the production of the fuel stations. Only this emission is 25% higher, than the entire charging system. The high weight (3) of GWI has been determined in light of this great reduction compared to combustion engine emissions, and the fact that reducing global warming impact is one of the most important priorities in Europe in the upcoming decades.
- **Lithium and copper requirements:** These scores have simply been identified from Figure 23 and Table 7. Copper has lower weight as it has less significant impact on reserve exploitation.
- **Cost:** Preliminary cost estimations have been carried out using values from Bi et al., 2019 for charger and battery prices. Their study assumes approximately 580,000 EUR/km for WDPT charger installation and approximately 200 EUR/kWh for lithium-ion batteries. Price for WDPT was initially 2.5 times higher in the study, however they assume reductions by 2025, as a result of learning curve and mass production. The price for plug-in charger installation has been identified by Nicholas, (2019) they assume approximately 1000 EUR/charger installed. This price is an average between different public and private chargers. Using these rough prices, an approximation of costs has been carried out. The smart plug-in charging scenario would cost approximately €910 billion, only 25% of which is the charger installation cost and 75% is the battery cost. For WDPT charging system the cost is approximately €1.12 trillion, where the charging system accounts for 80% and the batteries only 20%. Despite the fact that the hybrid scenario requires WDPT and plug-in chargers as well, this scenario has the lowest costs involved with €700 billion. Chargers are responsible for 40% of the price and batteries for the other 60%. The weight of this impact category is kept slightly lower (2), than supply-demand and GWI, since changing transport infrastructure generally involves significant costs. For comparison, the construction of new motorways can reach 11 million EUR/km in Europe (EC, 2013).
- **Implementation:** This impact category is measured by complexity of installation and integration to the road transport system. Installing home plug-in chargers is highly convenient, EV owners around the world already. Also, these plug-in chargers can be introduced gradually and proportionally with the increase of EVs. In terms of WDPT, the system is only effective when significant road coverage is achieved. Therefore, gradual integration can be highly problematic in the next decades. Moreover, installation of road coils interferes with road traffic. The weight is the same as cost (2) as environmental impact and energy system impact must be prioritised, over the convenience of implementation.
- **Infrastructural simplicity:** this impact category has been introduced, since infrastructure plays significant role in road transport and it has not been included extensively in costs. Infrastructural complexity is determined by the complexity of the payment, maintenance and general control and management during operation. Plug-in charging is highly advantageous in this case, since EV charging electricity bills can be integrated into the monthly electricity bill. On the other hand, WDPT charging requires the development of a complex payment system.

The weight is lower (1), since the complexity of infrastructure does not damage the environment or energy systems.

- **Social acceptance:** this impact factor has been determined by convenience and familiarity. Smart plug-in charging is restricting consumers, since charging takes 5-10 hours and they can only charge at home (or at a few public charging points), hence the lack of convenience. WDPT is highly convenient, since everything is automatic and, on the road, EV owners do not have to stop. However, WDPT is a highly innovative technology and alien to consumers, it would take time to reach acceptance. (Park et al., 2018) Social acceptance is just as important as costs or implementation, therefore the allocated weight is 2.
- **Adaptability:** the road transport sector is experiencing paradigm shift technologically and infrastructurally speaking as well. This impact category is determined by the level of how accommodating these systems are to possible technological changes in the next decades. The most significant changes expected are autonomous vehicles and vehicle sharing. In terms of autonomous vehicles, WDPT is highly accommodating since charging is automatic without the need of plug-in. Also, with autonomous vehicles, the driver does not get tired as fast, therefore less stops are required, which means less opportunities for stationary recharging. Similarly, with car sharing, vehicles can be expected to constantly be available and on the move. Therefore, stationary charging would be disadvantageous for shared vehicles. (Krueger et al., 2016) The low weight (0.5) is allocated, as this impact category more of a bonus, the least accommodating scenario (plug-in) does not cause any damage on the energy systems nor the environment.

Table 7 – Multicriteria Analysis



Multi-Criteria Analysis

🟩 +1
⬜ 0
🟥 -1

	Weight	Plug-In	WDPT	Hybrid
Supply demand matching [%]	x3	🟥 80.3%	⬜ 83.4%	🟩 87.3%
Global warming impact [gCO2eq/kWh]	X2	🟥 155.6	⬜ 151.5	🟩 136.8
Lithium requirements	X3	🟥 22.0%	🟩 3.2%	⬜ 6.4%
Copper requirements	x1	🟩 0.0%	🟥 0.2%	⬜ 0.1%
Costs	X2	⬜ €0.9 trillion	🟥 €1.1 trillion	🟩 €0.7 trillion
Implementation	x2	🟩	🟥	⬜
Infrastructural simplicity	x1	🟩	⬜	🟥
Social acceptance	x2	🟥	🟩	⬜
Adaptability	x0.5	🟥	🟩	⬜
Total		**-6.5**	**+2.5**	**+6**

The multicriteria analysis in Table 8 shows that with all the impact categories weighted, plug-in charging is the least advantageous, and the hybrid scenario remains the most advantageous, even after new factors introduced. The highest scores of the chosen plug-in scenario are in implementation and infrastructural simplicity, however it could not overpower the low scores of lithium requirements and global warming impact. WDPT with a mediocre +2.5 score proved to be highly advantageous in global warming impact, adaptability and lithium requirements, however the points have been reduced by the high costs involved and implementation issues. The hybrid scenario has been identified through model optimization; therefore, it is not surprising that it has the highest scores in the first categories. Additional categories also showed promising results for the optimised hybrid scenario, most noticeably the lowest cost. Even though charger costs are higher, than in the plug-in scenario, the reduced battery size drives down the total costs, since battery was responsible for 75% of the costs in the plug-in charging scenario. The only negative score for hybrid scenario has been found under infrastructural complexity, as this scenario, with two different charging methods combined would be the most complex system.

5. SENSITIVITY ANALYSIS

Sensitivity analysis have been carried out to identify the input variables with the greatest impact on the model. These input variables then can be labelled as the number one priority to reduce/increase for improvements in the future.

This sensitivity analysis is measuring changes in supply-demand matching score and global warming impact. In terms of equipment requirements (battery size and number of chargers); since global warming impact directly depends on these variables, similar results can be expected in terms of sensitivity. Therefore, the results of global warming impact can be backtracked to either battery size, charger requirements or electricity requirements. Similarly, with copper and lithium requirements, they are all embedded in a global warming impact sensitivity.

Sensitivity analysis have been carried out testing the impact of changing input variables by +/-10% individually. The sensitivity analysis of supply-demand score can be seen on figure 24.

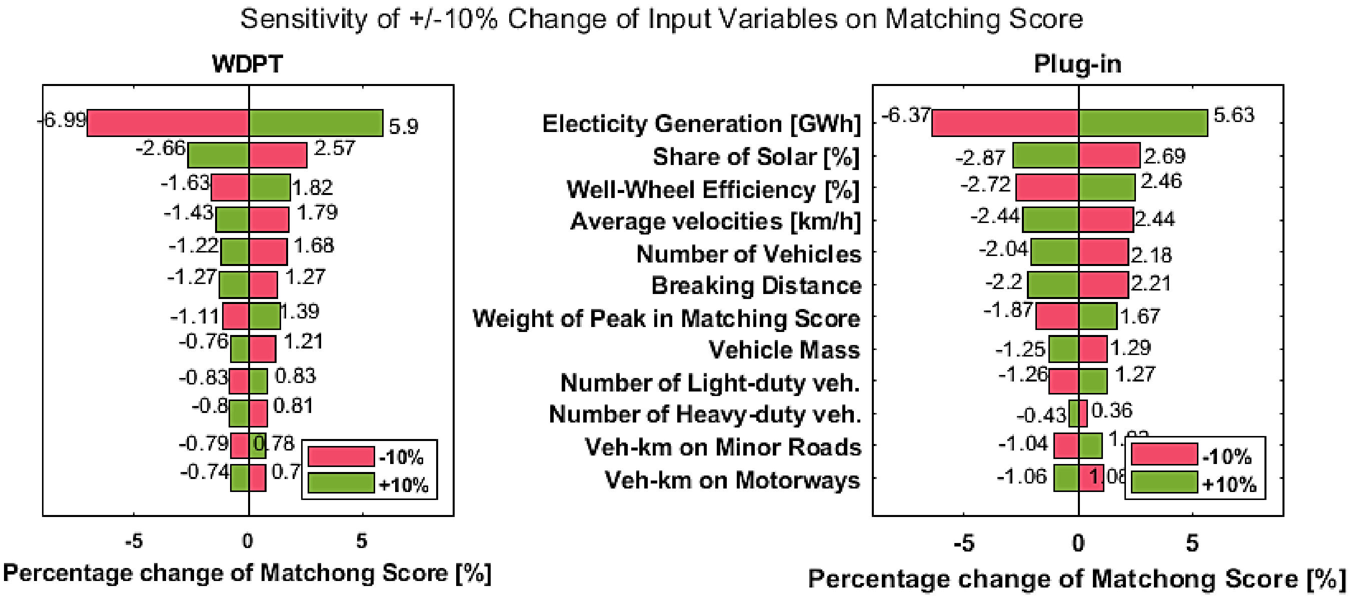


Figure 24 – Sensitivity analysis of supply-demand matching score

Change in electricity generation has significantly higher impact on the final supply-demand score, than any other input variable. Moreover, increasing the electricity generation by approximately 40% would result in a matched system, without any deficit. However, in this case, 40% more energy would be generated, than required on an average day, which can be inefficient. Figure 24 clearly shows that, high share of solar energy generation is disadvantageous in terms of integrating EVs to the system. It means that countries with high solar energy share will have to face significant mismatch between supply and demand, if EV integration is also considered. Figure also shows that efficiency increase throughout the value chain can improve the grid balance significantly. Efficiency improvements show higher impact on plug-in charging than on WDPT. Most of the variables on the second half of the graph show similar tendency. This is a result of greater mismatch caused by plug-in than WDPT on the basic demand curve. Therefore, changes made on it will also result in greater impact. Decreasing the average velocity can also significantly improve the matching score. Besides the lower consumption with lower velocity, for WDPT it also means longer time spent on the road, which means longer charging time. The supply-demand matching score is taking 50% of the total energy mismatch and 50% of the peak of the mismatch. Increasing the weight of the peak by 10% (and decreasing total energy accordingly) would be beneficial to both WDPT and plug-in. This is the result of the total energy deficit is more radical in both cases. In terms of changing the ratios of different vehicle types, only the increase of HDVs shows improvement on both systems. HDVs (trucks, lorries and buses) have evenly distributed plug-in and WDPT charging patterns as well. Therefore, the increase of their presence in road-transport could help grid-balance.

A sensitivity analysis has been carried out to compute the percentage change in global warming impact (CO_2eq per kWh charged) as well. The results are present on Figure 25.

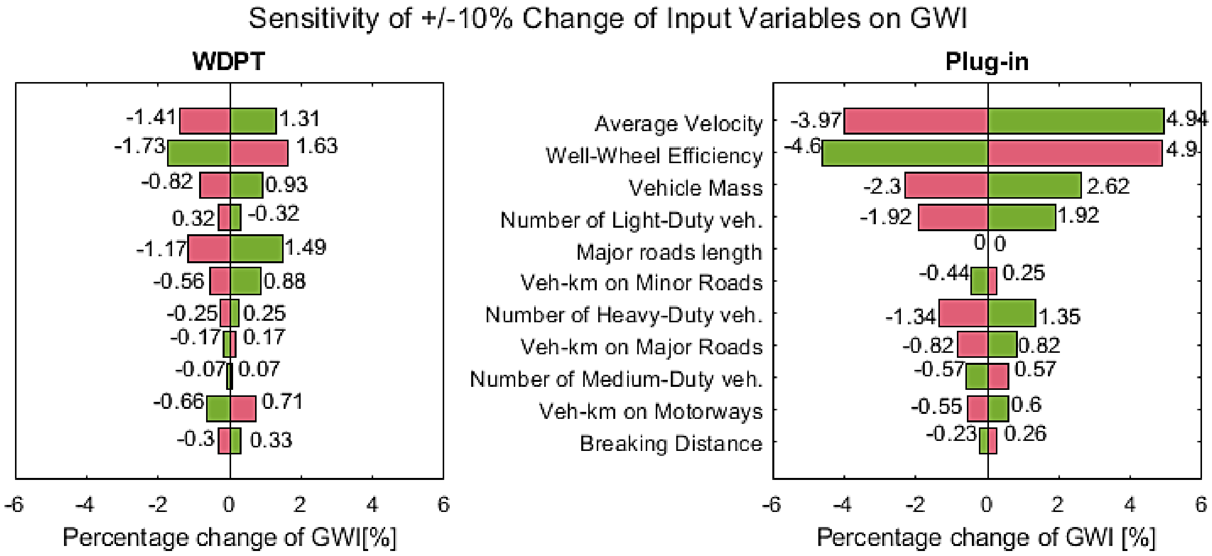


Figure 25 – Sensitivity analysis of global warming impact

The analysis on global warming impact revealed higher sensitivity of plug-in charging (almost 2.5 times higher in most cases), than WDPT. This is the result of predominantly larger battery requirements in cases of plug-in scenarios, than in WDPT scenarios (approximately 2-3 times higher). The lithium-ion batteries are the most GHG intensive per vehicle, therefore, changes in consumption will make the greatest change in the global warming impact of the battery. Changes in consumption (deriving from change in average velocity, efficiency, vehicle mass etc.) are also directly related to electricity global warming impact. With decreasing consumption, global warming impact will also decrease. On the other hand, global warming impact deriving from charger production shows inverse relationship with consumption. If consumption decreases, charger global warming impact per kWh charged will increase, since the chargers will serve less kWh in their 12 years lifetime. Increase in road length, either motorway, major or minor road length; will only impact WDPT global warming impact, since more roads would need to be covered to ensure the desired coverage. Therefore, significant road extensions in the future, could increase the emissions deriving from WDPT, while plug-in emissions would remain the same.

Generally, plug-in charging proved to be more vulnerable to system changes, than WDPT, with greater changes in the results. The reason for that is the larger batteries on board, that are highly impacted by changing consumption. Also, in case of WDPT EV consumption occurs the same time as charging; therefore variables that change consumption, most likely to impact charging on the other hand as well.

100% EV share has also been important for WDPT charging scenarios, since that is when they reach their full potential. In case of lower shares of EVs on road, plug-in charging can become gradually more and more advantageous in terms of emissions per kWh charged. With plug-in charging scenarios, power generation and charger equipment installed are linked to the number of EVs in the model and adjusting accordingly. On the other hand, lower share of EVs in WDPT charging would not decrease the global warming impact with the same gradient, since road coverage by coils would still have to be guaranteed, even if the number of EVs decreases. Figure 26. shows how different shares of EVs impact emissions from WDPT and from Plug-in charging.

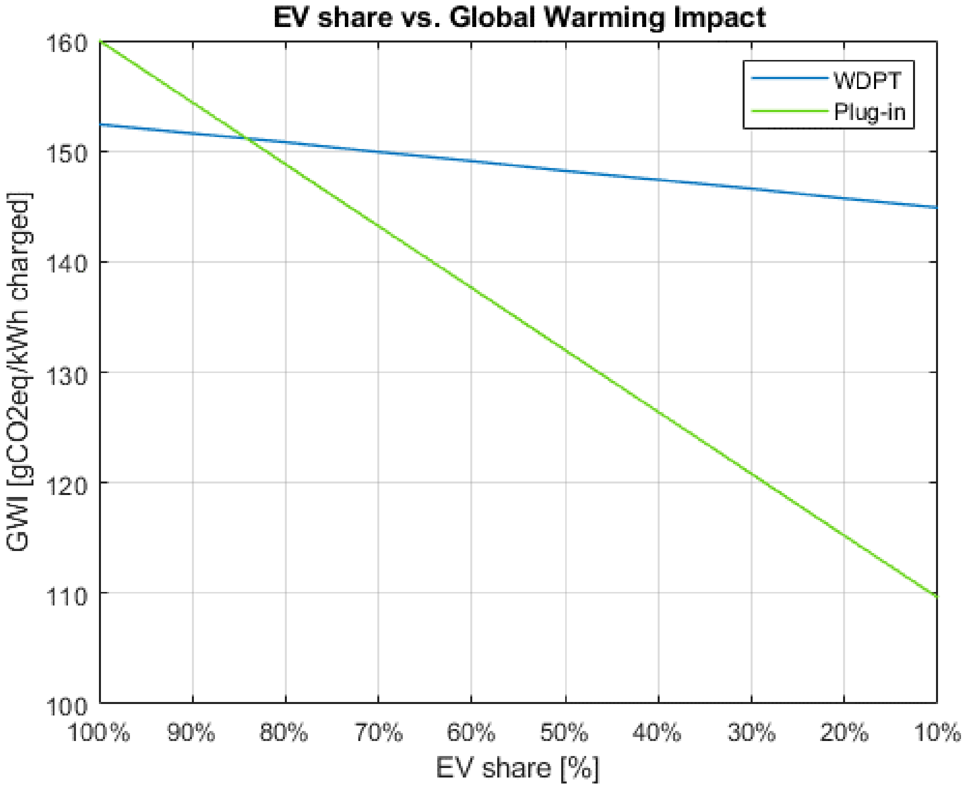


Figure 26 - Impact of the share of EVs on GWI

Figure 26 shows that the point of intersection is at 84%. This means that EV shares under 84% would have lower global warming impact using plug-in charging. More vehicles are using the same charging coils, the more its environmental impact will improve. Therefore, 100% EVs assumed on road is beneficial for the WDPT charging scenarios and shows their full potential.

6. DISCUSSION

In this chapter, the most important factors of this research will be discussed, by exploring the accountability of assumptions, characteristics of the model, validity of input data and interpretation of results. Throughout this exploration, the reliability and significance of the research will be evaluated.

6.1. Limitations

In order to ensure an accurate interpretation of the results, the limitations of the methodology, data and model need to be emphasised.

Firstly, all the scenarios have been built to model 2050, 30 years from now. The assumptions made in technological improvements, demand curve and traffic patterns can significantly vary in the future, as these all depend on multiple factors. For example, if working hours, or shop opening times will change in the future, that could significantly impact traffic patterns and therefore grid balance. However, predicting these changes can be highly difficult. Also, the model is calculating with yearly hourly patterns averaged in 24 hours days. This method has been used for solar generation, wind generation, traffic patterns and distances travelled. For solar generation, and distance travelled, the differences are significant and for hourly wind energy generation there is negligible correlation, considering hours of the day patterns. The variation of wind and solar power generation over 3 years (2013-2016), compared to the baseline (mean) can be seen on figure 27 (APARICIO, 2016).

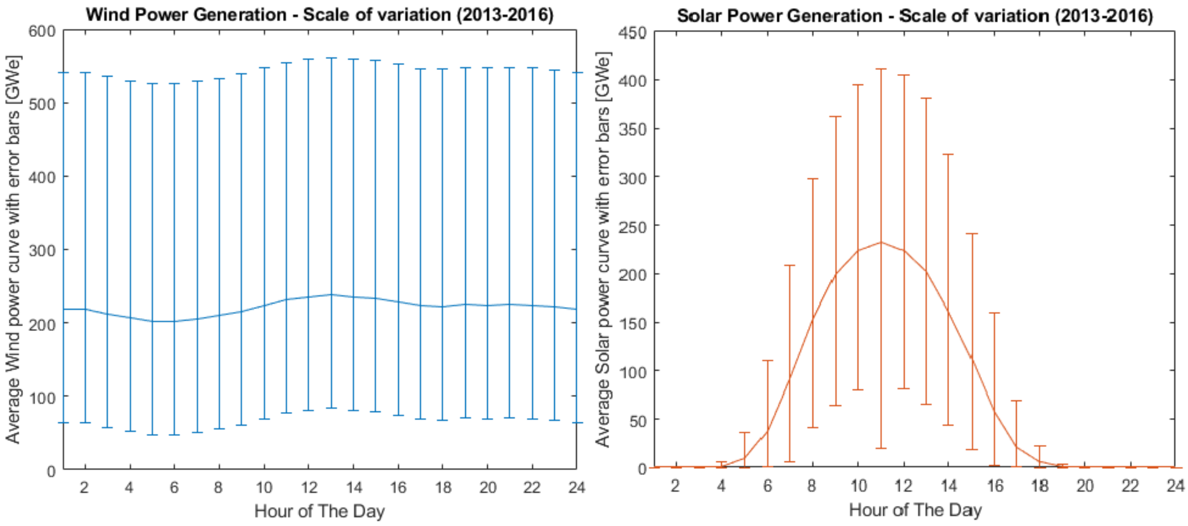


Figure 27 – Variation of wind and solar generation compared to mean

Distance travelled per day can be considered a positively skewed normal distribution, since large scale and long period of time are being considered. Light duty vehicle daily distance can vary from 0 up to about 1000km with 36km mean. This means that 68.2% of vehicles drives 24km-350km a day. Sensitivity analysis revealed that change in vehicle-kilometre has a significant impact on results, therefore, it must be established that the model only considerers an average weekday and average weekend.

One of the greatest assumptions that has been made in this study is about the integrated European system. This research considers Europe as one large electricity system/grid, where electricity produced at any point can be used at any other point almost instantly. In reality, that will most likely will be true, only to a certain level. However, countries will mostly rely on their own electricity systems, which can significantly vary, depending on the available resources and political background. The study, however, offers a solar energy dominated (southern countries) and a wind energy dominated (northern countries) scenario to discover the possible different electricity generation.

In terms of the scenario formation, there is a lack of variety of medium and HDVs plug-in charging. The reason for that is the lack of available information on electric lorries or vans. Also, the purpose of commercial vehicles is highly diverse, therefore it is highly unlikely to successful allocate charging patterns for them.

It is highly important to emphasize that the battery requirements identified are a minimum battery requirement. In reality, EV owners can possibly aim for larger batteries for safety, which would completely change the results, especially in terms of environmental impact. As Dr Hans Bludszuweit expressed his opinion in an interview (2019), WDPT will not reduce battery size on-board as much as scientists expect, as a result of remaining range anxiety. Nevertheless, if lithium prices significantly increase as a result of scarcity, battery sizes onboard will have to be minimized (Miedema & Moll, 2013).

6.2. Assumptions

As discussed in the limitations chapter, the assumptions made for this model have considerable impacts on the results. Therefore, their significance must be emphasized. Choosing Europe as a whole for this assessment, as oppose to countries or regions segmented was important in this model. The reason for that is the law of large numbers. In order to assume average driving and charging behaviours, the largest possible socio-economic whole must be taken into account. Europe, especially the EU and EEA countries have high correlation in many socioeconomic factors, that this research requires: working/office hours, distances travelled or peak hours (Jovanovic et al., 2009; Pasaoglu et al., 2012). Study by Babrowski et al., 2014 also indicates highly similar EV charging patterns by different European countries (Figure 28.).

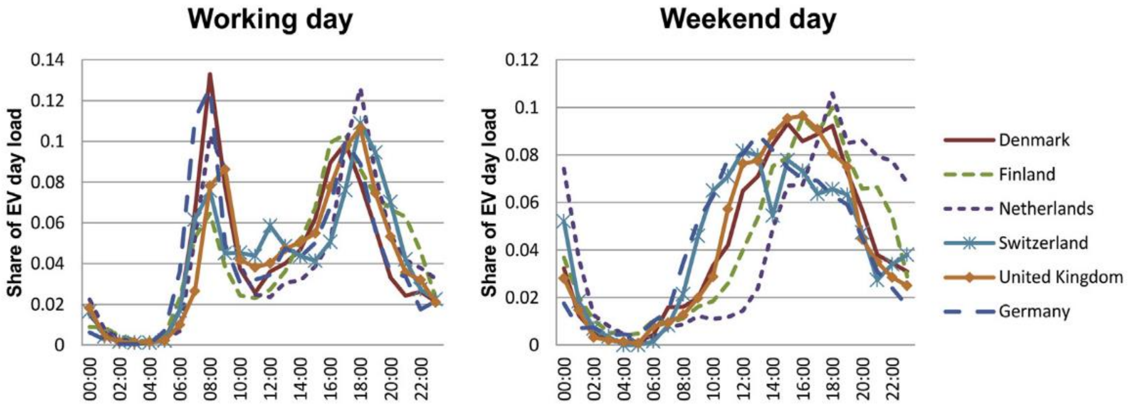


Fig. 3. Country-specific charging load curves on a working day (left) and on a weekend day (right).

Figure 28 – European charging patterns by 6 different countries (Babrowski et al., 2014)

As a result, considering Europe as a whole in terms of driving and charging behaviours has several advantages carried in big numbers. Furthermore, the road transport sector in general would be challenging to isolate into smaller segments in Europe (countries or regions), since the high rates of interflow. Driving within Europe between counties is especially common by medium, and heavy-duty transport. Additionally, crossing borders is increasingly common in daily commute of passenger vehicles as well. Major examples are France to Germany, France to Switzerland, Germany to Denmark or Hungary to Austria. (Decoville et al., 2013)

For electricity generation however, assuming a ‘borderless’ Europe was potentially overly optimistic. Although there is an ongoing development of a highly interconnected grid and trade network in Europe, to achieve 100% renewable generation by 2050 (EC, 2014); with several billions of Euros invested in the high voltage network connecting countries to reduce the need of storage and improve grid efficiency (EP, 2019). Electricity market and regulation however, will most likely remain autonomous and diverse by countries (EC, 2017). As a result, electricity supply curve can result in highly different supply-demand matching scores from country to country. Nevertheless, this study has offered a predominantly solar and a predominantly wind powered alternative to the Roadmap 2050 High-RES scenario to demonstrate the impact of different generation patterns. The results reassuringly showed that the recommended hybrid and moderate WDPT scenarios would still be the most advantageous for grid balance.

Further assumptions have been made in terms of the technological setting, that can be expected in the automotive industry over the next decades (Sarlioglu et al., 2017). Most importantly, the assumption that, similar lithium-ion batteries will be used in the future to the ones that the automotive industry is using today. Even though improvements are being considered in efficiency, depth of discharge and energy density, the possibility that the entire battery system on board could be different, cannot be overlooked. According to Corsatea et al., 2016 private investments into energy storage research and development has been around €50-€100 million per year in the last decade. With these high investment rates, significant developments and innovations can be expected in the field of energy storage. There are already other competitive battery technologies that could potentially overtake the market, such as supercapacitors, MH-air and Li-air batteries, all with higher specific power or specific energy, than Li-ion batteries (Young et al., 2013).

However, the lithium-ion battery market has already experienced rapid growth and the largest battery factories, including LG, Panasonic, Tesla, CATL and BYD account for a total battery production capacity of 179 GWh/year in 2018 and it can be expected to reach almost a 1TWh by 2028 (Benchmark Mineral Intelligence, 2019). These production capacities could satisfy the battery requirements of any charging scenarios in this study over a few years. Therefore, high level of exploitation of lithium for the battery market can be expected, regardless of future inventions.

For environmental impact calculations, the minimum battery size required of everyday commute has been considered. This resulted in significantly smaller battery size, compared to the ones used today. Batteries used today by the most popular EV models have 4-8 times larger batteries, that the minimum requirement taken into account in the model. As a result, environmental impact by batteries are significantly smaller, than in the reference, 300km range scenario. This may seem like a bold assumption; however, it was essential to model the true battery downsizing potential of the charging methods, and the scenarios within. In case of fixed larger batteries considered for scenarios, battery downsizing could not have been calculated. Minimum battery requirements, to get around with average, everyday driving habits can reveal the true battery requirements, as oppose to trends of consumer demands observed presently. Nonetheless, a scenario has been design to represent a ‘business as usual’ case, where consumer demands for large range do not change in the future.

An additional assumption that needs to be discussed is the 100% electric vehicle presence on the roads. The Energy Roadmap 2050 Europe report only assumes 80% of light and medium duty vehicles to be electric and that is already considered highly optimistic (EC, 2011). Therefore, assuming all road vehicles to be electric by 2050 can be a debatable decision. However, the assumption was useful to reveal the potential strengths and weaknesses of a fully electrified road transport setup, including HDVs as well. HDVs face the greatest challenges, in terms of vehicle electrification. An average truck with plug-in charging would require approximately 1.5 tons of battery mass on-board, which would increase the consumption by 5% (Carlson et al., 2013). The extreme battery requirements would also result in significant environmental impact and lithium exploitation with 2.7% of the global reserves used only for European heavy-duty transport. Also, a 750 kWh battery required by an average truck would cost nearly €150,000, which is approximately the price of the entire truck (Meszler et al., 2018).

These figures reflect a few of the many challenges that electric heavy-duty transport needs to face. In the moderate WDPT scenario however, battery requirements on trucks can be reduced by 91%, which would also reduce the cost of battery to about €15,000. These results of the study revealed potentially the greatest advantage of WDPT charging. This could only be estimated by assuming all HDVs to be electric, as oppose to keeping the model to a more feasible and realistic reference scenario. Consequently, 100% EV share has been important for WDPT charging scenarios, since that is when they reach their full potential. In case of lower shares of EVs on road, plug-in charging can become gradually more and more advantageous in terms of emissions per kWh charged and financially as well. With plug-in charging scenarios, power generation and charger equipment installed are linked to the number of EVs in the model and adjusting accordingly. On the other hand, lower share of EVs in WDPT charging would not decrease the global warming impact with the same gradient, since road coverage by coils would still have to be guaranteed, even if the number of EVs decreases. Sensitivity analysis revealed that EV shares under 84% would make Plug-in charging more advantageous in terms of global warming impact.

6.3. Model

The integrated MATLAB model had a central role in this research. The structure and design of the model describes the results and their legitimacy. The model has been designed to be multipurpose, flexible and adaptable. The individual modules of the model compute intermediate results for this study however, they can be taken out from the model to serve other purposes. For instance, the EV consumption model is only the first module in this model, nevertheless, by creating more elaborate consumption scenarios, the consumption model can serve greater purposes. This statement can be adapted to every part of the model. As a result, the model can be repurposed with different input data applied and it is also easily scalable. With customized input data (traffic, road network and power supply-demand parameters), the model can produce tailored results for the specific city, country, continent or even globally. Moreover, all of the individual modules can be changed separately to run different scenario simulations. However, to complete this research, most modules have been kept constant. The main reason for that is to retain the scope, which is concentrated around charging behaviours. Using multiple scenarios at every submodule would have resulted in countless combinations that could have potentially made the research chaotic with numerous detours from the original scope. Therefore, keeping the modules constant apart from the charging patterns is defensible, however, it still carries risks towards the creditability of the results. There are certain parts of the constant modules of the model that impact plug-in and WDPT charging differently. A great example is the abovementioned number of EVs or share of EVs on road. Decreasing the number of vehicles on road would put plug-in charging in a more favourable position in terms of global warming impact and costs. Considering traffic modelling, there are other factors that can potentially cause biased results, as traffic patterns are directly influencing WDPT charging patterns. On the other hand, plug-in charging is influenced only by the changing consumption in different cases. Average velocity, acceleration or route choice will all influence charging behaviour for WDPT. Therefore, choosing the accurate traffic input data was crucial for creditability.

6.4. Data

Data for the traffic model had key significance. Consequently, historical traffic data has been analysed from the past 5-10, where data was available. This method enabled a highly realistic traffic pattern. Nonetheless, the precision of historical data excludes the possibility of forecasting future traffic. Driving patterns are highly likely to change by 2050. Up until 2010, the number of vehicles and km travelled both have been increasing. However, in the last 10 years, the gradient of vehicle-kilometres travelled is declining, despite the still increasing GDP (Dender, 2013). This indicates a habitual change in driving. Other studies, such as Litman, 2011 also suggests decrease in vehicle-kilometre travelled and number of new vehicles purchased annually as well. However, an attempt to predict a future scenario would be on the expense of reliability of the data.

Possibly the most reliable input data is the WLTP driving cycle used to model driving behaviour. It has been established in 2015 and since 2019, it serves as the official driving cycle in Europe for testing and modelling (UNECE, 2019). This driving cycle has replaced the NEDC (New European Driving Cycle) which was the standard for over 20 years. In case WLTP can be expected to stay around for the same period, the traffic patterns in this study could potentially stay up to date until 2040. (Marotta, 2015)

The daily patterns for power supply and demand have also been drawn from historical data. These however have been updated to a future scenario, with technological improvement assumed on the power generation side and rapid electrification of heating and industry assumed on the demand side. Nonetheless, changes in supply and demand curves have highly similar impact on plug-in and WDPT charging, according to the sensitivity analysis.

6.5. Scenarios

The most important variables in this study were the different scenarios. The legitimacy of the scenario design could decide the success of the results on its own. Therefore, eight charging scenarios have been designed to reflect on the main different charging behaviours expected. The scenarios are kept on constant values. All charging scenarios are standing for the entire spectrum of their particular setup. The 3:2 ratio between home and work charging scenario is the most realistic, however the best matching score would be achieved by the less realistic 100% work charging, which would mean 7% improvement in the matching score. This improvement would not be enough to change the rank of the scenario compared to the other scenarios. This is true to all of the scenarios: if the optimum set up would be taken, as oppose to the most realistic one, it would not change the rank order from lowest to highest matching score.

Furthermore, there are possible future scenarios, that have not been considered for this study. With the development of fast chargers, plug-in charging on road is approaching the convenience of fuel filling at gas stations today. Despite the fact that Hõimoja et al., 2012 states that only a charger with 6.3MW power output could match the autonomy and convenience of combustion engine refilling, with already available 250kW ultrafast chargers, it takes 5 minutes to charge 20kWh, which is about 100km range (Aggeler et al., 2010; Schroeder & Traber, 2012). As a result, there is a potential scenario of consumers charging more on road, and plug-in charging could have similar, traffic correlated curve such as WDPT charging. However, it is highly unlikely that electricity from ultrafast chargers could be sold at the same price as domestic electricity per kWh, as investment cost of ultrafast charger is 125 times higher, than a home charger (Schroeder & Traber, 2012). This could raise the question if consumers would still choose the cheaper and more convenient home charging over fast charging on an average day. Similarly, in the hybrid scenario, depending on the price of WDPT charging on motorways, consumers could potentially decide not to charge on the road to save money. However, here the convenience of charging while driving could lead to the decision of recharging regardless of the higher price for security. This all depends on how electricity prices can affect consumer behaviour.

In terms of plug-in charging, there could be several other combinations designed. For example, charging only at work, or only on road. However, these possibilities were not realistic enough. Most EV owners will own home charger for security. In case home charger is installed, it can be expected to be the dominant charging method for the abovementioned convenience and financial reasons. Yang & Timmermans, 2015 conclude in their study that sudden fluctuations in fuel price does not affect driving related decisions (in the Netherlands), however, in case of expected or scheduled price fluctuations (such as off-peak tariffs), consumer response can somewhat improve. In terms of electricity tariffs, IRENA, 2019 stresses the problem that effective domestic consumer response have not been achieved by the Time-of-Use tariff scheme and increasing automation would be more effective to eliminate the need of active participation via manual response. Therefore, electricity tariff fluctuations did not play a significant role in scenario formation, as their effectiveness on the domestic sector is yet to be determined.

6.6. Results

Results have shown that plug-in charging would damage the grid balance by 13%-22%, compared to a no EV scenario. This significant impact on the grid can be reduced to 4% damage if smart charging is being applied, where charging is spread out through the night, when power demand from other sectors is low. Even though smart plug-in charging could significantly improve supply-demand matching score, it would not help reducing the severe battery requirements and therefore, the global warming impact involved in the production of such a system. As a result, a total of 4TWh EV battery capacity would be required, as well as 2TWh storage for the daily deficit caused by EVs only. According to Gimeno-Gutiérrez & Lacal-Arántegui, 2015, there is a theoretical pumped hydro storage capacity of 29TWh in Europe. Therefore, the daily deficit could be stored in 7% of the pumped hydro potential only. Also, there are other electricity storage possibilities, such as CAES (compressed air energy storage), hydrogen or large-scale battery storage. However, storing electricity comes with a price. Storing the 2TWh daily deficit would cost approximately €200 billion. Furthermore, the operation and maintenance cost would be a further €4 billion/year (Zakeri & Syri, 2015). The moderate WDPT scenario on the other hand requires only 0.6TWh battery capacity for all EVs in Europe and additional storage of 0.7TWh for daily power deficit caused by EV charging. Considering lithium for EV batteries, plug-in scenario would require almost 1 quarter of the global lithium reserves only for Europe, which can be considered particularly unfeasible. Furthermore, the lithium requirements of the reference scenario, considering 300km range would exceed the global lithium reserves available by 13%. This result shows a highly important problem, concerning EV deployment in the future, with today's battery trends. WDPT charging could reduce the requirements to 3.2% of the global lithium reserves, which would enable medium and HDVs to also become fully electric. In this case however, copper requirements of road transport would significantly increase, as a result of intensive copper demand by inductive coils for WDPT. On-road wireless charging would require 5 times more copper, than plug-in charging. However, global copper reserves are more extensive and therefore, copper requirements would be less impactful with only 0.16% exploitation. Also, copper recycling is significantly more advanced, than lithium recycling in Europe.

The Hybrid scenario has proved to be the most advantageous in the assessed categories. The Hybrid scenario has been the only scenario that improved the supply-demand matching score by 4%, compared to the No EV matching score. Also, it has the lowest environmental impact. Although the lithium requirement is double of the moderate WDPT scenario, with the reduced charger requirements, the overall global warming impact would be 3% less for the hybrid scenario. Also, the supply-demand matching score for the hybrid scenario is 4.6% greater than for the WDPT. On the other hand, increasing the share of solar energy in the grid-mix has revealed that a solar dominated power generation pattern would be more balanced with WDPT charging, than with hybrid charging. That can be an important addition to the grid balance of solar dominated southern countries.

In the multicriteria analysis, additional impact categories have been included to reveal further advantages/disadvantages of the different charging methods. The involved costs, complexity of implementation and social acceptance were highly important additions.

The hybrid scenario has proven to be the most cost efficient, as WDPT charger requirements have been significantly reduced by applying smart home chargers. Also, it improves the highly challenging implementation procedure of WDPT charging. The power and road transport infrastructure can only benefit fully from WDPT charging, if the desired coverage have been achieved. Therefore, gradual installation of the charging coils would not provide all the benefits for EV owners. Nevertheless, in the hybrid scenario, smart home chargers can be highly beneficial throughout the transition period and the gradual installation of WDPT coils.

Furthermore, social acceptance also carries key importance. The bargaining power of buyers can shape the future of EVs and the charging methods as well. Statistics show that home charging is the most preferred charging method presently (IEA, 2019). Also, acceptance is highly correlated to familiarity, especially for the target market of new automobile purchase, which is over the age of 25 (Dender, 2013). In that case, plug-in charging has the advantage, as the stationary charging by plugging the fuel source to the back of the car is similar procedure to the one that consumers are used to with combustion engine vehicles. WDPT charging however is an unknown method that works highly differently. This would probably decelerate the acceptance of the technology. (Wüstenhagen et al., 2007) Also, studies show that the idea of wireless, inductive power transfer receives criticism and concerns about health and safety by the public (Lin, 2013). However, new technologies typically receive such a distrust, and some become highly popular regardless. For instance, at the beginning of wireless internet adaptation, the technology has received highly similar concerns however, it gained public acceptance nevertheless (Lu et al., 2003).

6.7. Overall Interpretation

The additional impact categories in the multicriteria analysis helped to reveal further important factors that could influence the charging scenarios. However, there are some major technological competitors or upgrades, that have not been included in this study and their significance must be addressed.

In terms of sustainable road transport, fuel-cell EVs yet to be discussed. Fuel-cell EVs are using hydrogen as intermediate storage. This can be highly beneficial, as electricity turning into hydrogen is an independent event from traffic patterns and consumer behaviour. Therefore, where and when electricity is turned into hydrogen is highly flexible and can be harmonized with renewable energy generation curves and surpluses could be directly turned into the vehicle fuel: hydrogen. If fuel-cells were considered as a scenario for supply-demand matching score, it would undoubtedly be the most beneficial one with potentially perfect supply-demand match. However, fuel-cells have their own challenges in other categories (higher energy losses etc.), that they are yet to overcome. (Alavi et al., 2017) This study only focuses on battery electric vehicles, since

Another important possibility, that has not been considered in this study is V2G (vehicle to grid

V2G) direction of power transfer. In this study, only G2V has been studied, where EVs represent the consumer end only. Considering EV batteries to be part of the European grid storage system, that could potentially further improve the grid balance (Lund & Kempton, 2008).

Research questions all have been answered quantitatively or qualitatively. Consumption patterns have been successfully modelled by determining consumption per km per vehicle type and applying that throughout the modelled hourly traffic pattern in vehicle-kilometre. WDPT and/or plug-in charging systems have also been designed showing the number of chargers and the size of battery required to support the traffic patterns. Results in each scenario showed significant difference in battery and charger requirements. Supply-demand matching score on the other hand had lower degree of diversity amongst the results, with only 25% difference between the worst and the best-case scenario. Even though the differences between matching scores are less significant, their impact on grid storage requirements are still significant, since the 25% difference means hundreds of billions of euros investment.

7. CONCLUSION

In order to mitigate climate change, numerous initiatives have been designed by the EU. Decarbonization of all sectors is one of the most important point on the agenda. The transport sector accounts for over 20% of GHG emissions; therefore, reducing emissions in this area is crucial to meet targets set by Climate Action. EVs appear to be the number one choice of future sustainable transport with 5.2 million EVs on-road as of 2018. EVs experience an exponential increase in Europe, with the greatest market after China. Electrification of road transport paired with renewable power generation can significantly reduce emissions from road transport. However, that means the integration of the transport sector to the electricity infrastructure, which can be highly challenging, as a result of increasing electricity demand, as well as increasing power demand from unbalanced daily peaks, that do not match the daily renewable energy power output. One of the reasons for that is the trend of home charging amongst EV owners. Home charging is highly popular, as oppose to public charging, since it is mostly cheaper and more convenient. As a result, peak EV charging load demand can be experienced on top of the already existing residential evening peak demand. This charging behaviour also result in another concerning consequence, namely that EV owners demand batteries that can last all day long, so intermediate charging throughout the day is not necessary. Since the automotive industry is mostly using lithium-ion batteries for EVs, with large battery requirements on board, lithium exploitation quickly becomes excessive. Also, lithium ion batteries have significantly high global warming impact. Therefore, using large lithium-ion batteries to reduce emissions is debatable. In terms of medium and heavy-duty vehicles, battery size remains a crucial issue. The large batteries required by trucks and buses have extremely high cost (the price of the entire truck), high environmental impact and have impact on consumption due to large additional weight.

Exploitation of lithium reserves, high global warming impact of battery production and the increasing peaks and mismatch in electricity supply-demand by EVs have all been addressed in this study. In this research, the mitigation of the above-mentioned issues of EV implementation has been addressed by assessing different charging technologies. How the method and time of EV charging influences battery capacity requirements and grid balance, considering renewable power generation. There were two different charging methods considered: conventional plug-in charging and WDPT charging whilst driving. The research questions have been targeted to explore the impact of different charging methods and behaviours on grid balance, battery requirements and environmental impact. The study is considering Europe in 2050, to allow a transition period of 30 years and rationalize the assumption of 100% EVs on road and mature charging infrastructure. In order to answer research question, a comprehensive energy model has been created in MATLAB. This model takes into account renewable power generation and load demand curve assumed for 2050, traffic patterns and driving behaviour to identify the matching of power-supply demand, battery capacity required for driving habits and the global warming impact of batteries, chargers and electricity required for the charging system in Europe.

Results have shown that Plug-in charging or WDPT charging cannot improve grid-balance, compared to the No EV grid balance. However, WDPT charging scenarios did only worsen grid balance by 0.4%. Plug-in scenarios on the other hand have significantly worsened the grid balance with 21.6% damage in case of home charging scenario. This large impact can be softened by the application of smart charging, in which case, only 4% percent damage is done. Improvement, compared to No EV scenario only could be achieved by an optimized scenario that is combining smart plug-in charging and WDPT motorway coverage, resulting in 4% improvement. This improvement saves 75% or 1.45 TWh storage capacity requirement in Europe, compared to the home charging scenario.

In terms of battery size, capacity requirement can be reduced by spreading out the one evening charging to several smaller charging throughout the day. The MATLAB model has revealed that distributing 60% of the plug-in home charging throughout the day, to work charging and public charging can reduce battery requirements by 60%. Heavy-duty and MDVs do not experience battery reduction as commercial vehicles do not have time to stop for charging throughout the day. With

WDPT charging however, commercial vehicles can also benefit from public charging, since they do not have to stop for power transfer. As a result, with Minimum WDPT coverage, battery capacity required on-board of heavy and MDVs can be halved. Moderate WDPT scenario is one of the 2 most beneficial scenarios in terms of battery demand. Heavy-duty batteries can be reduced by as much as 91% and medium-duty vehicle batteries can be 83% smaller, compared to plug-in scenarios. Theoretically, Maximum WDPT scenario (all roads installed with charging coils) would not need battery on board. However, all road coverage would require almost 3 times more chargers, than the moderate WDPT scenario. The global warming impact created by this drastic charger production in this case increases global warming impact by 30%. Which clearly shows that covering all roads in Europe would not make road transport sufficiently sustainable. Furthermore, in terms of scarce material exploitation, Maximum WDPT scenario requires 50% more copper, than it saves in lithium. Moderate WDPT and Hybrid scenario, however, show more advantageous tendency. These 2 scenarios have an inverse proportionality with ratio between increasing copper and decreasing lithium of 2:3. This means that 50% more lithium is being saved, than copper invested. As a result, Moderate WDPT charging has been chosen as the most beneficial from the WDPT scenarios and smart charging from plug-in scenarios. Additionally, the optimum hybrid scenario has been designed to complete the top three scenarios. The top three scenarios do not have significant difference in overall global warming impact, nor supply-demand matching score. The most significant difference is on overall battery capacity requirement for Europe, where smart plug-in charging is nearly 3 times greater, than WDPT and hybrid scenarios. In total, hybrid scenario has proved to be the most beneficial.

As mentioned above, not all the result categories have shown significant differences. Therefore, other important impact categories have been introduced in the framework of a multicriteria analysis, however, it did not change the rank of hybrid scenario being the most advantageous, followed by moderate WDPT charging scenario.

Research questions all have been answered quantitatively or qualitatively. Consumption patterns have been successfully modelled by determining consumption per km per vehicle type and applying that throughout the modelled hourly traffic pattern in veh-km. WDPT and/or plug-in charging systems have also been designed showing the number of chargers and the size of battery required to support the traffic patterns. Results in each scenario showed considerable difference, especially in battery and charger requirements.

Sensitivity analysis has shown the most impactful variables. It revealed that increase of solar generation in electricity mix worsens grid-balance. Also, it has indicated that consumer behaviour can have a significant impact on sustainability. With conscious EV charging, and driving habits, such as charging daytime, and avoid unnecessarily high velocities and accelerations, battery requirements and grid balance can be significantly improved.

Even though plug-in charging is the simpler way to go at the implementation phase, once EVs reach significant shares on road, WDPT charging is considerably more beneficial for the grid balance and in terms of battery downsizing as well. Moreover, 100% EV share could not be achieved without WDPT, as the lithium requirement for plug-in charging is unfeasibly excessive. HDVs would have to be equipped with 1.5 tons battery, which would double the price of the vehicle. Reducing the battery requirements by 91%, WDPT charging could make heavy-duty vehicle electrification possible.

WDPT and hybrid charging can undoubtably improve some of the greatest challenges of future EV charging, according to the results. The significant decrease of the evening peak demand, compared to plug-in charging, as well as the overall grid balance improvement by the hybrid scenario mean benefits for the European electricity infrastructure. The possibility of charging on road whilst driving could be a convenient solution for consumers, that decreases range anxiety and therefore, the need of large EV batteries. WDPT charging, however, requires greater investments and implementation is considerably more complex. The question remains, if the described future benefits make it worth for governments to invest in WDPT charging systems.

8. RECOMMENDATIONS FOR FUTURE RESEARCH

As mentioned above implementation of WDPT can be highly complex. Therefore, a dynamic model could affectively asses the gradual adaptation on a timeline. This missing piece could truly reveal if future benefits worth investing. Also, a similar study showing yearly patterns instead of daily could show more detailed variations of electricity generation and demand. In terms of feasibility, a more detailed cost breakdown and return on investment calculations could measure the financial competitiveness of this designed system. This would be highly important to determine the feasibility.

In this study only a G2V setup has been considered. Including V2G in a future EV system could go one step further to show how EV batteries can be part of the grid storage system, as this would have a considerable impact on grid balance.

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10. APPENDICES

10.1. Appendix I. - WLTP Driving Cycle

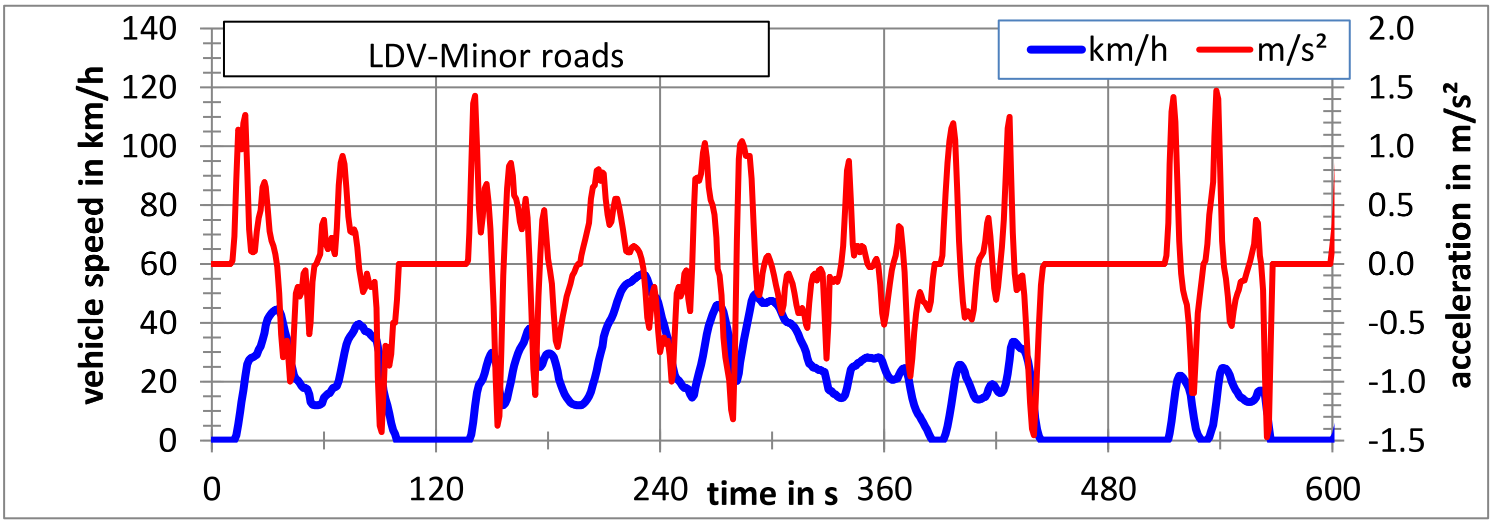


Figure 30 -WLTP driving cycle light-duty vehicles on minor roads acceleration and velocity

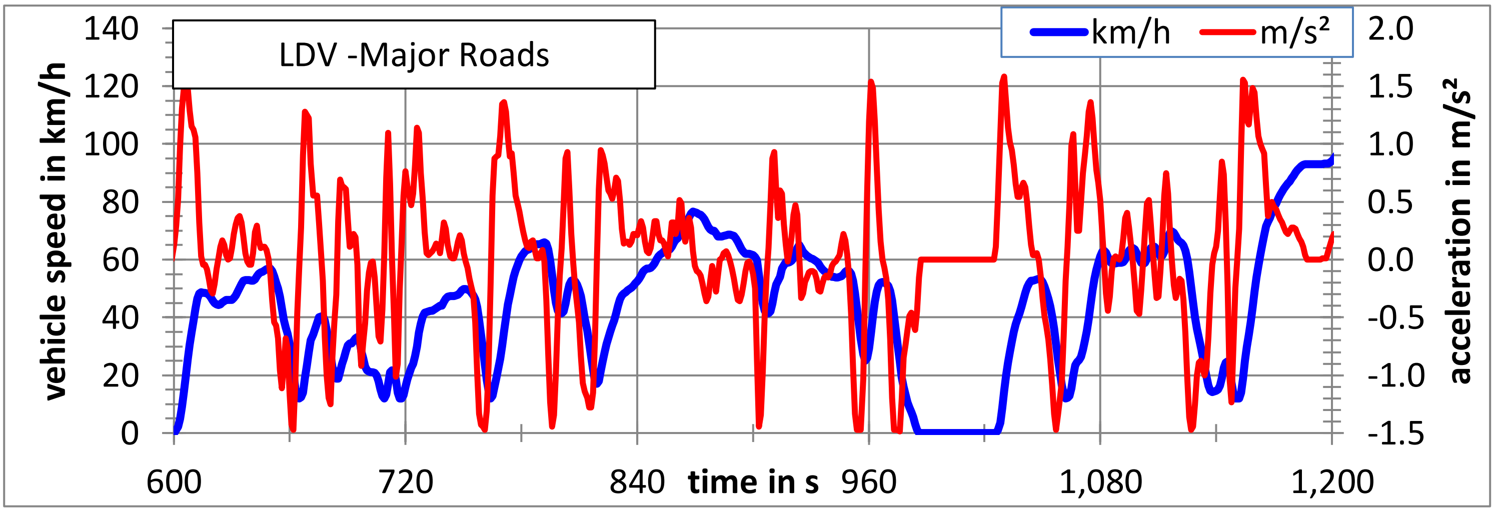


Figure 29 – WLTP Driving cycle light-duty vehicle major road

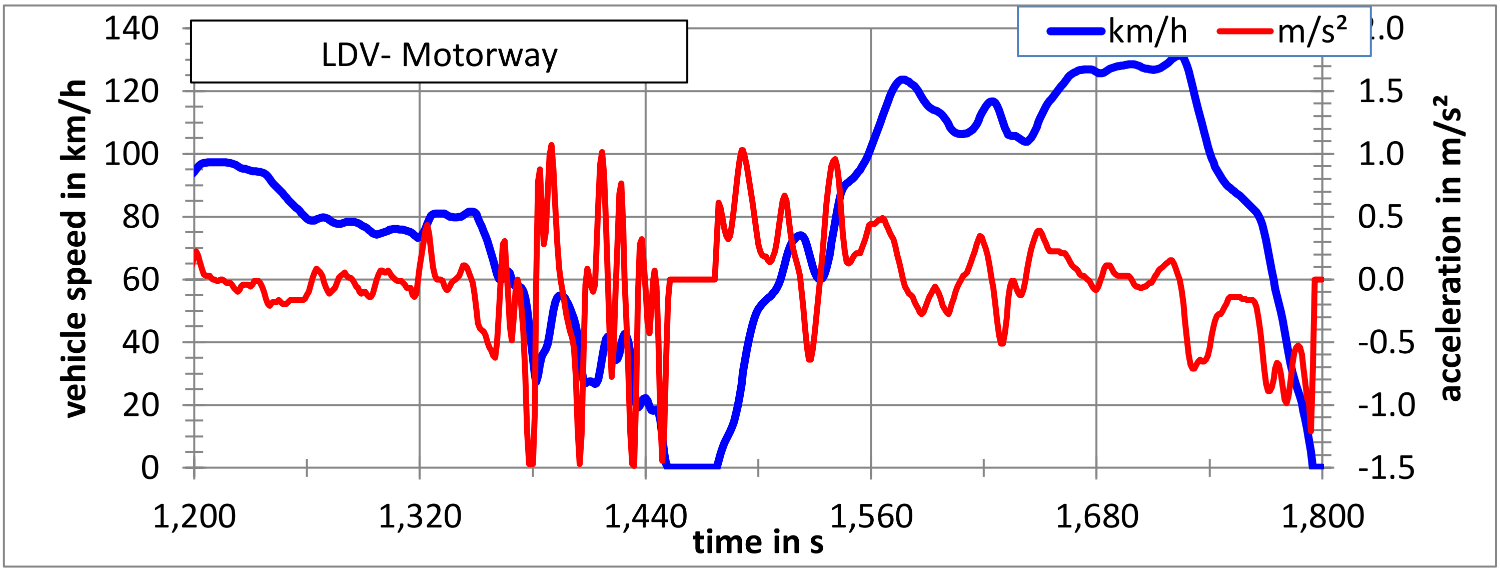


Figure 32 – WLTP driving cycle light-duty vehicle motorway

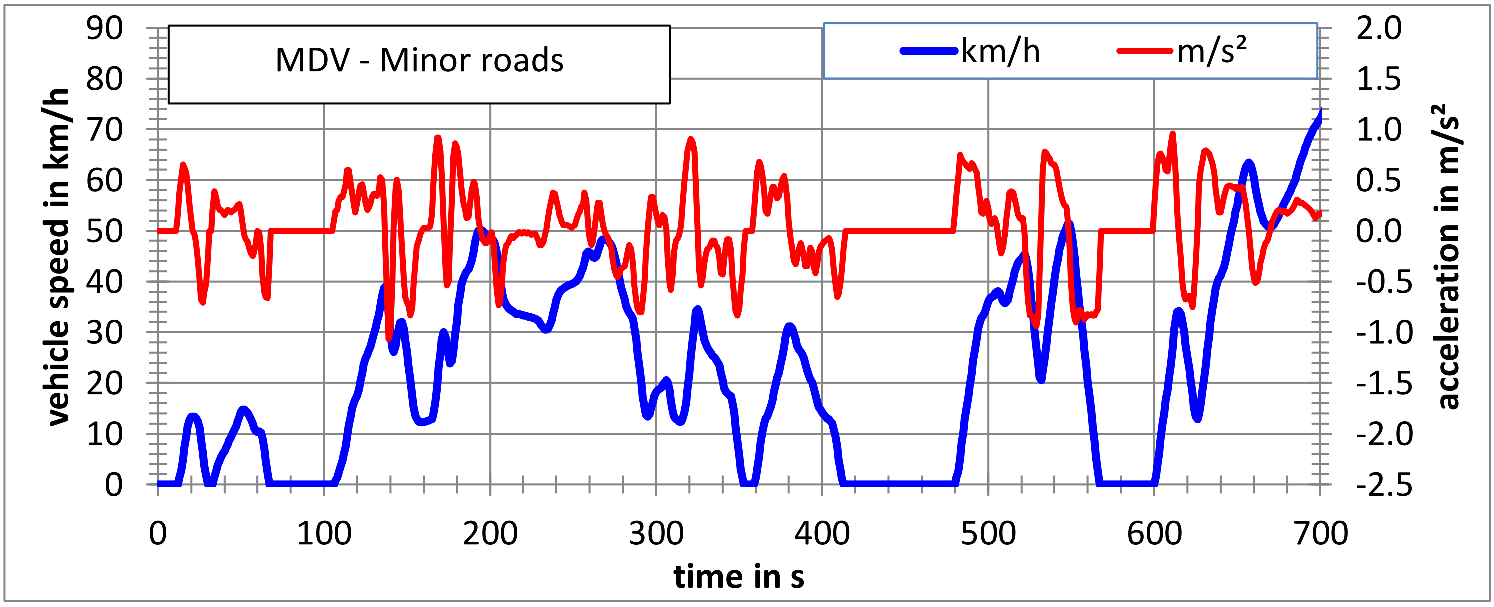


Figure 31 – WLTP Driving cycle medium-duty vehicle driving patterns velocity and acceleration

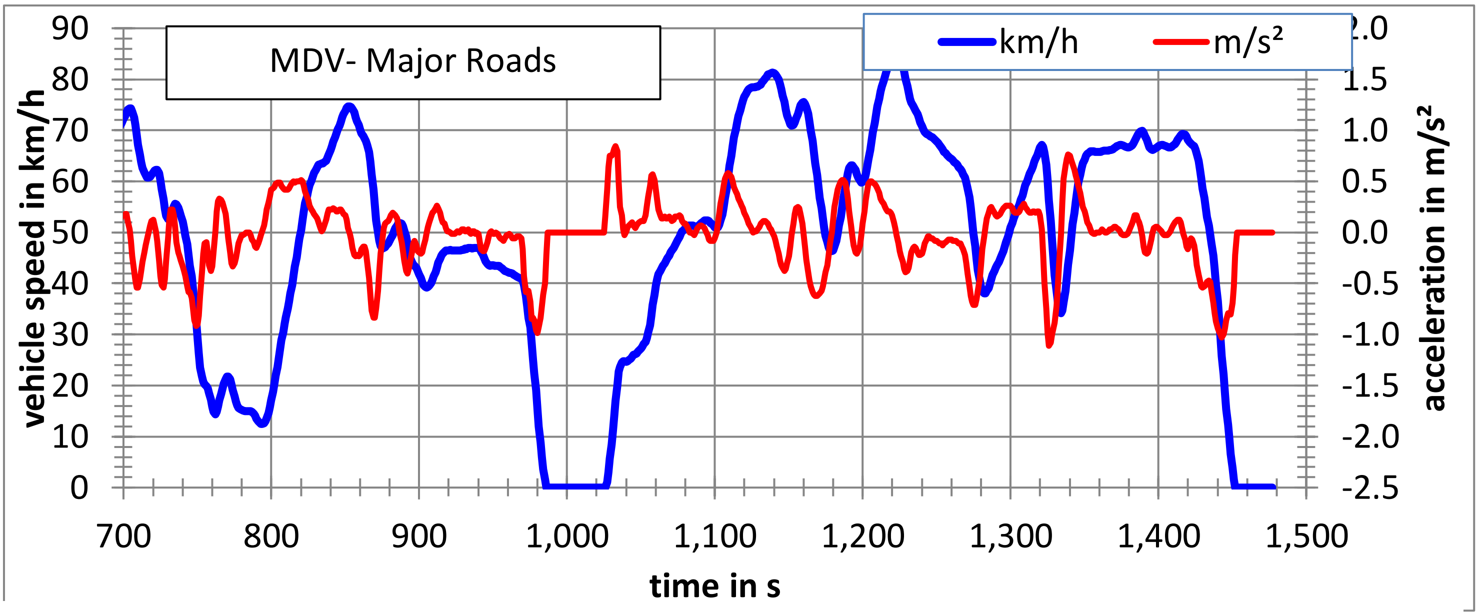


Figure 33 – WLTP driving cycle medium duty vehicles on major roads driving patterns

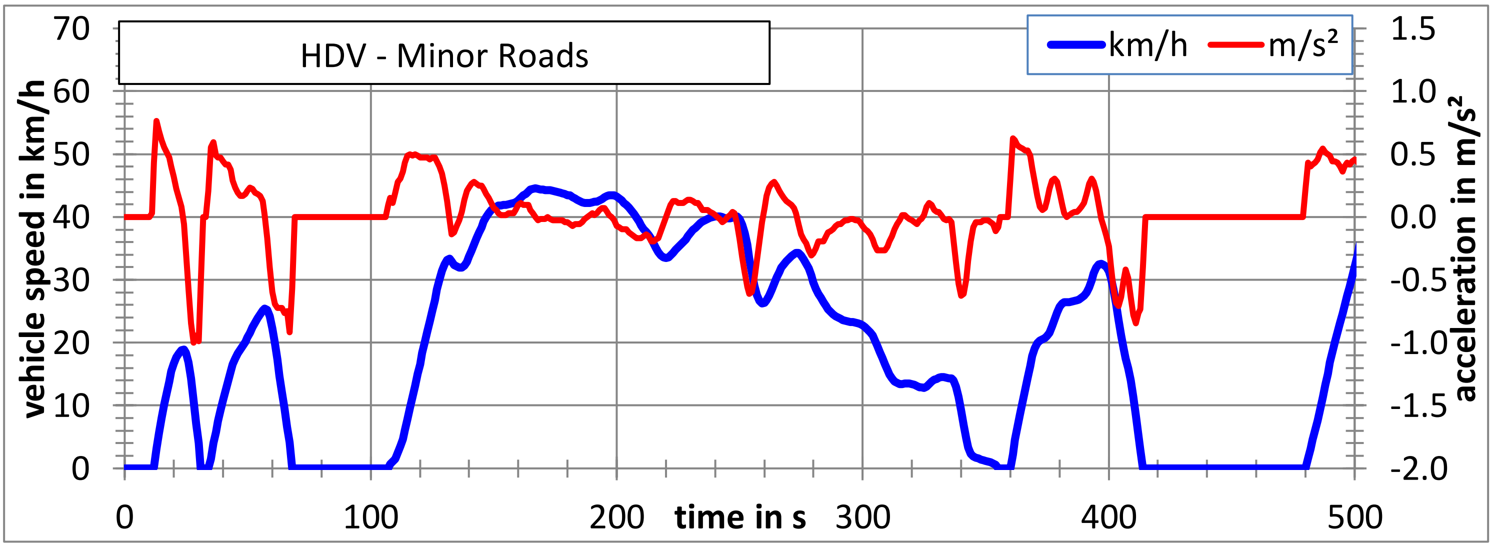


Figure 35 – WLTP driving cycle heavy-duty vehicle driving pattern on minor roads

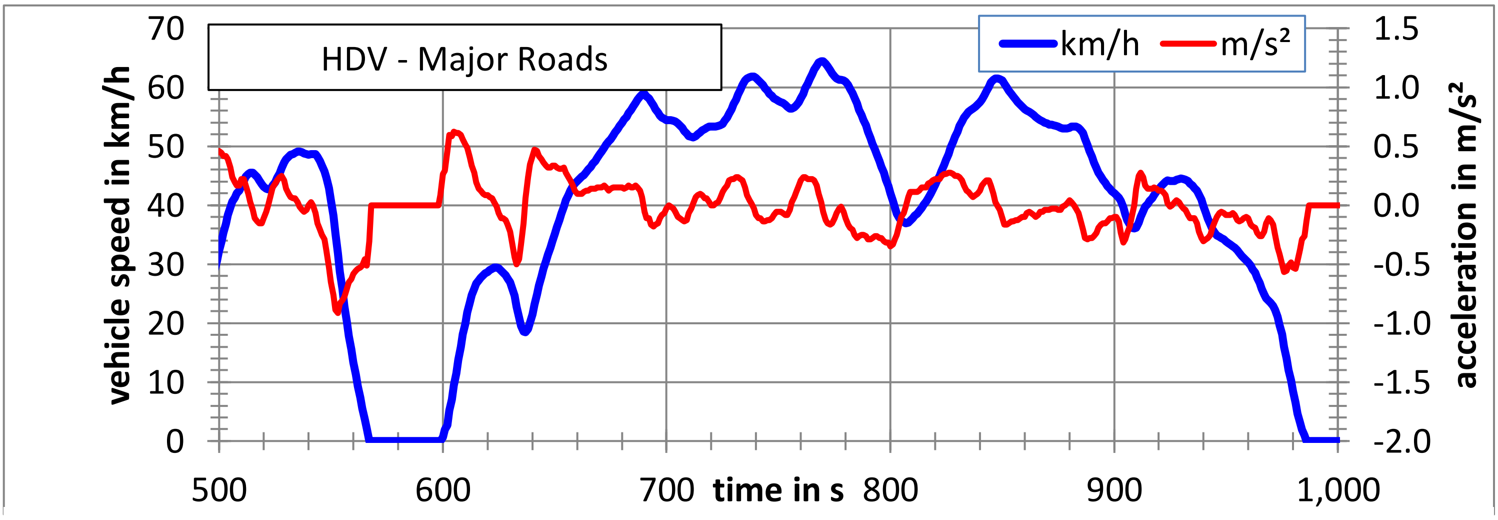


Figure 34 – WLTP driving cycle heavy-duty vehicles major roads

10.2. Appendix II. –Consumption Model

10.2.1. Model Input

Table 8 – Vehicle Specifications[7]

Vehicles Specs	**Unit**	**Light Duty**	**Medium Duty**	**Heavy Duty**
Mass	kg	1500	8000	18500
area	m2	3	5.66	7.96
Air res	-	0.3	0.6	0.65
Friction	-	0.01	0.009	0.007
Efficiency	%	90	90	90
Breaking Efficiency	%	55	65	66
Vehicle length	m	4	8	16
Average distance per day	km	36	200	400
Number of vehicles		144230000	4538200	715480

10.2.2. Consumption per vehicle

10.2.2.1. Model Calculations

Acceleration and velocity from WLTP in relation to the second of traveling

$$a_t\left[\frac{m}{s^2}\right] = v_t - v_{t-1};\quad where\ t = time\ in\ seconds\ of\ WLTP\ cycle\ [s]$$

$a: acceleration\ [\frac{m}{s^2}]$

$v: velocity\ [\frac{m}{s}]$

The forces acting on the vehicle can be determined by the equation below (Juan Luis Villa, 2018) Unit: Newton[N]:

$$\mathrm{F_{total}} = \mathrm{F_{friction}} + \mathrm{F_{aerodynamics}} + \mathrm{F_{linear\ acceleration}} + \mathrm{F_{angular\ acceleration}}$$

$$\mathrm{F_{total_t}} = \mathrm{C_r mg} + 0.5\rho \mathrm{AC_d v_t^2} + \mathrm{ma_t} + 0.05\mathrm{ma_t}$$

---

[7] Vehicle Specifications References: Light duty specifications (Villa, 2018; *Oh et al., 2014*); Medium duty specs *(Katrašnik, 2013)*; Heavy duty vehicle specs *(Delorme et. al, 2009)*; Friction Coefficients (*Delorme et. al, 2009); battery to wheel efficiency (Hofman & Dai, 2010)*; regenerative breaking efficiency *(Apter & Präthaler, 2002)*

Power required by vehicle in P [W]:

$$\text{for } F_{\text{total}} \geq 0; \rightarrow \quad P_t\,[W] = F_{\text{total}_t} * v_t/\eta_{\text{tank-to-wheel}}$$
$$\text{for } F_{\text{total}} < 0\,; \rightarrow \quad P_t[W] = F_{\text{total}_t} * \Delta v/\eta_{\text{tank-to-wheel}} - \Delta F_{\text{total}} * \Delta v * \eta_{\text{regenerative}}$$

$$E_{total\_consumption}[kWh] = \frac{\sum P_t}{3600 \; x \; 1000}$$

Consumption in kWh can be expressed as the sum of hourly average power demand, deriving from total forces multiplied by average velocity.

The variables that will determine the characteristics of different vehicle types:

C_r − Friction coefficient
m − Mass of the vehicle [kg]
A − Frontal area of the vehicle [m^2]
C_d − Aerodynamic coefficient
v − velocity of vehicle [m/s]
a − Acceleration of vehicle [m/s^2]

$\eta_{\text{tank-to-wheel}}$ − Tank to wheel efficiency
$\eta_{\text{regenerative}}$ − regeneration efficiency by breaking or deceleration

ρ − air density and g − gravitational acceleration are constant)

$$P_t[W] = F_t \times v_t$$
$$E_{total\_consumption}[kWh] = \frac{\sum P_t}{\eta_{tank-wheel} \; x \; 3600 \; x \; 1000}$$

10.2.2.2. Model Input

Table 9 – Consumption per vehicle main model inputs

	Light-Duty	**Medium-Duty**	**Heavy-Duty**
$\boldsymbol{C_d}$	0.3	0.6	0.65
$\boldsymbol{m[kg]}$	2000	8000	18500
$\boldsymbol{A[m^2]}$	3	5.66	7.96
$\boldsymbol{C_r}$	0.015	0.009	0.007
$\boldsymbol{v \text{ and } a}$	WLTP Driving Cycle		
$\boldsymbol{\eta_{tank-to-wheel}}$	90%	90%	90%
$\boldsymbol{\eta_{regenerative}}$	55.6%	65.3%	66.4%

10.2.3. Traffic

10.2.3.1. Road input variables

Table 10 – Road specifications input data

Road specs	**Unit**	**Motorway**	**Major road**	**Minor road**	**References**
Road length (Europe)	km	78654	903613	3537016	(UNECE, 2018)
Vehicle-km per road	veh.km	3.5346×10^9	4.1314×10^9	1.0647×10^9	(DFT, n.d.)
Average number of lanes	-	2	1.5	1	(GOV.UK, 2019)

Table 11- Ratios of the model

Input Variables	**Unit**	**Quantity**	**Reference**
Driver reaction time	seconds	2	(Bludszuweit et al., 2018)
Weekday share in average	-	5/7	
Weekend share in average	-	2/7	

10.2.3.2. Traffic model calculations

$$RoadCapacity = Traffic_{maximum} = \frac{RoadLength}{(t_{reaction}\ x\ v_{average}) + VehicleLength}$$

Where:

$Roadlength: length\ of\ the\ analysed\ road\ [m]$
$VehicleLength: length\ of\ vehicles\ on\ road\ [m]$
$t_{reaction}: reaction\ time$
$v_{average}: average\ velocity\ on\ the\ analysed\ road$

$$ADTD = RoadCapacity\ x \frac{((5\ x\ Wday_{distribution}) + (2\ x\ Wend_{distribution}\ ))}{7}$$

Where:

$ADPD: Average\ Daily\ Traffic\ Distribution\ (weejend\ and\ weekday)\ [veh - km/h\ of\ the\ day$
$Wday_{distribution}: Normalised\ averaged\ weekday\ traffic\ distribution\ throughout\ the\ year$
$Wend_{distribution}: Normalised\ averaged\ weekend\ traffic\ distribution\ throughout\ the\ year$

Table 12- Normalized distribution throughout the day

		Vehicle and Road Types								
		HDV-Motorway	HDV-Major	HDV-Minor	MDV-Motorway	MDV-Major	MDV - Minor	LDV - Motorway	LDV - Major	LDV - Minor
Hour of the Day	0:00	0.00149	0.00062	0.00015	0.00087	0.00084	0.00094	0.00406	0.00446	0.00457
	1:00	0.00147	0.00061	0.00015	0.00061	0.00060	0.00066	0.00237	0.00260	0.00266
	2:00	0.00155	0.00064	0.00016	0.00053	0.00052	0.00057	0.00178	0.00196	0.00201
	3:00	0.00185	0.00077	0.00019	0.00064	0.00062	0.00069	0.00202	0.00222	0.00228
	4:00	0.00271	0.00113	0.00028	0.00115	0.00112	0.00124	0.00365	0.00401	0.00411
	5:00	0.00443	0.00184	0.00046	0.00306	0.00298	0.00331	0.01142	0.01254	0.01285
	6:00	0.00668	0.00277	0.00069	0.00804	0.00784	0.00869	0.02980	0.03273	0.03354
	7:00	0.00747	0.00310	0.00078	0.01191	0.01160	0.01286	0.05132	0.05638	0.05777
	8:00	0.00748	0.00310	0.00078	0.01119	0.01091	0.01209	0.05238	0.05754	0.05896
	9:00	0.00785	0.00325	0.00081	0.00987	0.00962	0.01066	0.04131	0.04538	0.04650
	10:00	0.00785	0.00326	0.00082	0.00909	0.00886	0.00982	0.03920	0.04306	0.04413
	11:00	0.00788	0.00327	0.00082	0.00919	0.00895	0.00992	0.04059	0.04459	0.04569
	12:00	0.00776	0.00322	0.00081	0.00941	0.00917	0.01016	0.04214	0.04629	0.04743
	13:00	0.00783	0.00325	0.00081	0.00969	0.00944	0.01047	0.04298	0.04721	0.04838
	14:00	0.00781	0.00324	0.00081	0.01035	0.01008	0.01118	0.04585	0.05037	0.05161
	15:00	0.00732	0.00304	0.00076	0.01144	0.01115	0.01236	0.05126	0.05631	0.05769
	16:00	0.00618	0.00256	0.00064	0.01211	0.01180	0.01308	0.05965	0.06553	0.06714
	17:00	0.00481	0.00200	0.00050	0.01077	0.01050	0.01163	0.06187	0.06796	0.06963
	18:00	0.00397	0.00165	0.00041	0.00837	0.00815	0.00904	0.04907	0.05390	0.05523
	19:00	0.00324	0.00134	0.00034	0.00571	0.00556	0.00616	0.03395	0.03729	0.03821
	20:00	0.00268	0.00111	0.00028	0.00387	0.00377	0.00418	0.02385	0.02620	0.02684
	21:00	0.00221	0.00092	0.00023	0.00278	0.00271	0.00300	0.01787	0.01964	0.02012
	22:00	0.00187	0.00078	0.00019	0.00206	0.00201	0.00223	0.01335	0.01466	0.01502
	23:00	0.00167	0.00069	0.00017	0.00141	0.00138	0.00153	0.00808	0.00887	0.00909

Table 13- veh-km distribution throughout the hours of the day

		Vehicle and Road Types								
		HDV-Motorway	HDV-Major	HDV-Minor	MDV-Motorway	MDV-Major	MDV - Minor	LDV - Motorway	LDV - Major	LDV - Minor
Hour of the Day	0:00	47381	39597	5525	22981	64817	41784	110060	359472	234562
	1:00	45730	38217	5333	16150	45550	29364	65732	214690	140089
	2:00	47093	39356	5492	13162	37123	23931	47480	155077	101190
	3:00	53742	44913	6267	14290	40304	25982	48736	159179	103867
	4:00	73235	61204	8540	22420	63235	40764	75771	247477	161483
	5:00	110181	92079	12849	53595	151161	97445	211064	689365	449823
	6:00	159386	133200	18587	133756	377247	243190	524129	1711877	1117031
	7:00	180493	150840	21048	199432	562480	362599	896970	2929626	1911635
	8:00	182803	152771	21317	197637	557419	359337	965838	3154558	2058408
	9:00	191233	159816	22300	189488	534435	344520	863780	2821222	1840899
	10:00	192103	160543	22402	187882	529904	341600	898800	2935603	1915535
	11:00	192663	161010	22467	195415	551150	355296	959235	3132989	2044333
	12:00	189341	158234	22080	199933	563894	363511	992362	3241189	2114936
	13:00	189008	157956	22041	201679	568819	366686	993585	3245182	2117541
	14:00	187040	156312	21811	208326	587567	378771	1022966	3341145	2180159
	15:00	176349	147377	20565	222747	628238	404990	1099486	3591070	2343239
	16:00	153045	127902	17847	231774	653698	421403	1230554	4019154	2622572
	17:00	124970	104439	14573	208704	588632	379458	1249189	4080018	2662287
	18:00	106174	88731	12381	166458	469480	302648	1010680	3301015	2153974
	19:00	88763	74180	10351	118971	335547	216309	725565	2369791	1546333
	20:00	74533	62288	8692	83746	236199	152264	521045	1701802	1110457
	21:00	61976	51794	7227	60975	171974	110862	389960	1273662	831088
	22:00	52685	44030	6144	45858	129338	83377	293147	957457	624758
	23:00	47433	39640	5531	32672	92147	59402	186305	608499	397057

10.2.4. Total Consumption be EVs:

$$Totat\ Caonsumption\ Curve = ADPD\ x\ E_{total\_consumption}\ x\ lanes$$

Where:

$Totat\ Caonsumption\ Curve$: $total\ consumption\ curve\ throughout\ the\ day\ [kWh\ per\ hour\ of\ the\ day]$
$lanes$: $the\ number\ of\ lanes\ on\ roadtype$

10.2.5. WDPT charging:

10.2.5.1. WDPT Input Data

Table 14 – WDPT specifications

Input Variables	**Unit**	**Quantity**	**Reference**
WDPT efficiency	%	90	(Bludszuweit et al., 2018)
Power output per WDPT coil	kW	60	(Rubino et al., 2017)
Length of coils	m	3	(Bludszuweit et al., 2018)
Misalignment	%	30	(Bludszuweit et al., 2018)

10.2.5.2. WDPT Model calculations

Energy charged

$$E_{WDPT\_charged} = \frac{\eta_{WDPT}\, x P_{transmission\_coil}}{v_{average}}$$

Where:

$E_{WDPT_{charged}}: total\ energy\ charged\ per\ km$

$\eta_{WDPT}: charging\ efficiency$

$P_{transmission_{coil}}: power\ output\ of\ transmission\ coil\ [kW]$

$v_{average}: average\ speed\ on\ road\ [\frac{km}{h}]$

WDPT Charging vs Consumption (excess energy daily)

$$ExcessEnergy = \sum E_{WDPT\_charged} - \sum Totat\ Caonsumption\ Curve$$

Number of coils

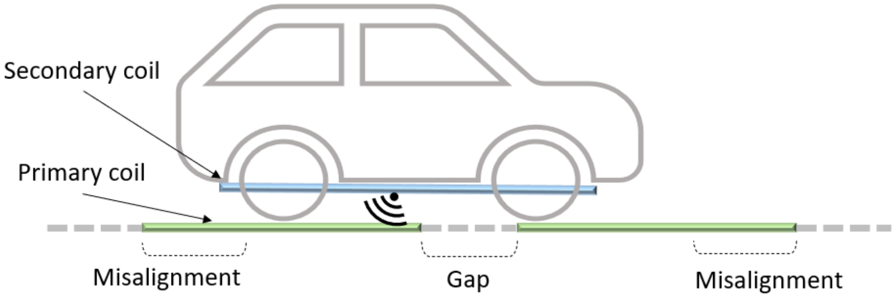


Figure 36 – calculation of gaps between road coils for continuous power output

$$if\ misalignment > 50\% \ \rightarrow\ Gap = (2m-1)Coil_{length}$$

$$\boldsymbol{else} \rightarrow\ Gap = 0;$$

$$Number\ of\ Coils = \frac{Road\_length}{(Coil_{length} + Gap_{length})}$$

10.2.6. Plug-in charging

10.2.6.1. *Plug-in charging input data*

Table 15 – Plug in charging main input variables

Input Variables	**Unit**	**Quantity**	**Reference**
Home charging peak	-	19:30	(Babrowski et al., 2014)
Work charging peak	-	08:30	(Babrowski et al., 2014)
Standard deviation from peaks	hours	1.5	(Babrowski et al., 2014)
Plug-in efficiency	%	97.5	(Bi et al., 2015)

10.2.6.2. *Plug-in charging model calculations*

Peak charging (home and work charging, MDV) → Normal distribution

$$f(h) = \frac{e^{-\frac{1}{2}\left(\frac{\mu-h}{\sigma}\right)^2}}{\sigma\sqrt{2\pi}}; where\ 1 \leq h \leq 24$$

$h = hour\ of\ the\ day$
$\sigma: standard\ deviation\ of\ charging\ peak\ [hours]$
$\mu: charging\ peak\ time\ [hour\ of\ the\ day]$

Table 16 – Normal distribution input variables

	Mean (μ)	**Standard deviation** (σ)
LDV -Home charging	18:30	1.5
LDV- Work charging	08:30	1.5
MDV - Work charging	18:00	2

Charging without peak (other LDV, MDV, HDV) → uniform distribution

$$f(h) = \begin{cases} NR \rightarrow 0 \leq h < 5 \\ \frac{h-5}{7-5} \rightarrow 5 < h < 7 \\ DR \rightarrow 7 \leq h \leq 23 \end{cases}$$

Where:

$NR: Night\ ratio\ of\ charging\ compared\ to\ daytime\ (23:00 - 06:00)$
$DR: Daytime\ ratio\ of\ charging\ (06:00 - 23:00)$

Table 17 – Uniform distribution specifications

	DR	NR
LDV – other charging	7%	93%
LDV- smart charging	0%	100%
HDV	50%	50%

Final plug-in curve:

$HR - Home\ chaging\ ratio$
$Home_{curve} - Home\ charging\ distribution\ curve$
$WR - Work\ charging\ ratio$
$Work_{curve} - Work\ charging\ distribution\ curve$
$OR - other\ charging\ ratio$
$Other_{curve} - Other\ charging\ distribution\ curve$
$LDV_{consumption} = total\ consumption\ by\ light\ duty\ vehicles$
$MDV_{curve} - Medium\ duty\ vehicle\ distribution\ curve$
$MDV_{consumption} -\ Total\ consumption\ by\ medium\ duty\ vehicles$
$LDV_{curve} - Heavy\ duty\ vehicle\ distribution\ curve$
$LDV_{consumption} -\ Total\ consumption\ by\ heavy\ duty\ vehicles$

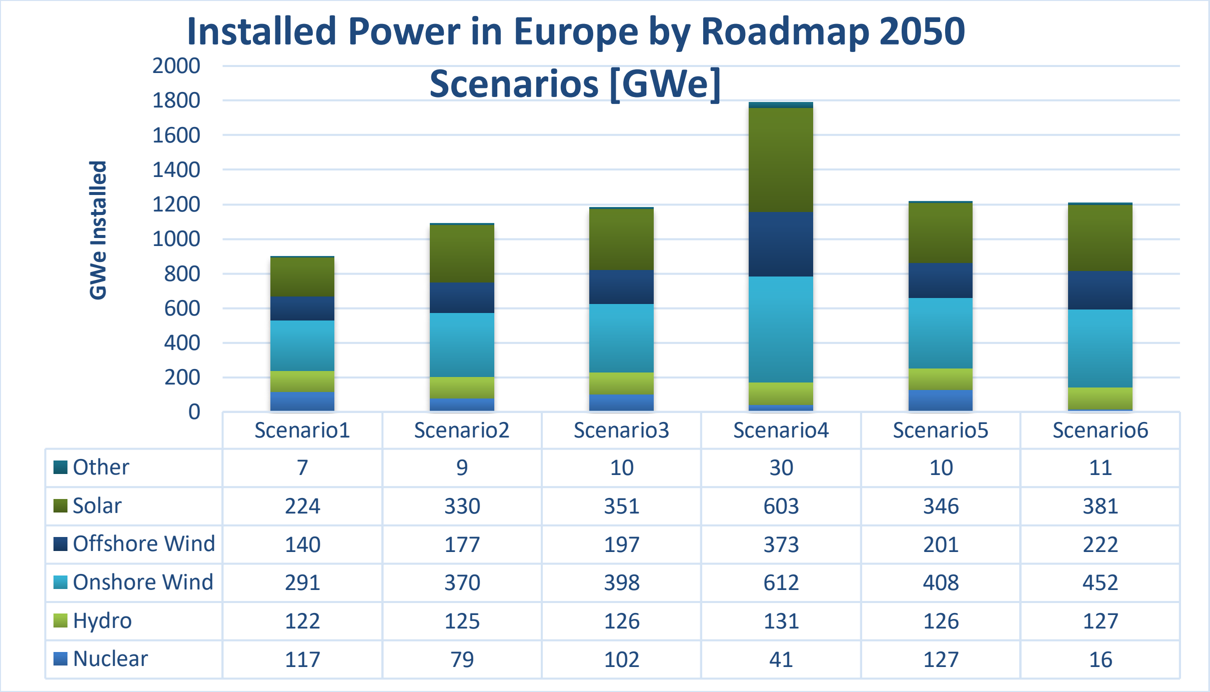
$$\begin{aligned}Charging\ Load\ Curve_{plugin} &= LDV_{consumption}\big((HR\ x\ Home_{curve}) + (WR\ x\ Work_{curve}) + (OR\ x\ Other_{curve})\big)\\ &+ \big(MDV_{curve} x MDV_{consumption}\big) + \big(HDV_{curve} x HDV_{consumption}\big)\end{aligned}$$

10.3. Appendix III. Electricity Supply-Demand

10.3.1. Electricity Generation

10.3.1.1. EU Roadmap 2050 Scenarios

From the EU Roadmap 2050 scenarios below, the High-RES, Scenario 4 has been chosen as base scenario



	Scenario1	Scenario2	Scenario3	Scenario4	Scenario5	Scenario6
■ Other	7	9	10	30	10	11
■ Solar	224	330	351	603	346	381
■ Offshore Wind	140	177	197	373	201	222
■ Onshore Wind	291	370	398	612	408	452
■ Hydro	122	125	126	131	126	127
■ Nuclear	117	79	102	41	127	16

Figure 37 – Installed power by EU Roadmap 2050 scenarios

10.3.1.2. EMHIRES Capacity factors

The hourly capacity factors throughout an average day have been calculated by identifying the two decimal range mode of the hour of the day throughout the 3 years. This mode range then has been averaged

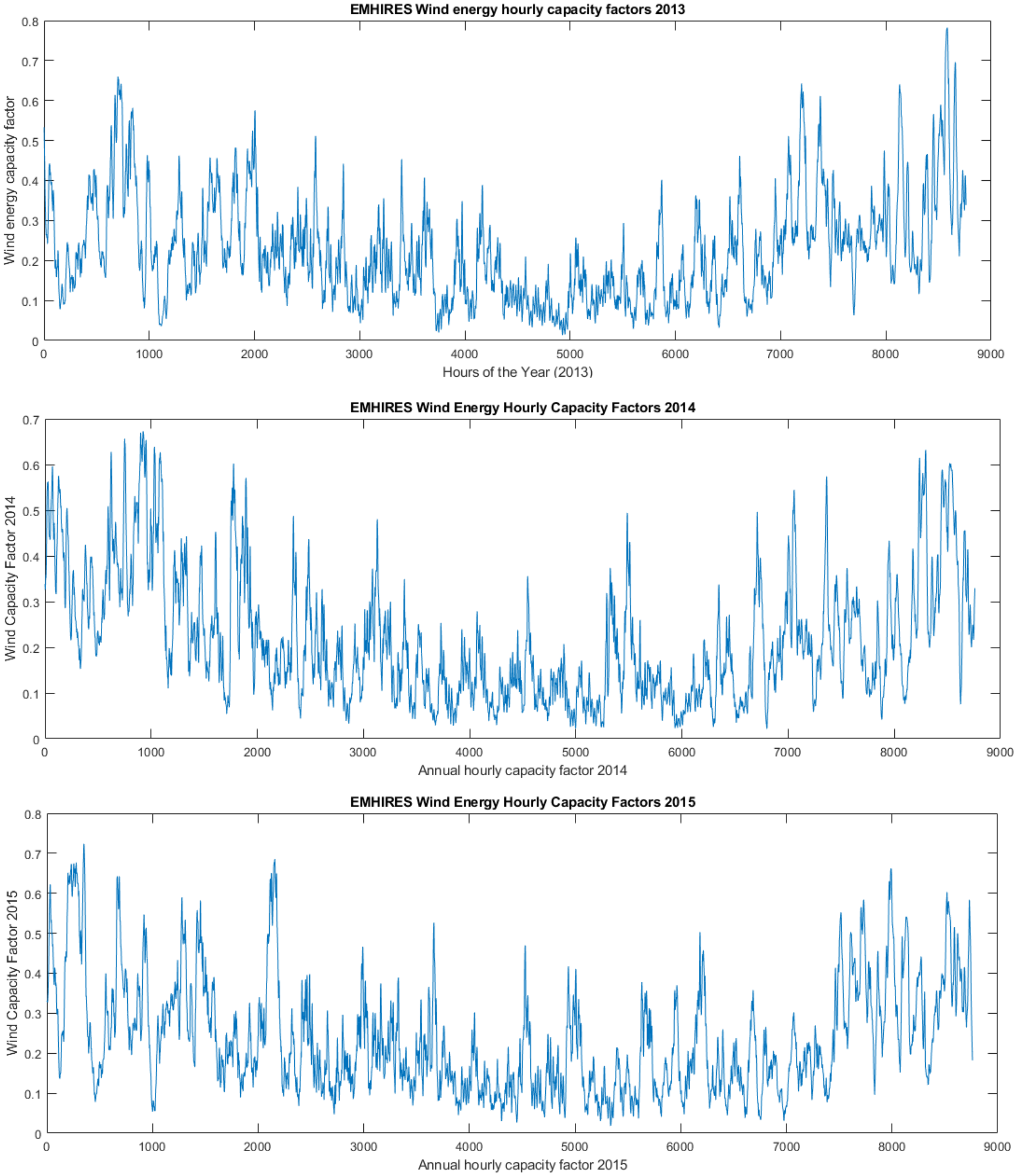


Figure 38 - EMHIRES wind capacity factors used from databased (year 2013, 2014 and 2015)

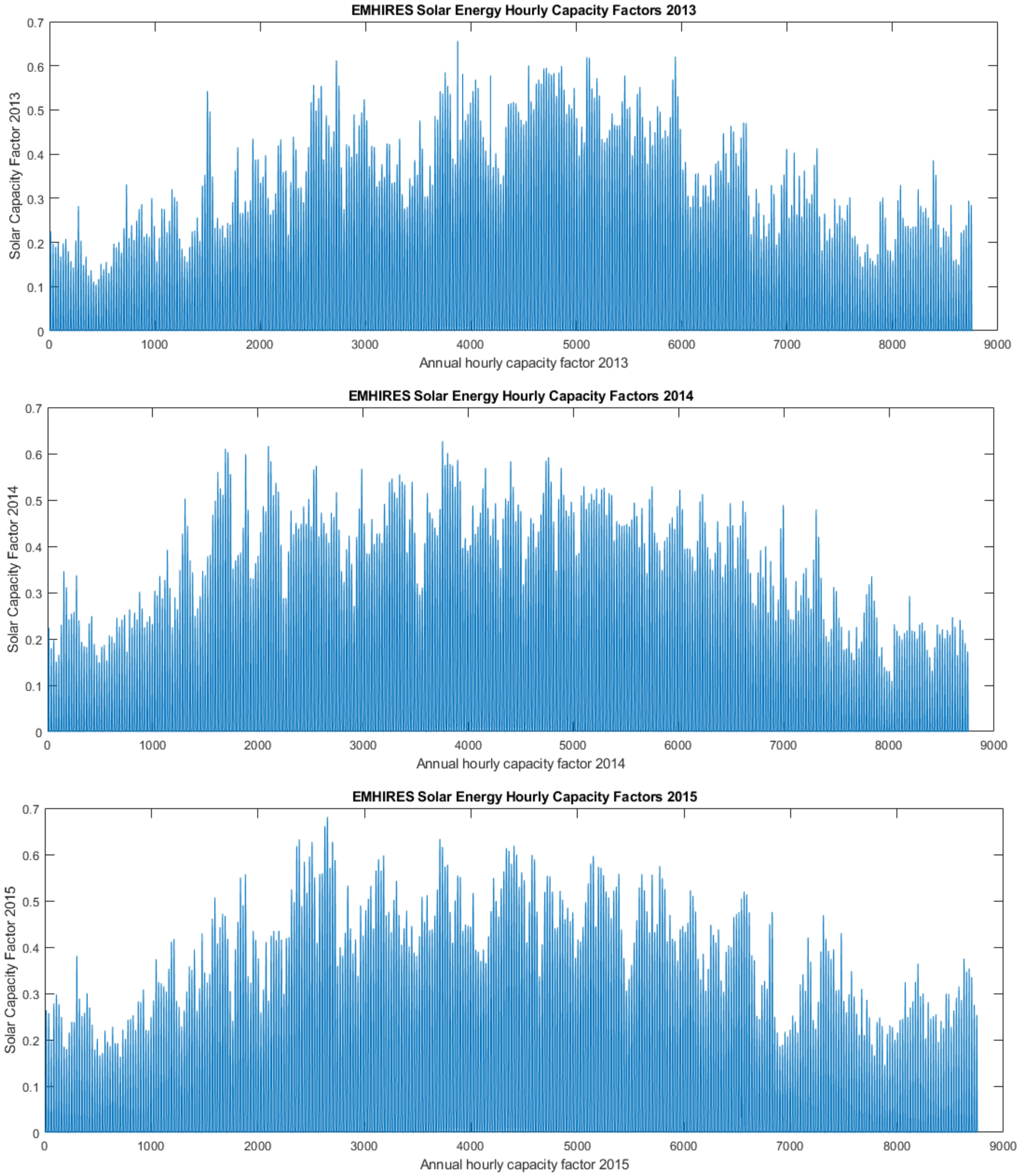


Figure 39 - EMHIRES Solar PV capacity factors used in the model from database (year 2013, 2014 and 2015)

10.4. Appendix IV. Supply demand matching score

10.4.1. Model Calculations

$$MatchingScore = 1 - 0.5\ x \left(\frac{\max\limits_{1 \leq h \leq 24} Supply_h - Demand_h}{\max\limits_{1 \leq h \leq 24} Supply_h} + \frac{\sum_{1 \leq h \leq 24} Supply_h - Demand_h}{\sum_{1 \leq h \leq 24} Demand_h} \right),$$

$$where: Supply_h - Demand_h \geq 0$$

10.4.2. Additional Model output

Peak and Energy deficit of different scenarios:

Table 18 – peak power deficit and peak energy deficit by scenarios

Scenarios	**Peak [GW] Deficit**	**Energy deficit [GWh]**
No EV	67	433
H100%	444	1992
H60%-W40%	343	1371
H40%-W30%-O30%	315	1244
S100%	192	925
WDPT	167	666
Optimized Hybrid	173	661

Table 19 – Total battery requirement and total grid energy storage requirement by scenarios

Scenario	**Total EV battery requirement [TWh]**	**Grid Electricity Storage [TWh]**
H100%	3.95	1.93
H60%-W40%	3.12	1.37
H40%-W30%-O30%	2.69	1.24
S100%	3.95	0.92
Min-WDPT	1.74	0.66
Mod-WDPT	0.37	0.66
Max-WDPT	0.00	0.66
Opt.Hybrid	1.15	0.48

10.5. Appendix V. Number of Chargers

Number of Chargers per EV:

$$\begin{aligned}&if\ Work\ Charging\ > 0, then\ 2\ chargers\ per\ EV,\\&elseif\ Other\ Charging > 0\ \&\ Work\ Charging = 0, then\ 1.5\ chargers\ per\ EV\\&elseif\ Other\ Charging\ > 0\ \&\ Work\ Charging > 0, then\ 2.5\ chargers\ per\ EV\\&Else\ 1.2\ chargers\ per\ EV\end{aligned}$$

$$Plugin_{total} = total\ number\ of\ vehicles\ x\ Chargers\ per\ EV$$
$$WDPT\ Road_{total} = Roadlength[km]\ x\ Coil\ per\ km\ x\ lanes$$
$$WDPT\ Vehicle_{total} = total\ number\ of\ evhicles\ x\ coils\ per\ vehicle$$

10.6. Appendix VI. - Global warming Impact [GWI]

10.6.1. Model equations

$$GWI[kWh\ charged] = \frac{\left(Charger_{total} x\ CO2eq_{per\ charger}\right) + (\sum Battery_{demand}\ x\ CO2er_{kWh\ battery})}{Total\ Consumption\ per\ day\ x\ 365\ x\ life\ time\ [years]} + \frac{CO2eq_{kWh\ electricity}}{\eta_{grid\ to\ wheel}}$$

10.6.2. Global Warming Impact Charger inventory

Detailed component inventories of a 6 kW on-board portion of wireless charger (on-WC), off-board portion of wireless charger (off-WC) and plug-in charger (PC) are summarized in the tables below.

Table 20 – Global warming impact model input

GWI		**WDPT road coil**	**WDPT board coil**	**Plug-in charger**	**Battery per kWh**	**References**
CO2 emission	tCO2	3.365	0.765	3.387	0.106	(Bi et al., 2015; Emilsson & Dahllöf, 2019)
Energy demand	GJ	76	18	75		(Bi et al., 2015)
lifespan	years	12	12	12	12	(Bi et al., 2015)

Table 21 – Summary of equipment requirement for chargers by Bi et al., (2015)

Charger Type	**Name**	**Quantity**	**Unit**
On-board portion of wireless charger (on-WC)	*Main components:*		
	Coil Plate	1	piece
	Power Conditioner and Protection, Output Rectifier & Filter (with Driver Circuit)	1	piece
	In-vehicle Cooling System	1	piece
	Control Board 2	1	piece
	Accessories:		
	Aluminum sheet	1701	g
Off-board portion of wireless charger (off-WC)	*Main components:*		
	Input Filter & Rectifier	1	piece
	Power Factor Correction (with Driver Circuit)	1	piece
	DC/DC Converter (with Driver Circuit)	1	piece
	High Frequency Inverter/Resonant Converter	1	piece
	Coil Plate	1	piece
	Off-vehicle Cooling System	1	piece
	Control Board 1	1	piece
	Driver Board	1	piece
	Accessories:		
	Aluminium Sheet	1701	g
	Steel Case	5000	g
	Extra Cables Connecting the Grid	5	meters
	LCD Flat Screen	1	piece
Plug-in charger (PC)	*Main components:*		
	Plug & Cable	1	piece
	Input Filter & Rectifier	1	piece
	Power Factor Correction (with Driver Circuit)	1	piece
	High Frequency Inverter/Resonant Converter	1	piece
	Transformer	1	piece
	Output Rectifier & Filter	1	piece
	Control Board 1	1	piece
	Driver Board	1	piece
	Cooling System (all in vehicle)	1	piece
	Accessories:		
	LCD Flat Screen	1	piece

Table 22- Inventory of Coil Plate (Either On or Off Board) (Bi et al., 2015)

Name	**Weight (g)**
Litz wire:	
Pure Copper Wire	2444.7
Enamel	24.7
Polyester	54.5
Other components:	
Capacitors (film)	169.9
Printed circuit board	80.0
Ferrite bars	4680.0
Total Weight	7453.8

Table 23 - Inventory of Plug & Cable for plug in charging (Bi et al., 2015)

Name	**Weight (g)**
Cables	1017.0
Electronic components (unspecified)	227.0
Glass fiber reinforced plastic (polyamide)	33.5
Glass fiber reinforced plastic (polyester)	556.7
Magnetic materials	15.0
Plug (connecting grid through socket)	42.6
Polycarbonate materials	537.5
Polymethyl methacrylate materials	7.3
EPDM foamed cord	2.8
Printed circuit board	56.8
Silicone materials	27.0
Steel	35.0
Tellurium copper	38.2
Thermoplastic Elastomer Compound	58.3
Total Weight	2654.6

Appendix 6.2 – GWI result table

Table 24 – Output results of GWI

Scenarios	**GWI of production gCO2eq/kWh charged**		
	Chargers	**Battery**	**Electricity**
H100%	17.46	34.14	104.00
H60%-W40%	29.1	26.87	104.00
H40%-W30%-O30%	32.00	23.24	104.00
S100%	17.46	34.14	104.00
Min.WDPT	17.04	15.09	109.50
Mod.WDPT	37.02	4.97	109.50
Max.WDPT	118.56	0.00	109.50
Optimized Hybrid	22.43	10.36	106.40

10.7. Appendix VII. Lithium and Copper Requirement

Table 25 – Most important input data of Copper vs lithium model

Input Variables	**Unit**	**Quantity**	**Reference**
Copper per WDPT charger	g/piece	2444.7	(Bi et al., 2015)
Copper per plug-in charger	g/piece	1017	(Bi et al., 2015)
Lithium per kWh	g/kWh	781	(Zackrisson et al., 2010)
GWI of copper	gCO2eq/g	2.31	(Manshila et al., 2018)
GWI of lithium	gCO2eq/g	2.63	(Hao et al., 2017)

Model Calculations:

$$Copper_{total}[kg] = Charger_{total}\ x\ copper_{per\ charger}[kg]$$
$$Lithium_{total}[kg] = Battery_{demand}[kWh]\ x\ Lithium_{per\ kWh}[kg/kWh]$$