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A FRAMEWORK FOR COMPARISON OF INTERNAL COMBUSTION ENGINE AND ELECTRIC VEHICLES CAR SHARING SYSTEMS

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ABSTRACT

The main purpose of this thesis is to study the differences between an electric car sharing service and an internal combustion engine car sharing service in terms of different performance parameters such as the percentage of users' unsatisfied demand, the total mobility emissions, the total time spent and total emissions in fleet management, the net profits derived from three months of service simulated in the respective cities, based on the results output by the simulator "Odysseus". On the environmental side, the research is focused only on the Global Warming Potential category estimation, measuring the greenhouse gas emission impact. "Odysseus" was built to model car sharing demand from data coming from real car sharing systems, it runs a simulation based on some input parameters, and as output provided tools to show the trend of different parameters, both space and time dependent. A linear model of fuel and energy consumption, recharging and CO_2 emissions has been added to reproduce realistically the total amount of charging needed for the whole fleet of vehicles, the amount of energy needed in mobility, how many time is needed to bring the car to charging, how many emissions have been released due both to the user mobility trips but also to the fleet management, given the total distance of each trip. Energy and emissions are considered on a Well-to-Wheel metric. In the simulations, four internal combustion engine vehicles have been chosen: a Volkswagen Golf, sold in 2018, available in gasoline, diesel, CNG and electric fuels and an LPG Opel Corsa from 2018. The city chosen are Turin and Amsterdam, simulated over a period of three months from October to December 2017. It is taken in consideration the energy mix of Italy and the Netherlands in 2017. Three different simulations have been performed. Considering the internal combustion engine fleet, the real positions of the charging points in the city has been recreated from OpenStreetMap, and the vehicle fleet size has been varied. Considering the electric fleet, both the real charging infrastructure and a placement of the charging poles based on the zones with the highest number of parkings, are taken in consideration, varying both the fleet size and the number of charging poles. An electric fleet does not bring any improvements in terms of user unsatisfied demand than a conventional engine one. If the car-sharing operator need to install an electric charging infrastructure based on the "Number of parkings" policy, for lower charging power, a higher number of poles is needed. The time spent in the fleet management by the workers in the electric fleet depends on the infrastructure: a more dense one would drop the amount of hours. A less dense one, may increase the time more than the one needed for gasoline and diesel. The LPG and CNG fleets are the one spending more time in management, due to the position of the stations in the city periphery. A conventional engine vehicle fleet, as expected, contributes more in polluting not only the global environment, but mostly the urban environment. The advantages offered by an electric fleet in car-sharing seems to be disproven by the lower profit of the electric fleet in a car-sharing service, both using the real infrastructure and the one built under the "Number of parkings" policy.

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1 INTRODUCTION

1.1 THE TRANSPORT PROBLEM

The transport sector is very important in cities, particularly on the largest one. In fact, the larger amount of trips taken have as origin and destination zones inside the city. It is also relevant the amount of trips that originate in the countryside, and has the city as a destination. This transport demand is explained for different reasons. The main one is that the city has a lot of attractions for people, such as workplace, since most of the systematic demand comes from people that use motorized vehicles to reach fast the place where they work, shops and leisure activities. These kind of trips are facilitated by motorized vehicles, since car is a fast and comfortable mode for the users. Since a lot of people choose the car as their main mode of transport to take their trips, a lot of traffic is suffered on the main city's traffic arteries. The high volumes of traffic goes together with the urbanization phenomenon started in the '50s, which resulted in an increase of the urban population density, and then in an increasing amount of people which need transportation services in urban areas.

Having large volumes of traffic in cities shows several drawbacks. The amount of traffic in cities often leads to congestion, which causes: huge waste of time waiting on the road, huge waste of fuel, dramatic increase of air and noise pollutions, derived from the engine noise, gas emissions (major contributing to the greenhouse phenomenon) and particulate matter emissions produced by large amount of traffic, jeopardizing the urban environmental quality, increased accident rates. Congestion also causes negative psychological effects on people, such as stress, fatigue, irritability, and rage. These effects are directly impacting on the people health, worsening their quality of life and quality of the activities they perform. As a result, congestion causes huge monetary costs. This phenomenon is setting particularly in large cities of developing countries, mostly because developing country needed more time to develop strategies for dealing with traffic problems.

1.1.1 Common solutions to the transport problem

In the largest cities around the world, city-planners tried to manage the problem of traffic by considering different solutions:

- Car-free zones, which are off-limits zones for cars, allowing to offer better access to services and a more efficient public transport. These are planned in the shape of:
  - Car-free cities, like the city of Venice, over which the car circulation is avoided to favor the on-water public transport
  - Pedestrian zones, many cities have streets or areas which are used only by the pedestrian, and in some case also by the cyclists.
  - Car-free neighborhoods, the plan of some city neighborhoods is to exclude traffic, benefiting non-ownership of vehicles
  - Car-free periods, during some period, the car city traffic is completely stopped. This is often promoted to improve the air quality and to induce people to change towards less pollutant transport modes (walk, bicycle, public transport)
- Congestion charging, which is a particular form of road pricing. The aim of road pricing is to charge the user of the additional cost produced to the other

users due to its road occupancy. Congestion charging tries to discourage road users to enter congested city areas by charging them with a fixed or variable (dependent on the congestion severity) monetary fee. This has been found to be time saving for travellers and positively decreasing the car ownership in the long period. However, a good design and implementation is needed, together with a global public acceptance.

- Traffic signals control, which are an effective tool to control traffic, achieving given objectives. The objective may consist in minimizing the travel delay, balancing at best the network capacity and managing queues. The traffic signals control impacts on the travellers' route choice.

- Low emission zones, which are areas on which is in force an access restriction to vehicles which are polluting more than a given threshold. Depending on the strictness of the threshold, the zones are classified in: low emissions zone, ultra-low emission zones, which have an extremely low threshold, and the zero emissions zones, in which any vehicle which is polluting is allowed the access to (only full electric vehicles, pedestrian, bicycle and electric public transport). The objective of these areas is to improve the air quality.

- Improvements to public transport and walking/cycling infrastructure, it is possible to reduce the city traffic by making the public transport more attractive, since it will induce a shift of mode from the car. In case of public transport, the service reliability is a very important factor for passengers. An other possibility would be to rely on inter-modality hubs, because only the undertaking of different modal choice may replace trips otherwise possible only by car. The provisioning of walking and biking infrastructures is important to encourage "slow" but "clean" modes instead of cars. These infrastructures are reinforced by the use of the technology (especially smartphone apps) to promote their use.

1.1.2 Future management of the transport problem

In Fulton Lewis, 2017 is written about three revolutions in urban transportation that may significantly impact the mobility in the future:

- Electrification, referring to the recent thrust in the diffusion of electric vehicles in the market.

- Automation, referring to the development of the technologies according to different levels, allowing the vehicle to be aware of what is happening on the short distance, and eventually to correct the driver behaviour to prevent accidents, up to the fully autonomous (self driving) vehicles.

- Shared mobility, which is "an innovative transportation strategy that enables users to gain short-term access to transportation modes on an 'as-needed' basis" Cohen and Shaheen, 2016. The philosophy may be branched into different services according to the mode in question: car-sharing, bike-sharing, ride-sharing (car pooling and van pooling), and on-demand ride services.

1.2 OBJECTIVE

The main contribution of this thesis is focused on the electrification and on the sharing mobility, in which is dealt the problem of the electric vehicles inclusion in the car sharing service, the environmental improvements and possible drawbacks, the quality of service offered to the users, the costs in maintaining the service. The main purpose of this thesis is to study the differences between an electric car sharing service and an internal combustion engine car sharing service in terms of different performance parameters, based on the results output by the simulator "Odysseus". In order to do so, the research may be deepen from two point of views: on the technological side and on the environmental one. The technological part would enlight the technical and technological improvements that an electric powertrain bring with respect to an internal combustion engine powertrain. This topic may be only developed following general theoretical considerations, both because of the huge amount of details needed to build a realistic model of an electric and an internal combustion engine powertrain, and because, as it was previously developed "Odysseus", the simulator was not thought to model the realistic behaviour of the car in its physics, motion dynamics and thermodynamics aspects, since the resulted model would be too complex. Instead, the simulator will do its job basically considering some few average parameters, which allows to reproduce in a fairly realistic way both the car and service dynamics.

The other aspect is the sustainability one, in which the impact due to the use of an electric and an internal combustion engine vehicle is studied. As shown in Wilken et al., 2020, the impacts can be summed up over different criteria grouped in the "Environment & human health" category, such as:

- Global Warming Potential (GWP), expressed in gCO_2eq/km, which measures the negative impact on the global climate due to the increased greenhouse effects
- Terrestrial Acidification Potential (TAP), expressed in gSO_2eq/km, measuring the negative impact on the natural and built environment
- Metal Depletion Potential (MDP) and Fossil resources depletion potential (FRDP), expressed respectively in gFe-eq/km and g-oil-eq/km, measuring the negative impact on the natural resources
- Photochemical Oxidant Formation Potential (POFP), expressed in g-NMVOC/km, measuring the negative impact both in reducing the thickness of the ozone layer and on the human health
- Particulate Matter Formation Potential (PMFP) and Human Toxicity Potential (HTP), expressed respectively in g-PM10 eq/km and g-1,4-DB eq/km, both measuring a negative impact on the human health

In this thesis case study, regarding emissions, the research is focused only on the Global Warming Potential category, measuring the greenhouse gas emission impact. A full and detailed analysis of all the impact categories would be too difficult, in the sense that the model to represent each category (especially particulate matter concentration) would be too complex, it would depend both over time and space and no data available online have been found. Considering the actual implementation of the simulator, this would imply a complete review of its development. Summarily, the final objective of the thesis is to develop an analysis of the service performances, sustainability and costs between a car-sharing service based on internal combustion engine vehicles and one based on electric vehicles.

1.3 STATE OF THE ART

The data-driven comparison of car sharing services based on internal combustion engine and electric vehicle on a simulator seems to be an undiscovered path in literature. In fact, no previous works have been found on this particular topic. However, many different comparisons, not data-driven, between internal combustion engine and electric car sharing services have been studied. Shaheen and Cohen, 2008 analyzes the key factors that characterize worldwide car sharing operations, which includes: member-to-vehicle ratios, market segments, parking approaches, vehicles and fuels, insurance, and technology. This is performed by interviewing different experts coming from different countries all over the world.

Luan et al., 2018 integrates the results from some researches related to the environmental impact of car-sharing. The impacts are illustrated from four aspects. First, the improved mobility of vehicles reduces the parking demand, meaning that parking space and traffic facilities are saved. Then, the convenience and the flexibility of car sharing have negative impacts on the purchase of private cars. In addition, with more electric cars joining into car sharing, the automotive exhaust product tends to be reduced. Car-sharing has two challenges that need to be strengthen in the future: more efficient vehicle relocation and an improved interaction of car sharing service with public transport.

Chen and Kockelman, 2016 examines the life-cycle inventory impacts on energy use and greenhouse gas (GHG) emissions as a result of candidate travelers adopting car-sharing in US. Candidates considered are who is residing in dense urban neighborhoods with good access to public transit and travelling a short distance in private vehicles (10% US population). The analysis considers impact of car-sharing cradle-to-grave on vehicle ownerships, travel distance, fleet fuel economy, parking demand, and alternative modes. Results suggests that current car-sharing members reduce their average individual transportation energy use and GHG emissions by 51%. Collectively, these individual-level effects translates to roughly 5% savings in all household energy use and GHG emissions. These are due to modal shifts and avoided travel, followed by savings in parking infrastructure demands and fuel consumption. Net savings are expected to be 3% across all US household, when indirect rebound are considered (savings from car-sharing are spent in other goods or service wasting energy and emissions).

Jung and Koo, 2018 examines the GHG emission impacts resulting from shifts in transportation mode to car-sharing. Using a mixed logit model and a binary logit model, consumer preferences and the probability of choosing car sharing or forfeiting ownership when using car sharing services were analyzed. To estimate the environmental impacts, the modal shift proportion and reduction in vehicle ownership resulting from the introduction of car-sharing services were considered, and estimated using a binary logit model. Moreover, individual characteristic variables, like more flexible services as one-way and delivery options, are included when estimating user preferences, replacement rate and changes in mobility associated with the adoption of car sharing. Results shows that the extra GHG emission resulting from the shift from PT or privately owned vehicle outweight the GHG reduction due to unpurchased or unproducted vehicles. It is shown that a decrease in car ownership did not correspond to a reduction in the number of miles traveled, which increases among non-car owners. The analysis of car sharing vehicle preferences indicates that additional services, like vehicle delivery and one-way trip options, would lead to an increases in vehicle travel. Then, a larger proportion of EVs among car sharing fleets is important to reduce the negative environmental impacts of car sharing. To reduce emissions in transport through car sharing, it is important to create an environment in which more people could choose an EV. In order to do this, it is important to achieve a greener mix of electricity generation options.

Wilken et al., 2020 presented an approach that assesses various types of electric vehicles against internal combustion engine vehicles over a number of criteria from different sustainability dimensions. The results were integrated and aggregated across a wide range of weighting and preference-threshold scenarios. The assessments showed that battery electric vehicles charged with renewable electricity appear generally more sustainable than their internal combustion engine vehicle counterparts and battery electric vehicles charged with electricity from mixed sources. Fuel cells electric vehicles do in general perform worse as compared to all other alternatives.

Fournier et al., 2017 analyzes if a shared autonomous Electric Vehicle fleet can meet the economic, ecological and social limits, and at the same time can satisfy the current requirements of privately owned Internal Combustion Engine Vehicles. A model has been developed to compute the fleet size and to simulate the impact on mobility in Berlin. The collected data were used to calculate the cost effects, the energy consumption, the carbon footprint of different shared autonomous electric vehicles in comparison with privately owned ICEVs. The approach shows that the system of a shared autonomous EV fleet could lower journey time, reduce CO2 emissions, free up parking spaces in urban areas and generate cost benefits for customers.

IEA, n.d. the report examines key areas of interest such as electric vehicle and charging infrastructure deployment, ownership cost, energy use, carbon dioxide emissions and battery material demand, assessing the technologies and policies that will be needed to ensure that EV battery end-of-life treatment contributes to the fullest extent to sustainability and CO_2 emissions reductions objectives. Finally, it analyses how off-peak electricity demand charging, dynamic controlled charging (V1G) and vehicle-to-grid (V2G) could mitigate the impact of EVs on peak demand, facilitate the integration of variable renewables and reduce electricity generation capacity needs.

Luna et al., 2020 investigates the impacts of an e-car-sharing scheme in carbon emissions and in electric vehicle adoption using a system dynamics modeling approach. The VAMO scheme located in Fortaleza, Brazil, is studied, as the first e-car-sharing scheme in the country. Two policies combined are studied: a VAMO planned growth policy and a retirement policy for conventional vehicles. The retirement policy in combination with the VAMO incentive policy obtained the best results in our simulations, reducing 29% of CO2 emissions and increasing 36% electric vehicle adoption, when compared to the business-as-usual scenario.

Rietmann et al., 2020 presents a long-term forecast of the electric vehicle inventory in 26 countries across the five continents by means of a logistic growth model. Using sales data from 2010 to 2018, predictions were made for these countries until 2035. It claims that 30% of the overall passenger vehicle fleet will be electric vehicle in 2032. Electric vehicles growth predictions were then analyzed in terms of sustainability impact. It is shown that reduction of CO2 is a possible scenario with the predicted growth, given that the countries invest in renewable energy sources. Given the current energy mix, worldwide CO2 emissions will rise until 2035. Then, it is discussed how to achieve the electricity production needed to meet the growing demand. The production of electric vehicles batteries will be the bottleneck of the electric vehicle development.

Rievaj and Synák, 2017 focuses on the comparison of the amount of emissions produced by vehicles with a combustion engine and electric cars. The comparison, which is based on the Life Cycle Assessment factor results, indicates that an electric car produces more emissions than a vehicle with combustion engine. The implementation of electric cars will lead to an increase in the production of greenhouse gases.

Biondi et al., 2016 which gives two main contributions. First, it is formulated a stochastic facility location problem for the optimal deployment of the car sharing stations to provide probabilistic guarantees on parking availability. Second, it is analysed the energy demands of the car sharing system under different deployment scenarios and charging technologies, including power sharing. Results show that most stations require a small capacity (less than four parking slots) but a few large stations (up to 15 parking slots) are necessary to provide guarantees on parking availability in areas with large car turnovers. Furthermore, results indicate that power sharing may have a negligible impact on charging power peaks when fast charging technologies are employed because charging periods are quite short.

Dell'Amico et al., 2020 proposes a methodology to assess the impact of shared light electric vehicles in urban areas. The approach consists in a comparison between the emissions and costs of travels carried out by traditional cars fueled by gasoline and those performed by shared light electric vehicles in six European cities (Bari, Berlin, Genoa, Malaga, Rome and Trikala). Based on the number of kilometers travelled and a set of conversion factors, the environmental impact and the cost of fuel/electricity are assessed for the two transport modes. Data analyzed revealed that the travel time of L-category electric vehicles might be longer compared to cars. Furthermore, by replacing car trips with L-category electric vehicles, CO2 emissions could decrease >70% in a year, reducing 6082 kg of CO2 emissions.

Other studies have been considered for retrieving the data and the strategies needed to evaluate the metrics performed. Noussan and Neirotti, 2020 studies the energy mixes to produce electricity over different countries. It is performed an analysis of the CO2 emission due to the electricity production (gCO2/Kwh), the variability of the CO2 emission on daily, monthly and yearly analysis. **prussi_2020** belongs to a series of JEC Well-To-Wheel related reports where the process of producing, transporting, manufacturing and distributing a number of fuels suitable for road transport powertrains is described. The JEC Well-to-Tank v5 assesses the incremental emissions (marginal approach) associated with the production of a unit of alternative fuel, with respect to the current status of production. Gupta et al., 2017 carried out a comparative study of tailpipe and well to wheel emissions from EVs and ICE vehicles in India. Three vehicle categories namely: Heavy Duty Vehicles, Passenger cars and scooter, and four major pollutants, namely: CO_2 , NO_x, PM and CH (hydrocarbons) are taken into consideration. It has been found out that there has been continuous rise in emissions in terms of tonnes of CO_2eq/MWh up to the year 2012-13, but it became constant for following years. This was mainly due to increase in renewable energy sources for electricity generation. After calculating the emissions/km for different vehicle categories it has been concluded that over all emissions from internal combustion engine vehicles in India are still much more as compared to their counter parts in electric vehicles.

1.4 THESIS ORGANIZATION

The thesis has been organized in the following chapters:

- In Chapter 2 the combination of the car-sharing service and the electric vehicle use has been described, with their improvements to the mobility efficiency with respect to the use of a private vehicle based mobility, their environmental drawbacks due to the incoming massive production of electric vehicles, the upcoming technologies helping to increase even more the service efficiency, and the different service characterizations around the world.

- In Chapter 3 the simulator "Odysseus", with which the results have been produced, is described in its main functionalities, structure, potentialities and limits. Even if the simulator is in continuous evolution, here are presented the "historical" principles, which has been though following its initial development in Ciociola, Mellia, et al., 2019

- In Chapter 4, the work done on the simulator, such as the additions, the improvements and their motivations are here explained. In particular, will be explained the consumption model, developed for a generic vehicle acting in the simulator, the recharging model, which estimates the time the vehicle spends in recharging before being again operative, the emissions and energy model which tries to estimate the environmental impact due to the vehicle usage. Finally, the costs model used to evaluate the economical effort in maintaining the service is described

- In Chapter 5 are shown the results obtained by applying the developed models in a car-sharing scenario using mobility traces from real car-sharing companies around different cities around the world. Here are compared finally the car-sharing services with fleet of different fuel type, but considering a similar sample vehicle available on the market.

The topics described in chapter 3 do not come from the contribution of this thesis, but from the software author Dr. Alessandro Ciociola in its thesis, together with the E-Mobility research group in SmartData@Polito. These results are reported only to explain briefly the software. The contribution of this thesis is explained in chapter 4 and 5.

2 CAR SHARING AS A SOLUTION

2.1 MOBILITY TRENDS

People often travel for different reasons, some of which persist after millenias of human living on the Earth: the need to find resources and to socialize. In the earliest periods, the amount of time people spent in travelling was relatively constant, up to the moment in which the human beings developed faster mean of transport. From that moment, the distance travelled by human beings on average has increased more and more. This was particularly evident after the invention of the motor car. In fact, Millard-Ball and Schipper, 2011 declares that, after the 1950s, the distance travelled by motorized mode increased and became very rapid after the 1970s in the developed countries. GDP (Gross Domestic Product) growth has been the principal motivation of the increase of travel demand, meaning that a greater prosperity translates into a higher car ownership. From the early twenty-first century there are signs of saturation of the total passenger travel. The saturation, as shown in 1, occurs when the GDP is in the range between 25000$ - 30000$ in most country, and 37000$ in the USA.

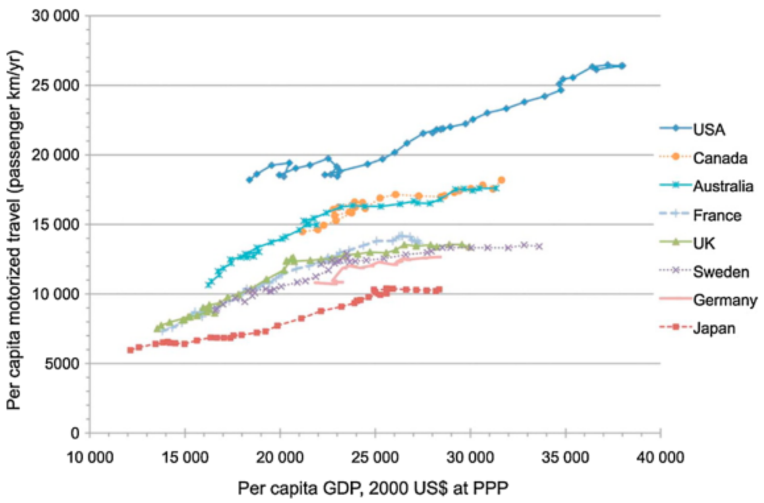


Figure 1: Total motorized travels 1970-2007/08 Millard-Ball and Schipper, 2011

Today is clear that the attitudes towards mobility are changing, especially on the dependence on the car and on the people's changing lifestyles. Changing in mobility are largely driven by developments in different technologies. These are including driver assistances (Lane Departure Warning, Park Assistant, etc.), communication capabilities (use of Wi-Fi, cellular and Vehicle-to-Infrastructure (V2I) technologies). In particular, the developments in the Information and Communication Technologies (ICT) are mainly driving changes in mobility. The communication technologies are basing their potential on the proliferation of mobile phones, the diffusion of navigation systems, and Internet. These technologies are converging together in the smartphone, which is commonly used in the developed world. The smartphone allows to provide informations to travellers about the current state of network and services, like timetable of the public transports, which line is in delay, how much delay they reached during the trip; at the same time, it provides access to travel services, like buying tickets, etc. The presence of a navigation system would allow route guidance to the destination.

Different are the current and developing trends in mobility:

- Decline in car ownership in the developed countries; there are proves that car ownership has begun to level off in many developed countries, with car ownership dropping particularly among younger people and millennials. In the past, the car-ownership saturation was interpreted as everyone desires to have a car, but instead, the reality shows that congestion is reducing the appeal of private car in many areas. This produces a shift from car ownership towards car-access services

- The emerging of electric vehicles in the motor market; the adoption of electric vehicles contributes to the increase of the air quality

- The emerging of "cars-on-demand"; in L. and Robyn, 2016 is defined as a form of transit involving collaborative use of the car which is based around ride-sharing / lift-sharing (car-pooling), and car-sharing. Car-sharing is considered to be hugely important, since it can considerably reduce car ownership and reduce the pressure on parking space. Car-pooling is when one or more groups of people travelling uses a single vehicle at the same time. It has the potential to sensitively reduce the number of vehicles on the road. Car-pooling tend to be more appropriate for long distance trips, especially for commuting, while the car-sharing is more appropriated for shorter journeys.

- The development of autonomous vehicles. Many countries are developing the prototype of the self-driving vehicle, but some points are still critical and not yet overcome, which are the public acceptability of the autonomous vehicle, especially in terms of safety and reliability, and the problem of "liability" (who is guilty in case of accident). The autonomous vehicle is considered to be a "disruptive" technology, since can radically alter how the transport system works.

- The potential shift towards "Mobility as a Service". The principal idea behind Mobility as a Service (MaaS) is that transport and mobility is not viewed as a physical good to purchase, but a customized service. This service would be available on demand and incorporating multiple transport services from cars to buses to rail, with a demand-responsive and flexible transport. The result is the need reduction of vehicle ownership. However, a good MaaS is not an alternative choice to public transport. Instead, it would strengthen the role of public transport and shared transport.

- Developments in teleworking and virtual mobility. The diffusion of affordable broadband internet access for both private residences and public spaces, through a Wi-Fi technology, has eased and encouraged the growth in telecommuting, in which workers can be operative from home without being physically present in the workplace. The growth in telecommuting has the potential to radically reduce the number of people who travels every day for commuting purposes. Since most traffic of the peak hours comes from commuting travellers, the teleworking could reduce significantly the probability of congestion. At the same time telecommunications make possible to maintain geographically-distant social and business relationships, meaning that people may then travel further when they meet face-to-face. Then, teleworking may contribute to a shift of travel patterns than a reduction in the overall traffic demand.

2.2 THE CAR-SHARING ASCENT

Car-sharing is a model of car rental in which users take the vehicles for a relatively short time from an operator who owns a fleet of vehicles and takes care for their maintenance. People in possession of a private car usually do not exploit them to transport much people over long distances, but most cars are used to transport a single person for less than an hour per day. Instead, as stated by Shaheen and Cohen, 2008, car-sharing can increase significantly the utilization of cars and then reduce the costs of vehicle travel both for individuals and society. In particular, it can reduce the number of cars on the road, by accomodating up to 15 prior car owners into one car-sharing vehicle. At the same time, the smaller size of the car-sharing fleet is exploited more to accomodate the same mobility demand. Further than that, the adoption of a car-sharing service, and the consequent reduction of car ownership, can increase the parking availability and reduce the parking demand together. In fact, in a car-sharing vehicle, the share amount of usage time may be higher than the one of parking time, while instead for a private car usually the contrary happens, where the car much of the time is spent parked.

People owning a vehicle are more inclined to use their own vehicle they bought, than to prefer a car-sharing rental option. This is due to the fact that this kind of people, if they need to move, they are assured to find their vehicle available to bring them to destination. Instead, relying on a car-sharing service, does not guarantee the user to find an available vehicle when needed. This makes people owning a car to be reluctant to renounce at the vehicle ownership in favor of a car-sharing service, even if incentives are offered. Apart from that, car-sharing services are attractive towards people that occasionally use a car to move and do not want to encounter the problems related to owning a car, like the vehicle purchase, paying for an assurance, ownership taxes, maintenance and depreciation. Since a car-sharing operator can offer different kind of cars, the user can choose the one which prefers to perform different kind of trips. Moreover, the parking availability is a key factor for people deciding to use their own vehicle to move, the lack of parking slot may induce a negative feedback, inducing them to see a car-sharing service to be more attractive than to own a private vehicle, since a car-sharing service would potentially free parking slots. As stated by Skinner and Bidwell, 2016, the freed parking slots may be then reallocated strategically to promote car-sharing and make cities more liveable and attractive as destinations.

The car-sharing service is most diffused where there is a good implementation of the public transport service, suggesting that a good car-sharing service should not be put in competition with the public transport service, instead it should be organized to be complementary with public transport. Given that, car-sharing should not be cheaper than public-transport, public space should be correctly segmented and the placement of the charging stations should be planned smartly. Speaking about a correct segmentation of spaces, if the stations are large-sized, locating them in limited space in the city could be problematic, so the service should rely on the access to on-street parkings. In fact, since the road space is limited in many cities, providing additional space for car-sharing parking infrastructure is tough. The access to on-street parkings is a high priority for a car-sharing service, such that the lack of on-street parkings could limit the service expansion.

The public authorities have to assist the car-sharing operators by helping them in reaching their goal with a proper regulation of the urban territory. As a matter of fact, in order to facilitate the service survival, the local authorities must grant exclusive use of portions of public spaces to a private business. As explained by L. and Robyn, 2016, the public involvement in the developing of a car-sharing service (often established by private entities), leads likely to benefit to society. As stated in Zhou, 2014, some public policies and incentives look up for mechanisms that change the people behaviour, also called "soft measures", such as the distribution of brochures, maintenance of web-services that provide informations, subsidies for employees in using car-sharing. Other incentives include physical measures in terms of concession of public land space for parking or stations, as it has been stated above.

That is said because car-sharing allows to perform trips which otherwise would be possible only with the use of a private car, and at the same eliminating the parking need. That's why car-sharing can be used as a travel option. The result is that people used to private car tend to use car-sharing as a substitute of private car, by selling, shedding the actual private car, or postponing the purchase of a new one, while people used to public transport often use it together with the car-sharing service in order to compensate where the public transport lacks in service. In sum, as stated by Cohen and Shaheen, 2016,Martin et al., 2010,Shaheen, Cohen, et al., 2017, users decrease in kilometers travelled by vehicle, an increase of the other modes to end up the commuting trips, by biking, walking, by public transport. Ideally, car-sharing may be perfectly integrated with public transport, in order to maximize the user benefits. People usually may argue that shifting from public transportation to individual modes thanks to car-sharing, increases the traffic congestion, emissions and distance travelled by vehicle (VKT). However, on literature, there is no evidence of those negative effects.

Car-sharing services have been diffused particularly in the developed world, since the high density of population, which is typical in the developed world, gives a higher number of potential users. Moreover, a more heterogeneous population in terms of living and working patterns may give advantages to the practical operations of car-sharing, such as increasing vehicle availability and vehicle distribution (people with similar temporal and spatial habits would probably pick up cars at the same time, reducing more the vehicle availability in a given moment, and concentrate more vehicles at the same zone in the city).

In the development history of the car-sharing service, two principal models have been settled out:

- the one-way car-sharing, also called station-based car-sharing. In this type of service, the user picks up a vehicle from a station nearby and, after the trips, releases it to an other station, which is next to their destination. As stated in Boldrini and Bruno, 2017, in the station-based service, vehicles' positions are often unbalanced over time, meaning that the vehicles are parked, after the trips, in zones where they are not useful anymore for trips by other users. Then, workers may have hard time in relocating the vehicles in strategic positions.

- the free-floating car-sharing. When this service is available, the users can pick up a vehicle and leave it after the trip at whatever legal parking place available in the operative area of the service. Users generally locates an available vehicle and book it through the use of an application on the smartphone. The great flexibility of the free-floating service makes car-sharing the optimal choice to perform the first or the last mile of a multimodal trip. Such a characteristic makes this second service type more attractive to users than the station-based service and other service types.

- the peer-to-peer car-sharing. In this service, users make their private vehicles available for rentals for a short period of time. The operator charges commission on transaction but does not have the overheads of vehicle acquisition, maintenance, etc., as a normal car-sharing operator have.

The current trend for car-sharing operator is to offer both free-floating and station-based trips within one single tariff.

2.3 THE ELECTRIC VEHICLE ROLE IN CAR MARKET

Before the COVID-19 pandemic exploded in 2020, when the car market has seen its sellings hugely falling down, due to the progressive mobility stop imposed by the countries governments to limit the virus diffusion, there has been a rapid growth of vehicle production from the half of the last century. As seen in Figure 2, the production has risen from the 11 million cars per year in 1961, to the 90 millions in 2015. It is noticeable, in Figure 3, that from the previous decade, China is the largest car producing country.

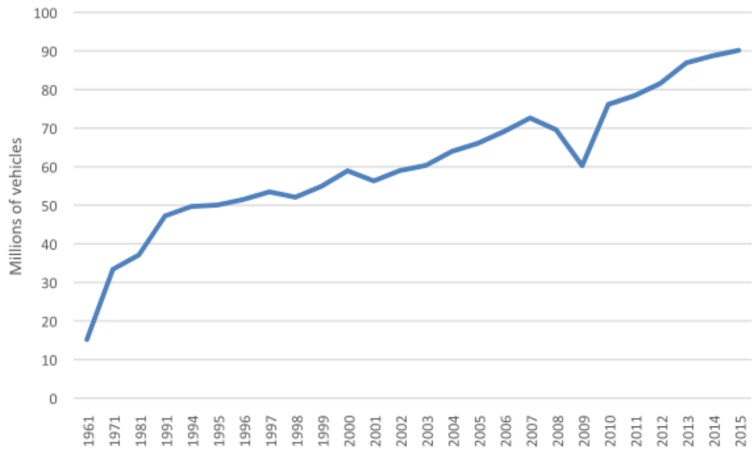


Figure 2: Total world vehicle production

In 2014, as stated in this table[1], 1.2 billions of cars have been estimated in the whole world, 95% of which classified as light-duty vehicles, including: passengers cars, trucks and weighting up to 3.5 tons. The majority of these vehicles, around 96% of the total light vehicles, uses a conventional internal combustion engine powered by gasoline, diesel, LPG (Liquid Petroleum Gas) or CNG (Compressed Natural Gas). Instead, vehicles powered by alternative power sources such as electric batteries or hydrogen fuel cells represents a small portion of the global vehicle fleet. Given that, a relevant share of hybrid electric vehicles is present. Hybrid vehicles combine an internal combustion engine to a small electric powertrain to increase the efficiency and performances. There is an increasing share of vehicle using the Start&Stop technology, which automatically shut the vehicle down when stopping in the traffic for increasing the fuel economy and reduce drastically the pollutions when stuck on traffic. Finally, there are the plug-in electric vehicles, which include both PHEV (Plug-in Hybrid Electric Vehicle), which are hybrid vehicles whose battery can be recharged by a power plug, and BEV (Battery Electric Vehicle), powered only by rechargeable batteries.

In the development history of motor vehicle, the internal combustion engine had not always been the dominant powertrain of market vehicles. A said by Hoffman, 1967, at the beginning of the twentieth century, the most diffused vehicles in the USA on the road were electric-battery powered, more than the gasoline or steam powered one. However, the important limitations of power storage in the battery, make them leave the scene quite soon. In fact, since the rise of the first mass production vehicle born thanks to Henry Ford, the Model T, gasoline powered, and the outstanding diffusion it had during that period, the internal combustion engine powertrain dominated almost everywhere from that moment. Hoffman, 1967 also said that only in the '60s and '70s there was an increasing interest in electric vehicles, mostly due to the increased pollutions and the increase of the oil prices in that period. However, the development of the internal combustion engine was so large,

1 https://www.oica.net/wp-content/uploads/total-inuse-2014.pdf

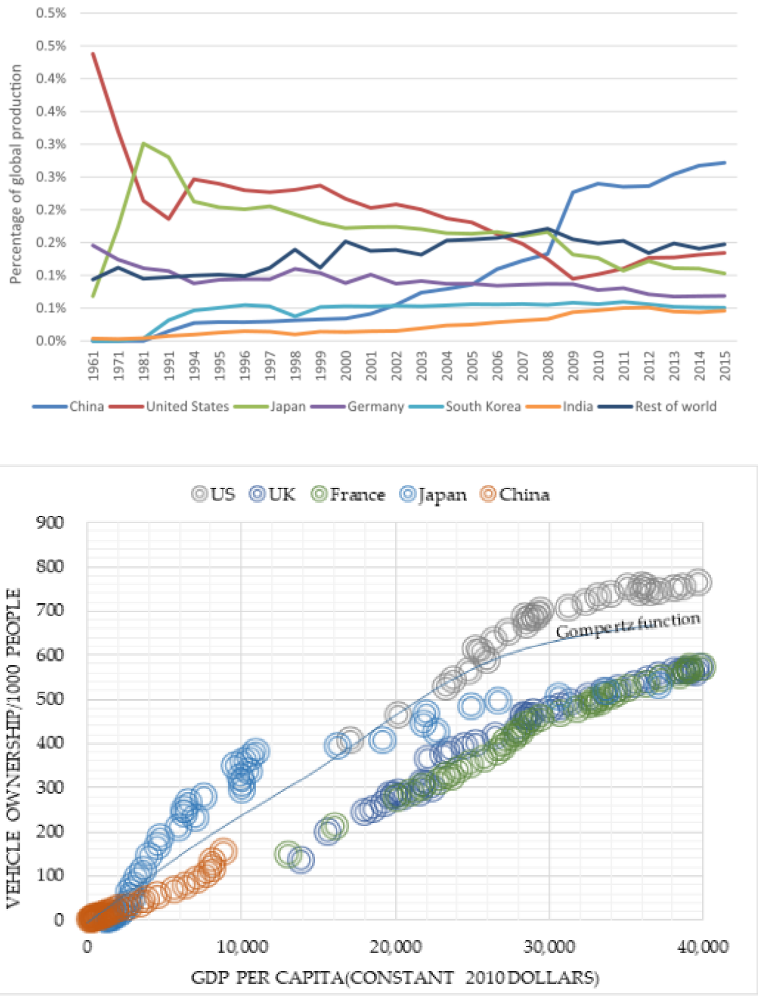


Figure 3: Vehicle production per country and ownership (Li et al., 2019)

that electric vehicle could simply not compete in terms of price and performances, and they had been forgotten again. There was a sudden interest in the '90s, but again customers were not satisfied again due to limited range and functioning, high cost, due to a limited evolution in the battery technology.

In the present days, there has been a technological advances and evolutions in the social context of car mobility, as stated in Dijk et al., 2013. In particular, aimed policies was developed to aim at contrasting the climate change phenomenon. These were enforced by establishing targets for emissions of greenhouse gases in events such as the Kyoto Protocol. After the Kyoto Protocol, many green and fuel-efficient vehicles were commissioned in the most developed countries. This allowed to provide many investments in research and development, needed especially to increase the battery range, since manufacturers recognize that the battery technology is critical to improve the characteristics of the electric vehicles. To remedy, manufacturers have tighten ventures with battery manufacturers. The actual state of art of electric vehicles makes them slightly more affordable to the public in terms of cost, but also their range is exponentially increasing. Moreover, the today city transport plans often foresee much money to invest in the building of an efficient charging infrastructure, which is fundamental for the resilience and success of electric vehicles.

The Figure 4 shows that in the last years, the production of electric vehicles has increased more and more in all the most developed countries, in particular China being the country having the most important stock of electric vehicles in the world.

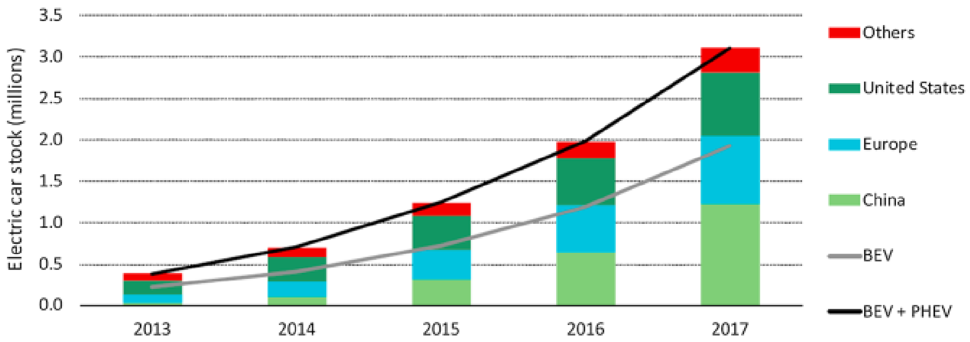
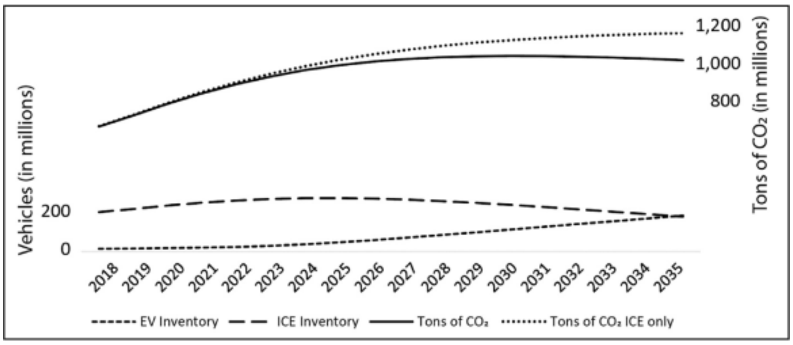
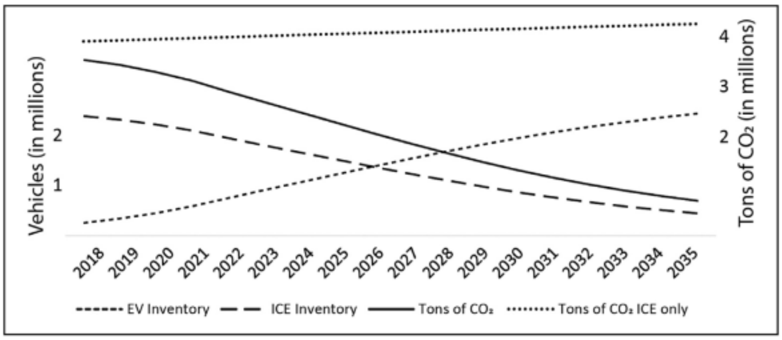


Figure 4: Electric vehicle car production per country (Bunsen et al., n.d.)

Due to its significant growth, in Rietmann et al., 2020, a logistic growth model has been applied to the total actual inventory of cars and electric vehicles in the year interval of 2005-2018 in China, and a forecast inventory have been traced up to the 2035. As shown in Figure 5, the penetration of the electric vehicles may go up to more than 150 millions, which is a prediction that may have significant variations in terms of sustainability implications in different countries, by assuming a similar growth.



(a) China



(b) Norway

Figure 5: Electric vs Internal Combustion Engine vehicle inventory and CO_2 emissions (Rietmann et al., 2020)

2.3.1 Electricity demand increase

The growth will dramatically increase the electricity demand in the future years. Assuming that in 2035, 439 million of electric cars will be in circulation all over the world, equipped by an hypothetical 70 kWh battery allowing more than 400 km of range, this would require a total energy production of 2.94 Terawatt hours per vehicle. Today, as stated by the article Korosec, 2019, the largest existing power plant is producing 35 Gigawatt hours, which is about 1% of the energy required, and in the future years is planning to produce about 150 Gigawatt hours, which is about 5% of the energy required. If then the vehicles travel annually approximately 17000 km, with an average consumption of 185 Watt hours/km, the required energy will be 1381 Terawatt hours. This requires an average charging demand of 7% of the total electricity production in each country, as shown in Figure 6.

Country	Electricity production in 2000 (TWh)	Electricity production in 2017/18 (TWh)	Total inventory EVs in 2035 (in 1000)	Charging demand in 2035 (TWh)	% from total production in 2017/18
Australia	210.2	261.1	6913	21.7	8.3%
Austria	61.3	68.6	3438	10.8	15.8%
Belgium	84.0	75.0	5457	17.2	22.9%
Brazil	348.9	601.4	7104	22.3	3.7%
Canada	605.7	650.8	7917	24.9	3.8%
China	1387.1	6671.9	177,776	559.1	8.4%
Denmark	36.1	30.0	2033	6.4	21.3%
Finland	70.0	70.0	1782	5.6	8.0%
France	540.0	580.7	19,670	61.9	10.7%
Germany	576.5	649.9	34,615	108.9	16.8%
Hong Kong	31.3	37.0	524	1.6	4.5%
India	569.7	1532.2	2302	7.2	0.5%
Italy	276.6	290.6	15,792	49.7	17.1%
Japan	1067.8	1025.8	17,031	53.6	5.2%
Korea	290.1	579.9	4557	14.3	2.5%
Netherlands	89.6	113.5	5333	16.8	14.8%
Norway	143.0	147.5	2400	7.5	5.1%
Portugal	43.8	59.8	3010	9.5	15.8%
Russia	877.8	1109.2	14,675	46.2	4.2%
South Africa	210.7	255.1	281	0.9	0.3%
Spain	224.5	273.8	12,510	39.3	14.4%
Sweden	145.3	159.3	4492	14.1	8.9%
Switzerland	67.5	69.2	3223	10.1	14.6%
Taiwan	238.3	270.3	125	0.4	0.1%
UK	377.1	333.9	24,276	76.3	22.9%
USA	4052.7	4434.9	61,970	194.9	4.4%
Total	12,625.4	20,351.7	439,206	1381.3	6.8%

Figure 6: Electricity production and predicted charging demand (Dudley, 2019,IEA, n.d.)

It seems that while some countries have had a huge increase in electricity production, some other countries produced more electricity in 2000 than now. This second category will probably increase again their production, based on the previous high production rate. Some other countries, like United Kingdom, may have issues in increasing their electricity production. Given that, most of them will need to act now, to be able to cope with the increase of electricity demand caused by the growth of the electric vehicles, by improving the distribution of the last mile in the grid.

As said before, the sustainability implications vary hugely from country to country. In particular, in Rietmann et al., 2020, 26 countries have been clustered into six groups based on the penetration of the electric vehicles in that countries and their CO_2 impact variation due to the mobility "electrification". The groups are:

- "Fast electric vehicle diffusion and high CO_2 reduction", to which belong: Norway, Sweden, Switzerland, Belgium, France, Finland. Norway has deeply adopted electric vehicles, due to policies implemented since the 1990s. As stated by Milne, 2017 and Figenbaum et al., 2015, Norway aims to have all new cars emission-free in 2025 and to be carbon-free by 2050. Norway's goal was to reach 200000 electric vehicles on the road by 2020, which has been achieved in 2018 with 254000 electric vehicles. Norway hugely rely on hydroelectric, emitting only 24 g/kWh [2]. By the 2035, the country is predicted to reduce more than 80% of the CO_2 emissions, with the expected electric vehicles growth. The other countries are expected to achieve similar results in CO_2 reductions. This is given by the low emissions of their energy mixes, lying way below the average EU mix emissions of about 432 g/kWh. In the energy generation however, there are some differences: some of them relies mostly on renewable sources (Norway, Sweden and Switzerland), some others on nuclear energy (France and Belgium)

- "Fast electric vehicle diffusion and moderate CO_2 reduction", to which belong: Austria, Denmark, Portugal, UK, Germany, Netherlands. These countries have implemented policies in the past years allowing to propagate fast the electric

2 http://www.electricitymap.org/map, Norway - Electricity production, visited in February 2021

vehicle stock. Their energy mix in electricity production is slightly worse than the previous group, having a CO_2 emissions ranging from 166 to 486 g/kWh. So, the reduction will not be significant if there will not be an energy mix improvements.

- "Slow electric vehicle diffusion and moderate CO_2 reduction", to which belong: USA, Canada, Spain, Italy. On these countries is expected to reach a 50% of electric vehicle diffusion only after the 2035. Even if policies have been developed in this countries, there is an important lack of charging infrastructure. As an example, in Spain there are only 6 fast charging points every 100 km highway. In these countries is expected a moderate reduction of CO_2, so there are expectations on these countries to improve their sustainability with the growth of electric vehicle market.

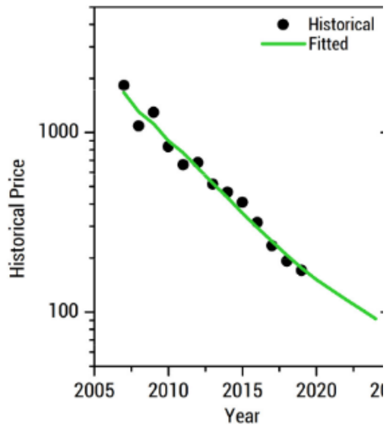
- "Slow electric vehicle diffusion and no CO_2 reduction", to which belong: Russia and Japan. These countries have shown a very low impact on the sharing of electric vehicles, ranging from 0% to 0.4% in 2018. Japan only recently has considered some policies and incentives toward electric vehicles adoption. Instead, from Russia there is still no government supports on this aspect. Since also their energy mixes is also heavily based on fossil fuels, for sustainability improvements, both the energy mix and the incentives be improved.

- "Slow electric vehicle diffusion and CO_2 increase", to which belongs: Australia, Brazil, Taiwan, South Africa, Hong Kong, Korea. Australia, South Africa and Korea have an energy mix which includes few renewable sources. Instead, in Brazil have been installed large hydroelectric plants for the 80% of the domestic electricity generation, so a potential is clear for adoption of electric vehicles. However, the traditional automotive based on Internal Combustion Engine is well rooted and the government has few interest in supporting this change, as stated in Domingues and Pecorelli-Peres, 2013.

- "Slow electric vehicle diffusion and strong CO_2 increase", to which belongs: China and India. The Indian government has shown low support and mostly local for the electric vehicles adoption. China instead, implemented subsidies since 2009 and then successive incentives, but in 2019, it reduces the incentives dramatically. The reduction has caused a sudden slow down of the 25% in the period July - October 2019, after a huge increase of sale by 50% with respect to the annual one in the period January - July 2019. However, whenever electric vehicles were supported more in these countries, with their current energy mix a growth would lead to unsustainability. In fact, India accounts for 56% of coal in electricity generation, as stated by Dudley, 2019 and China for 70-80% according to Wu et al., 2018, so, if China reaches a 50% share of electric vehicles, the CO_2 emissions will grow of the 54.2%. The result would be better than an internal combustion engine only inventory in 2035 though, with a reduction of 12.6% of CO_2 emissions. These countries have to raise both sales in electric vehicles and switch towards renewable energy sources

2.3.2 Battery production implications

The major limitation in the electric vehicle development seems to be the battery production, since the availability of the raw material has become a crucial issue. The main challenge in the development are due to the progression in the battery technology, espiacially on the main battery specifications like: specific energy, the lifetime and safety [Anderson and Patino-Echeverri, 2009,Axsen et al., 2010]. These issues translate directly into high production costs of the battery systems, breaking the competitiveness of the electric vehicles with respect to internal combustion engine alternative. If the general expert opinion is that actual battery costs are too high to be competitive in the present days, there are some uncertainty about the current estimates and the expected one. This variability can be significant according to the application, for ex. application for Battery Electric Vehicles or Plug-in Hybrid Electric Vehicles, because of the different specific power requirements, and to the scale of production. Actually, the battery costs for PHEV are higher of 1.5 times than the BEV one, but this is expected to fall down, given the lower PHEV battery capacity. A great summary of the literature in battery cost and its prediction up to the 2030 is provided in Figure 7. In Penisa et al., 2020, the competitiveness of Battery Electric Vehicles can be reached when the battery price will fall below the threshold of 100 $/kWh, which is expected to be around the 2024.



Year	Price [USD_{2018}/kWh]	NMC Cumulative Demand [GWh]	Cumulative PCT Count	Li Metal Price [USD/t]	Co Metal Price [USD/t]
2007	1824.41	2	142	4321.91	74,832.08
2008	1087.22	4	258	5237.05	109,980.50
2009	1294.06	6	363	5364.66	96,238.51
2010	834.42	11	506	5070.37	54,760.50
2011	661.17	16	730	4371.01	43,291.51
2012	680.23	26	1046	4668.29	34,552.50
2013	514.50	41	1450	4784.58	26,618.75
2014	464.92	61	1931	5417.22	29,072.89
2015	407.95	96	2418	6965.70	36,290.42
2016	314.99	141	2900	7830.45	24,996.06
2017	234.05	211	3323	9318.40	38,243.72
2018	192.49	311	3770	16,500.00	80,490.68
2019	170.62	441	4240	10,492.27	35,993.58
2020		585	4757	11,060.97	34,089.25
2021		745	5233	11,629.67	32,184.92
2022		923	5756	12,198.37	30,280.58
2023		1121	6332	12,767.07	28,376.25
2024		1340	6965	13,335.77	26,471.92
2025		1583	7661	13,904.47	24,567.59

Figure 7: Costs of Li-ion battery in BEV Penisa et al., 2020

The reduction of the costs may result in an improvement of the material properties, which would lead towards higher energy density and an increased production, as stated in Beach, 2008, Cluzel and Douglas, 2012, Kalhammer et al., 2007. The amount of flexibility in using replaceable alternative materials in batteries is very important. As an example, in the metal-oxide cathodes, not only cobalt can be used, but also nickel, aluminium and manganese, which deliver a higher energy density than the materials used up to now [Amirault et al., 2009]. The side effects on this may be the cost of the primary materials (e.g lithium, cobalt, manganese, nickel), which will play an important factor in the future.

However, the great expectation of the falling cost in battery production is related mostly to the potential of Li-ion batteries being the dominant chemical battery production technique for electric vehicles. In fact, they have shown greater performances in both specific energy and specific power, since they have three times the energy density than other batteries [Canis, 2013, Kromer and Heywood, 2007], which is an important need in Battery Electric Vehicles. From a higher density derives savings in battery production materials, an improved range for electric vehicles, and then a costs reduction. Their success is mostly based on the coupling efficiency of the Li-ion cells with battery systems for vehicles being robust enough. Li-ion batteries benefit from the combined use with materials with higher voltages and capacity in the cathode and anode, from the improved separator stability and thinness, from the development of innovative additives in the electrolyte. With the raising of the production, these advances in technology will bring down the Li-ion battery cost. Some drawbacks derive in guaranteeing a maximum level of safety, since thermal leakages represent a possible hazard, and in the improvement of battery life.

Other promising technologies are under study from the researchers, and could provide a valuable alternative to Li-ion batteries, since they could offer drastically higher energy densities. The interest is mostly related to the Li-Sulphur and Li-air batteries, as reported in Christensen et al., 2011. In theory, they could achieve an energy density which is higher than 2500 Wh/kg (instead, Li-ion batteries in transports provide around 100-180 Wh/kg).

In the end, there are negative effects on both the environment and society, which may come together with the increased battery production incoming. The main two, identified by the larger amount of experts, consist in:

- the need to find an efficient recycling process of the exhausted batteries;
- the huge impact of mining and metals extraction

The battery production is an extremely energy-intensive and human toxic process which may deliver to an offset in the beneficial of using an electric vehicle with respect than an internal combustion engine vehicle. The presence of reserves of the most important materials for producing batteries in few countries makes the governments be dependant to them and makes the availability of the resources be more uncertain both physically and politically. As stated by the article from Balch, 2020, most of the lithium used in batteries is imported. More than half the world major production comes from Australia, of about 55%, then comes Chile, producing the 23%, the third is China with 10% and, in the end, Argentina with the 8%. In Europe, lithium deposits have been found in Austria, Serbia and Finland. However, the largest one, where the European Union seems to place the bet for moving up a gear in the electric vehicle battery production, is Portugal. The Portuguese government is offering license to mining companies to allow to exploit the lithium reserves. This partnership is very convenient for the European Union, since guarantees lower prices, simpler logistics and lower transport emissions, due to the lower distances. Moreover, the large amount of lithium supply would assure Europe enough product to compensate the lag in production due to the COVID-19 pandemic, to increase the EU lithium supply and reduce the dependency from other countries. The paradox is that this urgency has flowed into an explosion of mining activities, causing damages to the natural environment where it is found, but mining companies are covered by their guilt from the European Union, because they are helping in reducing the emissions. The importance statement in this article is that according to our model of consumption and production, the electric mobility is simply not sustainable, because a popular spread of electric vehicles require a large amount of mining, producing quarries shaping as open wounds in the terrain, refining and the consequent polluting activities. The article reports a second story, set in Chile, San Pedro de Atacama. The locality of San Pedro rises on the western point of a huge mining area expanding across the Atacama desert to Bolivia and the west Argentina. The dry surface of the area shows an underworld full of minerals. Historically, mining companies there have exploited the copper reserve and iodine and nitrates (to a lower extent), but it has been found containing lithium reserves large as half the world. As the Portugal, the country give licenses to companies, which settled down and start extracting, by expanding more and more the facilities. Unlike Portugal, however, lithium is found in brine, so the extraction consist in evaporation pools with millions of liters of brine pumped up to the surface and let it evaporated to the ground. In this case, no dynamites or diggers have been used, so no craters are produced on the land. The problem here is the subterranean aquifers, situated above the brine, are risking to become contaminated by dirting the clean water. The proof of this were different: the failing of the crops, the disappearing of the fauna and flora, the reduction of pasturlands, which all lead to the process of desertification due to lithium extraction. However, the expansion plan of lithium mining has been blocked by the Chilean court, but the backing up from the authorities has never been obtained, because, in Chile, it seems that the natural environment is sacrificable for the sake of progress.

In the article, it is also proposed a way of producing battery-grade lithium from the recycling of exhausted lithium battery. The researchers, called Christian Hanisch, PhD at Braunschweig University of Technology, has founded a company which extracts lithium from exhausted batteries. Since the battery from common devices contains small amount of lithium, he started from electric vehicle car batteries to make his business more profitable. The scientist said that the most difficult passage is to access the lithium inside the battery cell. Two options are available: heat the components to about 300 °C to evaporate lithium, or apply acids or reducing agent to extract it. All of them are complicated because of the extreme volatility of lithium (tend to explode) and of the tendency to create amalgama with other metals which are added for increasing conductivity. This type of industry is predicted to grow hugely in the following years, up to $18 * 10^9$\$ by 2030, thanks to the building competition. Up to now, two other similar companies are there, one in Belgium called Umicore and in France, called Snam. The procedure proposed by Hanisch does not provide the smelting, which is energy intensive, or the chemical leaching, which is extremely toxic, but the mechanical separation. It consists in breaking the battery in different parts, and then extracting the residual lithium by magnetisation and distillation. In the article, the author underlines that the processes are extremely noisy, due to the use of the crusher, but Hanisch assures it is the greenest way to recycle lithium. Lithium, however, represent a small share of the whole battery cost, meaning that manufacturers are less prone to change towards alternatives. By now, the recycling of lithium costs more than extracting it from the natural sources. In particular, the conversion between recycled lithium (lithium sulphate) into a battery-grade quality (lithium carbonate) is expensive. As stated by Linda Gaines (expert in battery recycling at Argonne National Laboratory in Illinois), for the existing recycling companies, lithium does not provide enough profit and does not add much, instead, the intention is to recycle cobalt, nickel and copper. Together with the scaling up of the battery production, the recycling cost is expected to fall down too. However, given that and the prediction of growth of the electric vehicles in the previous section, a huge imbalance between the supply and the demand of battery production is to be overcome. The demand of lithium will be increased, predicted to be up to $7 * 10^5$ tons by 2025. Unfortunately, recycling companies would recover only the amount of battery-grade lithium enough to power electric vehicles of nine months. This affirmation is stated also in Paulikas et al., 2020, which says that even in the assumption of the use of full recycling electric batteries, the demand of metal to build the predicted amount of electric vehicle cannot be satisfied.

Recently, a new study has been published showing another possibility for retrieving battery metals. As stated in Paulikas et al., 2020, this consists in retrieving the polymetallic nodules, which are metals deposit located in the deep sea. Their characteristics can be summed up as:

- they lie on a soft sediment, unattached to the ocean floor and they can be collected without cutting the rock, destroying the environment [Beaudoin and Baker, 2013]
- contains a medium-high battery-grade of four metals used in batteries in a single ore. Moreover, it does not contain a high amount of heavy toxic metals [Haynes et al., 1985]
- the metal content is inline with the need of battery for electric vehicles and for assembly manufacturers [2021]
- they are present in vast quantities in the surveyed Clarion Clipperton Zone, which is stated to become a major source of battery metals for the next decades. This zone is estimated to host 34 billion tons of nodules containing 6 billions tons of manganese, 270 millions tons of nickel, 234 million tons of copper and 46 millions of cobalt.

The research, instead of lithium, is expecting a growth of the nickel sulfate and cobalt sulfate markets to build batteries for electric vehicles from 2018 to 2035, to produce nickel-manganese-cobalt and other nickel-heavy metals battery. The research proposes a Life Cycle Assessment study by comparing the production of nickel sulfate, cobalt sulfate, manganese sulfate and copper cathode through the land-ore processes and the deep-sea nodule collection processes, in terms of maximum released CO_2 per year and amount of sequestered carbon, scaling up to the production of metals for one billions of electric vehicles. All the four metals generate significantly less CO_2eq when produced from nodules, as stated in Figure 9. Among the four metals, the higher impact comes from nickel sulfate and copper, which have the highest share of metal mass per electric vehicle, and also the greatest difference in terms of emissions between the land ores and nodules.

Nodules are a source of nearly zero-emission. The Gross Weight Product of emissions by producing metals from a kilogram of nodules, split in collection, processing and refining phase, is shown in Figure 8. A small share of the emissions (less than 10%) is due to the offshore collection and transport, which includes the infrastructures, fuel and operations. It is impressive how this achievement is in contrast with the one of land-ores, whose half of the emissions are deriving from the phases of mining and concentration. This is mostly due to the low energy- intensive phase of collection, the high grades of the metal in the ore, for which no concentration is needed, and the oceanic location, which allows lower impact with the ship-based transport to the plant (on-shore). The highest contribution in terms of emissions in nodules is given by the pyrometallic processing step, which allows the reduction of the oxides in the nodules, and the process makes large use of coal. This step takes the 75% of the CO_2eq emissions per kilogram of nodules. In particular, this step may be object of a first step of improvements in reducing the emissions, for instance in the use of low emitting reductant. However, this high impacting step is counteract by the use of hydroelectric power, whose impact is very low. This is observed especially in the refining phase, which makes use of electricity in the copper electrowinning.

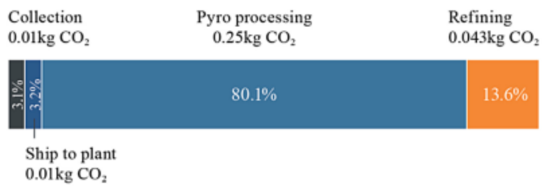


Figure 8: Emissions from battery-grade metals production with 1 kilogram of nodules Paulikas et al., 2020

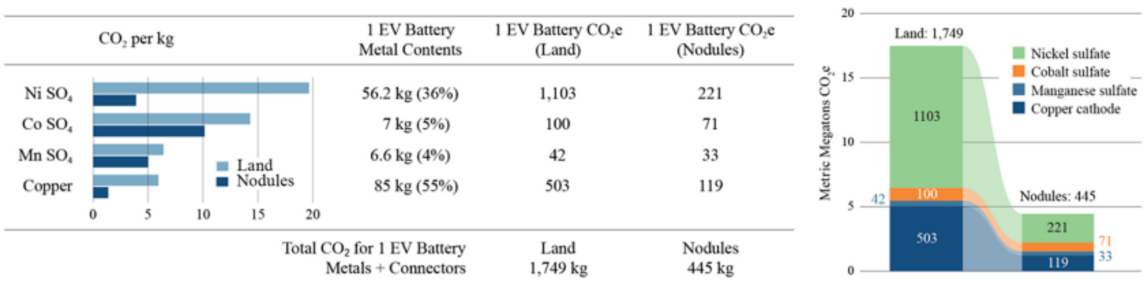


Figure 9: Emissions results from producing battery-grade metals for 1 billion electric vehicles: land-ores vs nodules Paulikas et al., 2020

At the same time, the large use of hydroelectric power in the land-ores' cobalt processing may suppress the emissions. The mining on the land needs often metallurgical plants located close to the mine, because the shipping of the metal ores, which are low-grade and have a high mass, is very costly (both in money and emissions). This condition hugely constraints the local grid electricity production, allowing to increase the environmental impact, the waste and emissions. Instead, the flexibility of the nodules collection allows placing metallurgical plants anywhere near the waters of a port, giving easy access to hydroelectric power or other renewable energy sources. Moreover it allows to market or to reuse the byproducts, providing some environmental advantages.

Harmness to the carbon sequestration in the future from nodules collection are possible, if the sediment disturbance compromises the rate at which abyssal bacteria assimilate the inorganic carbon dissolved in deep-water. The rate of sequestration of those bacteria normally has a rate of $0.5gC/m^2$ annually ($0.25 * 10^9$ tons of carbon in 100 year). Without their "job", the carbon absorbed from the atmosphere at the ocean surface would remain in the water, accumulating and forming the "carbon-enriched" waters, slowing after a long time the absorption of CO_2 from the atmosphere. Moreover, nodule collection is unlikely to release carbon sequestered to the atmosphere. The risk is much lower than the one of land-ore mining methods, as shown in Figure 10. This is mostly due to the better environmental impact of the nodules processing onshore.

Mechanism for releasing sequestered carbon	Carbon at risk (metric Mt CO_2)	
	Land ores	Nodules
Mechanism 1: Seabed disruption	0	2.8
Mechanism 2: Riser water	0	0.15
Mechanism 3: Land disruption	9300	580
Total	9300	583

Figure 10: Carbon sequestered at risk from producing battery-grade metals for 1 billion electric vehicles: land-ores vs nodules (Paulikas et al., 2020)

2.4 THE FREE FLOATING ELECTRIC CAR SHARING POTENTIAL

The success of the free floating car-sharing service is guaranteed by the amount of vehicles accessible when and where the user needs them. In fact, if people need to walk a long distance to reach a vehicle, they would probably choose for another transport mode to take their trip. It is frequent in this kind of car-sharing services that vehicles are densely parked in city zones where the demand is not so high, and there may be lack of vehicles in some other zones in a given moment of increased demand. There is a need to have an efficient relocation system that assures that the vehicles are positioned and available in the city zones where they are needed, given the instantaneous zone demand. The vehicle relocation is often up to the operator, but sometimes is performed by the user through incentives of the operator, which applies some kind of bonus/reductions on particular trips from zones with low demand to the one with high demand, as did by the former company Autolib, that operated in Paris. The relocation performed by the operator is usually expensive though, because to move the vehicle from one place to another, one workers is needed, but then, the workers may need some kind of transportation to move from the zone where the vehicle has been released or to move to the zone where the vehicle need to be moved. This problem is pretty solved with the vehicles from ESPRIT project, which can be connected together in road train of up to eight vehicles, which reduces drastically the costs of moving the vehicles. In the future, autonomous vehicles in car-sharing may help in this sense, because they can self-drive up to the highest demand zones, after the completion of a trip. However, the autonomous vehicles will be needed to deal correctly with the urban environment, which is an important capability for car-sharing. Many relocation strategies have been implemented in literature to optimize these costs.

As stated before, the charging infrastructure is really important to the electric car-sharing service. In fact, the majority of the trip in car-sharing are short, but the vehicles used by the car-sharing service might have shorter range batteries than usual, so the vehicles must be charged when they are parked and not used. Most of the companies, install the charging points in each one of their reserved parking spots or in the most populated zone where people are more likely to pick or leave a vehicle. This strategy is not efficient at all, since most of the stations are not used because the vehicles cannot be parked. Moreover, usually the charging infrastructure is not available only to charge the car-sharing vehicles but also the private ones, like the former BlueTorino electric car-sharing service in Turin, which will result in a lower charging capacity when needed to the car-sharing service. Regarding the presence of an adequate charging infrastructure for electric vehicle car-sharing service, in Michele Cocca et al., 2019 different strategies have been studied to place charging stations around cities. They showed that placing few charging stations in some city zones (5% of the city zones in Turin) are enough to make all the trips feasible. This is given, assuming that customers collaborate for the service sustainability, by returning the car to the charging station when needed. Then, through a charging station placement based on a genetic algorithm, they show that it is possible to reduce the discomfort for the few customers that are asked to return the vehicle to a station for charging. In practice, the charging stations should be placed to offer coverage, allowing users to reach the nearest station without running out of fuel, and capacity, to minimize most the queuing delay to recharge the vehicles, when much traffic is on the road. The same results are obtained in Biondi et al., 2016, stating that "most stations require small capacity", meaning that the number of charging poles may be less than four, "but a few large stations", which are considered to be large no more than 15 parking slots.

Even in this case, the ESPRIT project car may come in handy, in order to increase the efficiency of the charging infrastructure and improve the service at the same time. As stated in Biondi et al., 2016, this is a vehicle capable of the power sharing. The power sharing is the capability to use one single charging station to recharge multiple electric vehicles simultaneously. This technology has the potential to reduce the cost of the charging infrastructure. At the same time, the charging process may behave in an unexpected way, because the power delivered by one station has to be distributed among a train of vehicles, decreasing the average charging rate. Their results shows that the power sharing may have little impact on charging power peaks when a fast charging power is implemented, mostly because the charging time is short. As they state, the ESPRIT vehicle is capable of sharing part of the power from the highest energy vehicle to the one which has insufficient residual energy, not only when connected to a charging dock, but also when they are unplugged, up to eight vehicles concurrently connected. The vehicle standing in the front of the train would have the maximum priority, to allow that the vehicle in the front would be available for the user when needed.

In the results they show in Figure 11, as expected, the higher the charging power, the lower is the charging time. However, there is a very small difference between the average charging duration with the use of power sharing and not, for the same charging speed. This is explained because, in their results, the energy requested by car which are parked at a charging station is small, and the time between two bookings is usually longer than the average charging period. With a higher rate of utilization and a larger battery consumption, this would be different. The distribution of the charging powers used is very similar between the case with the use of power sharing and without (Figure 12), and the most used ones are placed on a little range of small charging powers, suggesting that power charging would not affect the quality of the charging process. At the same time, the power grid would not be affected by the use of power sharing, and it is easy to manage that (Figure 13). This would easily reduce the number of required charging stations, and consequently, the installation and maintenance costs. Moreover, less charging stations

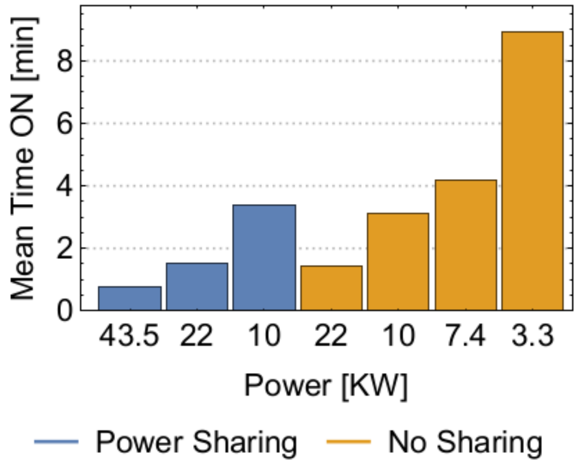
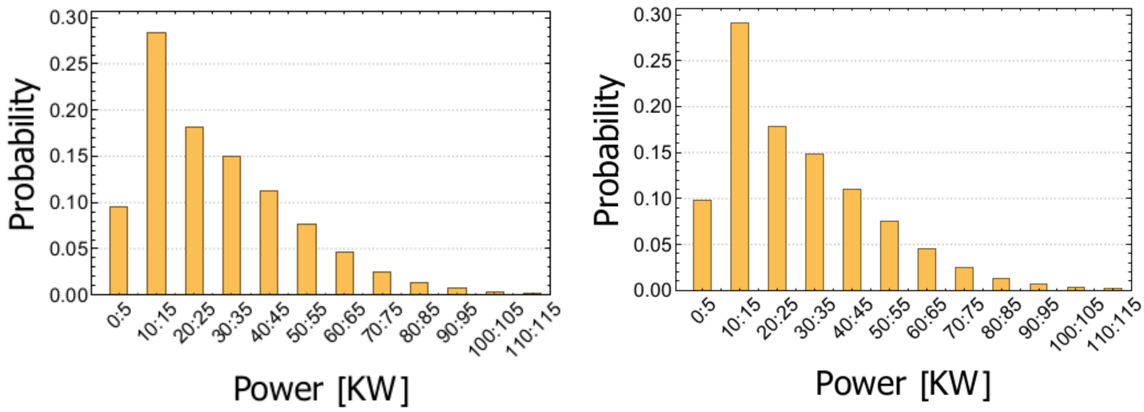


Figure 11: Avg charging duration: power sharing vs no power sharing Biondi et al., 2016



(a) With power-sharing

(b) No power-sharing

Figure 12: Power distribution with power equal to 10 kW Biondi et al., 2016

are needed than the traditional infrastructure. The power grid would benefit too, since the production load would be reduced.

It is crucial to create a model before deploying a car sharing service under different aspects: it allows to study its effects with the variation of different scenarios: both urban and suburban, to analyze the modal share dynamics due to the introduction of the service, understanding its potentialities in the long term life. The exploitation of a model allows to study an optimal strategy for placing the stations to increase as much as possible the user satisfied demand and its efficiency and reliability, as stated in Biondi et al., 2016, to optimally decide how many vehicles to place in the system, and where to move them, mainly studied by Weikl and Bogenberger, 2015. The model should be initialized by a demand model to estimate the demand for the system in a particular city, provided with a supply model, to manage the operations inside the car-sharing service, and a business model, to estimate the profitability of the service, including revenues and costs, based on different input variables given to the system model.

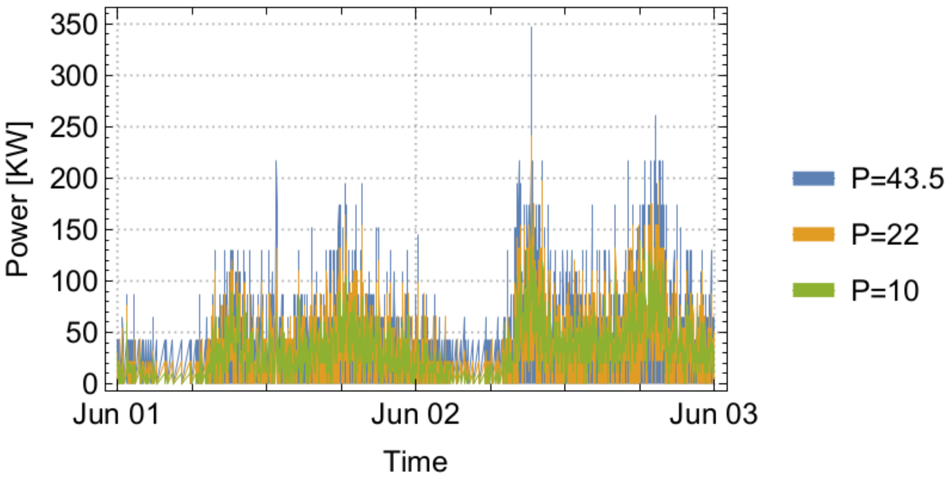


Figure 13: Charging demand with power sharing Biondi et al., 2016

3 SIMULATOR DEVELOPMENT HISTORY

“Odysseus” is a software written in Python by Dr. Alessandro Ciociola as the result of his thesis Ciociola, Mellia, et al., 2019, and based on the Python’s package simpy[1], which allows to model the evolution of dynamic systems on a discrete timebase. While the software was born under the "eC2s" name, it has been changed to "Odysseus" during its intermediate development steps. Originally, the purpose of e3f2s was to be a data-driven, discrete-event simulator for electric car sharing systems. "Odysseus" was built to model car sharing demand from data coming from real car sharing systems, run a simulation based on some input parameters, and provide as output tools to show the trend of different parameters, both space and time dependent. These were useful to compare the performances of the electric car sharing service over different parameters, different charging and relocation strategies, and different placement of the charging station strategies.

"Odysseus" was built on many layers:

- the city_data_manager module, containing data about demand and positions of the charging stations collected about a certain city. This layer is divided in two submodules: the retrieval and the preprocessing module

- the data structures, containing the objects which are interacting together in the simulation, such as the city, the vehicle, the charging station and the workers (later they will be better explained)

- the simulation input, which allow to manage the simulation initial conditions. It contains different configuration files by which it is possible to change the input parameters

- the simulator, containing the classes which allow to manage the user mobility requests, the vehicle assignment to users (if possible), the vehicle charging tasks, the vehicle relocation tasks

- the simulation output, which is responsible of producing statistics and plots at the end of the simulation

3.1 DEMAND MODELLING

In order to be useful to a company which is strategically planning to settle down a car-sharing services, the simulator need real users mobility data. Thanks to the user mobility data, the simulator is able to reproduce in a quite accurate fashion the car-sharing quality of service granted to the users. These data are very difficult to be obtained. What ideally is needed to be known by policymakers or mobility companies are the type of mode, the origin and destination and path’s preferences of the people systematic trips. However, partly due to privacy issues related to the collection of the users’ personal informations, and partly due to the impossibility to accurately describe in a general way the human behaviour in their modal and trip choice, the deepest informations in possession are the origin and destination couples.

1 https://simpy.readthedocs.io/en/latest/

3.1.1 UMAP

The mobility data used by the simulator are collected thanks to UMAP. As described in Ciociola, M. Cocca, et al., 2017, UMAP (Urban Mobility Analysis Platform) is a platform to collect, process, augment and store mobility data in a data lake, from which it is possible to perform analytics to get insights from the raw data. Two crawlers have been built to collect mobility data from the car2go (now Share Now) and Enjoy car-sharing platforms. Data were collected from the car2go API (today are closed-source, since their mobility data are no longer publicly available) and Enjoy website, on which some reverse engineering had been performed on the Enjoy website to retrieve the source on which data are stored. The mobility data used in the simulator for this thesis are from car2go service in the city of Turin.

How have these data been collected? The crawler was programmed to repeatedly send requests every minute to the API or website. The response is a JSON dictionary, a snapshot with the position of the available cars in the system in the time instant t. A car is described by the car-sharing web-service as an object with several informations, such as: plate, vehicle ID number, location, fuel level, model, ... Each car disappears from the system when it is rented by a user and then reappears (in the same or in a different location) when the rental is ended. This is the booking period, or the time period between the rental starts and ends (the car first disappears and then reappears in the system). The parking period is the time between one rental end and another start (the car first appears in the system and then disappears again). Since every platform has different data format, a data integration was done to use a common terminology. The idea was to track the availability of each vehicle over the sampled snapshots collected over time, and rebuild the history of bookings and parkings. The events of bookings and parkings are recorded with their initial and final times and positions. Also, the information has been improved by adding the estimated driving time. This has been done thanks to the Google Maps API, which, given the origin and destination coordinates, returns the driving time duration of the best driving path. It has been observed that a good estimation of the driving time can be achieved by multiplying by 1.4 the Eucledian distance between the centroids of the two zones of origin and destination. The data has been stored in the data-lake using MongoDB, a schema-less database. They are available by performing a query on that database. In the end, the bookings trace has been converted to a Dataframe and loaded in the simulator, ready to be processed.

These data allow to model the users' mobility demand in terms of time and space. From this, it is possible to derive a demand model which summarizes the users' demand obtained from the real data. The real trace was used to generate a generic realistic trace describing the possible user trips and to derive realistic performance figures at the same time. This was performed by producing samples from a fitted distribution on the real trace, then the samples were used to feed the simulator. The demand was estimated both in time and space.

3.1.2 Time estimation

During the simulation, the occurring of a mobility request over time is described through a statistical distribution. As it is described in Barulli et al., 2020, the distribution of the inter-arrival time between user bookings is assumed to behave like an exponential random variable. Moreover, the user bookings' rate of arrival is modelled differently based on two defined type of days, workdays (from Monday to Friday) or weekends (Saturday and Sunday), and based on the hour of the day, so there is a different rate of arrival per each of the 24 hours, per each day type. In total, 48 temporal bookings inter-arrival time slots are modelled (24 for workdays, 24 for weekends days). The rate of bookings in a certain temporal time slot is fitted according to the average number of bookings occurred in the corresponding time slot in the real trace. In few words, the fitted distribution would take the form of an inhomogeneous Poisson.

3.1.3 Space estimation

The coordinates of the positions of the origin and the destination of the mobility requests are modelled fitting a generic multidimensional distribution, the Kernel Density Estimation (KDE), on the origin and destination positions of the real trace. For a detailed explanation of KDE, a good reference is Ciociola, Mellia, et al., 2019 and Ciociola, Markudova, et al., 2020. Here, it will be explained only the main purposes of its use. The Kernel Density Estimate is a statistical tool which allows to estimate the probability density function of a generic random process. It is meant to reproduce better a distribution of a data sample.

Definition: Let be $(x_1, x_2, ..., x_N)$ an independent and identically distributed of N d-dimensional vectors drawn from a distribution of unknown density f. Its kernel density estimator $\hat{f}$ of f is:

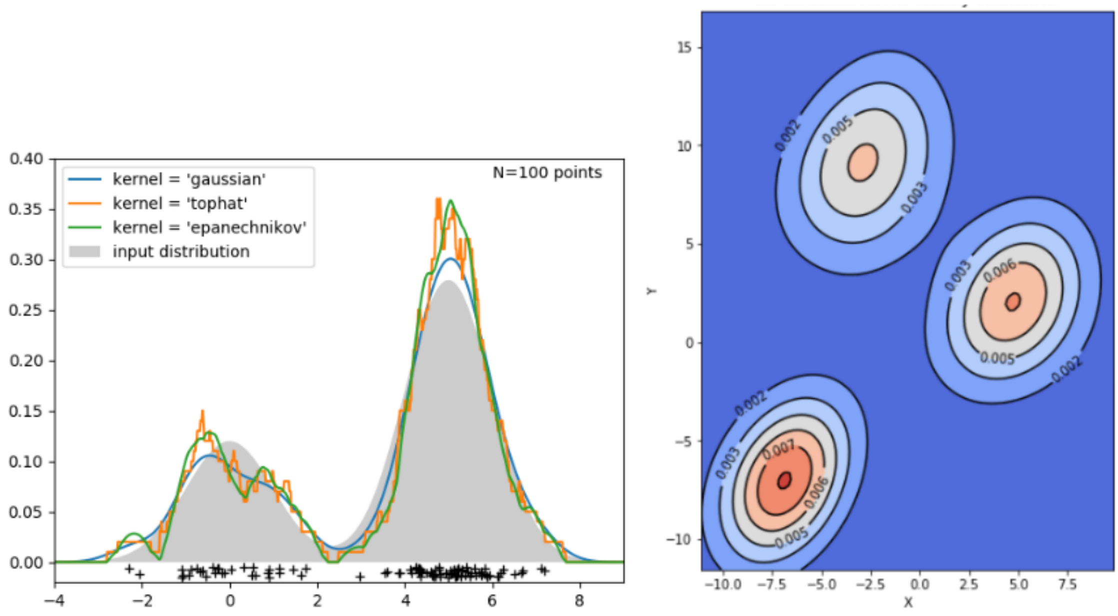
$$\hat{f}(x) = \frac{1}{N} * \sum_{n=1}^{N} K(\frac{x - x_i}{H}) \tag{1}$$

where K is the kernel function and H is the bandwidth of dimension d x d. The input vectors are 2-dimensional, containing origin latitude and longitude. The output is a 2-d entry as well, containing the destination ones. The city surface has been divided in rectangular zones of 500 x 500 meters, and then to each one is assigned an integer identifier. The spatial resolution is given by the zone size and the bandwidth of the KDE. The bandwidth is the parameter which allows to smooth and to remove some spacial outliers present in the demand real trace. In general, it allows to generalize better the demand over the city space. A smaller bandwidth allows to keep the granularity of the demand by filtering less the demand outliers. A bigger bandwidth produce a loss of granularity, causing a smoother demand distribution, and a progressive loss of precision in finding the spatial patterns. A bandwidth equal to 1 would set the granularity same as the city zone. For the simulator, a Gaussian kernel, as shown in Figure 14(a) and the bandwidth for the KDE was set as a 2x2 identity matrix. Referring to Ciociola, Markudova, et al., 2020, a smaller bandwidth does not bring significant advantages for estimation, and a bigger bandwidth would lead to a reduced precision in detecting spatial patterns, so a bandwidth equal to 1 has been chosen.

Then, the users, in order to satisfy their mobility demand, are allowed to pick up a vehicle which is within the same zone or in the 1-hop distance neighbouring zones. The choice was explained by the fact that users typically are willing to walk no more than 500 meters in order to reach a vehicle. A bi-dimensional KDE was used on the origins and destinations for each of the 48 temporal slots, both considering the workdays and the weekend days. An example for one couple of coordinates KDE estimate is shown in Figure 14(b). In this way, it was possible to sum up the users mobility habits both on workdays and weekend days across the hours of the day.

3.2 SIMULATION MODEL

The simulation model description is mostly explained in Ciociola, Markudova, et al., 2020 and Ciociola, Mellia, et al., 2019. In this introduction only the most important tasks performed by the simulator will be explained. The demand model, explained in the previous paragraph, was used to sample the occurring trips during the simulation, both in time and space domain. The simulation is considered to be stationary, so no transient is assumed in the evolution of the system over time.



(a) KDE of a univariate normal dist. with different kernels (b) 2D KDE contour for origin (destination) coordinates

Figure 14: KDE for spatial estimation in mobility (Ciociola, Mellia, et al., 2019)

3.2.1 User trip request

When a new mobility request is generated, the simulator searches for an available vehicle with enough charging level in the request zone and in the eight 1-hop neighbouring zones. If available, the simulator takes the car with the highest charging level and schedules a return event in the destination zone at a certain time which is dependant by the trip duration. This trip is considered satisfied. If instead there are no cars in the neighbouring zones, or the cars available do not have enough fuel level, the trip will not occur and the same is marked as unsatisfied. The unsatisfied demand represents an important metric to evaluate the quality of the service in terms of vehicle availability for users. As a consequence, from the satisfied demand depends the service survival and competitiveness in the market, since the rental incomes represent the biggest part of the service revenues.

3.2.2 Post-trip operations

When a return event is computed, then the simulation establishes the amount of fuel consumed, update the vehicle state of charge, and checks if the vehicle need to be charged, in this case when the fuel level goes down to a certain threshold α. If it is not needed, then the vehicle is parked in the destination zone. If instead it is needed, so the fuel level is smaller than α, a charging event is triggered for that vehicle according to the designated policy: centralized hub, where multiple charging points are located within the same zone in the whole city, and a distributed charging infrastructure, where multiple charging points are spread across different zones of the city. The vehicle may be brought to charging by two entities: the user (when the user contribution is set up in the input parameters), or by the worker, whose job is mainly to relocate vehicle both for charging or to balance the vehicle density across the zones. When the users are contributing to the vehicle charging, when on the destination trip a free charging point is available, they will bring the vehicle charging with probability w (willingness to contribute).

Otherwise, the vehicles that need to be recharged are moved by the workers to a charging point. This trip is marked as a charging relocation trip. The cumulative duration of the trips spent in charging relocation is an important performance metric, which measures the burdens the operator has to face in the charging process. The relocation time is computed using 15 km/h as average speed. In case the vehicle has not enough fuel level to reach a charging point during the relocation, it is relocated anyway, but this trip will be marked as an impossible charging trip. These represent an additional cost to the system operator (e.g the tow's cost to move the vehicle up to a charging point). The vehicle is always charged up to the vehicle full capacity (100%).

At the time of this thesis, the centralized hub policy has been discontinued. After a given simulation time, set up in the main configuration, some statistics about the behaviour of the system and the user satisfaction are extracted.

3.2.3 Fleet and charging station characteristics

In the original implementation, all charging points were of type electric powered at 3.7 kW nominal power and 92% charging efficiency. The vehicles were supposed to be cars of the same model, powered by an electric powertrain, which was the Smart fortwo Electric Drive, with a battery capacity of 17.6 kWh and 15.9 kWh/100 km of consumption. After this thesis work, e3f2s will be extended and generalized in its functionalities, allowing not only to simulate a free floating electric car sharing service but a general sharing mobility service composed by fleets of not only cars, but also bikes, scooters and other kind of vehicles, which can be powered by different kind of fuel.

4 WORK ON THE SIMULATOR

4.1 DEVELOPMENT OF THE STUDY CLASSES

The task to be performed immediately is the design of two general classes of the two main objects in the simulation:

- Vehicle class, which allows to generalize the type of vehicle to be deployed during the car-sharing service simulation. In the simulator, this will be the object the users search for in order to satisfy their mobility demand and move up to the destination

- Charging Station class, which generalize the object where the vehicles will be moved to, both by the user or by the worker, in order to be recharged. According to the different charging placement policy, they will be placed over different city zones.

4.1.1 Vehicle class

Regarding the class Vehicle, to allow a flexible change of the parameters, a database vehicle_conf was created, where all the vehicles' configuration can be stored and then can be changed from the scenario parameters. The vehicles are grouped by fuel type, described by a model name, and each one will contain the parameters needed to fed the models which will be described in the following. The vehicle parameters used in the simulation are:

- engine_type: a string describing the type of fuel which is powering the vehicle.

- fuel_capacity: a floating point number indicating the amount of fuel the vehicle is able to carry. The unit may be different depending on the engine_type parameter: in case of liquid fuel, will be liters, in case of gases, kilograms, in case of electricity, kWh.

- consumption: a floating point number indicating the amount of kilometers run by the vehicle to burn a unit of fuel. This could be km/L (liquid fuel powered vehicle), km/kg (gaseous fuel powered vehicle), km/kWh (electricity powered vehicle). This unit of measure has been chosen to use an understandable and standard metric in car specifications.

- max_charg_power: a parameter for the electric vehicles which reproduces the maximum charging power allowed by each vehicle, depending on the charging profile.

4.1.2 Charging station class

A similar task has been performed on the charging stations. A database station_conf has been created to store the different configurations in which a station could be deployed in the city. Generally, there are no specific configurations regarding the fuel-based charging station. Instead, for the electric charging station, there are different configurations based on the power they deliver. Basically, the station configurations are grouped by fuel and, on the electric charging stations, different configurations have been listed, according to the ones in Wikipedia[1] and in Electric Vehicle Database [2], in the specifications of each vehicle:

- fuel-based charging stations (gasoline, diesel, LPG and CNG) contains only fuel_type as parameter, a string indicating the type of fuel is considered in the simulation
- on electric charging stations (see Tab 1)

Table 1: Charging profiles implemented in simulator

profile_type	voltage_output (V)	current_output (A)
wall_plug	230	10
single_phase_1	230	16
single_phase_2	230	32
three_phase_1	400	16
three_phase_2	400	32
three_phase_3	400	64
dcfc_1	450	112
dcfc_2	400	325

Each configuration can be selected from the scenario parameters configuration file of the simulator. It has to be noticed that, as the simulator was built originally, there is no chance of setting up two or more different charging stations in the same city zone. Supposing it is needed to set up more than one charging station in a city zone, the simulator will place one charging station in the desired zone, with a number of poles equal to the sum of the poles in the charging stations. Moreover, in this implementation, it is not allowed to perform simulations using hybrid vehicles and hybrid charging stations. A fleet will not be made up of partially electric and partially gasoline vehicles, but only electric or gasoline vehicle fleet. Same issue regards the charging stations, such that only gasoline or electric charging stations are available around the city, not a mixture of electric and gasoline charging stations, for example. The final assumption is that the vehicle fleet and the charging station fuel type has to be the same.

4.2 CLASS MODELS

The next step would be to develop a model of fuel consumption and emission to model the dynamic behaviour of the vehicle after every trip. In this way, it is possible to reproduce realistically the total amount of charging needed for a certain vehicle, how many time is needed to bring the car to charging. This last aspect depends also on the charging relocation technique, which is not explained in this thesis. Consequently, it is possible to model how many emissions have been released due both to the user mobility trips but also to the charging relocation trips.

4.2.1 Consumption model

In many researches available on the literature, like Yang et al., 2014 and Aksoy et al., 2014, are proposed physical models which tries to describe the consumptions and emissions basing on the gravitational forces acting on the vehicle in the traffic system. The consumption is calculated by considering the vehicle technical specifications and load, and the trip distance.

1 https://en.wikipedia.org/wiki/Charging_station
2 https://ev-database.org/

In a nutshell, it is considered the total force needed to the vehicle to move at the constant speed. This should be equal to the total resistance forces Ft, indicated as the sum of the rolling resistance, the aerodynamic resistance, the grade resistance and the acceleration resistance. In the end, the total power needed to move the vehicle again these forces is given by:

$$P_t = F_t * v \quad (2)$$

where v is the speed in m/s at which the vehicle is moving. Then it is possible to retrieve the fuel consumption a as:

$$a = P_t * b \quad (3)$$

where b is a constant indicating the amount of fuel burnt per power released.

A very similar model is built in Yang et al., 2014, but two different power measurements are modelled for the electric vehicle: the output power of the electric vehicle's battery and the electric vehicle's regenerative braking power. This second power term is considered because, during the braking process, in the traditional vehicle the braking energy is wasted as heat, while in the electric vehicles the braking energy can be partially recovered and restored in the battery. Both the input power from the braking process and the output power from the battery depend on the vehicle speed in m/s.

The aim is not to build such models, because it would require a complex implementation of the vehicle dynamics in the simulator. In a nutshell, each trip performed by each vehicle during the simulation should be described over time in terms of position, speed, acceleration, so that it is possible to evaluate the forces acting on the vehicle, and finally the vehicle fuel consumption. However, as already explained, the simulator has not the purpose to describe the vehicle behaviour in a detailed fashion. Instead, it would try to simulate the behaviour of a car-sharing services in terms of the satisfaction of the user demand of mobility. Thus, it is enough to build a linear model of fuel consumption such that it is possible to depict the car behaviour as simply as possible, maintaining a sufficient level of accuracy with the real car behaviour. The model developed, inspired by Athanasopoulou et al., 2018, retrieves the amount of fuel consumed given the total distance of each trip through a linear relationship.

Summarily it works as follows: it is supposed a user has a need of mobility from an origin zone to a destination zone and succeed in picking up a vehicle to reach the destination. The vehicle keeps track of its status when it is booked or it is released. The status contain different informations which are updated as the simulation progresses:

- the time, at which the event happens
- the status, in which three type of events may happen:
  - booked, the user books the available vehicle to reach the destination
  - available, the user release the vehicle after reaching the destination
  - charging, the vehicle is moved to be charged (either by the user or the worker)
- the SoC (State of Charge), the percentage level of charge when the event happens
- the zone, the city zone where the event happens

At the end of each bookings, the SoC of the vehicle is decreased according to the driving distance driven during the rental. The amount of fuel decreased is evaluated thanks to the fuel consumption model. A visual representation of its work flow is in the Figure 15.

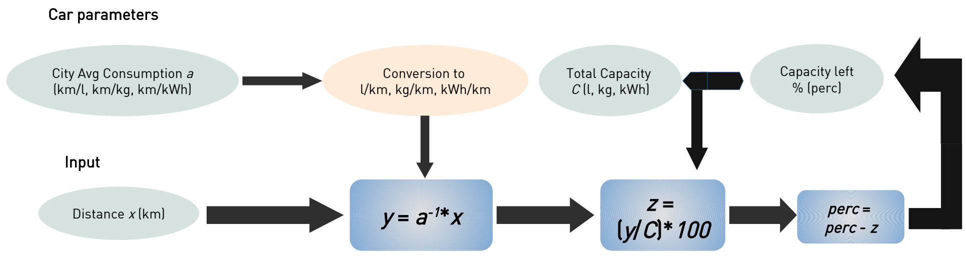


Figure 15: Consumption model scheme

To model the consumption, only one input parameter is required, the average city consumption of the car a, expressed in km/L (liquid fuels), in km/kg (compressed gas fuel), in km/kWh (electricity fuel). Given in input the distance in km, the amount of fuel consumed in the trip is:

$$\text{liters} = a^{-1} * \text{distance}_{\text{km}} \tag{4}$$

Then, the percentage of fuel SoC is updated on the vehicle. Given the total fuel capacity of the vehicle and the amount of liters burnt, the second is converted in percentage through this linear relation:

$$\text{percentage} = \frac{\text{liters} * 100}{\text{fuel\_capacity}} \tag{5}$$

In the end, this percentage is subtracted from the SoC of the vehicle at the booking start, resulting in a lower SoC for the following bookings of that vehicle, up to the situation in which the SoC goes down to the threshold α. When the SoC goes under α, a charging trip for that vehicle is issued. In a previous implementation of the simulator, the threshold α was static and set as a parameter in the scenario's configuration. Recently, it becomes dynamic, in the sense that it is set according to the fuel consumption calculated on the maximum driving distance trip performed by the users (evaluated in the demand model).

4.2.2 Charging model

When the charging trip is triggered, the vehicle is brought to a charging pole and starts charging up to β. β is indicating the SoC percentage after which the charge is stopped and the vehicle becomes available to the user. The value of threshold β was set to 100, so the vehicle will be charged to the full capacity (100% SoC). The time interval, during which the vehicle is charging, is described through a linear model, from which it is possible to derive the amount of fuel charged given the charging time and the other way around. These two relationships are implemented both for the internal combustion engine vehicles, considering the amount of fuel delivered per minute to the tank, and for the electric vehicles, for which the main speed contribution is due to the total power delivered to the vehicle's battery. The two relationships are:

$$\begin{array}{c} \hline \text{Internal Combustion Engine vehicle} \\ \hline time = \frac{(\beta - SoC\_level)*capacity}{(100*flow\_rate)} * 60 \\ \\ perc = \frac{100*(flow\_rate*time)}{60*capacity} \\ \hline \text{Electric vehicle} \\ \hline time = \frac{(\beta - SoC\_level)*capacity}{(100*power*\eta_c)} * 3600 \\ \\ perc = \frac{100*(power*\eta_c*time)}{3600*capacity} \\ \hline \end{array} \tag{6}$$

where time is the vehicle charging time in seconds, perc is the percentage of fuel charged, capacity is the maximum fuel load in the vehicle in L/kg/kWh, flow_rate is the speed at which the ICE vehicle is charged in L(kg)/min, power is the speed at which an electric vehicle is charged in kW, η_c is the charging efficiency of the electric vehicle.

Regarding the recharging of the vehicles, two assumptions have to be made. First, the realistic fuel pump does not work linearly in delivering the fuel, but as an exponential asymptotic, since the fuel flow will be maximum at the beginning of the refuelling and progressively decrease when the tank is filled up. Same considerations may be placed upon the recharge of the electric vehicle. As it is described in the figure 16, even if it is not related directly to the electric vehicle one, the battery is charged up to the 60 % of the total capacity at the maximum speed, then the charging current exponentially decreases up to the complete charging. In summary, even the battery charge curve over time may be described as an asymptotic exponential with different parameters than the refuelling of ICE vehicles. Moreover, in the simulator, the main assumption is that the voltage and current output by the charging pole is constant over time, which is not true, as shown in the figure. This was the choice, since the amount of complexity due to the real charging profile implementation does not balance the accuracy increase in estimating the charging time with respect to a constant value of voltage and current.

Second, regarding the electric vehicle, not all the battery capacity is useful to store energy. Usually, the car manufacturer declares the nominal capacity in electric vehicle's specifications. The nominal capacity would be the total capacity under the ideal condition in which all the energy delivered is stored in the battery without losses. However, during the battery charging process, some energy is cycled into and out of the battery itself on a given cycle. In lithium batteries, typically the useful capacity is about 80% of the nominal capacity[3]. On top of this, electric vehicle may support or not higher charging speed, depending on the manufacturer design choices of the vehicle plug or on the vehicle year of manufacturing. Finally, the on-board charger provided in each electric vehicle may deliver the power from the charging pole at a lower intensity with respect to the station one, mostly for safety reason and prevent the charging system of the vehicle from overheating, damages and electrical shocks. This is true especially for old designed electric vehicles.

The parameter a was not taken by the manufacturer specifications, because they are not considered accurate enough for different reasons. First, car manufacturer may inflate the fuel efficiency for marketing purposes. Second, the NEDC (New European Driving Cycle), the driving cycle with which all the car consumption was estimated since 1997, is not considered reflective of the real world driving (a deviation of more than 30% from real consumption was often measured). Third, the car's trip computer fuel consumption measurement may be optimistic of more than

3 https://www.spiritenergy.co.uk/kb-batteries-understanding-batteries

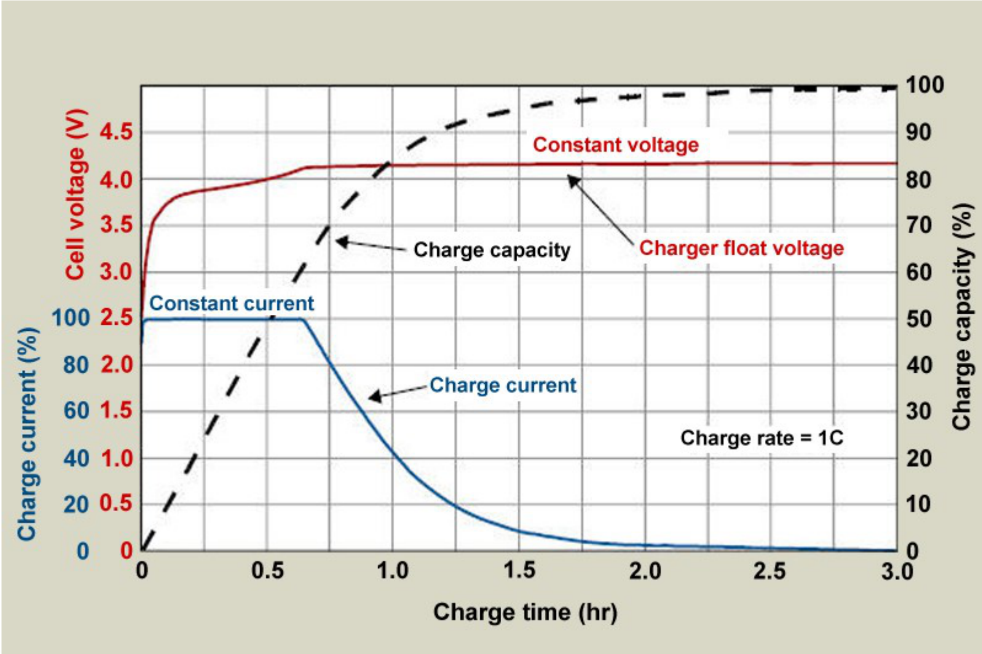


Figure 16: Battery recharging profile ("Charging Lithium-Ion Batteries" 2018)

6% compared than the real consumption. So, the consumption data was taken from Spritmonitor[4], which contains open source data of refuelling of a various number of cars from different users, and helps in calculating the real fuel consumption of each car, offering also some statistics from different users result. However, these results are often derived from a combined driving cycle (a mix of urban, extraurban and highway), so they may not be accurate and tailored to a car-sharing service usage of the vehicle (mostly on urban environment).

4.2.3 Emissions and energy model

Same as the consumption one, the emissions model has been developed as a linear model which given in input the distance travelled in kilometers, the amount of CO_2eq in grams is output, both for internal combustion engine vehicles and for electric vehicles. Together the emission model, an energy model was also developed to describe, with a linear model, the amount of energy needed to move the vehicle and the one needed to produce the fuel given the amount of mobility of each vehicle.

Well-to-Wheel process

To model both the emissions and the energy, the fuel Well-to-Wheel process is assessed. A complete Life Cycle Assessment, which is a complete evaluation on the emission associated not only to the use of the vehicle, but also to its manufacturing process and the vehicle dismantling and material recycling (end-of-life), was not performed. In fact, the amount of work to study the methodology to perform this kind of assessment is huge and databases related to the single components production of the vehicle is not easily available and, if so, they are not complete, in the sense that not every single vehicle production component is not always described in a detailed manner in terms of emission needed to produce that component. In this thesis work, it has been taken in account only the total emissions due to the production and the combustion of the fuel. However, different emissions life cycle assessments of both electric vehicles and internal combustion engine vehicles are available in the literature, and their results will be integrated with the ones of this

4 https://www.spritmonitor.de/en/

thesis. A detailed emission model is required in order to evaluate the real emissions produced by the vehicles, since, as covered in the previous chapter, an emission assessment based on the NEDC driving cycle test results would indeed lead towards an underestimated value of total emissions.

As explained in Athanasopoulou et al., 2018, the Well-to-Wheel process should be described according to the Internal Combustion Engine and to the Battery Electric Vehicles:

- The Well-to-Wheel process of Internal Combustion Engine vehicles consists of the phases of extraction of raw materials (well), transport, refining, distribution of the fuel, engine combustion of the fuel, power produced from combustion delivery to the wheels.

- The Well-to-Wheel process of Battery Electric Vehicles consists of the steps of extraction of the raw materials (well), transport, refining, distribution, power generation, power transmission and distribution, charging the battery and power delivery to the wheel

This metric may be categorized into the Well-to-Tank process and the Tank-to-Wheel process:

- The Well-to-Tank phase consists of the stages of production, refining and distribution of the energy source.

- The Tank-to-Wheel phase includes the fuel or electricity consumption during the driving of the vehicle

The total greenhouse gases Well-to-Wheel emissions is the sum of the emissions/energy produced by the Well-to-Tank phase and Tank-to-Wheel. This approach allows comparing vehicles with different fuel technology (gasoline, diesel, liquified petroleum gas, biofuels,...) or different drive-train technologies. The whole process is shown in Figure 17.

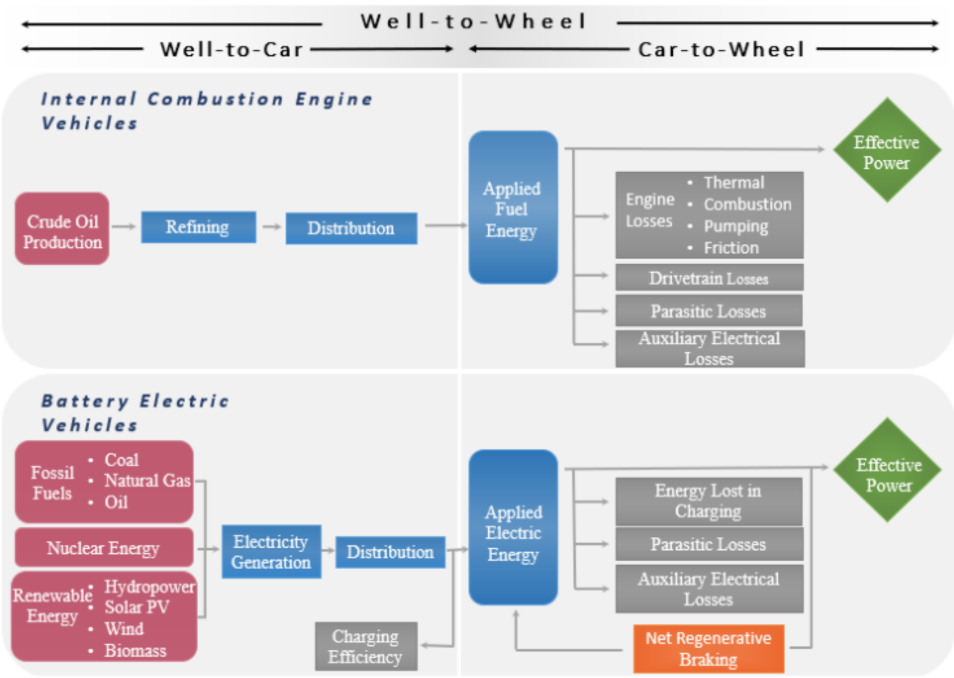


Figure 17: Well-to-Wheel process for ICEVs and BEVs

Well-to-Tank emissions and energy

The Well-to-Tank data for emissions and energy are analyzed both for the production of oil-based fuel and electricity. For oil-based fuel, finding detailed Well-to-Tank data is very difficult, because the data available online are very scarse. The only detailed one available is Prussi et al., 2020, from the Joint Research Center of the European Union. In this report, a number of existing and potential road transport fuels have been identified. Each final fuel can be produced from a single or several resources (source of primary energy), through an appropriate conversion process. The combination of steps necessary to turn a resource into a fuel, up to vehicle tank, is defined as a Well-to-Tank pathway (WTT). The pathways are split in different steps of the process, required to work the raw material into the final fuel for powering vehicles. Each process is characterised by a main input and a main output, secondary inputs, co-products as contributing to energy consumption and greenhouse gas (GHG) emissions. These processes are grouped into five main categories:

- Production and conditioning at source, which include all operations required to extract, capture the primary energy source. In most cases, the energy sources extracted requires some treatments or conditioning, before transport it in a convenient, economic and safety way
- Transformation at source is used for those cases where the industrial process is carried out at or near the production site of the primary energy, for instance a gas-to-liquids plant near a natural gas field.
- Transportation to EU is relevant to energy sources which are produced outside the EU and need to be transported over long distances.
- Transformation in EU, including the processing and transformation that takes place near the marketplace, in order to produce a final fuel according to agreed specifications, for instance oil refineries or steam reforming plants for hydrogen production.
- Conditioning and distribution relate to the final stages, as it is required to distribute the finished fuels from the point of production to the fuel charging points and available to the vehicle tank.

The oil-based fuel considered in this work are four with their relative pathways, which are:

- Gasoline - COG-1 and Diesel - COD-1; which analyses steps starting from crude oil from a typical EU supply, then its transport by sea, its refining in EU in gasoline, its typical distribution in the EU countries, and the gasoline retail in EU. The single emissions/energy figures in details are:
  - Crude oil production; including all energy and GHG emissions associated with crude oil production and conditioning at or near the wellhead (such as dewatering and associated gas separation). Production conditions for conventional crude oil vary considerably between producing regions, fields and even between individual wells and it is only meaningful to give typical or average energy consumption and GHG emission figures for the wide range of crudes relevant to Europe, hence the wide variability range indicated. These figures are good averages for crude oils in Europe.
  - Crude oil transport; since crude oil is mostly transported by ship. The ship used depends mostly on the distance to be travelled. The crude oil of the Arab Gulf is transported in large ships carrying between 200 and 500 kt. It travels via the Cape of Good Hope to Western Europe and America or towards the Far East. The crude oil from North Sea and

from Africa is transported over shorter distances to be carried by smaller ships of 100 kt typically. The pipelines are often used from the production fields to the terminal where is shipped. Some crude oil from Middle East are transported through a pipeline to a Mediterranean port. The developing regions of the Caspian basin will rely on one or several new pipelines to be built to the Black Sea. Crude oil from Central Russia is transported through pipelines to the Black Sea and directly to Eastern European refineries through an extensive network. The majority of EU refineries are located near the coast with direct access to a shipping terminal. The inland refineries are supplied by several pipelines such as the ones from the Mediterranean to North Eastern France and Germany, from the Rotterdam area to Germany and from Russia into Eastern and Central Europe.

  - Crude refining, marginal gasoline (EU); represents the energy and GHG emissions that can be saved, in the form of crude oil, by not producing a marginal amount of gasoline in Europe
  - Gasoline distribution (long distance); fuels by road are transported from refineries to depots via a number of transport modes. It has been included water (inland waterway or coastal), rail and pipeline (1/3 each). The energy consumption and distance are averaged for the whole EU. Barges and coastal tankers are using a mixture of marine diesel and Heavy Fuel Oil. Rail transport consumes electricity and includes some evaporation losses as non-methane VOCs which degrade into CO_2 in the atmosphere.
  - Liquid fuel depot; a small amount of energy is consumed in the depots mainly in the form of electricity for pumping operations.
  - Gasoline local distribution; from the depots, road fuels are transported to the retail stations by road tankers (notionally 26 t payload). Some evaporation losses are included as non-methane VOCs which degrade into CO2 in the atmosphere.
  - Gasoline dispensing at retail site; dispensing at retail stations requires energy, essentially as electricity, for lighting, pumping etc. Some evaporation losses are included as non-methane VOCs which degrade into CO2 in the atmosphere.

- LPG - LRLP-1; it describes LPG from remote natural gas field, its purification and liquefaction at source, its long-distance sea transport, its distribution by road to retail point.
  - LPG extraction and processing; it is assumed here that LPG is produced as part of the heavier hydrocarbons (condensate) associated with natural gas. Energy is required for cleaning the gas and separating the C3 and C4 hydrocarbons fractions. There is lack of data and this should be seen only as an estimate.
  - LPG liquefaction; Liquefaction requires electricity assume to be generated on site with a natural gas-fired CCGT.
  - LPG long-distance sea transport; representative of a typical LPG carrier.
  - LPG distribution; the road tanker figures pertain to a notional truck transporting 18.5 t of LPG in a 8.6 t tank. The return of the tank is also considered in the emissions/energy figures.
  - LPG dispensing at retail site; retail stations require energy, essentially as electricity, for lighting, pumping etc.

- CNG - GMCG-1; EU-mix piped natural gas supply, transport to EU by pipeline (1900 km), transport inside EU (500 km), distribution through high pressure trunk lines and low pressure grid, compression to CNG at retail point.

– Natural Gas extraction and processing; the process includes all energy and GHG emissions associated with the production and processing of the gas at or near the wellhead. Beside the extraction process itself, gas processing is required to separate heavier hydrocarbons, eliminate contaminants such as H_2S as well as separate inert gases, particularly CO_2 when they are present in large quantities. The energy and emission figures are much variable depending on the location, climatic conditions and quality of the gas. The figures used here are reasonable averages, with the large variabilities being included. A 0.4% of methane losses are included.

– Natural Gas long-distance pipeline transport to EU borders; transportation accounts for the largest part of the energy requirement because of the large distances involved. Western Siberian fields are about 5000 km from Europe (4300 km to EU border, which represents a mix of three corridors, and 700 km inside EU) whereas the typical South West Asian locations are at 4000 km distance. For the supply of marginal piped natural gas a transport distance of 4000 km has been assumed representing typical future South West Asian locations. In the pipelines, different stations are compressing the gas at regular intervals, typically powered by small quantities of the transported gas. The specific energy requirement increases with the distance because more gas has to be transported initially to have a unit of delivered gas. The actual energy consumption figures may vary considerably from one pipeline to another depending on the design and operation parameters (size vs. throughput, compressors and drivers' efficiency etc.). The energy consumption varies a lot with the pressure at which the pipeline is operating. The pipelines are working at pressures from 6 to 8 MPa. The trade-off between energy consumption and pipeline diameter need to be considered. The leakages in the transportation system result in methane losses sometimes, which is directly emitted to the atmosphere

– Natural Gas distribution (high pressure); the European gas distribution systems consist of high-pressure trunk lines operating at 4 to 7 MPa and a dense network of lower-pressure lines. The operations of the high pressure system include recompression stations which requires energy consumption on the path. The recompression stations are powered by electricity generated by the gas itself entering the turbines. The energy consumed depends on size and throughput of the lines and on the distance considered. The average energy consumption for a distance of 500 km is 0.27 MJ/t. Gas losses are reportedly very small.

– Natural Gas local distribution (low pressure); The low pressure networks are fed from the high-pressure trunk lines and supply small commercial and domestic customers. In these networks, no additional energy is needed, since the pressure energy from the trunk lines is more than adequate for the local transport.

– Compression and CNG dispensing at retail point; The current standard for CNG vehicle tanks is 20 MPa maximum which satisfies the range requirements of CNG vehicles. In order to fill the tank, the compressor must deliver a higher pressure which it has been set at 25 MPa. The pressure level available to a CNG refuelling station is critical for its energy consumption as compression energy is strongly influenced by the compression ratio (changing the inlet pressure from atmospheric (0.1 MPa absolute) to 0.1 MPa gauge (= 0.2 MPa absolute) results in half the compression ratio and a 20% reduction of the compression energy). The majority of CNG refuelling points will be positioned on existing sites for conventional fuels and therefore no additional marginal energy is spent. The methane losses documented are very few.

As it is described in the previous paragraph, this is not a full LCA, in fact the report allows estimating GHG emissions related to fossil, in the interval starting in the fuel production and ending in the vehicle tank. The ISO-14044 LCA guidelines have guided this research to evaluate the emissions released by the refineries. The energy figures are presented as total primary energy expended, regardless of its origin, to produce one MJ_f of the finished fuel under study. The heat content of the fuel itself is excluded by the figures (1 MJ/MJ_f means that the same amount of energy is required to produce the fuel that will be available to the final user, including fossil and renewable energy). The energy efficiency of the pathway are described. The WTT GHG figures as reported represent the total grams of CO_2 equivalent emitted in the process of obtaining 1 MJ of the finished fuel but do not include the emissions produced by combusting the fuel. The figures reported for individual steps of the energy and GHG balance of a pathway all relate to a MJ of the finished fuel produced by that pathway and delivered to the vehicle fuel tank (1 MJ_f). The data in use in this work is summed up in Table 2 and 3. The energy and emissions data published in the report are averaged over all the European Union. No reports about Well-to-Tank emissions and energy about specific countries have been found.

Table 2: Well-to-Tank emissions oil-based fuel

in gCO_2eq/MJ_{fuel}	Gasoline (COG-1)	Diesel (COD-1)	LPG (LRLP-1)	CNG (GMCG-1)
Production and conditioning at source	9.8	10.0	3.5	4.0
Transformation at source	-	-	0.3	-
Transportation to market	0.8	0.8	2.4	3.9
Transformation near market	5.5	7.2	-	-
Conditioning - Distribution	1.0	0.9	1.6	3.5
Total	17.0	18.9 min: 18.8 max: 18.9	7.8 min: 7.7 max: 8.3	11.4 min: 10.5 max: 12.7

Table 3: Well-to-Tank energy oil-based fuel

in MJ/MJ_{fuel}	Gasoline (COG-1)	Diesel (COD-1)	LPG (LRLP-1)	CNG (GMCG-1)
Production and conditioning at source	0.13	0.13	0.05	0.03
Transformation at source	-	-	0.00	-
Transportation to market	0.01	0.01	0.03	0.04
Transformation near market	0.08	0.11	-	-
Conditioning - Distribution	0.02	0.02	0.03	0.09
Total	0.24	0.26	0.12 min: 0.11 max: 0.12	0.15 min: 0.13 max: 0.18

Instead, regarding electricity production, data about emissions in order to produce electricity per country has been found, but regarding energy usage to produce electricity, no complete data has been found, or the energy LCA figures are not detailed enough to analyze Well-to-Tank energy flow of electricity production in the simulations. Due to this problem, the energy aspect will not be considered in the simulations, even if the oil-based fuel were implemented, waiting for the availability of more detailed researches in energy electricity production aspects. The data about emissions considered come from Noussan and Neirotti, 2020. Noussan and Neirotti evaluated a comprehensive assessment of the impact on greenhouse gas (GHG) emissions on multiple countries by considering detailed temporal analyses for both electricity generation and EVs' charging profiles. Their research shows a lot of emissions factors (including the contribution of CO_2, N_2O and CH_4, and it is expressed in gCO_2eq/kWh) in electricity production from different countries, at different depths, in particular at hourly, monthly and annual level. Moreover, the results come up with the analyzed range of emission factors variations due to the different charging profile analyzed (home, public and work).

Even if the research offers a lot of ready-to-use results to evaluate the emission factor of a country both on a daily, monthly and annual scale, with the aim of deriving in general the emission factor of a given country, the model thought by Noussan and Neirotti, 2020 was used. This model simply considers the LCA emission factors per each source as reported by the research, which has been taken from international standards, are shown in the table 4. Then, the average annual energy mix of a certain country in a given year is retrieved. The country's energy mix is the overall contribution in percentage of the sources used to produce the total amount of electricity in a given country. Then, the average annual emission factor in a given year is evaluated through the following expression:

$$avg\_gCO_2/kWh = \sum_{n=i} x_i * source_i \tag{7}$$

in which i represents the single component of the energy mix, x is the LCA emission needed to produce 1 kWh electricity using i, source is the percentage share of the resource i in the country energy mix.

Table 4: Well-to-Tank LCA emissions by sources for electricity generation

in g/kWh_{elect}	LCA emissions
Biomass	230
Coal	910
Gas	490
Geothermal	38
Hydro	24
Nuclear	12
Oil	650
Other	490
Solar	45
Waste	620
Wind	11

Speaking about the sources in the table 4, as explained by the research, the renewable sources category includes solar, hydro, wind, biomass and geothermal, while the fossil one includes coal, gas, oil and other. Electricity generation from waste is allocated in equal parts to fossil and renewable energy sources, in accordance to statistical rules that are applied in some countries, to account for the biological share of municipal solid waste.

Given these premises on the Well-to-Tank data, the Well-to-Tank emissions and energy are calculated for the Internal Combustion Engine vehicles, while only the emissions on the Electric vehicles. The amount of emissions and energy issued in order to produce a certain quantity of fuel is proportional to the amount of fuel burnt by the vehicle after a car-sharing trips. On Internal Combustion Engine vehicles, first it is required to know the lower heating value (LHV) of the fuel. The heating value of the fuel is the amount of heat released during the combustion of a specified amount of it. The LHV calculations assume that the water component of a combustion process is in vapor state at the end of combustion. The energy required to vaporize the water is not released as heat. The fuels' lower heating value is reported in the research by JEC in MJ/kg and it is reported in the table 5 with the fuel properties. Since the lower heating value is given in MJ/kg, the liquid

Table 5: Fuel properties used in this work

Fuel type	Density (g/L)	LHV (MJ/kg)	Elemental composition of Carbon (%)
Gasoline E5	745.8	42.3	84.7
Diesel B0	832	43.1	86.1
LPG	550	46	82.4
CNG	1000	48	73.5

fuels (gasoline, diesel, LPG) one should be converted in MJ/L to perform the next calculations. The conversion is done dividing the lower heating value in MJ/kg by the reciprocal of the density in kg/L:

$$LHV[MJ/L] = \frac{LHV[MJ/kg]}{\frac{1}{density[kg/L]}} \tag{8}$$

Given the LHV in that unit, the next step would be to calculate the energy released per kilometer travelled by the vehicle due to the fuel combustion:

$$ER_{km} = a^{-1} * LHV \tag{9}$$

where ER_{km} is the energy released per km, expressed in [MJ/km]; a is the vehicle city average consumption in [km/L](gasoline, diesel, LPG), [km/kg] (CNG); LHV is the lower heating value in [MJ/L] (gasoline, diesel, LPG), [MJ/kg] (CNG). Finally, the Well-to-Tank emissions and energy due to the fuel production calculated at the end of each trip is:

$$WTT\_ICEV\_emissions = \frac{WTT_{gCO2eq/MJf} * ER_{km} * distance_{km}}{1000} \tag{10}$$

$$WTT\_ICEV\_energy = \frac{WTT_{MJ/MJf} * ER_{km} * distance_{km}}{3.6} \tag{11}$$

given $WTT_{gCO2eq/MJ}$ and $WTT_{MJ/MJf}$ the total values from table 2 and 3; $distance_{km}$ the distance travelled after the trip in kilometers. In the WTT emissions result, it has been divided by 1000 to retrieve the kilograms of CO_2eq, while in the WTT energy result, the division by 3.6 is due to the conversion from MJ to kWh.

On the electric vehicles, the calculation of the Well-to-Tank emissions was slightly modified from the one shown in Athanasopoulou et al., 2018. It takes in account not only the country energy mix with which electricity is produced and the amount of electric charge that the vehicle is using during the mobility trips, but also the transmission and distribution losses in the power grid and the vehicle charging efficiency at the charging pole. The losses in transmission and distribution are due to the line resistances, the atmospheric conditions, damages or failures, miscalculations, etc... The losses incurred between the source of supply to the load center result to the increase of the electricity needed to power a Battery Electric Vehicle and therefore to the amount of CO_2 emitted. Finally, the Well-to-Tank emission calculated is:

$$WTT\_BEV\_emissions = \frac{WTT_{gCO2eq/kWh} * (1 + \frac{0.01*(100-\alpha)}{1-0.01*(100-\alpha)}) * \frac{1}{\alpha*\beta} * distance_{km}}{1000} \tag{12}$$

where $WTT_{gCO2eq/kWh}$ is the amount of emissions per kWh of electricity produced, α is the electricity transmission and distribution efficiency, β is the vehicle charging efficiency, a is the average city consumption in km/kWh, $distance_{km}$ is the total kilometers travelled by the vehicle. The result is divided by 1000 to retrieve the total emissions in kilograms. In this work, the transmission and distribution efficiency α was set to 92.5%, according to [Energy consumption, CO2 emissions and other considerations related to Battery Electric Vehicles], while the charging efficiency β to 80%, according to Jia et al., 2020.

Tank-to-Wheel emissions and energy

The Tank-to-Wheel emissions model developed in the simulator is built considering the one published in the Huss and Weingerl, 2020. The report analyzes the emissions produced by a generic passenger car during the use phase. The emission model in the report at chapter 4.3.3, is calculating the Tank-to-Wheel greenhouse gas emissions referring to the CO_2 exhaust emissions on one hand, and the Methane (CH_4) and Nitrous Oxide (N_2O) on the other hand. While the CO_2 emissions, in the report, are evaluated from the AVL CRUISE simulation, in this work, for simplicity, it has been considered the product of CO_2 from the following chemical reaction, after the combustion in the engine is happening:

$$C + O_2 \longrightarrow CO_2 \tag{13}$$

Given the carbon content in percentage, which describes the percentage of carbon in one liter of the fuel, and the fuel density in g/L, it is possible to evaluate the number of moles of carbon contained in one liter of fuel. These variables are published in a table both in the Tank-to-Wheel and in the Well-to-Tank reports. The number of moles of carbon is calculated through the following formula:

$$carb\_moles = \frac{\frac{carbon\_content_{\%}}{100} * density}{12.01} \tag{14}$$

where the constant 12.01 at denominator is the molar mass of carbon. As it is possible to observe, the stoichiometric ratio of the reaction is 1:1 for all the reagents in the reaction. So, with the same number of moles of oxygen needed to react with carbon during the combustion of one liter of fuel, it is easy to evaluate the amount of carbon dioxide produced per kilometer travelled:

$$oxygen\_grams = 32 * carb\_moles \tag{15}$$

$$CO_2\_pkt = \frac{1}{a} * (\frac{carbon\_content_{\%}}{100} * density + oxygen\_grams) \tag{16}$$

where 32 is the molar mass of oxygen gas in grams, oxygen_grams is the total amount of oxygen needed to burn one liter of fuel, a is the vehicle city consumption in km/L.

The emissions related to the Methane (CH_4) and Nitrous Oxide (N_2O) are calculated as it was done in the report. They are estimated based on the EURO 6 legislation limits for Total Hydro Carbon (THC) and NOx, respectively. The assumption done in the report is that, for instance, typically 70% of EURO 6 THC limits are really emitted as THC on an average NEDC or WLTP homologation test, and among these, approximately 7% consist of CH4. Thus, finally, the tailpipe CH4 GHG emission for a Gasoline fuel is estimated to be approximately 5% of the EURO 6 emission limit, which is given by the second column of table 6. The same can be assumed defining the total GHG emission percentages of the N2O over the total NOx emission limit. A stated by the report, in case of CNG fuel, these percentage numbers are also aligned with results in the EU-funded research project INGAS.

To obtain the resulting CO2 equivalent emissions of CH4 and N2O, the Global Warming Potential (GWP) factors for CH4 and N2O are considered: these factors are defined to be 25 gCO2eq / gCH4 and 298 gCO2eq / gN2O, expressing the greenhouse gas effect of the specific gas. So, the total CO2eq emissions due to Methane (CH_4) and Nitrous Oxide (N_2O) in gCO2eq/km are:

$$CO_2eq(CH_4) = (THC/1000) * \frac{CH_4}{THC} * GWP(CH_4) \tag{17}$$

$$CO_2eq(N_2O) = (NO_x/1000) * \frac{N_2O}{NO_x} * GWP(N_2O) \tag{18}$$

where THC, NO_x are legislation limits in mg/km in terms of THC or NO_x emissions; CH_4/THC is the percentage of the CH_4 over the total THC emission limit; N_2O / NO_x is the percentage of the N_2O over the total NO_x emission limit; GWP is the Global Warming Potential factor (gCO2eq / gCH4 and or gCO2eq / gN2O). Finally, the total Tank-to-Wheel emissions calculated for Internal Combustion Engine vehicles after each trip is:

Table 6: Impact of CH4 and N2O emission for fuels combustion in terms of CO2eq GHG

	EURO 6 THC or NOx limits (mg/km)	Percentage (N2O or CH4) of limit	GWP factor
Gasoline (CH4)	100	5%	25
LPG (CH4)	100	5%	25
CNG (CH4)	100	60%	25
Diesel (CH4)	90	10%	25
Gasoline (N20)	60	3%	298
LPG (N20)	60	3%	298
CNG (N20)	60	3%	298
Diesel (N20)	80	5%	298

$$TTW\_ICEV\_emissions = (CO_2\_pkt + CO_2eq(CH_4) + CO_2eq(N_2O)) * distance_{km} \tag{19}$$

The Tank-to-Wheel energy of internal combustion engine vehicle is the total amount of energy released by the vehicle engine during the mobility. The energy considered is the sum of both the useful energy which is delivered to the wheels to allow the movement of the vehicle, which is around 23% of the total energy, and the energy wasted as heat due to the low efficiency of the internal combustion engine powertrain, which has the largest share. The Tank-to-Wheel energy of internal combustion engine is calculated as:

$$TTW\_ICEV\_energy = \frac{ER_{km} * distance_{km}}{3.6} \tag{20}$$

In case of fully electrified vehicles, no CO2, Methane or Nitrous Oxide is emitted during the use phase, a part from the contact between the rubber of the tyres and the road, which here is not considered. Regarding the Tank-to-Wheel energy consumed by an electric vehicle, the same points about internal combustion engine vehicles can be reported here, a part from that the efficiency of the electric powertrain is much higher than the internal combustion engine. In this case, the efficiency is at least 75%, so many of the total energy used by the powertrain is useful for the mobility, while instead a much smaller amount is wasted as heat. That said, the total Tank-to-Wheel energy used by an electric vehicle is:

$$TTW\_BEV\_energy = \frac{1}{a} * distance_{km} \tag{21}$$

where a is the vehicle average city consumption in [km/kWh]

4.3 MODELS IMPLEMENTATION

In summary, the Vehicle and Charging Station classes are developed to work together, because the Vehicle class need parameters in the Charging Station one to implement the vehicle recharging, for example the fuel flow (ICE vehicles) and power (electric vehicles) parameter, and, at the same time, the Charging Station class need some parameters of the Vehicle class, such as the charging power limits of the vehicle (electric vehicles). The consumption and recharging model implemented in the class Vehicle has the following attributes:

- engine_type, indicating the fuel type powering the engine
- consumption, represents the vehicle fuel consumption in km/L (liquid fuel), km/kg (gaseous fuel), km/kWh (electric fuel)
- capacity, the amount of fuel stored in the vehicle in liters (liquid fuel), kilograms (gaseous fuel), kilowatt-hours (electric fuel)

The methods implemented for the fuel consumption and recharging are:

- get_charging_time_from_perc, it retrieves the amount of time in seconds needed to recharge the vehicle. It takes in input the SoC current level, the fuel flow speed from the charging station, the charging profile type (only on electric vehicles) and the threshold β
- get_percentage_from_charging_time, it returns the opposite variable of the previous method, the charged percentage of SoC given the amount of charging time in seconds. In input, the method requires the charging time, the fuel flow speed from the charging station and the charging profile type (only on electric vehicles)
- consumption_to_percentage, it returns the percentage of SoC related to the amount of fuel consumed given in input. It takes in input only the fuel consumed in liters (liquid fuel), kilograms (gaseous fuel), kilowatt-hours (electric fuel)
- percentage_to_consumption, opposite to the previous method, it retrieves the amount of fuel consumed in liters (liquid fuel), kilograms (gaseous fuel), kilowatt-hours (electric fuel) related to the SoC percentage given in input. In input, it takes only the SoC percentage of fuel consumed.
- distance_to_consumption, returns the amount of fuel consumption in liters (liquid fuel), kilograms (gaseous fuel), kilowatt-hours (electric fuel), given in input the amount of kilometers travelled after a rental trip. In input, it takes the distance in kilometers.

The attributes related to the emissions and energy models are added, which are:

- well_to_tank_emissions, indicating the total amount of emissions in gCO2eq to produce a MJ (oil-based fuel) or a kWh (electricity) of fuel
- well_to_tank_energy (only oil-based fuel), indicating the total amount of emissions in MJ to produce a MJ of fuel
- density (only oil-based fuel), expresses the fuel density in g/L
- lower_heating_value (only oil-based fuel), indicating the fuel lower heating value in MJ/kg

- carbon_content (only oil-based fuel), indicating the percentage of carbon contained in the fuel
- thc_limits (only oil-based fuel), indicating the limits of Total Hydro Carbon quantity based on EURO 6 regulations
- nox_limits (only oil-based fuel), indicating the limits of NO_x quantity based on EURO 6 regulations
- perc_ch4_limits (only oil-based fuel), indicating the percentage of CH_4 over the total THC emission limit
- perc_n2o_limits (only oil-based fuel), indicating the percentage of N_2O over the total NO_x emission limit
- gwp_ch4 (only oil-based fuel), indicating the amount of equivalent CO2 emissions in grams due to the emission of one gram of CH_4
- gwp_n2o (only oil-based fuel), indicating the amount of equivalent CO2 emissions in grams due to the emission of one gram of N_2O
- transmission_efficiency (only electricity), indicating the efficiency in percentage of the power grid in delivering electricity up to the charging pole
- charging_efficiency (only electricity), indicating the efficiency in percentage in delivering the charge to the vehicle battery supply from the charging pole
- supported_charge (only electricity), indicating the maximum charging power in kW the vehicle is able to carry for each of the charging profile

Also some methods have been implemented to calculate emissions and energy:

- tanktowheel_energy_from_perc, it retrieves the amount of Tank-to-Wheel energy in kWh, distinguishing from an internal combustion engine vehicle and an electric vehicle. It takes as input the SoC percentage drained during the trip.
- welltotank_energy_from_perc, it retrieves the amount of Well-to-Tank energy in kWh, distinguishing from an internal combustion engine vehicle and an electric vehicle. It takes as input the SoC percentage drained during the trip.
- distance_to_welltotank_emission, it retrieves the amount of Well-to-Tank emissions in kilograms of CO_2 equivalent from the total amount of kilometers travelled in the trip, distinguishing from an internal combustion engine vehicle and an electric vehicle. It takes as input the distance travelled in kilometers.
- distance_to_tanktowheel_emission, it retrieves the amount of Tank-to-Wheel emissions in kilograms of CO_2 equivalent from the total amount of kilometers travelled in the trip, distinguishing from an internal combustion engine vehicle and an electric vehicle. It takes as input the distance travelled in kilometers.

The attributes of the Charging Station class are related mainly to the charging model, and they are:

- fuel_type, indicating the fuel delivered by the charging station
- flow_rate, indicating the amount of fuel delivered per minute in the tank by the charging station. This is expressed in L/min (liquid fuel), kg/min (gaseous fuel) for ICE vehicles. In the electric charging pole, this value establishes the total power in kilowatt-hours delivered to the vehicle.
- voltage_output, indicating the voltage in output from the pole in Volts (V)
- current_output, indicating the amount of current from the pole in Ampere (A)

4.4 MODELS VALIDATION

After the emissions and energy model have been developed, their results should be validated with a model commonly accepted in literature, so that the results got in this work should not have significant gap with the literature. The report chosen to perform this validation is the Huss and Weingerl, 2020, already used to implement the Tank-to-Wheel model in this work. The motivations about this choice are different: first, this report containes detailed informations about the vehicles used to perform the study, which allows to use in the simulator the same vehicle with the same parameters; second, the report focuses on different internal combustion engine fuels and with battery electric engine, which comes useful to the results of this work; third, the report contains also the Tank-to-Wheel energy usage of the different fuel powered vehicles, which is handy to evaluate, at the same time, the Well-to-Tank emissions of the vehicles, allowing to validate the model at a Well-to-Wheels scale.

It should be highlighted that, even if the Tank-to-Wheel model considered in the simulator has the same structure as the one published in the report, they are different at the same time, since the CO_2 emissions evaluated in this work uses a completely different model than the one of the report, which uses the AVL CRUISE simulation. So, this procedure can be considered a genuine validation.

To perform the validation, the same vehicles used in the report are set in the simulator, and these are shown in the table 7 with their parameters. The vehicles considered are not from the actual retail market, but their characteristics, as it will be described in the followings, match the ones of a typical 5-seater sedan car of C-segment used in everyday life. The procedure to validate the models is the following:

Table 7: Vehicles characteristics of the JEC Tank-to-Wheel v5 report

Fuel_type	Capacity	Fuel consumption	Energy consumption
Gasoline	55 L	18.21 km/L	1.73 MJ/km
Diesel	55 L	24.63 km/L	1.45 MJ/km
LPG	80 L (+ 14L gasoline)	14.31 km/L	1.77 MJ/km
CNG	26 kg (+ 14L gasoline)	27.25 km/kg	1.76 MJ/km
Electric	16.6 kWh	-	0.46 MJ/km

- Set up the report's vehicle specifications on the simulator (capacity, fuel consumption)
- Given a trip distance of one kilometer, the Tank-to-Wheel emissions/energy and the Well-to-Tank emissions/energy are evaluated on the simulator with its own model
- While the total Tank-to-Wheel emissions per kilometer result is published on the report, the Well-to-Tank emissions/energy are evaluated by multiplying the energy consumption per kilometer published on the report with the Well-to-Tank fuel emissions/energy listed in table 2 and 3
- The Tank-to-wheel and Well-to-Tank emissions/energy are summed up, both on the simulator and in the report, and compared in the Table 8

The validation about the energy model is performed only on the internal combustion engine vehicles. In fact, as described before, the Well-to-Tank energy data on electricity were not complete and described enough to be used and perform a comparison. In the Table 8 are shown the results of the comparison.

Table 8: Simulator vs report: above Emissions (g/km), below Energy (MJ/km)

	WTT		TTW	
	Simulator	Report	Simulator	Report
Gasoline	29.44	29.47	128.10	127.83
Diesel	27.39	27.50	107.97	107.91
LPG	13.79	13.79	117.10	116.69
CNG	20.08	20.07	101.24	100.79
Electric	45.88	45.88	-	-
	WTT		TTW	
	Simulator	Report	Simulator	Report
Gasoline	0.416	0.416	1.731	1.733
Diesel	0.376	0.378	1.449	1.455
LPG	0.212	0.212	1.769	1.768
CNG	0.264	0.264	1.762	1.760

The results both on emissions and energy are differing from the Tank-to-Wheel emissions and energy published in the WEC Tank-to-Wheel v5 report to the order of mg for emissions and kJ for energy, same as the derived Well-to-Tank emissions and energy from the report WEC Well-to-Tank v5. Since the difference is negligible for emissions, while for energy, even if it is larger, is considered accurate enough, the two models are considered to be validated on a Well-to-Wheel scale with the literature. They can be used to derive some hints in the sustainability of the car-sharing mobility patterns both for the internal combustion engine vehicles and the electric vehicles.

4.5 PROFIT MODEL

The profit model implemented is very simple and it allows to understand if the car sharing service, given certain input conditions, is profitable in the time interval considered in the simulation. It is divided in two main cost categories:

- **scenario costs**, including the supply costs to satisfy the users' mobility demand. These include:
  - **vehicles cost**, related to the costs of leasing the number of vehicles deployed in the urban soil. It has been calculated as:

    $$vehicle\_cost = N * price * n\_months \tag{22}$$

    where N is the number of vehicle deployed in the city, price is the vehicle monthly cost of leasing, n_months is the number of months for which the car-sharing service simulation is run.
  - **charging infrastructure cost**, which considers the cost of installing the charging infrastructure on the city to recharge the vehicles. These costs are considered only for an electric vehicle car-sharing company which wants to settle and to install a charging infrastructure on a particular city which is supposed not to be provided of a public one. This is expressed as:

    $$ch\_infr\_cost = \frac{N\_poles * pole\_cost}{pole\_life} \tag{23}$$

    where N_poles is the charging capacity installed on the city; pole_cost is the installation, maintenance and taxes cost of placing a charging pole; pole_life is the total expected life of the charging infrastructure, which acts as an amortization of the infrastructure costs.

- **simulation costs**, including the costs due to the interaction of the resources deployed in the simulation (vehicles and workers). The cost contributions come from:
  - **relocation cost**, which evaluates the total cost of the workforce implemented in relocating the vehicles. This is implemented based on the time in hours spent in relocating the vehicles, through the following equation:

$$reloc\_cost = hours * WH\_cost \tag{24}$$

    where hours is the total time spent in relocating the vehicles during the study period in hours, WH_cost is the total workers wage per hour of relocation.
  - **energy cost**, related to the cost of the fuel consumed by the vehicles during the mobility. This is simply evaluated as:

$$fuel\_cost = price\_pu * tot\_fuel \tag{25}$$

    where price_pu is the price of the fuel per unit, tot_fuel is the total amount of fuel consumed in mobility in the simulation period. The amount of fuel consumed is calculated from the total TTW energy consumed. Based on the fuel type, the amount of fuel is found through two different relations:
    * Internal Combustion Engine vehicles:

$$tot\_fuel = \frac{TTW\_energy[MJ]}{LHV[MJ/L, kg]} \tag{26}$$

    * Electric vehicles:

$$tot\_fuel = \frac{TTW\_energy[kWh]}{\alpha} \tag{27}$$

    where TTW_energy is the Tank-to-wheel energy needed to allow mobility, LHV is the fuel lower heating value, α is the charging efficiency.
  - **cleaning cost**, related to the costs of washing and disinfection of the car. It has been supposed that a disinfection is performed at the end of each vehicle recharge, and the washing every 100 bookings, such that:

$$clean\_cost = dsinf\_cost * N_{ch} + wsh\_cost * \frac{N_{book}}{100} \tag{28}$$

    where dsinf_cost is the cost of disinfecting the vehicle, wsh_cost is the cost of washing the vehicle, N_{ch} is the number of vehicle charging, N_{book} is the number of mobility requests.

This is a model which allows to generalize better the profit of a car-sharing service. In fact, each cost component can be easily retrieved for different countries and allows to place a comparison between different cities. A more detailed cost model was found in Jia et al., 2020, including also a break-even cost analysis of two Chinese car-sharing companies. However, this model was not implemented because contains cost components which are related to China market, and they cannot be easily ported in other countries.

5 RESULTS

In this chapter, the mobility simulator, improved with the implementation of the models described in the previous chapters, will be exploited to derive different performance metrics. Basing the performances on these metrics, it is possible to compare the service offered by a car-sharing based on internal combustion engine vehicles and on electric vehicles.

5.1 INPUT PARAMETERS

5.1.1 Vehicles

First, four internal combustion engine vehicles have been chosen, one per fuel type, among gasoline, diesel, LPG, CNG and electric. The vehicles considered have to be as similar as possible in terms of engine displacement, weight, power, aerodynamics and transmission. Possibly, the vehicles have to be chosen among different fuel type versions of the same model and the same manufacturer. However, this is not possible, since actually there is not a single model available on the market which is sold in the five fuel type versions at issue. The car chosen which is available in most fuel type versions is the Volkswagen Golf, mark 7, sold in 2018, available in gasoline, diesel, CNG and electric fuels. Instead, no LPG versions was available, and a similar vehicle has been chosen, the Opel Corsa 1.4 EcoTech (LPG) from 2018. In the table 9, there is a summary of their specifications.

The vehicles powered by LPG and CNG fuel type are bi-fuel, meaning that they are provided, together with the main fuel tank, of a small gasoline fuel tank, and they can switch their power source. However, in the simulations, it is supposed that these vehicles are moving powered only by the main tank (LPG, CNG).

5.1.2 Geographical setup

The mobility demand considered in the simulations are first from Turin and then from Amsterdam, in the month of October, November and December, year 2017. The energy mix considered for Turin simulations is the one of Italy 2017, and shown in the pie chart 18. For the city of Amsterdam, the energy mix of the Netherlands in 2017 is considered. The data was taken by the International Energy Agency website for both countries[1].

5.1.3 Simulation setup

The type of simulations used is called internally "eventG", meaning that the mobility demand during the simulation is based on a model fitted on parameters such as inter-arrival time between booking requests, origin and destination coordinate, etc., according to the mobility data acquired in the trace. The simulations are "multiple runs", so that multiple simulations have been run by varying one or more input parameters according to a certain range and step. During these simulations, the number of mobility requests in a month is fixed to 10^5. The first analysis to be done is to evaluate the car-sharing service performances considering a vehicle fleet

1 https://www.iea.org/countries/italy - https://www.iea.org/countries/the-netherlands - Topic: Electricity and Heat - Indicator: Electricity generation by source

Table 9: Specifications of the sample vehicles

Model	Fuel type	Capacity (L,kg,kWh)	Charging mode available
VW Golf 7 1.0 TSI	Gasoline	50	-
VW Golf 7 2.0 TDI	Diesel	50	-
Opel Corsa 1.4 EcoTech	LPG	35	-
VW Golf 7 1.4 TGI	CNG	15	-
VW eGolf 2018	Electric	32	1. AC 230V 10,16,32A (1-3 phase, max 7.2A) 2. DC 450V 122A, 400V 325A (max 39A)
Smart Fortwo Electric Drive	Electric	16.7	1. AC 230V 10A, 16A, 32A (1-3 phase, max 4.6A)

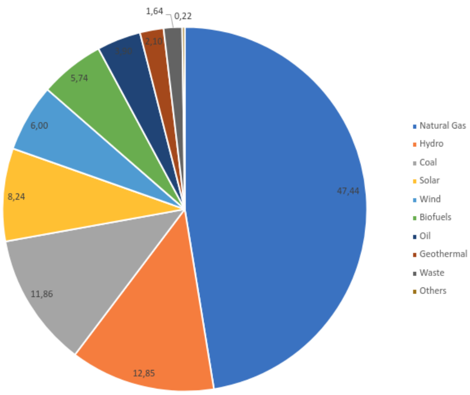
Model	Consumption (km/L,kg,kWh)	Range (km)	WTW GHG emissions (g/km)	Fuel cost (€/km)
VW Golf 7 1.0 TSI	12.987	649.35	220.554	0.1104
VW Golf 7 2.0 TDI	16.393	819.65	202.5135	0.0800
Opel Corsa 1.4 EcoTech	11.85	414.75	167.7679	0.05245
VW Golf 7 1.4 TGI	18.8679	283.0185	174.1447	0.065
VW eGolf 2018	10.309	329.888	36.2144	0.03194
Smart Fortwo Electric Drive	7.6046	126.997	49.0932	0.0433

of gasoline, diesel, LPG, CNG and electric powered. In this campaign, it is assumed that all the vehicle fleet are powered by the same fuel type, and the charging stations provide the same fuel type as the vehicle one. Consequently, the vehicle fleet and the charging stations deployed use a single fuel type, therefore there are not hybrid fleets and charging stations (no fleet composed by gasoline and diesel vehicles or charging stations providing gasoline and diesel together, for instance).

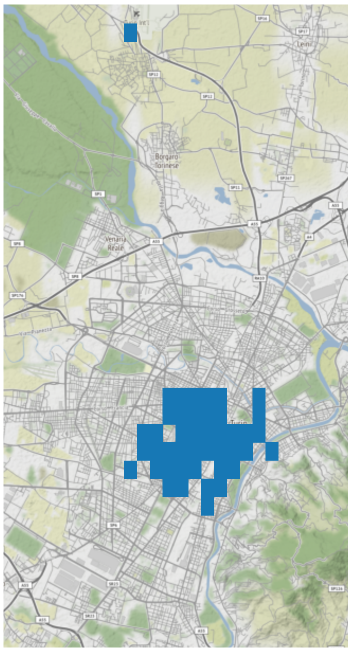
For the Internal Combustion Engine fleet, the real charging point positions in the city have been considered. In order to find the positions of the charging points, two information sources have been used:

- the first one is the OpenStreetMap API, which allows to retrieve the coordinate data of the fuel charging point of interest of a given city, through a request on the platform. The data coming from this sources are managed through the user's contribution, since they can add or remove point of interests based on their experience. The data offered by this platform are the only available, however they are not exempt from missing data or errors. In case of missing or wrong data, these are manually corrected by adding or correcting them through some checks on official data. Even if the data are quite complete in terms of gasoline, diesel and LPG fuels, some missing data have been discovered for CNG and in particular, electric charging point, for which data are almost completely missing.
- for electric charging point, the charging station's positions have been taken from the stations installed by BlueTorino (now bought by Leasys SpA) and the ones installed by Enel, through the Enel X electric vehicle charging network. Their positions can be retrieved on their websites.

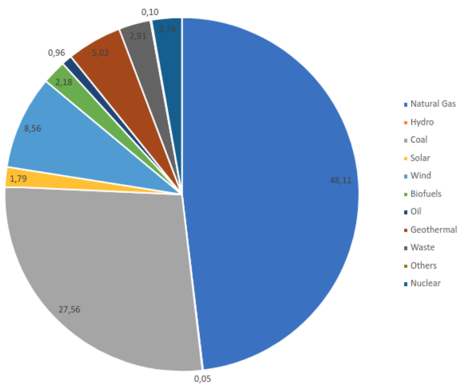
Each couple of latitude and longitude is intersected with the city grid zones developed at the starting of the simulation. If there is a correspondence between the coordinates and the polygon delimiting the zone, then a given number of poles is



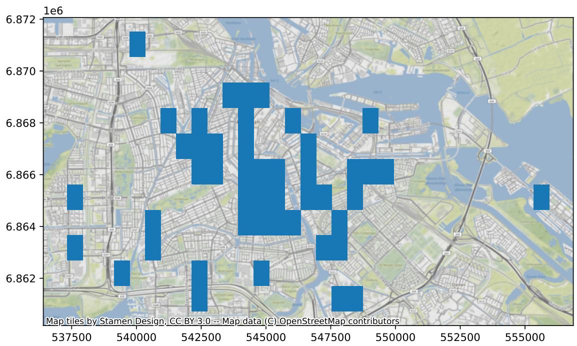
(a) Italy electricity production by sources 2017



(b) Number of parkings policy placement (Turin)



(c) The Netherlands electricity production by sources 2017



(d) Number of parkings policy placement (Amsterdam)

Figure 18: Simulation input parameters

assigned to that city zone. In the actual implementation of the simulator, it is not possible to distinguish geographically between one station from another one in the same city zone, but they are grouped together so that the number of poles lying in that city zone corresponds to the sum of the poles of all the charging station in that zone.

For the Electric Vehicles fleet, both the real charging point positions and the "Number of parkings" placement policy have been used, the second meaning that the poles are placed on the zones which has the highest probability of being destination zones. In particular, in this case, the charging zones chosen will be the top 20% among the highest number of destinations. It has been considered because it provides a good ratio between user satisfied demand and implementation time. This case has been considered as if there is no public charging infrastructure installed in the city, so the car-sharing company have to install it in order to deploy the electric vehicle fleet. The effect on the unsatisfied demand and on the charging relocation time are evaluated considering the different charging powers on the infrastructure. As reported in Table 9, the electric vehicles are limiting internally the power delivered by the charging pole due to safety. For this reason, in this part are not considered all the charging power implemented in the simulator as shown in Table 1, since most of the profiles' power will overtake the vehicle limits, producing redundant results. The charging station placement policy is the same one used in the previous experiment, which is placing the poles on the top 20% city zones for number of parkings. Also the three experiments performed in the previous section are considered in this try.

The charging power considered are:

Table 10: Charging profiles in exams

Profile type	Voltage (V)	Current (A)	Power (kW)
wall_plug	230	10	2.3
single_phase_1	230	16	3.7
single_phase_2	230	32	7.2
dcfc_1	450	112	50.4

The metrics analyzed on this campaign are two, these have been introduced already in the introductory chapter, here will be summarized:

- Unsatisfied demand, which is the fraction of requests that are not satisfied because there is no car with enough SoC (State of Charge) in the origin and the neighbouring zones. It is an indicator of the quality of the service in terms of car availability for user requests, and it should be minimized.
- Total charging relocation time, which measures the monthly time spent by the system to bring cars to the charging stations. It is the sum of the driving time spent by the workers to drive the cars to the nearest-free pole. Since it is a cost, it should be minimized.

During this campaign, two different experiments have been performed. In a nutshell, for each experiment, one variable is let varying over a given interval, while the others are fixed to a relatively large value, so that their correlation on the final metrics should be as minimized as possible. These are the experiments:

- Variation of the number of vehicles, both on the Internal Combustion Engine and Electric Vehicles fleet, in which the vehicles are increased from 1 to 400 with a step of 6. The number of charging poles is kept at 200, in case of the "Number of parkings" placement policy, while in case of the real infrastructure, the total number of the poles deployed in the city is considered.
- Variation of the number of charging pole, in which the poles are increased from 1 to 60 with a step of 1. The number of vehicle is kept at 400. This is considered only on the Electric Vehicle fleet, considering the "Number of parkings" placement policy.

5.2 TURIN CASE STUDY

The Turin charging zones placed with "Number of parkings" policy are shown in the Figure 18(b). In the Figure 19 are shown the zones containing charging stations per fuel type in the city of Turin, placed according to the real infrastructure. The charging stations lie mostly on the city center zone.

5.2.1 Unsatisfied demand

Looking at the unsatisfied demand over the number of vehicles (Figure 21(a)), it can be derived a threshold for # Vehicles > 150, over which the difference between an internal combustion engine vehicle and an electric vehicle is negligible in terms of quality of service. For a number of vehicles smaller than 150, the service starting to be stressed under a load of 10^5 requests, an internal combustion engine vehicle fleet guarantees a slightly better quality of service than the one offered by an electric vehicle fleet. This is explained by the larger range achieved by the internal combustion engine vehicle with respect to an electric vehicle. This is true if no relocation policies are applied. This difference tends to be negligible when a simple relocation policy is applied, as in this study, which is the most realistic scenario. Regarding the electric vehicles, shown in Figure 21 (b), for a number of vehicles larger than 150, which is a normal operating condition, a higher charging power does not improve the satisfied demand with respect to a lower one. However, in stressful conditions, for a number of vehicle lower than 150 vehicles, a higher charging power would help in keeping the unsatisfied demand much lower with respect to a lower charging power. The vehicle range has also importance in reducing the unsatisfied demand in stressful conditions. If the infrastructure is placed by the operator based on the "Number of parkings" policy and the number of charging poles is changed, different considerations have to be done. The result is shown at Figure 21 (d). Both the charging power and the vehicle dynamics characteristics impact largely on the minimum number of charging poles needed to let the service work properly and minimize the unsatisfied demand. On the minimum charging power, the VW e-Golf requires 23 poles, considering a fleet of 400 vehicles. This suggests that the minimum the power delivered, the larger the number of charging poles required. Moreover, the service performances depends on the maximum amount of power and the type of waveform supported by the vehicle charger. Since the e-Golf is supporting DC charging, the service would require a few DC charging poles to satisfy the maximum demand.

Instead, even if an internal combustion engine vehicle guarantees slightly better service performances, the amount of greenhouse gas emissions produced by them is much higher than the ones produced by the electric vehicle. In particular, the gasoline vehicle fleet is the most pollutant among the internal combustion engine fleet. It is important to underline that the emissions are increasing proportionally with the percentage of satisfied demand (consequently to the increase of the number of vehicles).

5.2.2 Relocation costs

On the Figure 23 and 24 are shown the relocation costs in terms of hours and emissions of the experiments. The considerations done for the unsatisfied demand are still valid in the relocation costs. However, it has to be noticed that the electric vehicle fleet needs more time spent in relocation than gasoline and diesel fleet. This is mostly dependent on the charging station distribution around the city and on the vehicle city consumption and capacity. Regarding the internal combustion engine vehicles, the CNG-powered Golf is the worst not only in charging relocation time, but also in terms of emissions released. The vehicle's fuel type which uses the least charging relocation hours is the diesel one. However, the least pollutant fuel in charging relocation is the electric one with the VW e-Golf fleet. If the charging infrastructure is placed according to the "Number of parkings" policy, the hours spent in relocation are much higher than the ones with the real infrastructure. The advantages brought by an electric car-sharing vehicle depends critically on the vehicle fleet model.

The different charging power on the charging relocation cost leaves to conclude that: when varying the number of vehicles, a higher charging power slightly reduces the number of hours needed to relocate the vehicles, with a "Number of parkings" policy. On the real infrastructure, a higher speed does not bring improvements. The vehicle dynamic performances and the charging station distribution impact most on the charging relocation hours. When the number of charging poles is varying, a higher charging power may bring great improvements than a lower one, when are placed the minimum number of charging pole to achieve a working service. If the number of charging poles increase, the difference between a higher charging power and a lower one is reduced.

5.2.3 Profit

The following costs and revenues have been applied in the model for the city of Turin.

Vehicles

The vehicles are supposed to be taken in leasing under a three-year long contract. The leasing costs are estimated mostly based on their retail costs. The annual leasing are reported. The user rental cost are estimated based on the Share Now tariff per minute of rental. The washing and disinfection costs are estimated based on an average cost in Italy.

Table 11: Vehicle-related costs (in €)

Model	Leasing	Washing	Disinfection	Rental price
VW Golf 7 1.0 TSI	2614.32	8	15	0.26
VW Golf 7 2.0 TDI	4970.64	8	15	0.26
Opel Corsa 1.4 EcoTech	2500.68	8	15	0.26
VW Golf 7 1.4 TGI	3324.24	8	15	0.26
VW eGolf 2018	5053.32	8	15	0.26

Charging infrastructure costs

The charging infrastructure costs are considered supposing that an electric car-sharing operator plan to build the infrastructure with a "Number of parkings" policy with different power output of the stations. The infrastructure useful life considered is 10 years. When considering the public city infrastructure, these costs will be set

Table 12: Charging pole cost (€) (by power profile)

Profile type	Hardware	Labor	Materials	Permit	Taxes
wall_plug	813	600	-	-	178.86
single_phase_1	3127	1544	1112	82	687.94
single_phase_2	3127	1544	1112	82	687.94
dcfc_1	31000	19200	26000	200	6820

to zero.

Relocation costs

The costs of the workers wage per hour spent in relocating vehicles is set to be 23 €per hour.

Energy costs

The energy costs will be set according to the average historic price of fuels in the three months from October to December 2017 in Italy. On the electricity price, two conditions have been considered: in case of the "Number of parkings" placement policy, the cost of industrial electricity per kWh is considered; with the public real infrastructure, the tariff of Enel X per kWh in recharging the vehicles is considered.

Table 13: Fuel costs (€/L, kg, kWh) - Italy Oct-Dec 2017

Gasoline	Diesel	LPG	CNG
1.580	1.440	0.650	0.973

Electricity (industrial)	Electricity (AC)	Electricity (DC)	Electricity (DC plus)
0.1449	0.40	0.50	0.79

The results are shown in Figure 25. Focusing on the real infrastructure, the profit resulted by the simulation is in favour of the Internal Combustion Engine fleet over the Electric vehicle one, with the prices considered above. On the electric fleet, a higher charging power would not influence the profit of the service. Instead, the vehicles among the Internal Combustion Engine category show different paths in terms of profit: while the LPG and the gasoline fleet are the most profitable, with a size of 100-150 vehicles, from the diesel powered fleet comes the least incomes. The vehicle leasing cost seems to be the key factor in profit achievement, since the diesel powered vehicle is also the one which costs more.

Instead, if the car-sharing operator need to install an electric charging infrastructure on the public soil with the "Number of parkings" policy, a trade-off between the number of vehicles and the number of charging poles should be considered in order to properly dimension the system and to guarantee incomes. From the figures (c) to (f), while the optimal fleet size has to be in the interval [46, 136] vehicles, the charging capacity varies according to the power output. A lower power output calls for a higher number of charging pole to get incomes, otherwise the car would spend too many time in recharging, and few vehicles would be available for user mobility. A higher charging speed, like in (f), requires few charging stations to get the maximum profit. In case of the "Number of parkings" policy, a higher charging power infrastructure would guarantee a higher profit than a lower charging power infrastructure.

5.3 AMSTERDAM CASE STUDY

The Amsterdam charging zones placed with "Number of parkings" policy are shown in the Figure 18(d). In the Figure 20 are shown the zones containing charging stations per fuel type in the city of Turin, placed according to the real infrastructure. The charging stations are spread around the city. As shown in Figure 26,27, 28 and 29, the results obtained with the Turin case are replicated, both for the unsatisfied demand and the hours spent in relocations. The only thing which is remarkable is the much higher pollution due to the electricity production in the Netherlands, which uses a larger share of fossil fuels (based mostly on natural gas) and a smaller amount of renewables. However, the amount of emissions to produce the electricity needed is lower than the total amount of emissions produced by the internal combustion engine vehicles. The LPG and CNG fleet are the ones for which most time is spent in relocation.

5.3.1 Profit

The costs and revenues applied in the model for the city of Amsterdam are the same of the city of Turin, except for the energy cost, slightly different, which is reported in the followings.

Energy costs

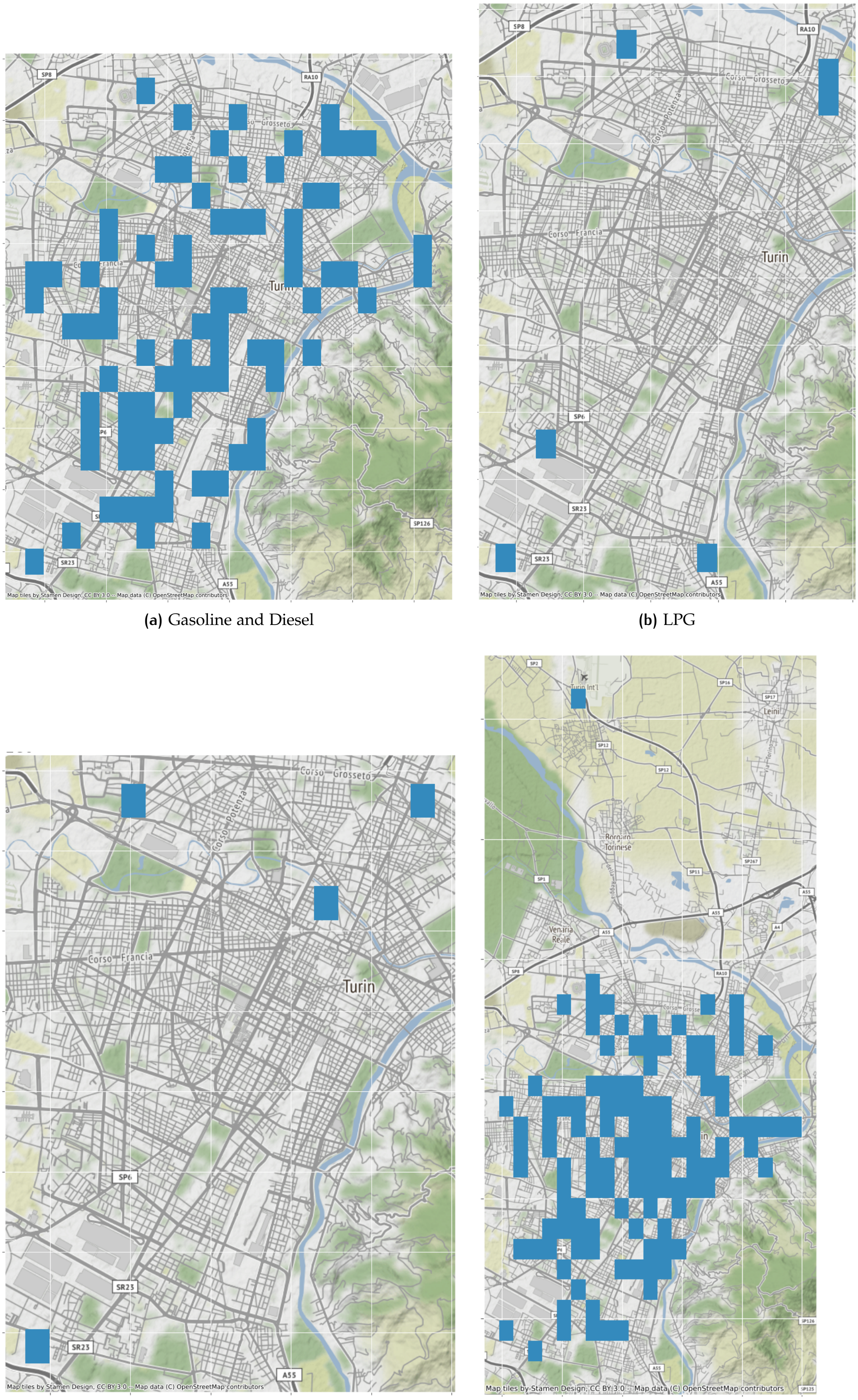
As for Turin, the energy costs will be set according to the average historic price of fuels in the three months from October to December 2017 in the Netherlands. On the electricity price, two conditions have been considered: in case of the "Number of parkings" placement policy, the cost of industrial electricity per kWh is considered; with the public real infrastructure, the average public cost per kWh in recharging the vehicles is considered.

Table 14: Fuel costs (€/L, kg, kWh) - The Netherlands Oct-Dec 2017

Gasoline	Diesel	LPG	CNG
1.670	1.340	0.880	1.022

Electricity (industrial)	Electricity (AC)	Electricity (DC)	Electricity (DC plus)
0.0764	0.36	0.62	0.62

The profits calculated for Amsterdam are shown in Figure 30 and reflect what already discovered in Turin: the gasoline, LPG and CNG fleets profit more than the electric fleet. The electric fleet profit is comparable with the one of the diesel fleet. If a car-sharing service install an electric charging infrastructure with the "Number of parkings" placement policy, a low-medium charging power would profit slightly more than installing a higher power charging one.



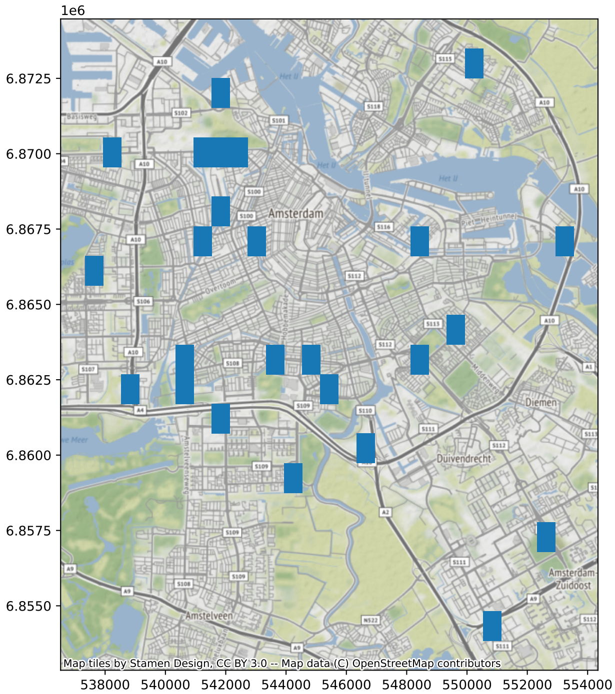
(a) Gasoline and Diesel

(b) LPG

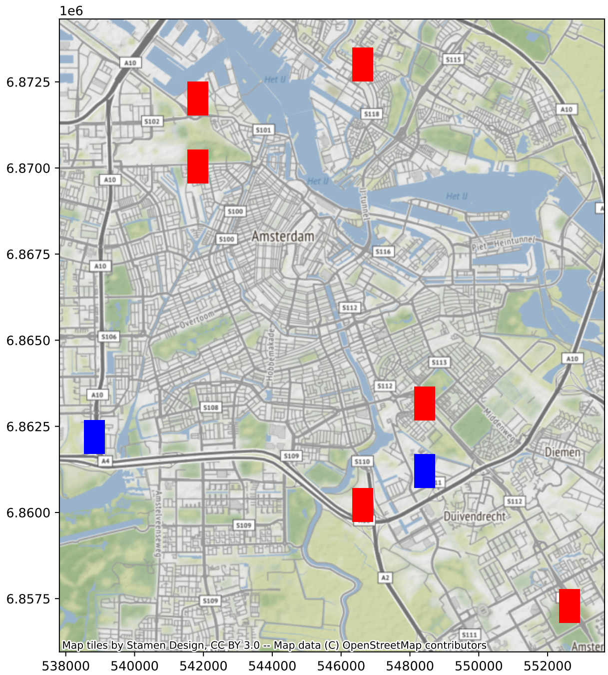
(c) CNG

(d) Electric

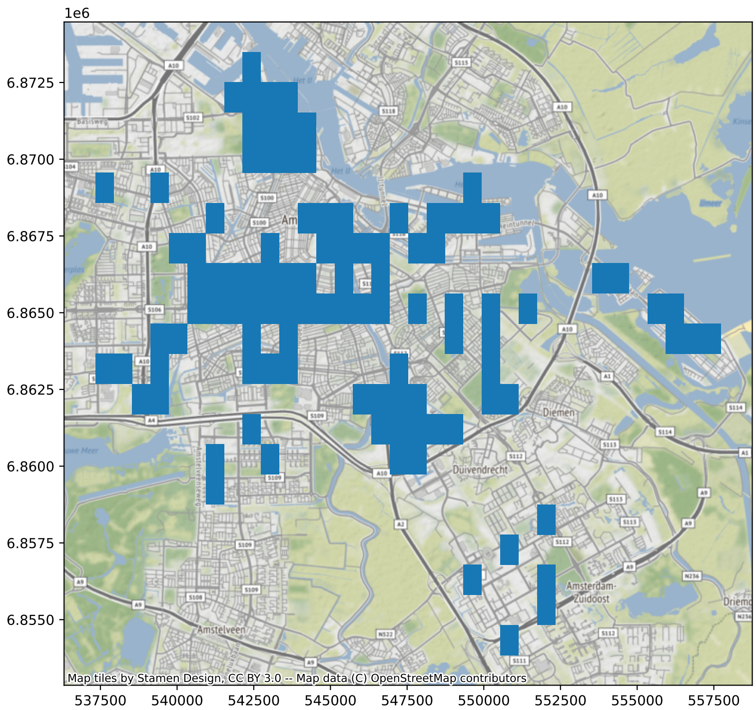
Figure 19: Turin - Real charging station positions



(a) Gasoline and Diesel

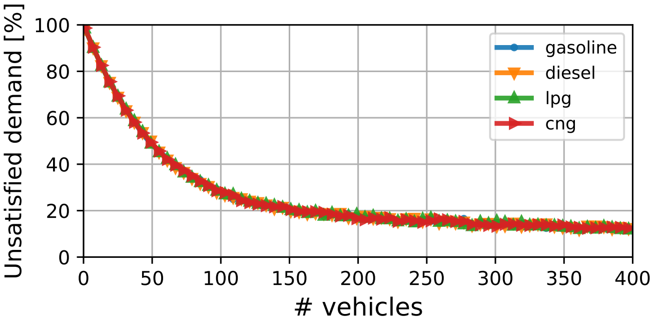


(b) LPG (red) and CNG (blue)

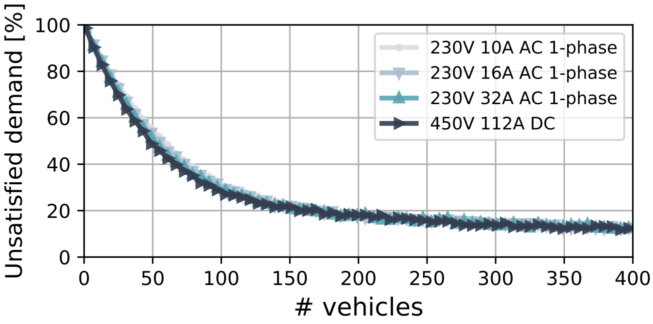


(c) Electric

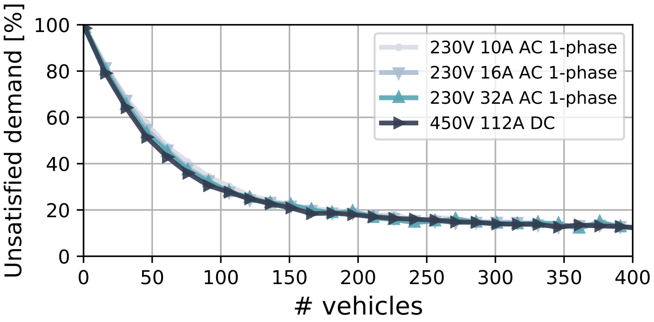
Figure 20: Amsterdam - Real charging station positions



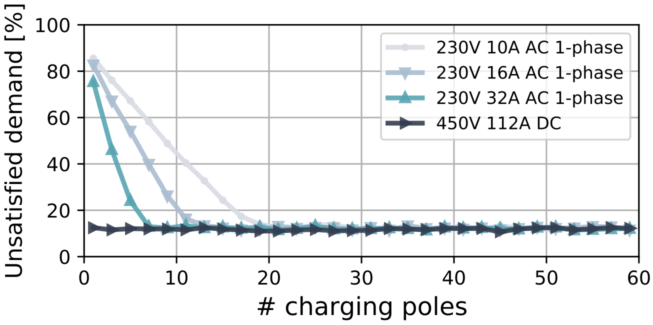
(a) Real infrastructure - ICE vehicles



(b) Real infrastructure - Electric vehicles

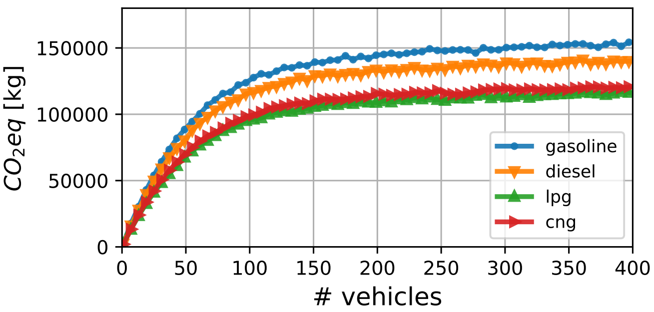


(c) Number of parkings (Vehicles) - Electric vehicles

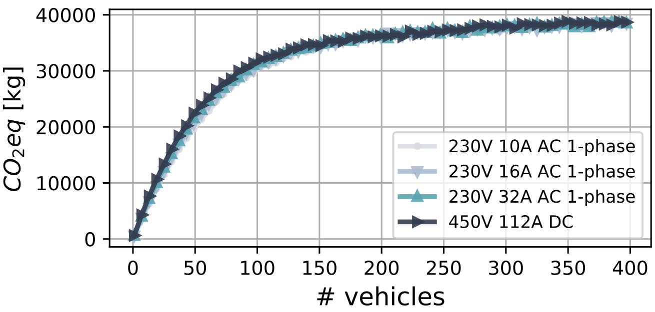


(d) Number of parkings (Charging poles) - Electric vehicles

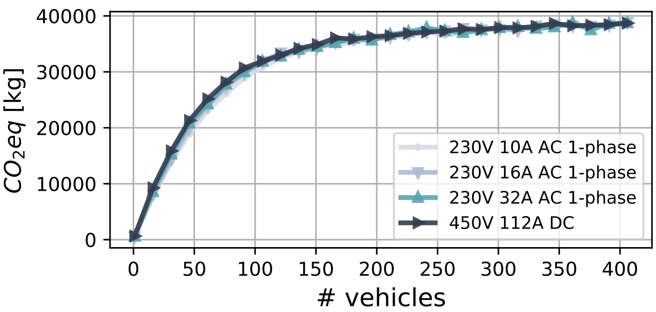
Figure 21: Unsatisfied demand - Turin



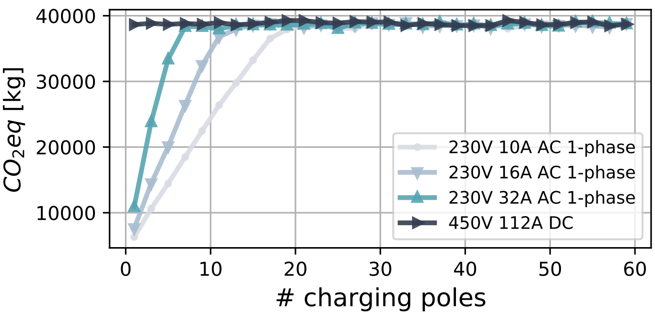
(a) Real infrastructure - ICE vehicles



(b) Real infrastructure - Electric vehicles

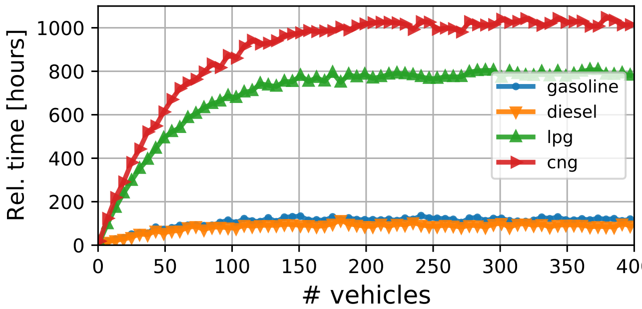


(c) Number of parkings (Vehicles) - Electric vehicles

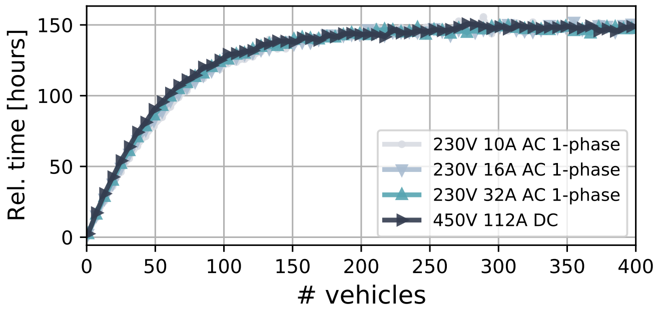


(d) Number of parkings (Charging poles) - Electric vehicles

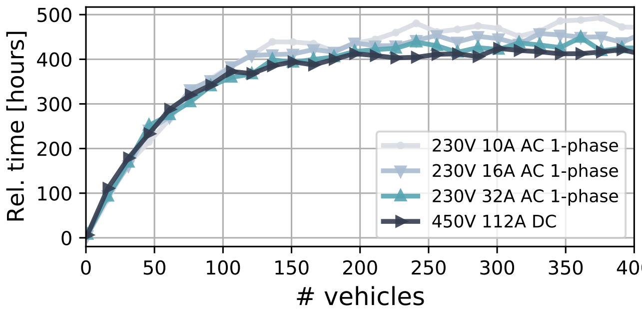
Figure 22: Mobility emissions - Turin



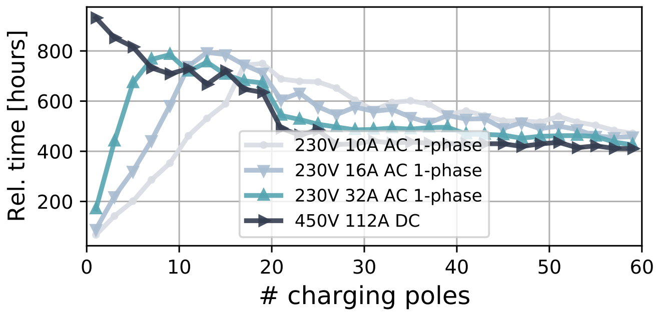
(a) Real infrastructure - ICE vehicles



(b) Real infrastructure - Electric vehicles

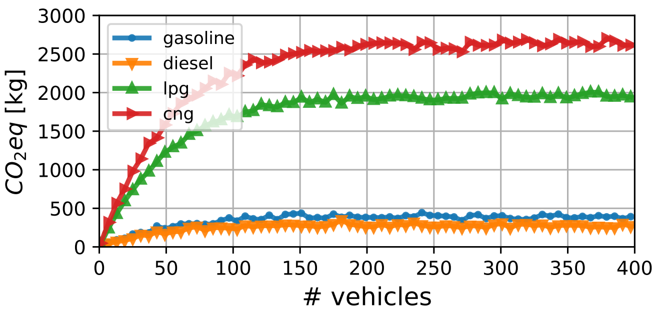


(c) Number of parkings (Vehicles) - Electric vehicles

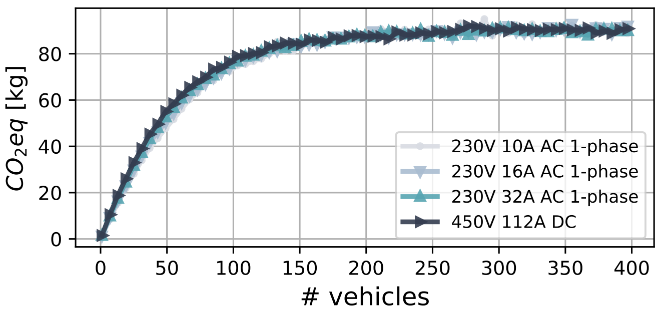


(d) Number of parkings (Charging poles) - Electric vehicles

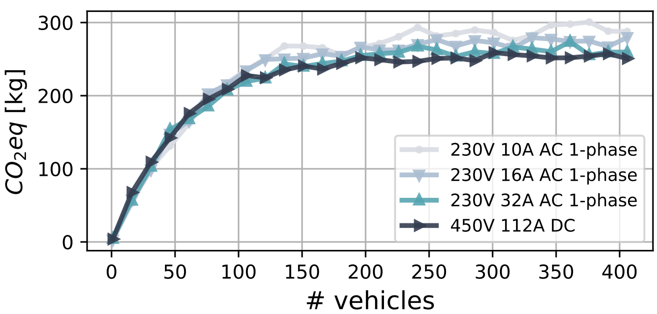
Figure 23: Relocation costs (hours) - Turin



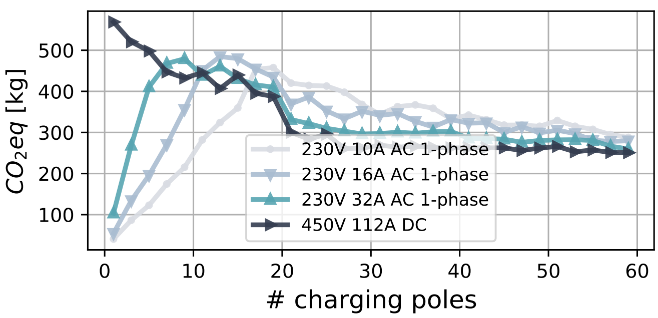
(a) Real infrastructure - ICE vehicles



(b) Real infrastructure - Electric vehicles

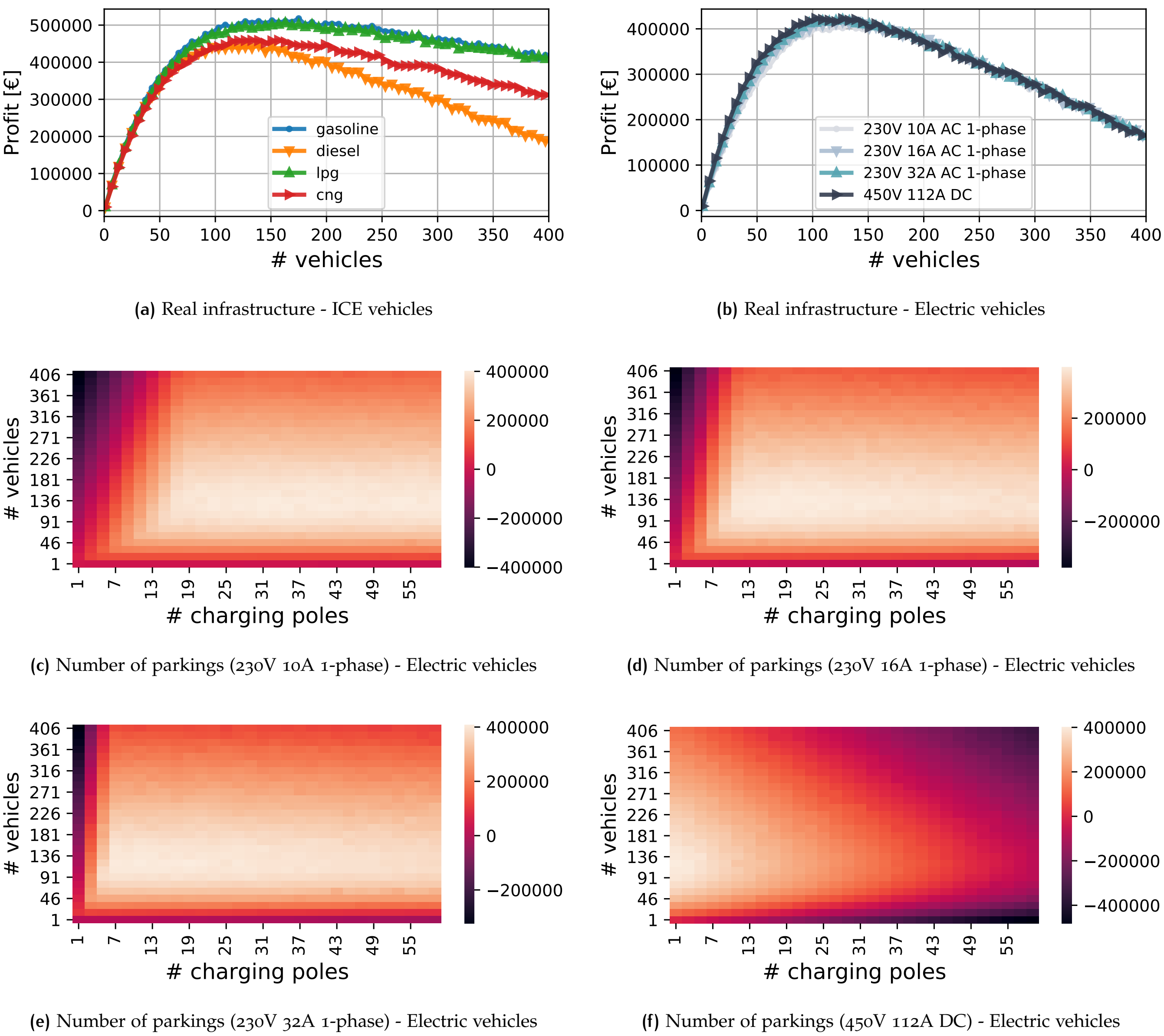


(c) Number of parkings (Vehicles) - Electric vehicles



(d) Number of parkings (Charging poles) - Electric vehicles

Figure 24: Relocation costs emissions - Turin



(a) Real infrastructure - ICE vehicles

(b) Real infrastructure - Electric vehicles

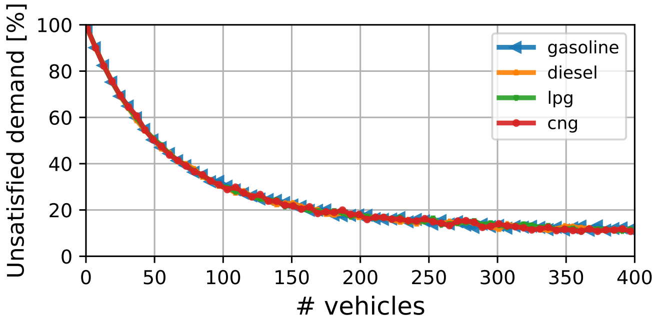
(c) Number of parkings (230V 10A 1-phase) - Electric vehicles

(d) Number of parkings (230V 16A 1-phase) - Electric vehicles

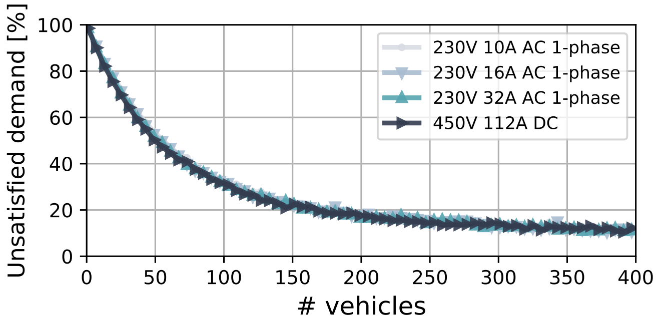
(e) Number of parkings (230V 32A 1-phase) - Electric vehicles

(f) Number of parkings (450V 112A DC) - Electric vehicles

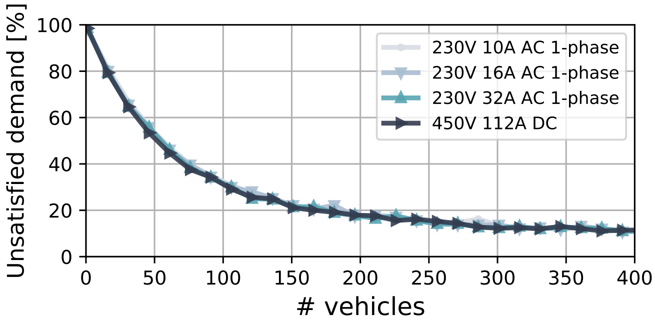
Figure 25: Profits - Turin



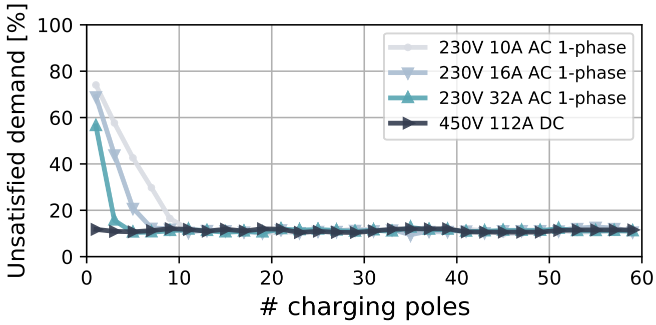
(a) Real infrastructure - ICE vehicles



(b) Real infrastructure - Electric vehicles

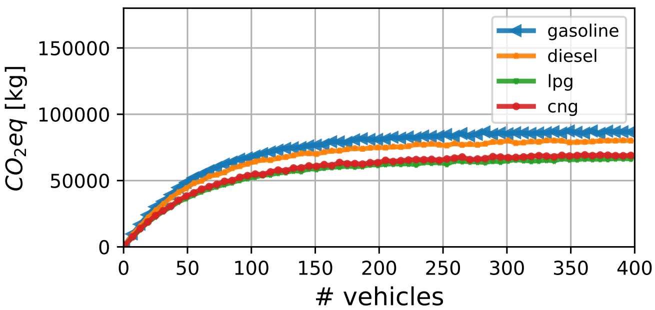


(c) Number of parkings (Vehicles) - Electric vehicles

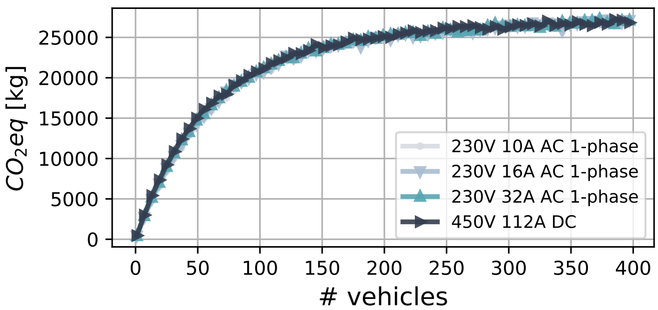


(d) Number of parkings (Charging poles) - Electric vehicles

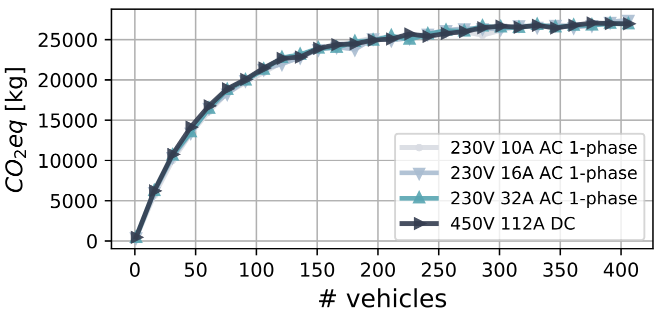
Figure 26: Unsatisfied demand - Amsterdam



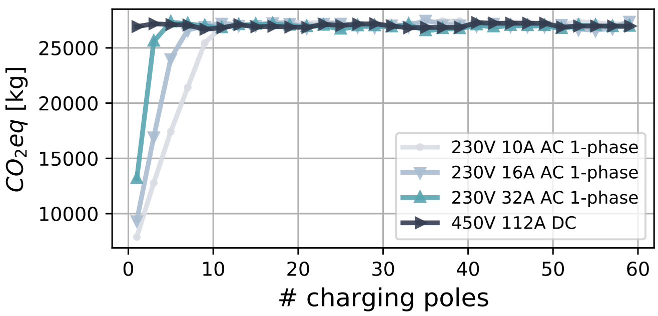
(a) Real infrastructure - ICE vehicles



(b) Real infrastructure - Electric vehicles

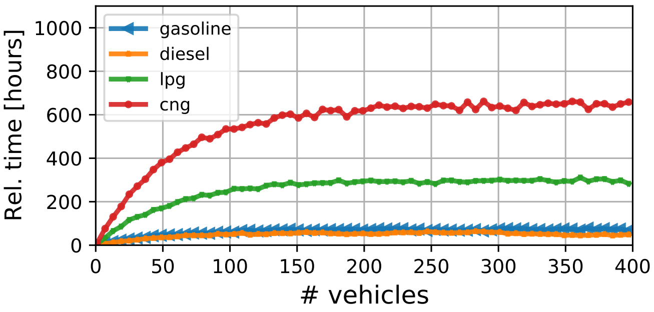


(c) Number of parkings (Vehicles) - Electric vehicles

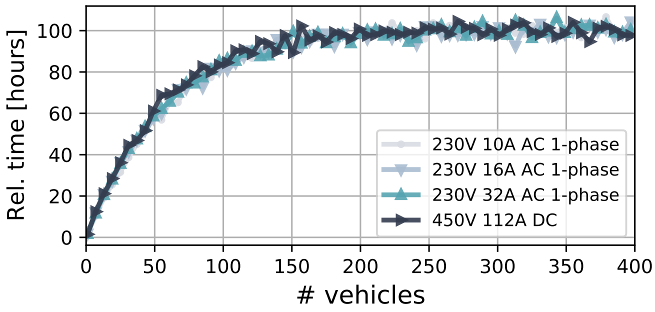


(d) Number of parkings (Charging poles) - Electric vehicles

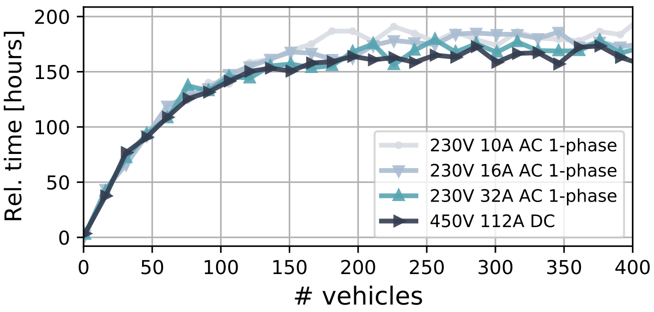
Figure 27: Mobility emissions - Amsterdam



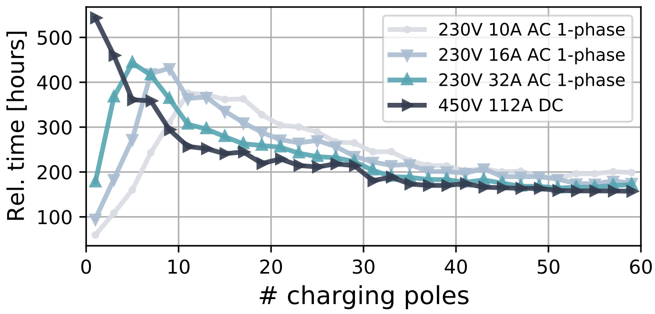
(a) Real infrastructure - ICE vehicles



(b) Real infrastructure - Electric vehicles

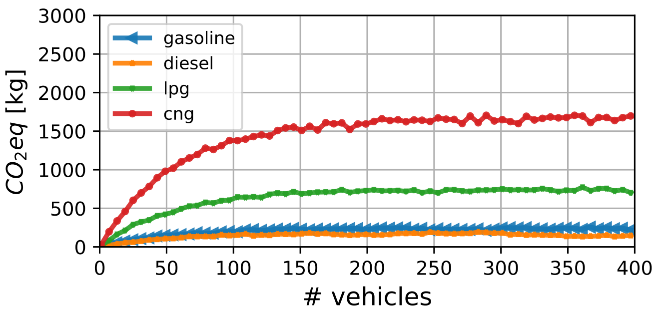


(c) Number of parkings (Vehicles) - Electric vehicles

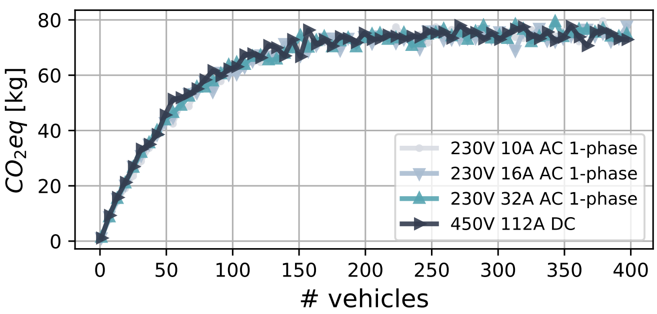


(d) Number of parkings (Charging poles) - Electric vehicles

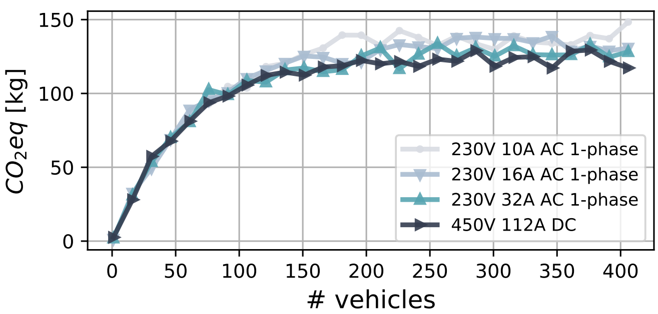
Figure 28: Relocation costs (hours) - Amsterdam



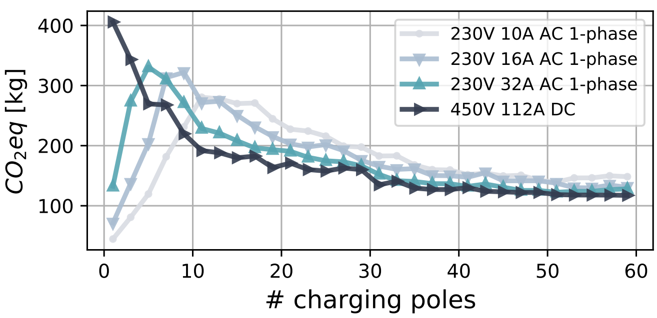
(a) Real infrastructure - ICE vehicles



(b) Real infrastructure - Electric vehicles

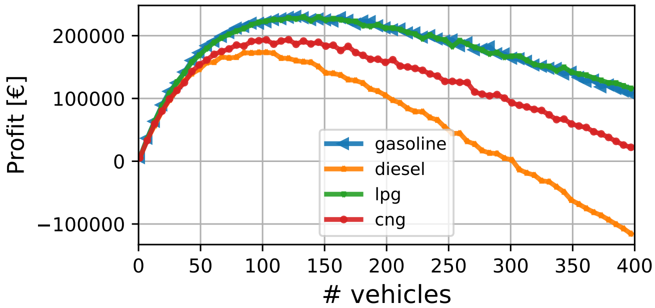


(c) Number of parkings (Vehicles) - Electric vehicles

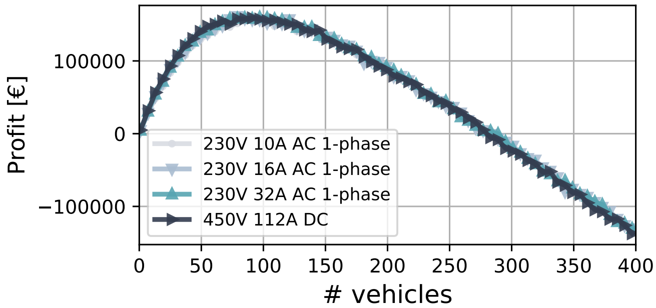


(d) Number of parkings (Charging poles) - Electric vehicles

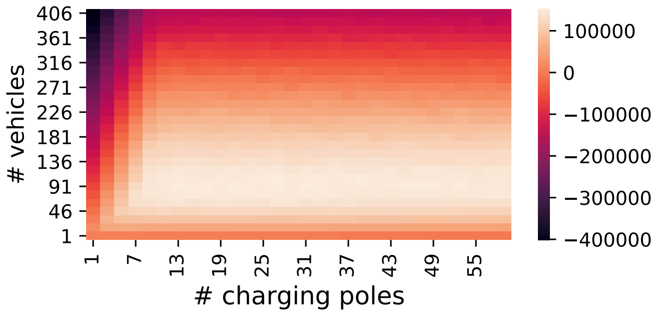
Figure 29: Relocation costs emissions - Amsterdam



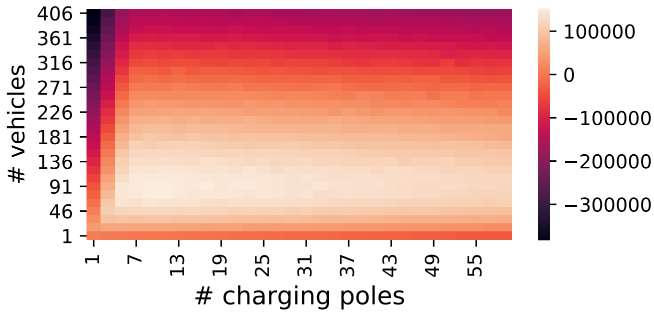
(a) Real infrastructure - ICE vehicles



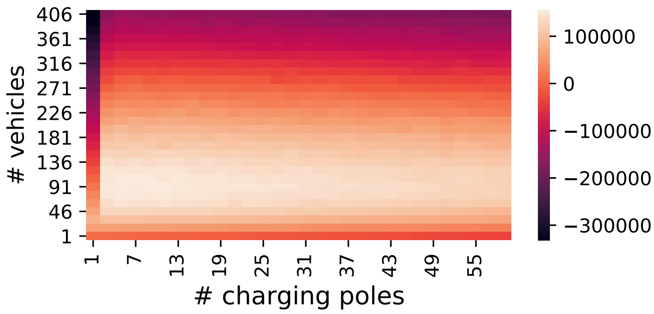
(b) Real infrastructure - Electric vehicles



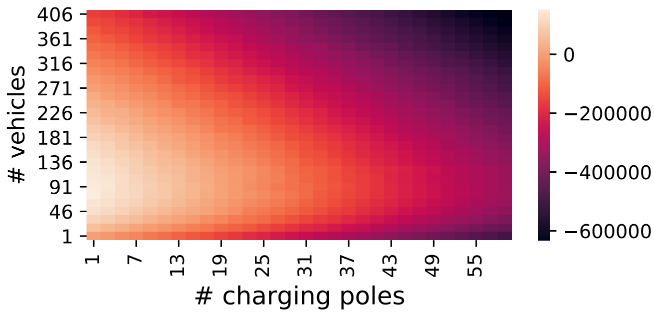
(c) Number of parkings (230V 10A 1-phase) - Electric vehicles



(d) Number of parkings (230V 16A 1-phase) - Electric vehicles



(e) Number of parkings (230V 32A 1-phase) - Electric vehicles



(f) Number of parkings (450V 112A DC) - Electric vehicles

Figure 30: Profits - Amsterdam

6 CONCLUSIONS

The objective of this thesis work is to compare the performances guaranteed by choosing a car-sharing fleet based on internal combustion engine or electric vehicles. The comparison has based on different metrics: the environmental one and on the profit that a car-sharing company can achieve by deploying a certain type of fleet in the city. As it has been observed during this work, most of the literature analyzed shows the benefit brought by a car-sharing service, which helps in reducing the demand for a private vehicle, in reducing the maximum number of vehicles using the road in the peak hours, allowing both to use better the urban environment and to use more efficiently the car, by spreading its use towards a higher number of users. The choice of an electric fleet with respect to a conventional one has several pro and drawbacks. Generally speaking, the large diffusion of electric vehicles may have several negative effects: first of all a large-scale production would push the demand of lithium, manganese, cobalt and other metals. These metals are often extracted using inefficient and environmentally irrespective methods, which leads both towards higher costs to refine them, bad grade of the battery's metals and to the land impoverishment and drying up. A second effect would be the huge drain of power from the grid needed to recharge all the electric vehicles in use, resulting in a big increase of greenhouse gas emissions to produce it. This issue may be counteracted with the improvement of the country energy mix, by increasing the share of renewables in producing electricity. Moreover, with the introduction of a smart grid, it will be possible to plan the time at which charging the vehicle, based on the actual load on the generation power plant. When the grid is suffering, vehicles may be recharged using a supplementary storage of charge (from an auxiliary battery, or an other vehicle, through the use of the power sharing technology). This would probably mitigate further the problem, but not completely resolve it. On the other side, an electric vehicle fleet on the city roads may help in reducing locally the emissions more than a conventional engine fleet, allowing to turn the city in a healthier place. This is given by the absence of tailpipe emissions during the use phase of electric vehicle.

Speaking about the car-sharing service, the simulator was used to derive some differences in the quality of services offered by the two fleet types in two cities. An electric fleet does not bring any improvements in terms of user unsatisfied demand compared to a conventional engine one. If the car-sharing operator need to install an electric charging infrastructure based on the "Number of parkings" policy, then for lower charging power, a higher number of poles is needed to maintain the unsatisfied demand low. The time spent in the fleet management by the workers in the electric fleet depends on the infrastructure configuration: a more dense one as the infrastructure deployed by BlueTorino and Enel X in Turin and the public one in Amsterdam, would drop the amount of hours spent in fleet management: in Turin the amount goes up to 150 hours, in Amsterdam up to 100 hours. A less dense one as "Number of parkings" increases the hours spent in fleet management more than the one needed for gasoline and diesel: this effect is visible particularly in Turin, requiring up to 500 hours, while Amsterdam requires up to 200 hours. However, the LPG and CNG fleets are the one spending more time in fleet management: in Turin, workers spend more than 1000 hours in managing CNG fleet, and 800 hours with LPG fleet; in Amsterdam workers spend more than 600 hours for CNG fleet, and 300 hours for LPG fleet, due to the position of the stations in the city periphery. A higher time spent in fleet management contributes to higher emissions of CO_2, even if its contribution is negligible with respect to the users' mobility emissions. However, a conventional engine vehicle fleet, as expected, contributes more in polluting not only the global environment, but mostly the urban environment, by emitting also small particles which are dangerously breathed and they are causing diseases to the living beings. In Turin, the conventional engine fleets are producing in three months between 100 and 150 tons of CO_2eq, while in Amsterdam, between 50 and 100 tons of CO_2eq are produced. The electric fleet, instead, does not pollute in the urban environment, but it does where the electricity is produced, contributing to the global greenhouse effect increasing. In Turin, the user mobility pollutes an amount of 40 tons in electricity production, while in Amsterdam more than 25 tons. The electric fleet potentially represents a step forward towards the target of emissions reduction, even if it is still far the zero-emissions target set to be in 2050. The advantages offered by the join of a electric vehicle powertrain in a fleet of a car-sharing service seems to be disproven by the lower profit of the electric fleet in a car-sharing service, both using the real infrastructure and the one built under the "Number of parkings" policy. This is explained by different reasons, among which can be the higher cost of the electric vehicles, given that the same mobility demand is satisfied. The cost model used is not detailed, so it is used only for general profit indications. In the cities under analysis, Turin has a higher user mobility demand, leading to higher emissions and to a more frequent fleet management than Amsterdam. Electric fleet emissions are similar in the two countries, however, due to the different energy mixes, in particular the one in the Netherlands relying more on fossil fuels than the one in Italy. The results obtained in this thesis would suggest that, even if the profits will be lower, a car-sharing company should aim towards an electric fleet in order to provide a cleaner urban environment. This statement should be supported by the political decisions: an electric car-sharing fleet may help in improving the urban mobility, but the service should be planned strategically, be funded through national subsidies, and people should be convinced to give up the use of a private car to run short trips around the city. The best results may be obtained by focusing on a fully integrated public transport system, in which people may exploit intermodality to reach their destination. This suggests that a good car-sharing service may not be enough in solving the transport problem and meeting at the same time the users' mobility demand, but should be planned to "cooperate" with other public transport modes such as tram, bicycle and bus such that the user can decide which is the optimum combination of modes use to reach the destination. Since the car-sharing service is often managed by private entities and public transport by public entities, a partnership between public and private companies has to be woven. This is very difficult to be achieved, since they aim at opposite targets. Privates tends to offer a good quality of service to get higher profits, basing their revenues on the high quality of the service, and the data collected helps them in doing so. Sharing their data to other entities means to lose competitiveness. Public entities instead, tend to keep the cost the lowest possible, often sacrificing the quality of service.

BIBLIOGRAPHY

2020 OICA 2019 Production Statistics, https://www.oica.net/category/production-statistics/2019-statistics/.

2021 Section Financial Plan, https://americanmanganeseinc.com/lithium-ion-battery-recycling-technology.

n.d. https://www.bts.gov/bts/archive/publications/national_transportation_statistics/table_01_23.

Aksoy, Aslı, İlker Küçükoğlu, Seval Ene, and Nursel Öztürk

2014 "Integrated Emission and Fuel Consumption Calculation Model for Green Supply Chain Management," *Procedia - Social and Behavioral Sciences*, 109, 2nd World Conference on Business, Economics and Management, pp. 1106-1109, ISSN: 1877-0428, DOI: https://doi.org/10.1016/j.sbspro.2013.12.595, https://www.sciencedirect.com/science/article/pii/S1877042813052348.

Albrahim, Mohammed, Ahmed Al Zahrani, Anvita Arora, Rubal Dua, Bassam Fattouh, and Adam Sieminski

2019 "An overview of key evolutions in the light-duty vehicle sector and their impact on oil demand," *Energy Transitions*, 3, 1 [Dec. 2019], pp. 81-103, ISSN: 2520-114X, DOI: 10.1007/s41825-019-00017-7, https://doi.org/10.1007/s41825-019-00017-7.

Amirault, Justin, Joshua Chien, Saurabh Garg, Drew Gibbons, Ben Ross, Maureen Tang, Jia Xing, Ikhlaq Sidhu (PI), Phil Kaminsky, and Burghardt Tenderich

2009 *The Electric Vehicle Battery Landscape: Opportunities and Challenges*, https://ikhlaqsidhu.files.wordpress.com/2010/03/nr-electricvehiclebatterylandscape_1221-1.pd%20f.

Anderson, David and Dalia Patino-Echeverri

2009 An Evaluation of Current and Future Costs for Lithium-Ion Batteries for Use in Electrified Vehicle Powertrains. Master's project, Duke University, https://hdl.handle.net/10161/1007.

Athanasopoulou, L., H. Bikas, and P. Stavropoulos

2018 "Comparative Well-to-Wheel Emissions Assessment of Internal Combustion Engine and Battery Electric Vehicles," *Procedia CIRP*, 78, 6th CIRP Global Web Conference – Envisaging the future manufacturing, design, technologies and systems in innovation era (CIRPe 2018), pp. 25-30, ISSN: 2212-8271, DOI: https://doi.org/10.1016/j.procir.2018.08.169, https://www.sciencedirect.com/science/article/pii/S2212827118309570.

Axsen, Jonn, Kenneth S. Kurani, and Andrew Burke

2010 "Are batteries ready for plug-in hybrid buyers?" *Transport Policy*, 17, 3 [May 2010], pp. 173-182, https://ideas.repec.org/a/eee/trapol/v17y2010i3p173-182.html.

Balch, Oliver

2020 "The curse of 'white oil': electric vehicles' dirty secret," *The Guardian*, https://www.theguardian.com/news/2020/dec/08/the-curse-of-white-oil-electric-vehicles-dirty-%20secret-lithium.

Barulli, M., A. Ciociola, M. Cocca, L. Vassio, D. Giordano, and M. Mellia

2020 "On Scalability of Electric Car Sharing in Smart Cities," in *2020 IEEE International Smart Cities Conference (ISC2)*, pp. 1-8, DOI: 10.1109/ISC251055.2020.9239086.

Beach, P.M.

2008 "Historical Perspective on Li-Ion Cell Technology and a Roadmap to Future Growth in Energy Densities," Unpublished White Paper.

Beaudoin, Yannick and Elaine Baker

2013 *Deep Sea Minerals: Manganese Nodules, a physical, biological, environmental and technical review*, ISBN: 978-82-7701-119-6.

Biondi, Elisabetta, Chiara Boldrini, and Raffaele Bruno

2016 "The impact of regulated electric fleets on the power grid: The car sharing case," in pp. 1-6, DOI: 10.1109/RTSI.2016.7740570.

Boldrini, C. and R. Bruno

2017 "Stackable vs autonomous cars for shared mobility systems: A preliminary performance evaluation," in *2017 IEEE 20th International Conference on Intelligent Transportation Systems (ITSC)*, pp. 232-237, DOI: 10.1109/ITSC.2017.8317960.

Bunsen, Till, Pierpaolo Cazzola, Marine Gorner, Leonardo Paoli, Sacha Scheffer, Renske Schuitmaker, Jacopo Tattini, and Jacob Teter

n.d. *Global EV Outlook 2018: Towards cross-modal electrification*, International Energy Agency.

Canis, Bill

2013 *Battery Manufacturing for Hybrid and Electric Vehicles: Policy Issues*, https://fas.org/sgp/crs/misc/R41709.pdf.

Catenacci, Michela, Elena Verdolini, Valentina Bosetti, and Giulia Fiorese

2013 "Going electric: Expert survey on the future of battery technologies for electric vehicles," *Energy Policy*, 61, pp. 403-413, ISSN: 0301-4215, DOI: https://doi.org/10.1016/j.enpol.2013.06.078, https://www.sciencedirect.com/science/article/pii/S0301421513005855.

"Charging Lithium-Ion Batteries"

2018 [Apr. 2018], Review simple guidelines for charging Lithium-based batteries and prolong battery life such as; a portable device should be turned off while charging and more., https://batteryuniversity.com/learn/article/charging_lithium_ion_batteries.

Chen, T. Donna and Kara M. Kockelman

2016 "Carsharing's life-cycle impacts on energy use and greenhouse gas emissions," *Transportation Research Part D: Transport and Environment*, 47, pp. 276-284, ISSN: 1361-9209, DOI: https://doi.org/10.1016/j.trd.2016.05.012, https://www.sciencedirect.com/science/article/pii/S1361920916303030.

Chicco, Andrea and Marco Diana

2021 "Air emissions impacts of modal diversion patterns induced by one-way car sharing: A case study from the city of Turin," *Transportation Research Part D: Transport and Environment*, 91, p. 102685, ISSN: 1361-9209, DOI: https://doi.org/10.1016/j.trd.2020.102685, https://www.sciencedirect.com/science/article/pii/S1361920920308695.

Christensen, Jake, Paul Albertus, Roel S. Sanchez-Carrera, Timm Lohmann, Boris Kozinsky, Ralf Liedtke, Jasim Ahmed, and Aleksandar Kojic

2011 "A Critical Review of Li/Air Batteries," *Journal of The Electrochemical Society*, 159, 2, R1-R30, DOI: 10.1149/2.086202jes, https://doi.org/10.1149/2.086202jes.

Ciociola, A., M. Cocca, D. Giordano, M. Mellia, A. Morichetta, A. Putina, and F. Salutari

2017 "UMAP: Urban mobility analysis platform to harvest car sharing data," in *2017 IEEE SmartWorld, Ubiquitous Intelligence Computing, Advanced Trusted Computed, Scalable Computing Communications, Cloud Big Data Computing, Internet of People and Smart City Innovation (SmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI)*, pp. 1-8, DOI: 10.1109/UIC-ATC.2017.8397566.

Ciociola, A., D. Markudova, L. Vassio, D. Giordano, M. Mellia, and M. Meo

2020 "Impact of Charging Infrastructure and Policies on Electric Car Sharing Systems," in *2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC)*, pp. 1-6, DOI: 10.1109/ITSC45102.2020.9294282.

Ciociola, A., M. Mellia, and M. Meo

2019 *Modelling, simulation and design of Electric Car Sharing systems with eC2S*, https://webthesis.biblio.polito.it/12567/.

Cluzel, C. and C. Douglas

2012 *Cost and performance of EV batteries, Element Energy,Final Report for the Committee on Climate Change*.

Cocca, Michele, Danilo Giordano, Marco Mellia, and Luca Vassio

2019 "Free floating electric car sharing design: Data driven optimisation," *Pervasive and Mobile Computing*, 55, pp. 59-75, ISSN: 1574-1192, DOI: https://doi.org/10.1016/j.pmcj.2019.02.007, https://www.sciencedirect.com/science/article/pii/S1574119218305170.

Cohen, Adam and Susan Shaheen

2016 "Planning for shared mobility," 2016 [July 2016], pp. 1-106.

Dell'Amico, M., N. S. Hadjidimitriou, and G. Renzi

2020 "Assessing the Impact of Shared L-Category Electric Vehicles in six European cities," in *2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC)*, pp. 1-5, DOI: 10.1109/ITSC45102.2020.9294355.

Dijk, Marc, Renato J. Orsato, and René Kemp

2013 "The emergence of an electric mobility trajectory," *Energy Policy*, 52, Special Section: Transition Pathways to a Low Carbon Economy, pp. 135-145, ISSN: 0301-4215, DOI: https://doi.org/10.1016/j.enpol.2012.04.024, https://www.sciencedirect.com/science/article/pii/S0301421512003242.

Domingues, Jose Marcos and Luiz Artur Pecorelli-Peres

2013 "Electric Vehicles, Energy Efficiency, Taxes, and Public Policy in Brazil," https://scholar.smu.edu/cgi/viewcontent.cgi?article=1119&context=lbra.

Dudley, Bob

2019 *BP Statistical Review of World Energy*, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf.

Figenbaum, Erik, Terje Assum, and Marika Kolbenstvedt

2015 "Electromobility in Norway: Experiences and Opportunities," *Research in Transportation Economics*, 50, Electric Vehicles: Modelling Demand and Market Penetration, pp. 29-38, ISSN: 0739-8859, DOI: https://doi.org/10.1016/j.retrec.2015.06.004, https://www.sciencedirect.com/science/article/pii/S0739885915000232.

Fournier, Guy, C. Pfeiffer, Manuel Baumann, and Ralf Wörner

2017 "Individual mobility by shared autonomous electric vehicle fleets: Cost and CO2 comparison with internal combustion engine vehicles in Berlin, Germany," in pp. 368-376, DOI: 10.1109/ICE.2017.8279909.

Fulton Lewis Jacob Mason, Dominique Meroux

2017 "Three revolutions in urban transportation: How to achieve the full potential of vehicle electrification, automation, and shared mobility in urban transportation systems around the world by 2050."

Gupta, Monanshi, Yasser Rafat, and M. Saad Alam

2017 "Well to Wheel Cum Tailpipe Emission Analysis: ICE vs xEV," in *SAE Technical Paper*, SAE International, DOI: 10.4271/2017-26-0107, https://doi.org/10.4271/2017-26-0107.

Haynes, B.W., S.L. Law, D.C. Barron, G.W. Kramer, R. Maeda, and M.J. Magyar

1985 *Pacific Manganese Nodules: Characterization and Processing*, Washington, D. C.

Hoffman, George A.

1967 "Systems design of electric automobiles," *Transportation Research*, 1, 1, pp. 3-19, ISSN: 0041-1647, DOI: https://doi.org/10.1016/0041-1647(67)90091-3, https://www.sciencedirect.com/science/article/pii/0041164767900913.

Huss, Arno and Petra Weingerl

2020 *JEC Tank-To-Wheels report v5*, Luxembourg, DOI: http://dx.doi.org/10.2760/557004, https://publications.jrc.ec.europa.eu/repository/handle/JRC117560.

IEA

n.d. *Global EV Outlook 2020*, Paris, https://www.iea.org/reports/global-ev-outlook-2020.

Jia, Jingjing, Shujie Ma, Yixi Xue, and Deyang Kong

2020 "Life-Cycle Break-Even Analysis of Electric Carsharing: A Comparative Study in China," *Sustainability*, 12, 16, ISSN: 2071-1050, DOI: 10.3390/su12166584, https://www.mdpi.com/2071-1050/12/16/6584.

Jung, Jiyeon and Yoonmo Koo

2018 "Analyzing the Effects of Car Sharing Services on the Reduction of Greenhouse Gas (GHG) Emissions," *Sustainability*, 10, 2 [Feb. 2018], p. 539, ISSN: 2071-1050, DOI: 10.3390/su10020539, http://dx.doi.org/10.3390/su10020539.

Kalhammer, F.R., B.M. Kopf, D.H. Swan, V.P. Roan, and M.P. Walsh

2007 *Status and Prospects for Zero Emissions Vehicle Technology: Report of the ARB Independent Expert Panel 2007, Sacramento, CA.*

Korosec, Kirsten

2019 "Tesla, Panasonic modify expansion plans for gigafactory," *TechCrunch*, https://tcrn.ch/2Iq87Uw.

Kromer, Matthew A. and John Heywood

2007 *Electric powertrains : opportunities and challenges in the US light-duty vehicle fleet*, http://hdl.handle.net/1721.1/40372.

L., Kent Jennifer and Dowling Robyn

2016 "The Future of Paratransit and DRT: Introducing Cars on Demand," in Transport and Sustainability, Emerald Group Publishing Limited, vol. 8, pp. 391-412, DOI: 10.1108/S2044-994120160000008019, https://doi.org/10.1108/S2044-994120160000008019.

Li, Yang, Lu Miao, Ying Chen, and Yike Hu

2019 "Exploration of Sustainable Urban Transportation Development in China through the Forecast of Private Vehicle Ownership," *Sustainability*, 11, 16, ISSN: 2071-1050, DOI: 10.3390/su11164259, https://www.mdpi.com/2071-1050/11/16/4259.

Luan, Xin, Lin Cheng, Qi Wang, and Cheng Cui

2018 "Environmental Impacts of Car Sharing," in pp. 191-195, DOI: 10.5220/0006967501910195.

Luna, Tiago Ferrari, Mauricio Uriona-Maldonado, Minelle E. Silva, and Caroline Rodrigues Vaz

2020 "The influence of e-carsharing schemes on electric vehicle adoption and carbon emissions: An emerging economy study," *Transportation Research Part D: Transport and Environment*, 79, p. 102226, ISSN: 1361-9209, DOI: https://doi.org/10.1016/j.trd.2020.102226, https://www.sciencedirect.com/science/article/pii/S1361920919309460.

Martin, Elliot, Susan Shaheen, and Jeffrey Lidicker

2010 "Carsharing's Impact On Household Vehicle Holdings: Results From A North American Shared-Use Vehicle Survey," *Institute of Transportation Studies, UC Davis, Institute of Transportation Studies, Working Paper Series* [Sept. 2010].

Millard-Ball, Adam and Lee Schipper

2011 "Are We Reaching Peak Travel? Trends in Passenger Transport in Eight Industrialized Countries," *Transport Reviews*, 31, 3, pp. 357-378, DOI: 10.1080/01441647.2010.518291, eprint: https://doi.org/10.1080/01441647.2010.518291, https://doi.org/10.1080/01441647.2010.518291.

Milne, Richard

2017 "Reality of subsidies drives Norway's electric car dream," *Financial Times*, https://www.ft.com/content/84e54440-3bc4-11e7-821a-6027b8a20f23.

Noussan, Michel and Francesco Neirotti

2020 "Cross-Country Comparison of Hourly Electricity Mixes for EV Charging Profiles," *Energies*, 13, 10, ISSN: 1996-1073, DOI: 10.3390/en13102527, https://www.mdpi.com/1996-1073/13/10/2527.

Nykvist, Bjorn and Måns Nilsson

2015 "Rapidly falling costs of battery packs for electric vehicles," *Nature Climate Change*, 5, 4 [Apr. 2015], pp. 329-332, ISSN: 1758-6798, DOI: 10.1038/nclimate2564, https://doi.org/10.1038/nclimate2564.

Paulikas, Daina, Steven Katona, Erika Ilves, and Saleem H. Ali

2020 "Life cycle climate change impacts of producing battery metals from land ores versus deep-sea polymetallic nodules," *Journal of Cleaner Production*, 275, p. 123822, ISSN: 0959-6526, DOI: https://doi.org/10.1016/j.jclepro.2020.123822, https://www.sciencedirect.com/science/article/pii/S0959652620338671.

Penisa, Xaviery N., Michael T. Castro, Jethro Daniel A. Pascasio, Eugene A. Esparcia, Oliver Schmidt, and Joey D. Ocon

2020 "Projecting the Price of Lithium-Ion NMC Battery Packs Using a Multifactor Learning Curve Model," *Energies*, 13, 20, ISSN: 1996-1073, DOI: 10.3390/en13205276, https://www.mdpi.com/1996-1073/13/20/5276.

Prussi, Matteo, Marta Yugo, Luis De Prada, Monica Padella, and Robert Edwards

2020 *JEC Well-To-Tank report v5*, Luxembourg, DOI: http://dx.doi.org/10.2760/959137, https://publications.jrc.ec.europa.eu/repository/handle/JRC119036.

Rietmann, Nele, Beatrice Hügler, and Theo Lieven

2020 "Forecasting the trajectory of electric vehicle sales and the consequences for worldwide CO2 emissions," *Journal of Cleaner Production*, 261, p. 121038, ISSN: 0959-6526, DOI: https://doi.org/10.1016/j.jclepro.2020.121038, https://www.sciencedirect.com/science/article/pii/S0959652620310854.

Rievaj, Vladimír and František Synák

2017 "Does electric car produce emissions?" *Scientific Journal of Silesian University of Technology. Series Transport*, 94 [Mar. 2017], pp. 187-197, DOI: 10.20858/sjsutst.2017.94.17.

Shaheen, Susan and Adam Cohen

2008 "Worldwide Carsharing Growth: An International Comparison," *Institute of Transportation Studies, UC Davis, Institute of Transportation Studies, Working Paper Series*, 1992 [Jan. 2008], DOI: 10.3141/1992-10.

Shaheen, Susan, Adam Cohen, Balaji Yelchuru, and Sara Sarkhili

2017 *Mobility on Demand Operational Concept Report*, English, FHWA-JPO-18-611, https://rosap.ntl.bts.gov/view/dot/34258.

Simon, Frédéric

2018 "Gas chief: 'We expect at least 10% of the car market in 2030'," *EURACTIV.com* [Mar. 2018], https://www.euractiv.com/section/energy/interview/gas-chief-we-expect-at-least-10-of-the-car%20-market-in-2030/.

Skinner, R. and N. Bidwell

2016 "Making better places: Autonomous vehicles and future opportunities," http://www.wsppb.com/Globaln/UK/WSPPB-Farrells-AV-whitepaper.pdf.

Weikl, Simone and Klaus Bogenberger

2015 "A practice-ready relocation model for free-floating carsharing systems with electric vehicles – Mesoscopic approach and field trial results," *Transportation Research Part C: Emerging Technologies*, 57, pp. 206-223, ISSN: 0968-090X, DOI: https://doi.org/10.1016/j.trc.2015.06.024, https://www.sciencedirect.com/science/article/pii/S0968090X15002399.

Wilken, Dennis, Matthias Oswald, Patrick Draheim, Christian Pade, Urte Brand, and Thomas Vogt

2020 "Multidimensional assessment of passenger cars: Comparison of electric vehicles with internal combustion engine vehicles," *Procedia CIRP*, 90 [Jan. 2020], pp. 291-296, DOI: 10.1016/j.procir.2020.01.101.

Wu, Zhixin, Michael Wang, Jihu Zheng, Xin Sun, Mingnan Zhao, and Xue Wang

2018 "Life cycle greenhouse gas emission reduction potential of battery electric vehicle," *Journal of Cleaner Production*, 190, pp. 462-470, ISSN: 0959-6526, DOI: https://doi.org/10.1016/j.jclepro.2018.04.036, https://www.sciencedirect.com/science/article/pii/S0959652618310497.

Yang, S.C., M. Li, Y. Lin, and T.Q. Tang

2014 "Electric vehicle's electricity consumption on a road with different slope," *Physica A: Statistical Mechanics and its Applications*, 402, pp. 41-48, ISSN: 0378-4371, DOI: https://doi.org/10.1016/j.physa.2014.01.062, https://www.sciencedirect.com/science/article/pii/S0378437114000831.

Zhou, Jiangping

2014 "Carsharing on university campus: Subsidies, commuter benefits, and their impacts on carsharing," *Transportation Research Part D: Transport and Environment*, 32 [Oct. 2014], pp. 316-319, DOI: 10.1016/j.trd.2014.08.015.