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Abstract

Electric vehicles (EV) are boasted as a key part of the solution to the pressing issue of climate change. Such claims have been upheld by numerous governments which provide financial incentives for EV ownership and invest heavily in infrastructure that would facilitate mass market introduction of EVs. However, the extent of EVs' environmental impact depends on a number of circumstances. This paper aims to assess EVs' contributions towards reduction of carbon dioxide (CO_2) emissions, by performing a comprehensive literature review of assessments performed on this topic, and assessing a survey of potential EV consumers' attitudes.

Based on a Well-to-Wheel (WTW) assessment, EVs charged by renewables generate emissions in the range of 0.6 g - 11.4 g CO_2-eq/km, whereas internal combustion engine vehicles (ICEV) are found to emit 60 to over 200 g CO_2-eq/km. EVs charged by coal on the other hand contribute to 120 - 207 g CO_2-eq/km, which is more than ICEVs in some categories. Considering a Life Cycle Assessment (LCA), EVs are found to be 35% to 115% more emissions intensive during the production phase, but can produce 50% lower emissions across their lifetime, if assuming charging from an average EU electricity mix during the use phase. Therefore, the key factor when assessing EV emissions is the source of electricity charging them. As a new electricity demand segment, EVs may be charged by peak power plants, in which case they would contribute to emissions comparable to those of ICEVs. EVs may still have potential to save some amounts of CO_2 on account of better efficiency, but these amounts would be insignificant. According to the consumer perception survey, most respondents perceive EVs to positively contribute to the environment, while majority would be inclined to pay a premium due to their perceived money savings potential, and a slightly smaller proportion due to their perceived environmental benefits. Out of the 24 potential indicators in the model, multiple regression results indicate strong correlation between perception on money saving potential and environmental benefits, while contrary to assumptions, demographic factors such as education and income bracket played no major roles in consumers' perception in this regard. EVs can make an impact on the environment only if they are accepted by consumers, whose motivations are mainly financial.

Zusammenfassung

Elektrofahrzeuge (EV) werden als ein wichtiger Ansatz zur Lösung des stetig drängenden Klimawandels betrachtet. Diese Feststellung wurde bereits von zahlreichen Regierungen anerkannt, welche finanzielle Anreize für den EV-Eigentum anbieten und stark in Infrastrukturen investieren, die die rasche Markteinführung von Elektrofahrzeugen erleichtern würden. Allerdings hängen die Auswirkungen der EVs auf die Umwelt von einer Reihe von Umständen ab. Ziel dieser Studie ist, die Beiträge von EVs zur Reduzierung von Kohlendioxid (CO_2) -Emissionen zu bewerten, indem eine umfassende Literaturrecherche zu diesem Thema, sowie eine Umfrage zur Einstellungen potenzieller EV-Verbraucher durchgeführt wird.

Basierend auf einer Well-to-Wheel-Bewertung (WTW) erzeugen EVs, die mit erneuerbaren Energien geladen werden, Emissionen im Bereich 0.6 g - 11.4 g CO_2-eq/km, während Fahrzeuge mit Verbrennungsmotor (ICEV) von 60 bis mehr als 200 g CO_2-eq/km ausstoßen. EVs, die mit Kohleenergie geladen werden, produzieren 120 - 207 g CO_2-eq/km, was in einigen Kategorien die Emissionen von ICEVs überschreitet. In Anbetracht der Life Cycle Assessment (LCA) sind Elektrofahrzeuge in der Produktionsphase um 35% bis 115% emissionsintensiver, können jedoch während ihrer gesamten Lebensdauer 50% weniger Emissionen verursachen, wenn sie während der Nutzungsphase von einem durchschnittlichen EU-Strommix aufgeladen wurden. Daher ist der Schlüsselfaktor bei der Bewertung von EV-Emissionen die Quelle der Elektrizität, die sie auflädt. Aufgrund dieser neuen Nachfrage an Elektrizität könnten EVs von Spitzenkraftwerken geladen werden, in welchem Fall sie mit den Emissionen von ICEVs vergleichbar wären. EVs könnten aufgrund einer besseren Effizienz möglicherweise noch einige CO_2-Mengen einsparen, aber diese Beträge wären unbedeutend. Laut der Umfrage zur Verbraucherwahrnehmung schätzen die meisten Befragten EVs als positiv für die Umwelt ein, während die Mehrheit aufgrund des wahrgenommenen Sparpotenzials dazu neigt, eine Prämie zu zahlen. Ein etwas geringerer Anteil würde dies aufgrund der wahrgenommenen Umweltvorteile tun. Von den 24 potenziellen Indikatoren im Modell weisen multiple Regressionsergebnisse auf eine starke Korrelation zwischen dem wahrgenommenen Geldeinsparpotenzial und dem Nutzen für die Umwelt hin, während demografische Faktoren wie Bildung und Einkommensverteilung entgegen der Annahme keine wesentliche Rolle für die Wahrnehmung der Verbraucher in dieser Hinsicht spielen. EVs können sich nur dann auf die Umwelt auswirken, wenn sie von den Verbrauchern angenommen werden, deren Motivationen hauptsächlich finanzieller Natur sind.

Contents

List of Figures

List of Tables

Acronyms and Abbreviations

AAA	Authentication, authorization, and accounting system
AC	Alternating current
AGC	Automatic generation control
AR5	IPCC's 2014 Fifth Assessment Report
BERR	UK Department of Business, Enterprise and Regulatory Reform and Transport
BEV	Battery Electric Vehicles
BMBF	German Federal Ministry for Research and Education
BP	British Petroleum
CCGT	Combined cycle gas turbines
CCP	Climate change potential
CCS	Carbon capture and storage
CHP	Combined heat and power plants
CNG	Compressed natural gas
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalents
DC	Direct current
DICI	Direct Injection Compression Ignition diesel vehicle
DISI	Direct-Injection Spark-Ignition gasoline vehicle
EC	European Commission
EEA	European Environment Agency
EIA	Environmental Impact Assessment
EOL	End of life
EPA	Environmental Protection Agency
EU	European Union
EV	Electric vehicle
FCEV	Fuel cell electric vehicles
FGC	Flue gas cleaning
FSEM	Systemforschung ElektroMobilität
GHG	Greenhouse Gases
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicles
ICEV	Internal combustion engine vehicle
IEA	International Energy Agency
IFEU	Institute for Energy and Environmental Research
IGCC	Integrated gasification combined cycle
IOA	Input Output Analysis
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Center of the European Commission
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment

LFP or $LiFePO_4$	Lithium Iron Phosphate
Li4Ti5O12	Lithium Titanate
$LiMn_2O_4$	Lithium Manganese Oxide
$LiNiCoAlO_2$	Lithium Nickel Cobalt Aluminum Oxide
$LiNiMnCoO_2$	Lithium Nickel Manganese Cobalt Oxide
LMO or $LiCoO_2$	Lithium Manganese Oxide
LPG	Liquefied petroleum gas
MPG	Miles per gallon
MSRP	Manufacturer's suggested retail price
NASA	National Aeronautics and Space Administration
NEDC	New European Driving Cycle
NH_3	Ammoniac
NMC	Manganese Cobalt Oxide
NMVOC	Non Methane volatile organic compounds
NO_X	Nitrogen Oxide
OEM	Original Equipment Manufacturer
OGP	International Association of Oil and Gas Producers
PBL	Netherlands Environmental Assessment Agency
PCA	Process Chain Analysis
PHEV	Plug- in hybrid electric vehicles
PISI	Port-injection spark-ignition gasoline vehicle
PM	Particulate matter
PWC	Pricewaterhouse Coopers
RCP	Representative Concentration Pathways
REEV	Range Extended Electric Vehicles
SEA	Strategic Environmental Assessment
SO_2	Sulphur Dioxide
SO_2 -eq	Sulphur Dioxide equivalents
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
TTW	Tank-to-Wheel
V2G	Vehicle-to-Grid
VCA	Vehicle Certification Agency
WLTP	World Harmonized Light Vehicle Test Procedure
WMO	World Meteorological Organization
WTT	Well-to-Tank
WTW	Well-to-Wheel
WWF	World Wide Fund for Nature

Introduction

Today more people than ever have access to health care, education, communication and transportation networks. The world has become smaller than ever, experiencing a decreasing trend in barriers to movement of people and goods. This is possible due to energy, which is converted to electricity and propulsion, needed to sustain our society as it is. Energy is in turn an industry within itself that employs many people and enables future research and development.

Generation of energy, however, comes at certain costs. The majority of the world's energy is produced from combustion of fossil fuels, which are limited resources and the extraction of which is detrimental to entire habitats (BP 2016). Moreover fuel combustion releases emissions into the air. The composition and intensity of emissions vary depending on the resource and technology in question, but their impacts are severe for wildlife, humans and the planet as a whole. Some impacts are local and direct such as respiratory problems associate with emission inhalations, while others occur on a global scale and take more time to manifest. Such is the case with climate change, caused by accumulation of greenhouse gases in the atmosphere over an extended period of time.

The majority of world authorities on environmental and energy issues such as the United Nations, the European Union, European Environmental Agency, International Energy Agency, National Aeronautics and Space Administration and governments of many developed countries have acknowledged the issue of climate change as one of the most pressing issues of our time (IEA 2013, IPCC 2014, EEA 2016, NASA 2018). Accordingly, numerous regulation, policies and strategies have been developed to address this issue. As the threat is global, efforts have to be undertaken across all industries and geographic regions, and include conservation, switching to utilization of renewable resources for energy production and implementing new technologies. However, the threat of climate change is not universally accepted, with the most notable example being the US announcing in June 2017 that it will withdraw from the Paris Agreement on Climate Change Mitigation (Milman et al. 2017).

The transportation sector accounts for 23% of the world's energy-related carbon dioxide emissions (World Bank 2018), and emission reductions in this segment would have a significant overall contribution. One technology that may have potential to make impacts in this sector is electric vehicles. Although electric propulsion has been developed before conventional vehicles, the personal transportation sector has been dominated by internal combustion engine vehicles for over a century, and only recently has the prospect of electric vehicles been seriously explored as a means of reducing the greenhouse gas emissions. However, while electric vehicles reduce pollution in some areas, they increase it in others, and the assessment of their overall environmental impact is very complex.

The main research question addressed by this paper is whether battery electric vehicles can make significant contributions to the reduction of carbon dioxide. The paper additionally treats the issues of feasibility of a transition to renewable sources of electricity and other types of pollution. To address the main research question, the paper presents a comprehensive literature review of the two leading methodologies used to compare environmental impacts of electric vehicles against those of internal combustion engine vehicles. It also includes a consumer perception survey as to assess the potential for future market penetration of electric vehicles.

The two assessment methods in focus of the paper are, the Well-to-Wheel assessment that treats the entire lifecycle of a fuel, from resource extraction to its conversion into motion, and the Life

Cycle Assessment that includes impacts from all phases of a vehicle's lifecycle from production, to use and disposal. Special consideration is given to implications electric vehicles have for the electricity market, including their effect on demand, interaction with electricity generation schemes, and impact on resource utilization. The paper also regards costs associated with owning electric and conventional vehicles.

To further address the research question, a consumer perception survey was developed and administered to potential future electric vehicle consumers. The purpose of the survey was to assess consumers' perception of the environmental impacts and cost implications of owning an electric vehicle and compare it to the findings from the literature reviewed. As environmental impacts of electric vehicles go only as far as the amount of market share they capture, consumer willingness to pay premiums for this expensive technology plays an important role, which is also regarded by the survey. The survey also explores consumer motivation and demographic implications on their attitudes towards electric propulsion.

Climate Change

According to the Intergovernmental Panel on Climate Change (IPCC 2014), climate change refers to a change in the state of the climate that can be identified, using statistical tests, by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity (IPCC 2014). On the other hand, according to the United Nations Framework Convention on Climate Change (UNFCCC), climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods (2007). In either case, currently there is strong consensus among the international community, global authorities on climate and scientific research institutions that there is clear human influence on the climate. Furthermore, this influence is manifested as warming of the atmosphere and ocean's, which is unequivocal, according to the IPCC's 2014 Fifth Assessment Report (AR5).

The AR5 indicates that it is extremely likely, namely 95-100% probable that human influence has been the dominant cause of observed warming since 1950. It is likely, with medium confidence, i.e. 66-100% probability, that 1983–2013 was the warmest 30-year period for 1400 years. It is virtually certain (99-100% probable) that the upper ocean warmed from 1971 to 2010, and this ocean warming accounts, with high confidence, for 90% of the energy accumulation between 1971 and 2010. The IPCC reports with high confidence that the Greenland and Antarctic ice sheets have been losing mass in the last two decades and that Arctic sea ice and Northern Hemisphere spring snow cover have continued to decrease in extent, as well as that the sea level rise since the middle of the 19th century has been larger than the mean sea level rise of the prior two millennia (IPCC 2014).

Evidently, climate change is taking place and there is a strong correlation between human activity, global warming and its effects. Moreover, the AR5 indicates that Concentration of greenhouse gases (GHG) in the atmosphere has increased to levels unprecedented on earth in 800,000 years. Total radiative forcing, relative to 1750, is positive and the most significant driver is the increase in Carbon Dioxide's (CO_2) atmospheric concentration (IPCC 2014). Radiative forcing is measured in watts per square meter and refers to the capacity of a gas or other forcing agents to affect that energy balance, thereby contributing to climate change (CORE 2011). It expresses the change in energy in the atmosphere due to GHG emissions. Positive radiative forcing implies that GHG absorb the infrared emissions from the earth and re-emit them back down. By not allowing this energy to escape, the earth becomes warmer, and thus global warming is created.

According to the National Aeronautics and Space Administration (NASA 2018), global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades depends primarily on the amount of heat-trapping gases emitted globally, and how sensitive the Earth's climate is to those emissions. The emissions of GHG are an unavoidable byproduct of mankind's development in the modern era when dependency on technology is becoming ever more prevalent. Electricity and independent individual transportation have become standard in modern society and the tendency is for such commodities to be even more dispersed among the population, while deforestation and expansion of land for development are occurring at an increasing pace and all these factors account for GHG generations. Nonetheless, considering the fact that humans are a significant contributor to the emission of gases responsible for climate change, there is potential for some of these emissions to be mitigated.

Intergovernmental Panel on Climate Change Assessment Report

The Intergovernmental Panel on Climate Change (IPCC) is the international body for assessing the science related to climate change. It was established by the World Meteorological Organization (WMO) and United Nations Environment Programme (UNEP) in 1988, with the aim of providing policymakers with regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation (IPCC 2013). Hence the IPCC provides governments with valuable information for developing effective climate change mitigations strategies and policies.

The IPCC does not perform primary research or direct monitoring of the state of climate, but it assesses all available peer reviewed and non-peer reviewed literature, which are then scrutinized by consortia of leading scientists and government experts in the field of climate change. The most relevant documents produced by the IPCC are its assessments reports. The most current is the Fifth Assessment Report (AR5), which was published in 2014, although the sixth assessment report is currently being developed.

The AR5 is the latest of a series of comprehensive reports published by the IPCC on climate change, compiled by 831 experts drawn from fields including meteorology, physics, oceanography, statistics, engineering, ecology, social sciences and economics. It provides an update of knowledge on the scientific, technical and socio-economic aspects of climate change (IPCC 2014). Considering the sheer number of countries and experts involved, the breadth of their expertise, the financial resources invested, the fact that it took 6 years for the report to be developed, and the fact that it was reviewed, criticized and amended by yet numerous other international institutions, amongst which are bodies belonging to the United Nations (UN), European Union (EU) and Environmental Protection Agency (EPA), the AR5 is the most comprehensive and relevant publication on this topic. The majority of literature reviews cite it as the baseline assessment of climate change, and numerous other publications on the subject refer to the AR5 as the benchmark.

Key conclusions from AR5 point that the warming of the atmosphere and ocean system is unequivocal, and that many of the associated impacts, such as sea level change taking place since 1950 have occurred at rates unprecedented in the historical record. Moreover, the report indicates that it is extremely likely that human influence is the dominant cause of the observed warming. The IPCC also noted that the longer we wait to reduce our emissions, the more expensive it will become (IPCC 2014).

The AR5 states predictions as to the possible outcomes regarding climate change under various assumptions. Therefore, the AR5 includes 4 future scenarios, whereby each one represents different assumptions made. These scenarios are known as Representative Concentration Pathways (RCPs) and they depict various possible changes in anthropogenic greenhouse gas emissions (IPCC 2014). Therefore, they describe four possible climate futures, depending on how much greenhouse gases are emitted in the years to come. They also provide a common and agreed upon basis for modelling climate change, facilitating the comparison of results across different research and saving time, money and effort on climate modelling.

The four RCPs include RCP 2.6, RCP 4.5, RCP 6, and RCP 8.5. Their name corresponds to the range of radiative forcing values, measured in watts per square meter, which will be reached by the year 2100 relative to pre-industrial values. Therefore each scenario represents a radiative forcing increase of 2.6, 4.5, 6.0, and 8.5 W/m^2, respectively. Although radiative forcing is the key metric in the RCPs, they also measure emission rates, the speed at which additional greenhouse gases are emitted into the atmosphere, and emission concentration, measured in parts per millions for each of the greenhouse gases including, but not limited to CO_2, methane and nitrous oxide. Each pathway also assumes two values in the year 2100, one for how much the planet has heated up, and one for the concentration of greenhouse gases (IPCC 2014).

According to the IPCC 2014, all RCPs indicate that further warming will continue if emissions of greenhouse gases continue, while the global surface temperature is likely to exceed 1.5° C relative to the 1850 to 1900 period in most scenarios, and is likely to exceed 2.0° C in many scenarios. The global water cycle will change, with increases in disparity between wet and dry regions, as well as wet and dry seasons, with some regional exceptions. The oceans will continue to warm, with heat extending to the deep ocean, affecting circulation patterns. Consequently the Arctic sea ice cover, Northern Hemisphere spring snow cover, and global glacier volume are likely to decrease, thus contributing to the rise in global sea levels at an unprecedented rate with estimation ranging from 0.26 to 0.82 m increase by the late 21st century. In addition, as the rate of CO_2 production increases, so will its uptake by the oceans, hence increasing their acidification.

As the IPCC (2014) indicates, increasing the magnitudes of global warming increase the likelihood of severe, pervasive, and irreversible impacts. Certain impacts can already be observed, such as the shrinking of glaciers, the earlier breaking up of ice on rivers and lakes, the shift in animal and plant ranges and the sooner flowering of trees (NASA 2018). The observed loss of sea ice, accelerated rise of sea levels and longer and more intense heat waves are also affecting humans already, causing great losses in the agricultural sector and an increase in the amount of flooding. Future impacts could manifest in a more severe range of phenomena, with some of the more commonly assumed ones across the relevant bodies including more frequent wildfires, longer periods of drought in some regions and increase in the number, duration and intensity of tropical storms (NASA 2018).

Accordingly, the bigger the increase, the greater the impact, with significant increases in temperature posing extinction threats for many animal species and potentially even human beings.

Due to the fact that human induced warming will affect a naturally varying climate, the temperature rise will not be uniform across the globe or over time. Consequently, some regions may benefit if considering a temperature increase of less than 1 to 3 °C. Some land where conditions are harsh, unlivable and non-arable would be milder and allow for life and agriculture. Nevertheless, according to NASA (2018), the net annual costs on the global scale would be much higher.

The IPCC (2014) concludes that the current trajectory of global greenhouse gas emissions is not consistent with limiting global warming to below 1.5 or 2 °C, relative to pre-industrial levels, and without new policies to mitigate climate change, projections suggest an increase in global mean temperature in 2100 of 3.7 to 4.8 °C, relative to pre-industrial levels.

Climate Change Policies

With the threat of climate change being recognized by the international community, many developed countries and major global organizations, numerous efforts to address this issue have been undertaken. Such efforts include treaties, conventions, policies and legislation aiming to enforce better environmental standards in emission generating activities.

Amongst the most important efforts to combat climate change is the Paris Agreement, which aims at strengthening, coordinating and supporting its signees to undertake efforts to keep the global temperature rise during this century under 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. To this purpose, the agreement foresees establishment of appropriate financial flows, a new technology framework and an enhanced capacity building framework, which will also support developing and the most vulnerable countries, in line with their own national objectives (UNFCCC 2018). In 2015, 196 parties, including the EU signed the Paris Agreement, which replaces the 1997 Kyoto Protocol, an international treaty requiring developed countries to limit their greenhouse gas emissions, which expires in 2020 (WWF 2017).

These agreements were made possible due to the United Nations Framework Convention on Climate Change (UNFCCC), which is a framework that prescribes the manner of negotiation of further action to the purpose of stabilizing greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (UN 1992). As of 2015, the UNFCC included 197 parties. UNFCCC is also the name of the United Nations Secretariat charged with supporting the operation of the Convention (UNFCCC 2018).

Pertinent to the UNFCC are the Bali Action Plan (2007), the Copenhagen Accord (2009), the Cancun agreements (2010), and the Durban Platform for Enhanced Action (2012) which all aim to reduce greenhouse gas emissions and support developing countries in doing so (UNFCCC 2018).

In line with these agreements and their own national policies, numerous countries have environmental goals addressing the issue of climate change. The EU has certain policies targets that it imposes on its members, as well as methods, systems and recommendations the upholding of which it encourages. Some of these efforts include the Renewable Energy Directive, the European

Emissions Trading Scheme, the CO_2 Passenger Car Regulation and the Fuel Quality Directive (Hacker et al. 2009).

Transportation Sector

The transportation sector has long since become a very important aspect of everyday lives of people in the modern age. It is unavoidable for social and economic existence in the world as we know it. Transport allows for mobility of persons and goods across air, water and land, enabling social interactions and business operations. It provides us with access to services and necessities. It connects numerous sectors and makes development possible. It employees millions. It spans across all areas of our society and constitutes one of the binding fabrics of the 21st century.

However, in order for it to serve a population of 7.63 billion people (World Bank 2018), the transportation sector has become enormous. The roads are driven by passenger vehicles, buses, trucks, vans, construction vehicles and countless other forms of commercial and private vehicles. On top, persons and freight are transported by rail, sea and air, which are also occupied by numerous forms of trains, ships, crafts, planes, helicopters and vessels.

Transport Sector Emissions

All of the modes of transportation comprising the transport sector require some form of energy for propulsion. Production of energy and its conversion to propulsion causes pollutions. The extent of pollution caused depends on the source of energy and the manner in which energy is produced from this source. In addition, as Hacker et al. (2009) indicate, the two main drivers of transport emissions are the amount of kilometers travelled and the carbon intensity of these trips. According to the World Bank (2018), transport accounts for about 64% of global oil consumption, 27% of all energy use, and 23% of the world's energy-related CO_2 emissions, and with motorization rates on the rise, the environmental impact of the sector is expected to grow dramatically.

According to the literature, transport has a significant impact on the environment and its impact is continuing to increase. The European Environment Agency (EEA) reported that in 2014, the transportation sector accounted for nearly one third of final energy consumption and a quarter of CO_2 emissions, with road transportation contributing about 70% of the sector's CO_2 emissions. Between 1990 and 2006, greenhouse gas (GHG) emissions from overall transport, including international aviation and marine transport in the EU-27 increased by over 35.8%. Concurrently, emissions from all other sectors together, excluding transport, have decreased by 12.4%. Road emissions in EU-27 have contributed to 61% of transport emissions' increase and accounted for about 71% of overall transport emissions in 2006. Moreover, international aviation and marine transport have exhibited a growth of 73%, contributing to 23.5% of overall transport emissions in 2006 (Hacker et al. 2009).

A similar trend was reported by the Environmental Protection Agency (EPA), for the USA, where 27% of the country's GHG emissions in 2015 were attributed to transportation, after having increased from 1990 to 2015 more in absolute terms than in any other sector. The EPA identifies transportation as being the second leading source of GHG in the US, behind electricity (EPA 2017).

Air pollution is a major risk for human health. It is estimated that it causes around two million deaths worldwide per year (Angerer et al. 2009). In addition to CO_2, the World Health Organization identified ozone, fine dust, NO_2 and SO_2 to be among the most dangerous kinds of air pollution. These pollutants are mainly produced by traffic, which was estimated to be responsible for half of the adverse health effects from pollution. Such is the case in industrialized countries as well. For instance, in 2007 almost 25% of the EU-25 population lived less than 500 meters from a road serving more than three million vehicles per year. As a result, nearly four million years of life are lost each year due to high pollution levels (Angerer et al. 2009). Many policies and efforts have been employed to mitigate this, as for instance the EU target for 2050 of an emissions reduction of 60% in the transportation sector, according to the European Commission (2010).

Vehicles

Many trials and errors have occurred on the quest to motorize mobility and abandon the horse drawn carriage era. Out of this quest came the automobile. In 1834, Thomas Davenport, an American inventor already built the electric car. It was not until 1886, that Benz and Daimler in Germany developed the first internal combustion engine vehicle. At the turn of the 19^{th} century, electric vehicles had a significant share of the automobile market. Around this time, the automobile engineer Ferdinand Porsche also invented a hybrid electric vehicle that was equipped with an internal combustion engine range extender and wheel hub electric engines. The various propulsion technologies were in close competition until 1908, when Henry Ford chose the internal combustion engine vehicle for the first mass production car in history, thus completely displacing electric vehicles from the market (Helmers et al. 2012).

This paper will discuss passenger vehicles. According to Statista (2018), 79.02 million cars were sold worldwide in 2017. In 2014, it was estimated that there were 1.2 billion vehicles in the world, with the US accounting for 258 million (Stacy et al. 2016). In China alone 24 million vehicles were produced in 2015 (Qiao et al. 2017). In the EU, the passenger fleet grew by 4.5 % from 2010 to 2015, going from 241 to 252 million vehicles on the road. In 2015, the transportation sector employed 12.6 million people which equates to 5.7% of the employed population in the EU (ACEA 2017). Out of new registrations that took place in the EU in 2015, diesel and petrol vehicles accounted for 97.4%, electric vehicles comprised 1%, while other alternative fuel vehicles such as liquefied petroleum gas (LPG) and compressed natural gas (NG-bio methane) vehicles covered 1.6 % (EEA 2016).

The EEA indicates that CO_2 average emissions for new cars sold in the EU, including all propulsion technology, in 2015 amounted to 119.5 g CO_2/km, while average emissions of new light commercial vehicles for the same year were estimated to be 168.3 g CO_2/km. When taking into account the EU, the highest average emitting cars were sold in Estonia and Latvia, producing 136 g CO_2/km, and Bulgaria where they emitted 137 g CO_2/km. The lowest emitting cars were registered in the Netherlands, producing 101 g CO_2/km, followed by Denmark, Greece and Portugal where they emitted 106 g CO_2/km (EEA 2016).

Conventional Vehicles

The term conventional vehicles today refers to vehicles using fossil fuels to power their internal combustion engine. Hence they are also referred to as Internal Combustion Engine Vehicles (ICEV). The two main fossil fuels utilized for their propulsion are petrol and diesel. They have been the dominant form of propulsion technology for the past century and hold this ranking even today. Accordingly, much necessary infrastructure to support them has been developed, including manufacturing plants, roads, fueling stations, parking spaces and repair facilities. As a result of their long market presence, there are numerous models available, while they were even at the forefront of planning city development. They have grown to be more than just a transportation vessel becoming part of personal style and cultural identity, with roars of motors and smells of gasoline bringing excitement to many people.

However, the nature of their propulsion technology is their main drawback and the reason why today alternatives are in demand. Combustion of fossil fuels generates a lot of noise and air pollution, degrading the quality of life in urban areas, especially those in proximity to busy roads. The associated tailpipe emissions are a major contributor to environmental degradation as well as health problems. They have contributed to the societal fossil fuel dependency, escalated the risk of resource depletion and polarized economic power amongst oil producers. Exacerbating this is also the fact that they are inefficient, converting only 18 - 25% of the energy available from the fuel for movement (EEA 2016).

Internal Combustion Engine Vehicles capture 95% of the personal transportation market (Hacker et al. 2009). The number of vehicles world-wide is expected to surpass 2 billion globally in the next few decades (Ager-Wick Ellingsen et al. 2016). Hence, the transportation sector is almost entirely reliant on one source of primary energy. This trend continues, as evident by the fact that in 2014 diesel and petrol cars accounted for 97.2% of new registrations, out of which diesel constituted 51.8% (EEA 2016).

Conventional Vehicle Fuel Consumption

A very important characteristic of petrol passenger vehicles is their fuel consumption. The fuel consumption determines the amount of money their owners will have to give for gas, and is a major factor in the vehicle's environmental performance. Fuel consumption is measured in units of fuel needed to cover a certain distance, or in distance that can be covered per unit of fuel. Typically in the US, consumption is expressed in miles that can be driven on a gallon of fuel (MPG), while in Europe it is the amount of liters of fuel needed to cover 100 kilometers (l/100 km). The global average consumption in 2013 was 7.1 liters per 100 km, which is a significant improvement from 2005, when it was 8.3 l/100 km. This trend is expected to continue, reaching 4.2 l/100 km in 2030 (Global Fuel Economy Initiative, 2018).

Gbegbaje-Das (2013) stated the base case 2012 average fuel economy for gasoline vehicles at 5.83 l/100 km, while proposing future scenarios of fuel consumption including typical 2020 scenario, best-case 2020 scenario, typical 2030 scenario and best-case 2030 scenario to be at 5.42, 5.19, 4.93 and 4.72 l/100 km respectively. The difference between scenarios relates to the level of technological development. It must be noted that these are average numbers for all car categories, and that fuel consumption cannot be measure independent of other factors.

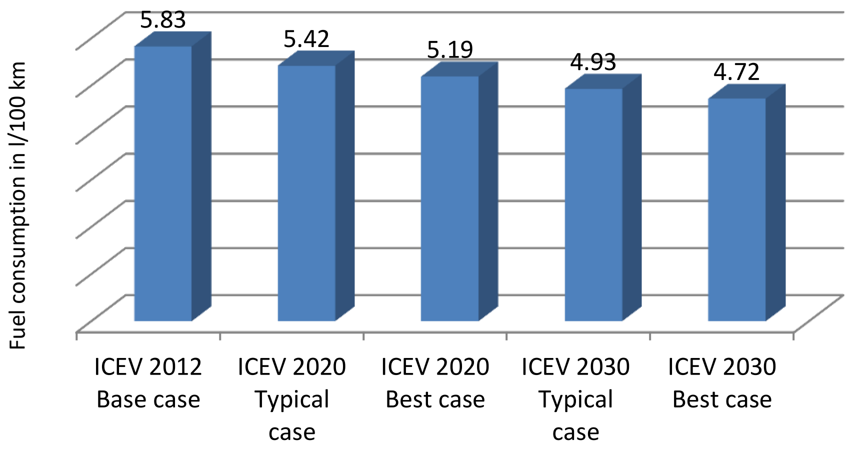
Fuel consumption is influenced by numerous factors. The literature lists a range of factors, including technological, environmental, behavioral, infrastructural and experimentation (Ericsson et al. 2001, Franke et al. 2012, Younes et al. 2013, Yuksel et al. 2015, Zacharof et al. 2016).

Technological aspects influence consumption in numerous ways. The size, configuration and technology of an engine influence the amount of power, fuel and weight associated with propulsion. The technology bringing fuel to the engine, as well as transmission also influence efficiency. The type of fuel burned plays a role as well. Vehicle construction characteristics include drivetrain and motor efficiency, vehicle mass, size and drag coefficients and rolling resistance due to tire design and pressure (Guzzella et al. 2013). In addition, auxiliaries, such as heating, air-conditioning, GPS, radio and lights all influence consumption.

A vehicle propels through the environment surrounding it, which has implications for its energy consumption. The artificial environment significantly impacts the way a car is driven, as it includes the infrastructure and other environment related to humans such as intersections, traffic, traffic lights and level of urbanization (Ericsson et al. 2001). Traffic represents the level of congestion which influences the flow and speed of a vehicle. Traffic is affected by the level of urbanization, as it determines population density, and consequently require more roads and infrastructure (Younes et al. 2013). This impacts intersections, traffic lights and speed limits, which all influence energy consumption. In addition, the natural environment, which includes topography, climate and numerous weather variables affects the resistance, operating temperature and use of auxiliaries, which is all reflected on the amount of energy necessary to propel a vehicle (Yuksel et al. 2015).

Furthermore, as vehicle autonomy is not yet in mass use, almost all vehicles are driven by drivers, who have human characteristics. Therefore, emotions and character traits such as anxiety, impatience and aggressiveness influence the driving behavior (Franke et al. 2012). This determines acceleration and breaking patterns, as well as use of auxiliaries. Also affecting driving behavior is the reason for a journey and the type of journey. Depending on the urgency, length and time of journey, a driver may vary the speed and amount of stops made.

The researcher's testing methodology can have profound effect on results as well. Assumptions and experiment design will contribute to different outcomes even for the same vehicle in question. Performance of every measurement will have to include some sort of configuration of the previously mentioned factors as well as numerous others. Furthermore, it must be noted that none of these factors act independently. Some are strongly correlated and even mutually reinforcing, while others may cancel each other out. Therefore energy consumption indicators are very relative and cannot be considered in isolation. Nonetheless, they can still provide relevant indications of performance and basis for comparison.



Source: Gbegbaje-Das (2013)

Figure 1: Future Fuel Consumption of Gasoline Vehicles in l/100 km

Conventional Vehicle Emission Reduction Efforts

As conventional combustion vehicles are the most prevalent form of propulsion technology for personal transportation, a direct step toward reducing pollution in the transportation sector is to address their efficiency. The IPCC report also warns that without aggressive and sustained mitigation policies being implemented, transport emissions could rise at a faster rate than emissions from the other energy end-use sectors (Ager-Wick Ellingsen et al. 2016). Although the question of whether new propulsion technologies can adequately address transportation emissions is still open, introduction of such substitutes will take a relatively long time. Alternative propulsion technologies are still developing and consumers appreciate the convenience of the established functionality of the current option. Furthermore, consumer loyalty plays a considerable role. Therefore, improving environmental performance of ICEVs is an immediate step undertaken by policy makers and car manufacturers.

Policy and regulation nudging manufacturers to produce more fuel efficient and less emitting vehicles are in place on national and international levels. For instance, to reduce CO_2 emissions in the road transport sector, the European Parliament and the Council adopted the Regulation (EC) No 443/2009, which introduced mandatory CO_2 emission performance standards for new passenger cars, and Regulation (EU) No 510/2011, which introduced mandatory CO_2 emission performance standards for new vans. Regulation (EC) No 443/2009 set a CO_2 emissions target for 2015 at 130 g CO_2/km for the average value for the fleet of newly registered passenger cars in the EU, and a more stringent target of 95 g CO_2/km for 2021. Regulation (EU) No 510/2011 set a target of 175 g CO_2/km for the average value of the fleet of newly registered vans in the EU in 2017, and a target of 147 g CO_2/km for 2020 (EEA 2016). As a result of this regulation, car manufacturers are evaluated every year in view of the set targets and penalized if they are not in compliance. Consequently this regulation pushes for the development of cleaner and more efficient technology.

Conventional Vehicle Emission Trends

Arising from the various technological developments in the car industry, as a consequence of regulation and competition for market share, there has been a noted improvement in the efficiency of petrol vehicles. This efficiency has benefits in the shape of better mileage per fuel unit and less emissions per distance unit driven. According to the European Environmental Agency, in 2015 new cars sold in the EU had average CO_2 emissions of 119.5 g/km, which is 3.1% lower than in 2014. Looking at the period 2005 to 2015, CO_2 emissions from new cars decreased by 27%. Although certain manufacturers exceeded their specific emission targets, such as Aston Martin Lagonda and Ferrari, for which they have to pay excess emission premiums, the trend remains positive. Since 2009, when the legislation entered into effect, average CO_2 emissions have decreased by 26.2 g/km, which represents an average decrease of 4.4 g CO_2/km per year (EEA 2016). This positive trend still needs to continue in order to meet the targets set to combat climate change, and policy makers and car manufacturers alike are aware of this. Hence more efforts to this purpose can be expected.

The emission average for new cars presented includes all propulsion technologies, including EVs. However, considering that by the end of 2015, EV market share in the EU reached 1% (EEA 2016), the 3.1% reduction in emissions noted compared to the previous year is in much greater part due to the efficiency improvements of ICEVs. The technologies contributing to reductions include direct fuel injection, variable valve timing and lift, cylinder deactivation, turbocharging and start–stop systems (EEA 2016).

It must also be noted that acquisition of new cars with clean technologies requires a certain amount of spending power. Significantly more efficient models were bought in the pre-2004 EU Member States than in the newer EU Member States. On average, the most efficient cars were bought in the Netherlands with 101 g CO_2/km, Portugal, Denmark and Greece, with 106 g CO_2/km each (EEA 2016). Thus there is a strong correlation amongst a country's level of development and the CO_2 emissions measured. On the one hand, not all countries were able to achieve improved emissions. But on the other hand, certain countries were able to achieve emissions significantly better than the average, which implies that further improvement is achievable and technologically viable, as it is a question of market share.

Electric Vehicles

According to the World Bank (1996), an electric vehicle is a vehicle which uses one or more electric motors or traction motors for propulsion. Many vessels powered by rotary or linear motors can be characterized as electric vehicles including cars, trucks, boats, airplanes, bicycles, skateboards, motorcycles, scooters and space craft. However for the purpose of this paper the term electric vehicles will exclusively imply passenger automobiles. Although electric vehicles were invented before their internal combustion engine counterparts, significant developments in technology and market penetration started to take place only in the 21st century, when they were identified as a potential means of mitigating climate change (IEA 2013).

Since the commercialization efforts of electric vehicles started, manufacturers have produced numerous motor types and configurations in an attempt to achieve the best performance with the smallest environmental impacts. Consequently, several types were successful to the extent that they are still available on the market as of 2018, including Battery Electric Vehicles (BEV), Hybrid Electric Vehicles (HEV), Plug-In Hybrid Electric Vehicles (PHEV), Range Extended Electric Vehicles (REEV) and Fuel Cell Electric Vehicles (FCEV) (EEA 2016). The focus of this paper will be exclusively on Battery Electric Vehicles (BEV), but nonetheless, one must bear in mind that they are not the only form of vehicle electrification.

Battery Electric Vehicles (BEV) are powered only by an electric motor, which uses electricity from a battery located on board the vehicle, which is then charged by connecting either to the grid or to a personal energy generator such as household photovoltaic panels. BEVs are the technology yielding the highest energy efficiency, converting a minimum of 80% of their battery's energy into motion. This is due to an efficient motor combined with regenerative breaking, which allows the vehicle to generate electricity while breaking, extending the range that a battery allows to drive. Being that BEVs are charged exclusively from electricity they do not produce any tailpipe emission thus directly improving local air quality. BEVs do not have a combustion engine and thus produce significantly less noise than ICEVs. The main drawbacks BEVs exhibit is range limitations, higher price than conventional vehicles, longer time of charging and limited availability of charging infrastructure (EEA 2016).

Hybrid Electric Vehicles (HEV) have both an internal combustion engine and an electric motor. The electric motor assists the combustion engine during acceleration. The battery for the electric motor is charged during regenerative braking and coasting, but cannot be charged from outside sources.

The electric motor is intended to enable the combustion engine to achieve greater fuel efficiency. There are many different models of hybrids and accordingly, the proportion the electric motor uptakes, as well as the way the two motors are combined differ vastly. Certain hybrids are able to drive solely on electricity for a certain mileage while others are not. HEVs yield better fuel efficiency, while being able to be fueled quickly, but on the other hand still cause tail pipe emissions and burn fossil fuels. Another drawback of HEV is their technological complexity (Graham et al. 2014, EEA 2016).

Plug-In Hybrid Electric Vehicles (PHEV), are essentially Hybrid Electric Vehicles, but whose battery can be charged by outside sources. The combustion motor and electric motor can work either together or separately. The combustion motor can separate the electric motor when more power is required or when the battery's state of charge is low. The amount of emissions depends on the motor configuration. Its main advantage, besides fuel efficiency is that it can be charged either at fuel stations or at charging stations, allowing for flexibility and saving money on fuel, but the drawback like with the HEV is its technological complexity. (Graham et al. 2014, EEA 2016).

Range-extended electric vehicles (REEV), have both a combustion engine and an electric engine, but which are configured in a serial manner, so that the combustion engine has no direct link to the wheels. It rather acts as an electricity generator or the electric motor, to power it or recharge the battery. Its battery can be charged from the grid. It allows for quick refueling, which extends the electric range, but also allows for charging. It shares the disadvantages of the hybrids, in terms of technological complexity (EEA 2016).

Fuel Cell Electric Vehicles (FCEV) are full electric vehicles, which are powered by a fuel cell stack that uses hydrogen from an onboard tank and oxygen from the air, instead of a large onboard battery. They yield a much larger driving range than conventional BEVs, as well as can be refueled quickly, at speeds comparable to conventional vehicles. This technology is much newer than that of other electric vehicle configurations, and therefore their commercial availability as well as charging infrastructure is very limited.

The 21st century has witnessed an ever-increasing speed of technological developments, with new innovations constantly coming about and evolving. This is also the case with electricity-based vehicle propulsion. The models presented in this section are just some of the many options developed in this field and they are also still at their early phases of development. This paper will exclusively focus on battery electric vehicles based on lithium-ion battery technology, which currently stands as the leading concept for such vehicles. By narrowing the focus on BEVs, comparing them against ICEVs, and excluding the numerous possible combined and alternative configurations, this paper aims to explore the environmental implications of this isolated factor. Henceforth the terms battery electric vehicles (BEV) and electric vehicles (EVs) will be used interchangeably, whereas the other forms of electric propulsion technology will be distinctly identified.

Electric Vehicle Trends

Although electric vehicles capture a very small share of the automobile market, they exhibit an extraordinary growth rate. According to the European Environmental Agency (2016), the proportion of plug-in hybrid and battery electric vehicles in the EU increased from 0.8% in 2014 to 1% in 2015. According to Quiao et al. (2017), in 2015 over 24 million vehicles were produced in China, 380,000 of which were new energy vehicles, whose growth rate was dominated by EVs, which is around 100 times higher than that of ICEVs. The Chinese government estimates cumulative output of EVs in that country to reach 5 million by 2020, which is over 10 times more than in 2015.

According to Original Equipment Manufacturer (OEM) ranking for 2017, published by “Inside EVs”, 1,224,000 plug-in electric cars were sold around the world in that year. The leading automotive group in the EV market in terms of sales in the year 2017 was the Renault-Nissan-Mitsubishi with 119,195 vehicles sold, followed by the BYD Group with 113,949 vehicles, the BAIC Group with 104,536 vehicles, the Geely Group with 103,194 vehicles, Tesla with 103,122 vehicles, the BMW Group with 103,080 vehicles, the Volkswagen Group with 70,314 vehicles, the SAIC Group with 56,149 vehicles, GM with 55,188 vehicles, and Toyota with 50,883 vehicles sold.

According to the portal “Best Selling Cars”, in 2017, China was again the world’s largest car market. Behind it were the USA and EU. Russia was the fastest growing car market, with sales increasing in Brazil, India and Japan (Bekker 2018). According to Bloomberg Businessweek, in 2017 the Nissan Leaf was the world’s bestselling full electric vehicle, with over 300,000 units sold worldwide since its introduction until the second half of 2017 (Ma and Horie 2017). Bloomberg Businessweek also reports that as of the first quarter of 2018, the Tesla Model 3 was the bestselling full electric vehicle in the US with 8,180 models sold within this period (Randal 2018).

Indicators such as the increasing availability of models in the market and the price reductions point that this trend is bound to continue. For instance, there were only 3 plug-in electric vehicle models on the market in 2010, while in 2014 seventeen models were available (Graham et al. 2014). In 2017, according to Bloomberg (2018), 25 battery electric models were offered on the market, in addition to 26 plug-in hybrids and 3 fuel cell electric vehicles, amounting to 54 models of vehicles running on electricity in some manner available to consumers.

Besides the expanded availability of models, the purchasing price is also decreasing, with more resources invested in research and development, and manufacturers moving along the learning curve over time, improving their production and recycling efficiency. The area where production efficiency and recycling have the most impact is the production of battery packs, which is the most expensive and environmentally intensive component of an electric vehicle’s production. Amidst these tendencies, however, the electric vehicle industry is still in the stage of early development and it will take some time before they start comprising significant portions of automobiles driven.

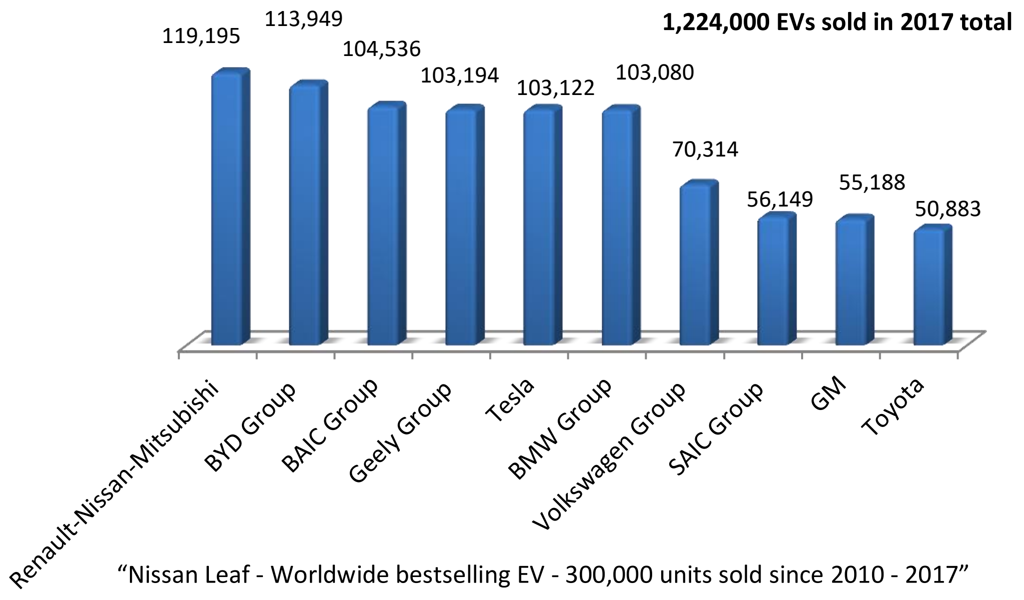


Figure 2: EV Sales in 2017 by Group

Energy Consumption of Electric Vehicles

The energy consumption of an electric vehicle is expressed in kilowatt hours (kWh) required to propel a vehicle per unit of distance. Kilowatt hours represent a unit of energy equal to one kilowatt of power sustained for one hour (Thompson et al. 2008). The unit of distance used in the various researches depends on whether the authors use the metric or US Customary System. Hence consumption of EVs is stated in kWh/km or kWh/mile in the literature reviewed. One important consideration when measuring energy consumption, and subsequently emissions of electric vehicles is whether the assessment regards only the energy required to propel the vehicle from one point to another, or whether the energy for vehicle manufacture and attainment of the sources of electricity are also accounted for. For purpose of such examination, life cycle assessments (LCA) and well-to-wheel (WTW) assessments are performed, which are described in more detail in their respective sections. This section focuses on the energy required for propulsion of vehicles from one point to another.

As with petrol vehicles, energy consumption of electric vehicles is influenced by a variety of factors, which do not act in isolation nor have always the same effect. For instance, Li et al. (2016) classified 16 main urban driving parameters that could affect the amount of energy required to propel an electric car. Depending on the level of detail and classification the number of factors can vary, but they generally include technology, the environment, driver behavior and testing methodology used.

As both, conventional and electric passenger vehicles have the same purpose of moving persons while providing certain levels of comfort, their consumption are mostly influenced by the same factors. The main difference is the technology factor, which includes battery systems, heating and ventilation, other auxiliary components and vehicle construction specifics. Young et al. (2013) place the battery as a key component of an EV, with the most crucial factor being the battery chemistry, number of cells, manner in which they are stacked and the battery management system design.

These factors in turn influence battery capacity, energy intensity, mass, amount of charging cycles, regeneration rate, temperature and state of charge, which all directly affect power requirements needed for movement. Heating and air-conditioning are power intensive features, with heating being particularly demanding in BEVs without a hot combustion engine, thus requiring a separate heat pump (Khayyam et al. 2011). Other auxiliary components including light, radio, GPS and other comfort related features, powered by a 12 Volt battery connected to the traction battery, and although according to Young et al. (2013), their impact on the overall energy requirement is low, it still needs to be accounted for.

Bearing in mind the same limitation of consumption indicators as for petrol vehicles, due to the various influencing factors which make these indicators relative, it is still useful to gain an idea of the amount of energy an EV is estimated to consume.

Helmers et al. (2012), performed a review of 21 studies performed from 1999 to 2009, 18 out of which took place from 2007 to 2009, where they identified a mean consumption for BEVs of 17.5 kWh/100 km. These studies however did not include the entire life cycle. Helms et al. (2010) performed a Life Cycle Assessment (LCA), the results of which indicate consumption of 20.4 kWh/100 km in urban areas, 20.8 kWh/100 km in extra-urban areas, and 24.9 kWh/100 km on the highway. Pehnt et al. (2010) found consumption of 21 - 24 kWh/100 km. Held and Baumen (2011) obtained LCA results of 18.7 kWh/100 km for a min BEV and 22.9 kWh/100 km for a compact one.

More recently, Nealer et al. (2015) examined the consumption of EVs in 2014. They estimated that the Nissan LEAF consumes 18.6 kWh/100 km, the BMW i3 consumes 16.8 kWh/100 km and the Tesla Model S consumes 23.6 kWh/100 km. They note however, that the assessed Nissan LEAF, BMW i3 and Tesla Model S have a 24 kWh, a 22 kWh and an 85 kWh battery respectively. These numbers could be the basis for calculation of greenhouse emissions, by multiplying them with distance driven and an appropriate emissions factor depending on the electricity mix supplying the grid where they would be charged. Thus we could obtain a relative picture of emissions from the movement of these vehicles. However, such emission results would not constitute a sound basis for comparison with other propulsion technologies, as they neglect the environmental impacts associated with vehicle production and disposal, as well as the environmental impacts associated with provision of electricity. These aspects are covered under LCA and WTW analysis, which are discussed later in the paper.

Energy Consumption of EVs (in kWh/100 km)	Model/Type	Conditions	Source
16			Davis et al. (2016)
18,6	Nissan Leaf		Nealer et al. (2015)
16,8	BMW i3		Nealer et al. (2015)
23,6	Tesla Model S		Nealer et al. (2015)
17,5			Helmers et al. (2012)
18,7	mini		Held and Baumen (2011)
22,9	compact		Held and Baumen (2011)
20,4		urban	Helms et al. (2010)
20,8		extra-urban	Helms et al. (2010)
24,9		highway	Helms et al. (2010)
21 - 24			Pehnt et al. (2010)
14			Hartmann et al. (2009)
15 - 20			WWF (2009)
18			Eurelectric (2009)
11 - 16			Ricardo Media Office (2009)
18			PWC (2009)

Table 1: Energy Consumption of EVs cited in the literature

Technology of Electric Vehicles

BEVs have a simpler structure than ICEVs as they have no fuel tank, internal combustion engine, starting system, exhaust and lubrication system. Most of them do not have a gear box, and sometimes they do not even have a cooling system. They consist of a battery pack, an electric drive motor, motor controller, power-control electronics and regenerative braking system (Nealer et al. 2015). BEVs' batteries can be charged either by plugging them in or through regenerative breaking. Hence the charger is an important component, with efficiency varying between 60 and 97%, wasting the remainder as heat. The motor controller supplies the electric motor with variable power, from the battery pack, depending on the load situation. The electric motor converts the electric energy into mechanical energy and then, in combination with the drivetrain, to torque. The electric motor can either be central or hub wheel (Helmers et al. 2012).

The main difference in the production of a BEV in comparison to an ICEV is the absence of a combustion engine, and the type and size of the battery pack. Also, contrary to ICEVs, in BEVs, the power train, transmission and traction motor are not a large part of the vehicle's materials and weight, but they do replace some functionalities of the conventional car's engine. BEVs and ICEVs do share certain components, such as the chassis and tires. Thus, when comparing environmental impact of production amongst the two propulsion technologies, the glider, which is the car minus the gearbox, motor, battery and fuel equipment is taken for modelling as it is the same in both kinds of vehicles.

Today's EVs are based on several motor technologies, which are classified by various means, but most commonly distinguished on the bases of whether they use permanent magnets or not, alternating current (AC) or direct current (DC), or other configurations and technologies. Hence there are DC motors, induction AC motors, wound rotor synchronous motor, switched reluctance motor and brushless permanent magnet motors (Baltatanu et al. 2013). No single technology has emerged as the absolute market winner, as each have their advantages and drawbacks. For instance, permanent magnet motors, which propel the Nissan Leaf, yield very high power density and efficiency, but are very expensive and prone to problems such as demagnetization in cases of high temperature. The strongest permanent magnets consist of alloys such as NdFeB and SmCo, which contain rare earth elements such as neodymium and samarium, respectively and thus there are resource scarcity concerns. Induction motors, on the other hand require no permanent magnets and thus risk no demagnetization and such resources limitations. The Tesla Roadster, Model S and the Toyota RAV4EV use AC induction motors (De Santiago et al. 2012).

In the early years of EVs' market penetration there was much research and experimentation to determine the most suitable battery for EVs. The resulting outcome was the Lithium Ion (Li-ion) technology in the voltage range between 300 and 400 V. The fuel cells are based on Proton Exchange Membrane technology because it is emerging as the most promising for automotive applications. As battery packs are identified to be the component of an EV with the highest environmental impact during production, price and potential for future savings, the next section takes a close look at some of their characteristics.

Batteries

While gasoline vehicles have a small lead-acid battery, used only for starting the engine and power accessories when the engine is off, the battery comprises a much larger proportion of an EV. As mentioned above Li-ion batteries have become the dominant technology in electric propulsion. This was concluded by numerous literature reviewed including Notter et al. (2010), Zackrisson et al. (2010), Majeau-Bettez et al. (2011), Omar et al. (2012), Dunn et al. (2012), Hawkins et al. (2012), Ellingsen et al. (2014), United States Environmental Protection Agency (2013), Dunn et al. (2015), Li et al. (2014) and Ager-Wick Ellingsen et al. (2016).

Lithium's dominance in the battery industry is attributed to its high energy density and better performance at changing temperatures (Van Mierlo et al. 2017). It is also expected that as production volumes of this battery technology increase, production techniques improve and economies of scale can be exploited, their price will decrease accordingly. There are concerns however about the future availability of lithium. On the other hand, certain literature, such as Gruber et al. (2010), quantified lithium supply and concluded there is enough lithium for large increases in BEV manufacturing. The uncertainty range for lithium availability is relatively high, spanning from 4.6 Mt to 39.4 Mt.

The approximate geographical distribution of lithium resources and production in 2011 is as follows: Australia (36%), Chile (35.6%), China (17%), Argentina (7.4%), Portugal (2%), Zimbabwe (1.4%) and Brazil (1%) (Van Mierlo et al. 2017). The uncertainty regarding the demand of lithium also has a great range, from 184,000 to 989,000 tons per year in 2050. Currently, the lithium market comprises 22% of the world's lithium demand (Oliveira et al. 2015).

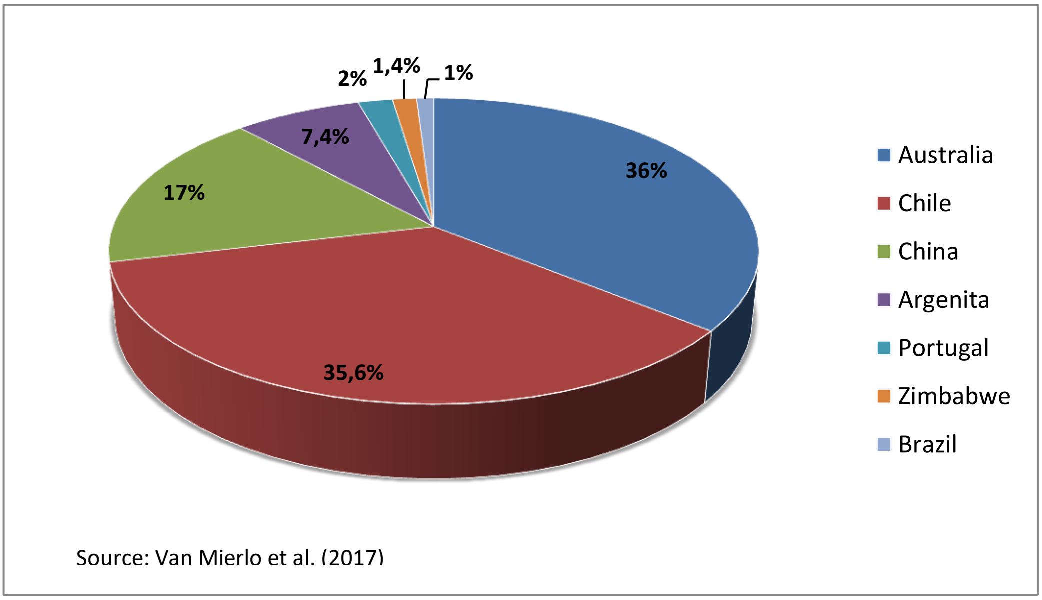


Figure 3: World Distribution of Lithium

Nevertheless, as the battery industry develops, battery recycling is expected to develop as well, and under an adequate recycling system, less and less new lithium will need to be extracted even if demand increases. Literature studies assessing the future availability and demand of lithium, mostly assume that there will be a large scale recycling in the future, and thus lithium shortage will not pose a hindrance for the EV industry (Gruber et al. 2011, Dunn et al. 2014, Nealer et al. 2015, Van Mierlo et al. 2015).

Amongst Li-ion batteries there are numerous chemical compositions, such as Lithium Cobalt Oxide (LiCoO2), Lithium Manganese Oxide (LiMn2O4), Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO2 or NMC), Lithium Iron Phosphate (LiFePO4), Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO2) and Lithium Titanate (Li4Ti5O12) (Types of Li-ion, 2018), and the literature differs with regards to the market penetration, performance and emissions of each. Consequently, production of batteries requires cobalt, nickel, and other metals, most of which are mined outside the United States, according to Nealer et al. (2015). Hence, they note security of supply as a concern from the US perspective. Nonetheless, as Dunn et al. (2014) point, cobalt and nickel are today's biggest economic drivers for recycling because the market prices of these metals are relatively high. Moreover, with further development in the recycling industry taking place, they will be abundant enough to support large scale EV integration without utilization of virgin materials.

Van Mierlo et al. (2017) indicate that Lithium Manganese Oxide (LMO) and Lithium Iron Phosphate (LFP) are the most common ones, as they have the most suitable energy density and power characteristics for electric propulsion. Hawkins et al. (2012) compared two different types of lithium batteries, LiNCM and LiFePO4, and found the former to outperform the latter in terms of GWP due to their greater energy density. Qiao et al. (2017) note that LFP batteries represented 52% of China's traction battery market in 2015, but also state that in the case of China in 2015, Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO2 or NMC) capture 39% of the market, hence they can also be considered amongst the more commonly used.

Environmental Impacts of Battery Production

As Nealer et al. (2015) indicate emissions from producing the battery come from extracting raw materials such as lithium, cobalt, copper, and iron ores, processing these materials into finished metals, and then fabricating them into the parts of the battery. Finally, when the battery is assembled and installed in the car, there are global warming emissions from the assembly. The environmental impact of battery production varies across literature, and depends heavily on the methodology used and chemistry considered.

For instance, Held and Baumann (2011) calculated GWP of battery production to be from 5 to 10 t CO_2-eq, in an LCA of mini and compact size EVs, assuming they are charged with renewable electricity. Additionally, they found acidification potential in such case to be 40 to 80 kg SO_2-eq for the whole battery. Hawkins et al. (2012) measured the impact of battery production under the European electricity mix (2012), and they found that the LiNCM EVs yielded GWP amounts of 197 g CO_2-eq/km, while the amount for LiFePO4 EVs was 206 g CO_2-eq/km. Qiao et al. (2017) claim that CO_2 emissions from electricity consumption during Li-ion battery production can be reduced by 95% to 98% if the production site is shifted from China/Europe to Iceland with its geothermal energy resources, as electricity production in Iceland causes a footprint of 18 to 23.5 g CO_2/kWh only.

Helmers et al. (2012) converted a conventional Smart to an EV, using an LiFePO4 battery containing 3.4% Li, 42% Fe, 16% P, 5% graphite, 3% C, 6% Al, and 10% Cu. They found the anode and cathode materials including graphite, copper, and aluminum to be of highest relevance for the battery LCA. Majeau-Bettez et al. (2011), however, identified battery and components manufacturing, as well as the positive electrode paste, as being the most GWP-intensive component, reporting environmental burden of manufacturing a LiFePO4 battery to be 250 kg CO_2-eq/kWh, and 200 kg CO_2-eq/kWh for the manufacture of a LiFe4CO2Mn4O2 battery according to industrial data.

Notter et al. (2010) evaluated the environmental impact of LiMn2O4 battery at 52 kg CO_2-eq/kWh, using a bottom up approach and found that two other of the often used active materials exhibit only a small increase of 12.8% (LiMnNiCoO2) and a decrease of 1.9% (LiFeO4), respectively, in environmental burden. They also conclude that Li-ion battery plays only a minor role ranging between 5% and 15%, regarding the overall environmental impact of EVs, regardless of the impact assessment method used. Relying on a top down modelling approach, Zackrisson et al. (2010) found the environmental burden of a LiFePO4 battery production to be 166 kg CO_2-eq/kWh. Ishihara et al. (2002) found LiNiCo and LiMn batteries to yield 75 kg CO_2-eq/kWh environmental impacts, using a bottom up LCA approach.

As evident by the instances mentioned above, the literature diverges on the environmental impact of batteries. The methodologies used differ greatly and so do the reported impacts. Further, the manner of reporting impacts varies as well, making comparison amongst the reported results in the literature very arbitrary. Nonetheless, it is evident that Li-ion battery technology emerged as the industry standard. Battery production methods and technology are constantly developing, and as renewables take up a larger proportion of world electricity production, this trend will continue as to accommodate the changes. The energy mix used in battery production significantly influences its environmental impact and, although a switch to renewables may soften this impact, battery production is still the major factor in the environmental impact of producing an EV.

Battery Size

A battery pack is comprised of modules that consist of cells, each yielding one to six volts (MIT 2008). Therefore, the more cells a battery contains, the more volts it provides, namely the bigger the battery the larger the range of an EV powered by it. However, the increased battery size adds considerable weight to a vehicle, thereby reducing its efficiency by imposing a requirement for more power to move the vehicle the same distance as would be the case if the vehicle was lighter. A larger battery also implies more emissions in the production phase. In terms of environmental impacts, thus, battery size presents a particular trade off.

The size of battery required to cover a certain range also varies amongst the literature. For example, the 24 kWh battery for the Nissan LEAF, allows a driving range of 84 miles and weighs about 650 pounds (Nissan 2015, as cite by Nealer et al. 2015). The much larger 85 kWh battery in the Tesla Model S weighs about 1,200 pounds and carries the vehicle 265 miles (Tesla Motors 2015, as cite by Nealer et al. 2015). However, Held and Baumann (2011) supposed that mini and compact size EVs should have batteries of 20 to 40 kWh capacities. Helmers et al. (2012) converted a Smart into an EV and found that it achieved an electrical range of more than 100 km with a 14-kWh Li-ion battery. In 2012, they found the compact class EV Nissan Leaf to have a cruising radius of 175 km with a 24-kWh battery. Hence, battery sizes required for EV operation seem to be partly overestimated.

With regards to the tradeoff between range and production intensity, Nealer et al. (2015) found that for the midsize 84-mile-range EV, battery production emissions amounted 24% of the total manufacturing emissions, but less than 8% of life time emissions, while for a full-size 265-mile-range EV, battery manufacturing constituted 36% of total manufacturing emissions and 12% of life time emissions.

To place the impacts of the range to intensity tradeoff into perspective, the use phase must be assessed. According to Van Mierlo et al. (2017), the use phase, that is the electricity used to charge the battery, has a significant impact on the environmental scores for climate change, particulate matter formation and human toxicity. Thus, they argue that the environmental performance of the battery can be improved by charging it with renewable electricity. However, not all charging points connected to grids are constantly powered by renewables.

Vehicle range can have implications for the emissions cause by charging EVs. On the one hand, longer range allows for flexibility with regards to charging times and choice of charging station, enabling the exploitation of further cleaner charging grids. On the other hand, the larger battery requires longer charging times, which may not always coincide with the span of availability of renewables, in addition to their requirements for more energy to cover the same distance as lighter EVs. Hence, the environmental impacts of various battery ranges are very case specific. The opposite would be true for lighter cars. They would be more energy efficient, requiring less resources to move, but would be more spatially limited to nearer charging points, reducing the availability of charging stations which may be supplied by renewables.

Battery Lifespan

Another factor that influences the environmental impact of EVs is the length of time a battery would be operational. Since it is a major part of emissions generated by EV production, the question of whether one battery would last throughout an EV's life-time or whether it may need to be replaced, is of great importance. Accordingly, the literature identifies certain parameters that influence the performance and lifespan of a battery.

One key element affecting the performance and aging of the lithium batteries is the mode of charging, as some stations offer normal, semi-fast and fast charging. Omar et al. (2014) thoroughly assessed the aging parameter of lithium-ion phosphate (LFP) based batteries, investigating different charging currents, temperature and depth of discharge. They performed their tests on 2.5 Ah 3.3 V rated LFP battery, tested with 100% depth of discharge and different magnitudes (1.25 I_t, 2.5 I_t…10 I_t, where current I_t represents the discharge current in amperes during 1 h discharge) of the charging current, under normal room temperature, they identified at about 25 degrees Celsius. The tests indicated that, under fast charging, at 2.5 I_t compared to 1.25 I_t (3.5 A), the amount of cycles to reach 80% of remaining capacity drops from about 2,900 to 1,600, thus drastically decreasing the length of durability of the battery. Hence increasing the current, shortens the length of battery life.

The Omar et al. (2014) study was performed on smaller battery cells than those of EVs. Nonetheless, they could conclude that in case of an EV with a 300 V, 80 Ah - 24 kWh battery pack, where the normal charging current was assumed to be 0.125 I_t (10 A), it was acceptable to charge under semi-fast charging of 1 I_t (80 A), but extreme high current charging (160 or 320 A) was not advisable.

Van Mierlo et al. (2015) also note that in addition to the current, the frequency of fast charging as compared to normal charging, the depth of discharge and working temperature of the battery all have very important impacts on battery durability. In addition, some vehicle manufacturers suggest that vehicle batteries can be used for energy storage during and after vehicle life. Vehicle use for energy storage, could have a negative impact on battery life time in terms of distance driven, as it would increase the charge-discharge cycles.

The mentioned factors all contribute to the battery longevity of EVs. In turn, each one of those factors can be greatly influenced by driver behavior and charging management systems. Nevertheless, depending on the assumed charging current, frequency, depth of discharge, energy storage and working temperature parameters, in addition to battery size, the literature states differing life spans, but the estimates fall between 150,000 and 200,000 km (Notter et al. 2010, Zackrisson et al. 2010, United States Environmental Protection Agency 2013, Li et al. 2014).

Battery warranties for different EV models range from 100,000 km within the first five years to unlimited km within the first eight years Van Mierlo et al. (2015). The battery warranties are set by the car manufacturers themselves, so it can be reasonable to assume that they state the minimum of what can be expected. Ager-Wick Ellingsen et al. (2016) for instance assume a total driving distance of 180,000 km, while Hawkins et al. (2012) assume a total driving distance of 150,000 km for a battery capacity of 24 kWh. In any case, the rapid aging of the battery will have a substantial effect on the environmental performance of EVs, because it will cost more than one battery to cover the life time driven distance of the vehicle.

The literature provides general overviews and assumptions about the life span of batteries. However how long a battery may last, will be case specific. Amongst the factors influencing this variable is the yearly distance traveled, driving behavior, the actual length of time an EV will be used, the charging batters, the quality of production of each battery pack and EV, the chemistry of the battery, temperature, the charge of current and many other case specific factors. The estimations provide a good insight into understanding trends and tendencies, however robust data that can be used for statistically significant analysis will only be available once this young industry matures and real world effects can be analyzed.

Battery End of Life

Usually, when gasoline cars reach the end of life, they are disassembled for spare parts and most materials left over are either re-used or recycled. After this process, only small remainders of a vehicle are sent to a landfill (Ager-Wick Ellingsen et al. 2016). Therefore, EVs would follow the exact process for the parts they share with ICEVs, such as chassis, wheels, tires etc. The major difference is the Li-ion battery which may face three different possibilities: reuse, recycle or landfill.

According to Nealer et al. (2015), a Li-ion battery is assumed to have 75% of its original energy storage capacity at the end of a vehicle's life. Hence, a major part of it is still functioning and usable. Therefore, the left-over battery could be used as is for other applications. Its most likely purpose would be to store intermittent renewable energy sources for use when they are not generating. Such a battery could also be connected to the grid, alleviating demand fluctuation and also decreasing peak demand, thus displacing coal or natural gas based electricity generation.

Another option would be to recycle. Parts or materials from the battery could be separated from the battery pack and used in the production of new batteries. The established recycling process produces a slag containing lithium, manganese, and aluminum, and a liquid alloy containing copper, iron, cobalt, and nickel (Ager-Wick Ellingsen et al. 2016). From this slag, the individual materials are easily extracted.

Literature studies assessing future availability of lithium, particularly for EV applications, mostly assume that there will be a large scale recycling in the future, and indicate that consequently lithium shortage will not pose a hindrance for the EV industry (Dunn et al. 2012, Tamayao et al. 2015, Nealer et al. 2015, Van Mierlo et al. 2015). Cobalt and nickel have very high market value and thus they are a very attractive focus of the recycling industry (Dunn et al. 2012). In addition to avoiding use of virgin materials, lowering the risk of resource scarcity, recycling will also generate huge cost savings. This will also contribute to improved battery recycling processes. The ability to recycle the battery materials or parts depends significantly on the design of the battery and the economics of recycling the materials (Nealer et al. 2015). Hence the battery production industry and recycling industry, could work together aligning their processes to minimize the overall environmental impact of battery production.

Battery recycling is considered a critical component of the end of life of an EV, as the battery pack is the element that contributes the most to the environmental production impacts of an EV. Although recycling requires energy and produces global warming emissions, it reduces emissions by avoiding the use of new materials. Certain literature also reported that emissions avoided due to the recycling of materials outweigh the emissions from the recycling process of the batteries (Dunn et al. 2012, Tamayao et al. 2015, Nealer et al. 2015).

The battery could also go directly to a landfill, where it would be neither reused nor recycled. This would imply that the vehicle owners, either do not give consideration to environmental matters or the infrastructure to employ one of the two other solutions is not in place. However, such a scenario would be difficult to conceive as most EV owners are environmentally conscious and EVs are driven in countries where the supporting infrastructure development keeps up with EV development. The literature also notes that experts see this scenario as the least expected, in view of concerns for localized pollution, global warming and resources scarcity (Dunn et al. 2014, Nealer et al. 2015).

Measuring Vehicle Global Warming Emissions

The impact of a vehicle on climate change is measured in greenhouse gas (GHG) emissions such as CO_2 and methane, which determine a vehicle's Global Warming Potential (GWP). Greenhouse gas emissions contribute to the increase of absorption of radiation emitted by the earth, thus causing a greenhouse effect (Gbegbaje-Das 2013). It is important to note that GWP represent impact potential and does not predict actual impacts.

The metric for assessing GWP that this paper focuses on is CO_2 emissions per unit of distance or energy, as CO_2 was identified by the literature reviewed as the biggest contributor to global warming. CO_2 is not the most environmentally damaging emissions per unit that the transportation sector produces, but due to the abundance of its production and long life span it has the greatest impact on climate change compared to the other gases produced by vehicles. Many researchers on this topic account for the GWP impact of other pollutants emitted from the transportation sector, by converting them to CO_2 equivalents through multiplication by certain coefficients. Therefore, the majority of results directly relating to global warming, reviewed in the literature and mentioned in this paper, will be expressed in terms of CO_2 and CO_2 equivalents (CO_2-eq). One additional metric reviewed by some literature covered by this paper is the percentage efficiency of the various propulsion technologies when converting energy into motion, as it also has implications for GWP but without directly considering CO_2.

The Inter-Governmental Panel on Climate Change (IPCC) prescribes CO_2 equivalence to be applied to the non-CO_2 greenhouse gases according to the 100 year conversion coefficients recommended by their fourth assessment report. Thus, in terms of t CO_2-eq/t, Methane (CH_4) would have a factor of 25, while Nitrous Oxide (N_2O) would have a factor of 298. This means that 1 ton of CH_4 corresponds to 25 tons of carbon dioxide, while 1 ton of N_20 contributes the same as 298 tons of CO_2, in terms of global warming potential (IPCC 2007).

In order for the emissions measured to be valid across studies and comparable amongst technologies, there should be common or universal assessment approaches. This regards the setup of experiments as well as the scope of testing. Hence, many researchers rely on standardized tests established by international authorities and accepted by the scientific community, such as the New European Driving Cycle and the proposed World Harmonized Light Vehicle Test Procedure.

When considering CO_2 emissions of any vehicle we must take into account a number of factors in addition to the emissions generated at the tailpipe, in order to comprehensively and more accurately account for the environmental impact. Two such comprehensive approaches, in focus of this paper are Life Cycle Assessment (LCA) and Well-to-Wheels assessment (WTW). The LCA takes into account the emissions created from manufacturing the vehicle, through maintaining it, to disposal or recycling. This approach is also referred to as cradle to the grave. The WTW approach accounts for CO_2 emissions generated from fuel extraction, delivery to the vehicles and utilization to power the vehicle. This approach is subdivided into the Well-to-Tank (WTT) and the Tank-to-Wheel (TTW) phase, where the former regards emissions associated with getting a fuel to a vehicle and the latter treats the emissions associated with driving the vehicle. Here too the system boundaries vary as some literature sources account for more details or different aspects than others. Nonetheless, an interesting metric pertaining to the TTW approach is the efficiency of converting fuel or electricity into motion, as it allows for comparison of environmental impact amongst vehicle technologies without specifically accounting for any pollutant.

One very important aspect when considering the emissions caused by vehicles is the source of electricity generation, which has a direct impact and is most profound when assessing the use phase of EVs charged by connecting to the grid. It also impacts other areas such as vehicle manufacturing and feedstock extraction. GWP impact of electricity generation depends on the type of feedstock used as well as on the way in which it is made. This differs by grid and is strongly influenced by the economic situation and resource availability. Consideration should also be given to the charging schemes grids employ, as for instance whether, when and for how long they rely on marginal in contrast to baseload power.

Although the studies reviewed in this paper employ the same approaches in terms of scope and experiment description, there are countless variables that are not harmonized amongst the studies. Due to these discrepancies, caution should be taken when comparing results from different authors and drawing conclusion, but nonetheless the findings can still serve as indicators of the different environmental impacts across various vehicle propulsion technologies.

Emissions Driving Tests

In order to assess the environmental impact of a vehicle, and to be able to compare the results across research and geographical regions, standardized tests are necessary. In 2016, the European Commission also proposed the adoption of the World Harmonized Light Vehicle Test Procedure (WLTP), which would be a globally harmonized test procedure for motor vehicles. This procedure is expected to become mandatory for all new vehicles as of September 2018, and it would provide stricter test conditions and more realistic CO_2/fuel consumption values, which will be beneficial to both consumers and regulators at EU and national levels, as it will allow for better assessment of the environmental footprints of their vehicles (EC 2017).

The WLTP will replace the New European Driving Cycle (NEDC), which is currently used as the standard for testing performance of vehicles and their environmental impacts, in terms of fuel consumption and CO_2 emissions. The NEDC was last updated in 1997 and has faced criticism in recent times with regards to conventional vehicles, and especially with regards to EVs. The main point against it is that it does not represent real life driving conditions, often leading to biased results, and leaving room for manipulation (Ager-Wick Ellingsen et al. 2016). These claims are enforced by the recent emissions testing scandals caused by Volkswagen and Nissan, where test manipulation was discovered.

Well-to-Wheel

In order estimate overall energy consumption and efficiency across various propulsion technologies many literature sources employ the Well-to-Wheels (WTW) assessment. According to the Well to Wheels Report published by the Joint Research Center of the European Commission a Well-to-Wheels (WTW) analysis is the essential basis to assess the impact of future fuel and powertrain options (Edwards et al. 2014). The WTW provides a comprehensive overview about the consumption of vehicles as it considers the entire supply chain of a fuel as well as its use during propulsion, as both the fuel production pathway and powertrain efficiency are key factors when considering GHG emissions and energy use. It is especially useful as it provides more realistic comparisons of BEVs and ICEVs, who are responsible for emissions in different stages of this process, as it captures the electricity generation emissions when determining the environmental impact of BEVs, which have zero tailpipe emissions.

According to Woo et al. (2017), the WTW assessment of ICEVs consists of 7 steps, including extraction (well), transport, refining, distribution, engine combustion, power delivery system and wheel. The WTW of a BEV consists of 9 steps, including extraction (well), transport, refining, distribution, power generation, power transmission and distribution, charging, motor, and wheel. The BEV WTW process includes more steps as a consequence of the power generation intermediaries, which are absent in the case of an ICEV.

The WTW process is then further divided into the Well-to-Tank (WTT) and Tank-to-Wheel (TTW) components. The WTT encompasses all steps from feedstock extraction until delivery of fuel to the vehicle. It describes the process of producing, transporting, manufacturing and distributing a number of fuels suitable for road transport powertrains. The TTW quantifies the performance of the drivetrain. It represents the end consumption of the different fuels and powertrain options, expressing efficiency of fuel use and tailpipe emissions. Once separate results for the WTT and TTW are obtained for a certain vehicle configuration, the WTW incorporates them to provide an integrated picture, which allows deriving attributed proportions for energy or fuel consumption and GHG emissions. (Helmers et al. 2012, Edwards et al. 2014).

Common Methodology

Although scopes and system boundaries vary across research, the JRC attempted to establish a benchmark by developing a common methodology and data-set which provides a basis for the evaluation of pathways and which can be updated as technologies evolve (Edwards et al. 2014). This comprehensive WTW based its assessment on a common vehicle platform, which reflects the most driven passenger vehicles in Europe, namely the C-Class European Compact Sedan with 5 seats. It also assumes various powertrain options, that all vehicles complied with the minimum performance criteria in Europe with regards to comfort, driving performance and interior, as well as that all vehicles where compliant with the emissions regulations. Fuel consumptions and GHG emissions were reported according to the New European Driving Cycle (NEDC). This benchmark is accepted amongst the scientific community and facilitates comparison amongst studies (Edwards et al. 2014, Woo et al. 2017).

The WTW methodology also assumes that energy use and GHG emissions have the same impact wherever they occur, which is true of GHG emissions as they have impacts globally. However, this would not be the case with local air pollution or water use which are strongly influenced by local conditions, and would then require different assessment methodologies (Edwards et al. 2014).

The WTT part of the assessment can also be replicated to other vehicle types including heavy duty trucks and buses, as the production and distribution impact of a fuel has already been evaluated, and could easily be multiplied by any amount dependent on the requirement of the engine in question. This would not be true of the TTW part of the analysis and consequently of the entire WTW, as here the specific characteristics of engine performance are taken into account.

Well to Tank

When assessing WTT, the literature considers the pathways and processes necessary to convert a certain primary resource into a final fuel. It thus accounts for extracting, producing, transporting, manufacturing and distributing the fuel to the vehicles in question.

In the case of crude oil, the pathways include production and conditioning at source, transformation at source, transportation to markets, transformation near market, conditioning and distribution (Helmers et al. 2012). In terms of crude oil production, there are two main sources of GHG emissions. One is associated with the extraction and pretreatment of the oil, while the other relates to flaring and venting, and fugitive losses that occur with volatile hydrocarbons. In modern times, the emissions from oil are well accounted for as oil companies have established very accurate emission reporting standards (Edwards et al. 2014). In 2011, according to BP Statistical review, total production of oil and gas amounted to 6,951 Mt/a (Megatons per year), out of which the International Association of Oil and Gas Producers (OGP), reported production of 2,221 Mt/a. The OGP reported that their total emission were 294 Mt CO_2/a or 364 Mt CO_2-eq/a, with specific emissions being 3.9 g CO_2-eq/MJ. Edwards et al. (2014) took the OGP averages and multiplied them by the BP data to obtain world CO_2-eq emissions from oil and gas of 1,077.2 Mt/a, for a total energy production of 10,969 PJ/a (Penta Joule per year), with specific GHG emissions equaling 3.69 g CO_2-eq/MJ (p. 21). Here, the emissions differ due to various considerations for energy production, flaring, venting and fugitive losses. The authors also estimated specific GHG emissions for OECD countries, taking into account regional specific GHG data from BP and OGP and applying it to the combination of crudes used in the OECD countries as reported by the International Energy Agency (IEA 2012), in which case they obtained specific emissions of 2.89 g CO_2-eq/MJ. The emissions are lower because of the comparatively large EU consumption of low energy-low emissions European and FSU crudes. Disaggregating the EU specific emissions, it can be noted in terms of g CO_2-eq/MJ that 1.5 is associated for energy use in production operations, 1.0 with flaring and 0.4 for venting and fugitive losses. At the time of the report the OGP covered 32% of global oil and gas production, and 48% EU production. Thus, the authors also presented specific emissions, based on data on flaring reported by the US National Oceanic and Atmospheric Administration (NOAA 2011) on the basis of satellite observations. NOAA estimates flaring emissions to be between 1.8 and 2.9 g CO_2-eq/MJ, and thus when taking the mean value of 2.4, the authors estimate 4.3 g CO_2-eq/MJ.

The oil also needs to be transported from extraction and initial treatment sites to refineries. This is mainly done by sea, whereby the size of ship strongly depends on the distance to be covered, with ships ranging in transport capability from 100 to 500 kt. Another possibility of transporting oil are pipelines, which extend both through sea and land, but are of particular use for inland refineries not accessible by ships. Although there are wide ranging emission assumptions regarding this phase of the crude oil pathway, it is estimated that on average crude oil transportation is accountable for 0.8 g CO_2-eq/MJ assuming a ship fueled by heavy fuel oil (p. 26, Edwards et al. 2014).

The concept of oil refining has shifted in modern times, whereby crude oil is not refined at or close to site of extraction and then shipped as finished product to the market in such large proportions any more. The current tendency, especially in Europe is to get crude shipped and then refine it in local refineries. Although it is possible to pin point the amount of energy consumed by a refinery, allocation of emissions to specific products in refineries is a highly debated process, since they produce a variety of products from a single feedstock. Allocation rules must be applied, the assumptions of which may have serious impacts on results. Thus, the authors focus on determining savings that can be achieved by using less of this conventional fuel rather than how much emissions spawn from making that fuel today. To this purpose they assess how EU refineries would adapt to a marginal reduction in demand. Accordingly, they estimate 7.0 g CO_2-eq/MJ for the production of gasoline and 8.6 g CO_2-eq/MJ for the production of diesel (Edwards et al. 2014).

The refined oil also has to be transported to where it is distributed to customers, by means of road, rail, water and pipeline. To assess the emission for the final transportation stage the authors assumed a mix of transportation methods representative of the proportion employed in Europe at the time of study. They estimate around 1 g CO_2-eq/MJ of transported fuel.

Aggregating the total balances resulting from the entire pathway, diesel falls within the range between 13.8 and 17.0 g CO_2-eq/MJ, with the mean of 15.4. Out of this 4.7 is attributed to production and conditioning at source, 1 to transportation to market, 8.6 to transformation near market and 1.1 to conditioning and distribution. Edwards et al. (2014) report, the total GHG emissions for diesel, when accounting for combustion factors at 88.6 g CO_2-eq/MJ. With regard to gasoline, the range of g CO_2-eq/MJ falls between 12.2 and 15.3, where the mean value is 13.8. Production and conditioning at source make up 4.6, transportation to the market 1, transformation near market 1.2 and conditioning and distribution 1.2 of the total without combustion. According to Edwards et al. (2014), when combustion is also accounted for, gasoline yields 87.1 g CO_2-eq/MJ.

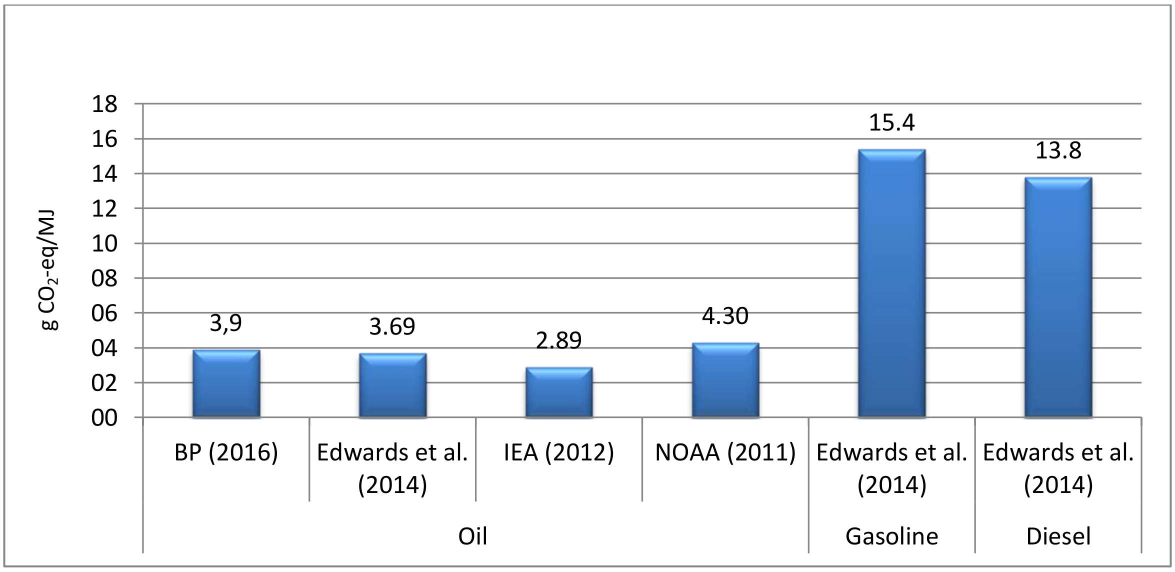
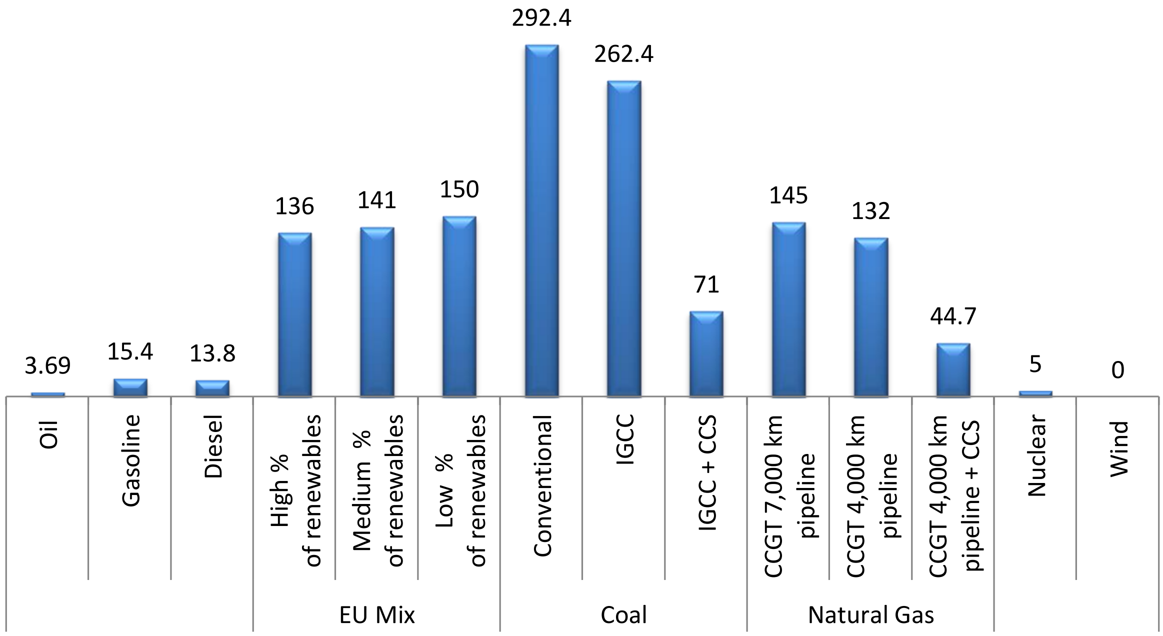


Figure 4: WTT Emissions from Oil, Gasoline and Diesel in g CO_2-eq/MJ

With regards to electricity, the source is of particular importance, as it can be obtained from many sources or a mix of sources being represented in various proportions. In order to assess the GHG emissions of electricity produced from various sources, the individual pathway of each source needs to be examined, and each source's individual GHG emissions must be evidenced. Only then can each source be attributed an appropriate proportion of the electricity mix in question to get a more relevant estimate.

Edwards et al. (2014) represented certain electricity generation scenarios. An EU mix with a high, medium and low proportion of renewables generated 136, 141 and 150 g CO_2-eq/ MJ of final fuel respectively. A grid supplied by conventional coal would generate around 292.4 g CO_2-eq/MJ of final fuel, while if the coal was produced using an integrated gasification combined cycle (IGCC) technology, emissions would be reduced to 262.4 g CO_2-eq/MJ, with the possibility of reduction to 71.0 g CO_2-eq/MJ if effective Carbon Capture and Storage (CCS) was employed. If natural gas would be the source of power, assuming CCGT it would yield 145 and 132 g CO_2-eq/MJ of fuel assuming either a 7000 or a 4000 KM long pipeline transporting it respectively. If CCS would be applied to the 4000 KM pipeline case, it would reduce its contribution to 44.7 g CO_2-eq/MJ of fuel. Nuclear would result in 5 g CO_2-eq/MJ of fuel, whereby the only GHG would occur during extraction, transportation and enrichment of uranium. Wind produces no GHG emissions, as it is assumed to be a free and unlimited resource and the WTT method does not include construction of turbines in its emission accounting (Edwards et al. 2014).



Source: Edwards et al. (2014)

Figure 5: WTT Emissions in g CO_2-eq/MJ by Source of Electricity Generation

Tank to Wheel

The TTW represents the end consumption of the different fuels and powertrain options, expressing efficiency of fuel use and tailpipe emissions. When calculating total Tank-to-Wheel GHG emissions it is important to consider that in addition to CO_2, Methane (CH_4) and Nitrous Oxide (N_20) are also emitted. For comparison purposes GWP is expressed in terms of $C0_2$ equivalents. CH_4 and N_2O emissions are assessed based on the legislation limits for Euro 5 and Euro 6 employed in case of 2010 and 2020+ vehicle configurations, respectively. CH_4 and N_2O are derived based on their Global Warming Potential (GWP) factor, which is the parameter that considers the GHG effect of the specific gas. This factor is equal to 25 for Methane and 298 for Nitrous Oxide (Edwards et al. 2014).

Once all emissions are accounted for and translated into a common comparable unit, the TTW results can be evaluated. The JRC report assessed the average fuel consumption of 3 ICEVs in the year 2010 and an assumed consumption in the year 2020, resulting from foreseen improvements in transmission, auxiliaries, weight reduction, aerodynamics and rolling resistance. It compared a Port-Injection Spark-Ignition gasoline vehicle (PISI), a Direct-Injection Spark-Ignition gasoline vehicle (DISI), and a Direct Injection Compression Ignition (DICI) diesel vehicle. It found that a PISI would produce 155.1 g CO_2/km (155.8 g CO_2-eq/km) in 2010 and 110.2 g CO_2/km (111 g CO_2-eq/km) in 2020. The DISI would yield 149.6 g CO_2/km (150.3 g CO_2-eq/km) in 2010 and 104.5 g CO_2/km (105.3 g CO2 eq/km) in 2020, while the DICI would produce 119 g CO_2/km (120.2 g CO_2-eq/km) in 2010 and 86.8 g CO_2/km (88.2 g CO_2-eq/km) in 2020. BEVs on the other hand, on a TTW assessment emit 0 g CO_2/km, however in the author’s 2010 base case they utilize 11.38 kWh/100 km, or 14.49 kWh/100 km when considering charging losses as well, whereas in 2020 they predict BEV energy consumption to be 8.89 kWh/100 km and 10.59 kWh/100 km without and with losses respectively (Edwards et al. 2014).

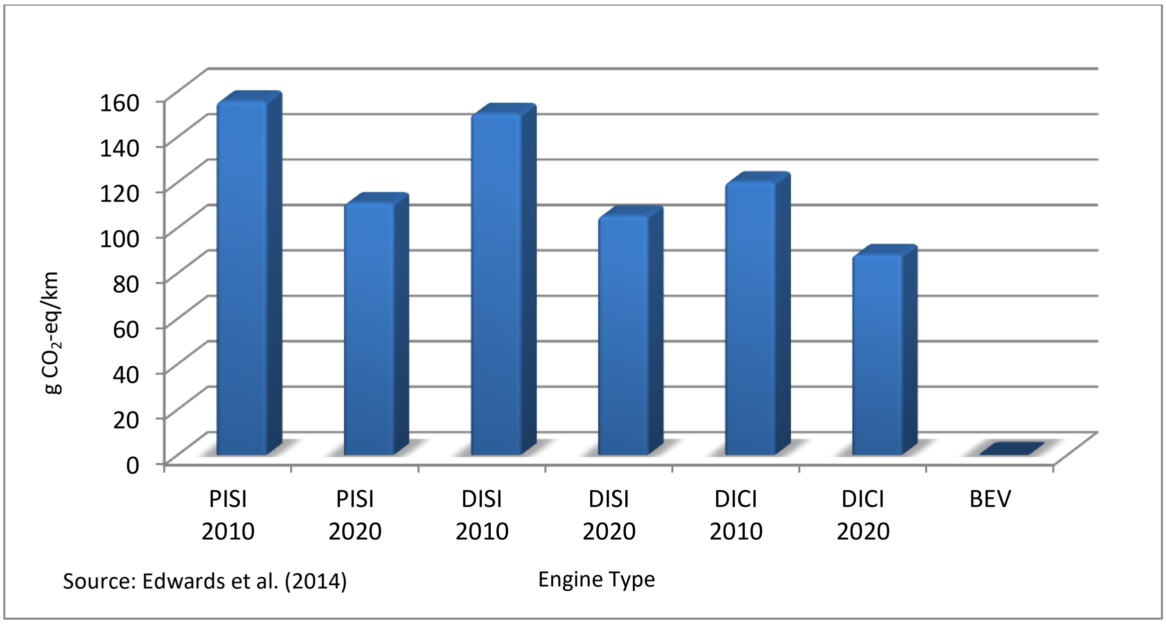


Figure 6: TTW Emissions in g CO_2-eq/km by Engine Type and Year

Well to Wheel Aggregated

According to a comprehensive literature review performed by Hacker et al. (2009), Euroelectric (2008) ranked a typical EV as consuming 18 kWh/100 km and determined its CO_2 emissions under the European electricity mix of 2008 with 410 g CO_2/kWh average carbon intensity, as well as under the projected European electricity mix of 2030 with 130 g CO_2/kWh average carbon intensity. Under the former, EVs yielded CO_2 emissions of 80 g/100 km, and 30 g/100 km under the later. According to their analysis conventional gasoline vehicles produced 160 g CO_2/100 km. The European Association for Battery Electric Vehicles (EABEV 2009) stated results of a WTW analysis amongst ICEVs and EVs of equal weight and performance, where they find EV consumption slightly lower, at 11-14 kWh/100 km. Thus, under 2009 EU electricity mix, with carbon intensity of 443 g CO_2/kWh, EVs emit 54 g CO_2/100 km, which is about half of the 108 g CO_2/100 km emissions they attribute to ICEVs. However, the outcome may be different depending on electricity mix, as in the case of grids supplied mainly from coal power plants, such as in Poland and Luxemburg, where carbon intensities were estimated to be 1000 g CO_2/kWh, placing EV CO_2 emissions at around 130 g/100 km, which would be higher than that of comparable ICEVs. The PBL Netherlands Environmental Assessment Agency (PBL 2009), estimated EV consumption to be at 14 kWh/100 km and the European electricity mix to have

389 g CO_2/kWh average carbon intensity, thus placing EVs at 60 g CO_2/100 km which is about one-third of the 170 g CO_2/100 km it estimates for ICEVs. Messagie et al. (2014) assessed the WTW implications from various sources of electricity charging. They report that BEVs powered by coal emitted 139 to 175 g CO_2-eq/100 km driven, which is comparable to ICEVs. BEVs powered by Compressed Natural Gas (CNG) produced 83 to 104 g CO_2-eq/km. In the case of wind, WTW emissions amounted to 1 to 2 g CO_2-eq/km, while the Belgium electricity mix in the year 2011 produced 24 to 31 g CO_2-eq/km.

The GHG emissions of ICEVs from the well-to-wheel viewpoint are the sum of the GHG emissions of the combined processes of WTT and TTW. This can be calculated by using the following equation (Edwards et al. 2014, Woo et al. 2017):

$$ICEV\_\mathrm{GHG}_{WtW} = (GHG_{WtT} + GHG_{TtW}) \times FE$$

- $ICEV\_\mathrm{GHG}_{WtW}$ is the total GHG an ICEV emits from the well-to-wheel viewpoint and it is measured in units of g CO_{2eq}/km.
- The terms GHG_{WtT} and GHG_{TtW} represent the total GHG emitted in the well-to-tank and tank-to-wheel processes, respectively, and are measured in units of g CO_{2eq}/L.
- *FE* refers to the fuel efficiency of an ICEV, which is measured in L/km

The first term in parenthesis accounts for the process of mining energy sources, refining it, transporting it to the car, the second term in parenthesis reflects the process of driving the car, and the both terms are multiplied by a vehicle's fuel efficiency as it determines how much fuel will be consumed during a given distance.

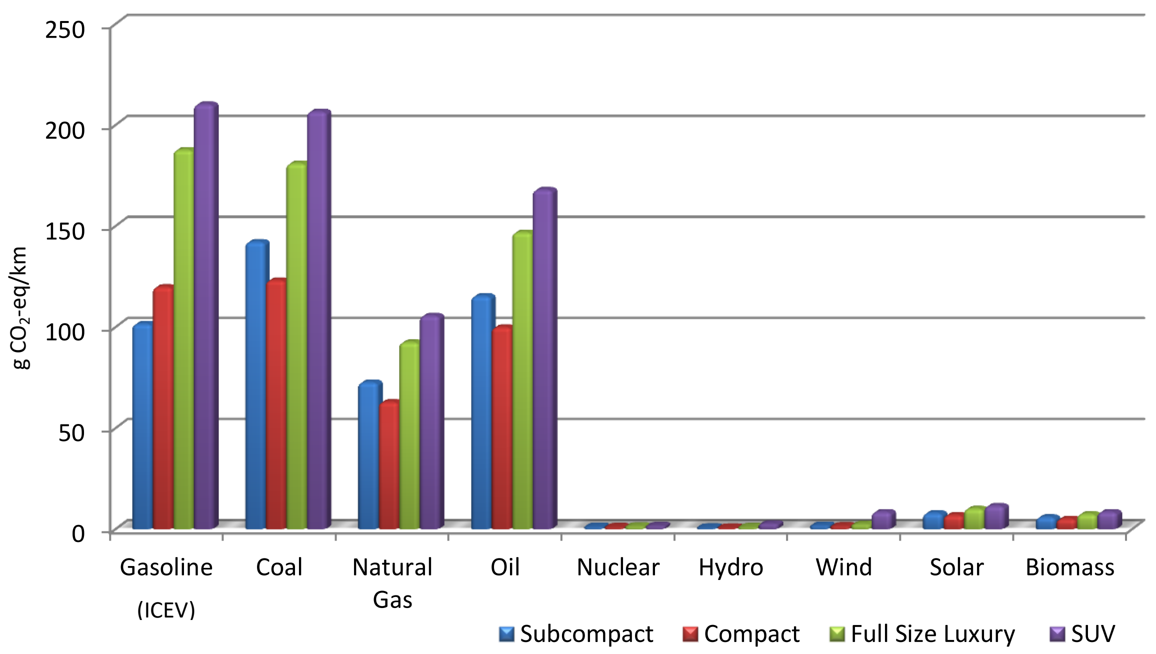
In the case of a BEV, when summing the WTT and TTW, the fact that feedstock is converted to energy in a power plant must be accounted for as well as the fact that a grid charging a vehicle will be fed by various types of power plants. To account for these factors the equation for GHG of a BEV disaggregates the electricity sources, attributing them various coefficients and accounting for their proportion in the grid. Once each source of power and its proportion is determined, it is summed up and multiplied by the energy consumption of an EV. This is represented in the following equation (Edwards et al. 2014, Woo et al. 2017):

$$EV\_\mathrm{GHG}_{WtW,i} = \left\{ \sum_e P_{e,i} \times (GHG_{e,WtPP} + GHG_{e,PPtW}) \right\} \times VE$$

- *i* denotes national grids (US, Chine, UK, Germany, France, South Korea....)
- *e* denotes types of power generation (Coal, Gas, Nuclear, Hydro, Wind, Biomass, Solar)
- $EV\_\mathrm{GHG}_{WtW,i}$ is the total GHG emitted by country i from the well-to-wheel viewpoint and it is measured in g CO_2-eq/km.
- $P_{e,i}$ is the ratio of the power source *e* in the electricity generation mix of country *i*
- $GHG_{e,WtPP}$ and $GHG_{e,PPtW}$ are the GHG emissions by the power source e in the well-to-power plant and power plant-to-wheel processes, respectively, and both are measured in g CO_2-eq/kWh
- *VE* refers to the electricity efficiency of BEVs and is measured in kWh/km.

Woo et al. (2017) assessed GHG emissions on a WTW basis for compact gasoline, diesel and battery electric cars. For ICEVs, they based their fuel economy data on reports from the Vehicle Certification Agency (VCA), which is the executive government agency of the United Kingdom Department of Transportation. Woo et al. (2017) took the emission factors from the JRC report on WTW, which reported the total value of WTW GHG emissions for diesel cars amounting to 3,241.3 g CO_2-eq/L (WTW: 2,676.9, TTW: 564.4), and 2,778.2 g CO_2-eq/L (WTW: 2,314.4, TTW: 463.8) for gasoline cars (Edwards et al. 2014). Woo et al. (2017) then assessed emission for BEVS and ICEVs in the subcompact, compact, full size luxury and SUV category. They found WTW for gasoline vehicles amounted to 101.4, 119.7, 187.5 and 210.1 g CO_2-eq/km, for the subcompact, compact, full size luxury and SUV category respectively. For diesel engines they obtained 59.8, 96.1, 143.1 and 164.6 g CO_2-eq/km for the same categories.

With regards to BEVs, Woo et al. (2017) first determined WTW emissions considering only one source of power for each car category. Hence, if a BEV was to be charge exclusively by coal it would produce 142.0, 123.0, 180.8 and 206.8 g CO_2-eq/km, for the subcompact, compact, full-size luxury and SUV categories, respectively. In the case of grids powered by natural gas, emissions would amount to 72.5, 62.8, 92.3 and 105.5 g CO_2-eq/km, for the respective categories. Considering BEVs powered by electricity made from oil emissions would be 115.2, 99.8, 146.7 and 167.8 g CO_2-eq/km for the four categories. Nuclear power generation would contribute to BEVs emitting 1.1, 0.9, 1.4 and 1.6 g CO_2-eq/km, emission of BEVs running on power generation from Hydro would amount to 0.7, 0.6, 0.9 and 2.6 g CO_2-eq/km, form wind they would amount to 1.8, 1.5, 2.3 and 8.4 g CO_2-eq/km, from solar to 7.8, 6.8, 10.0 and 11.4 g CO_2-eq/km, while emissions from BEVs powered by electricity produced from Biomass, would amount to 5.8, 5.0, 7.3 and 8.4 g CO_2-eq/km for the subcompact, compact, full-size luxury and SUV categories, respectively.



Source: Woo et al. (2017)

Figure 7: WTW Emissions in g CO_2-eq/km by Electricity Generation Source

However, since no grid is powered by only one source of power, Woo et al. (2017) also presented WTW emissions for their identified categories considering certain grid compositions. Thus they found the global average to be 78.1, 67.6, 99.3 and 113.6 g CO_2-eq/km for the subcompact, compact, full-size luxury and SUV categories, respectively. The average for Asia & Pacific was 98.7, 85.4, 125.5 and 143.6 g CO_2-eq/km respectively. The US average was 77.3, 67.0, 98.4 and 112.6 g CO_2-eq/km, with the North American average being 70.6, 61.1, 89.8 and 102.7 g CO_2-eq/km. The average considering the European 22-country electricity mix was 51.0, 44.1, 64.8 and 74.2 g CO_2-eq/km, with the German average being 74.8, 64.8, 95.2 and 108.9 g CO_2-eq/km, the UK average being 69.2, 59.9, 88.1 and 100.7 g CO_2-eq/km, the French being 8.7, 7.5, 11.1 and 12.7 g CO_2-eq/km, and the Norwegian average being 2.3, 2.0, 2.9 and 3.4 g CO_2-eq/km for the subcompact, compact, full-size luxury and SUV categories, respectively.

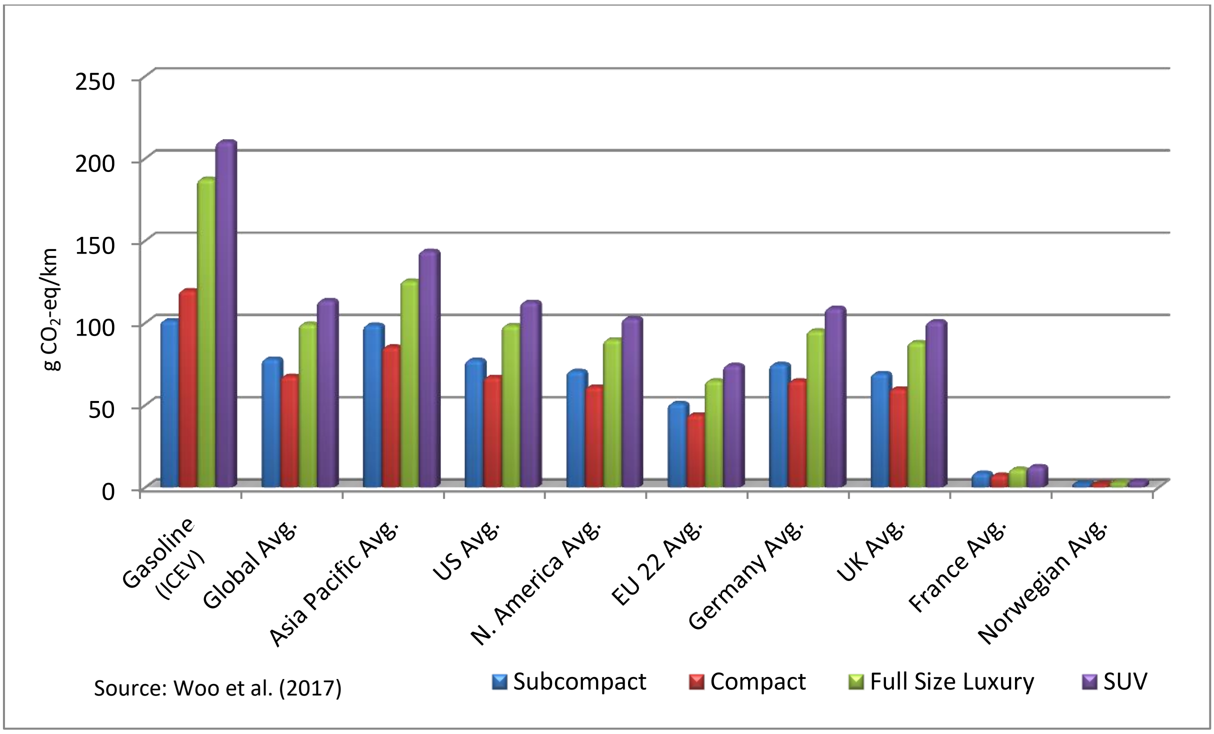


Figure 8: WTW Emissions in g CO_2-eq/km by Electricity Grid

Woo et al. (2017) based their BEV WTW results on electricity data from Turconi et al. (2013), who performed a review of 167 studies on the life cycle assessment of GHG emissions stemming from various power sources on a WTW basis. This study is discussed in further detail in the section regarding emissions of electricity generation.

Efficiency

One aspect of WTW analysis that influences GHG emissions but can be viewed as an indicator within itself is efficiency. WTW efficiency indicates the proportion of energy utilized which was converted to propulsion. Disaggregating amongst TTW and WTT, we can determine the efficiency of extraction, refinement and production of a certain fuel as well as the efficiency of the drivetrain of a vehicle. This is a very complex estimation, as losses have to be accounted for in all steps of the process.

Considering gasoline vehicles, Helmers et al. (2012) report WTW efficiency at 10 - 20%. The TTW efficiency of gasoline vehicles is significantly higher, at 79 - 86% considering that their fuels can be delivered to vehicles after refinement and does not first need to be converted to electricity.

However, the WTT efficiency of 16 - 23% reported by Helmers et al. (2012), or 18 - 25% reported by the EEA (2016), has a significant impact on overall WTW. Similarly, diesel vehicles yield WTW efficiency of 13 - 25%, with a relatively high WTT efficiency of 76 - 84% and a low TTW efficiency of 23 - 28% Helmers et al. (2012).

The assessment of the WTW efficiency of BEVs is much more complex as they can be powered by a variety of sources under a variety of schemes, making it very difficult to assess the WTT efficiency. Helmers et al. (2012) report that in a case where the energy used to charge the BEV is generated by an inefficient power plant and the BEV is loaded with an inefficient charger, up to 85% of the energy may be lost to heat, making their efficiency comparable to those of ICEVs. Such cases are very rare, with BEVs' estimated WTW efficiency to be between 59 - 80%, with a TTW efficiency of 73 - 90 % (Helmers et al. 2012, EEA 2016). The main reason why BEVs are much more efficient than their combustion engine counterparts is their drivetrain, which is much less complex, with less components and opportunities for losses.

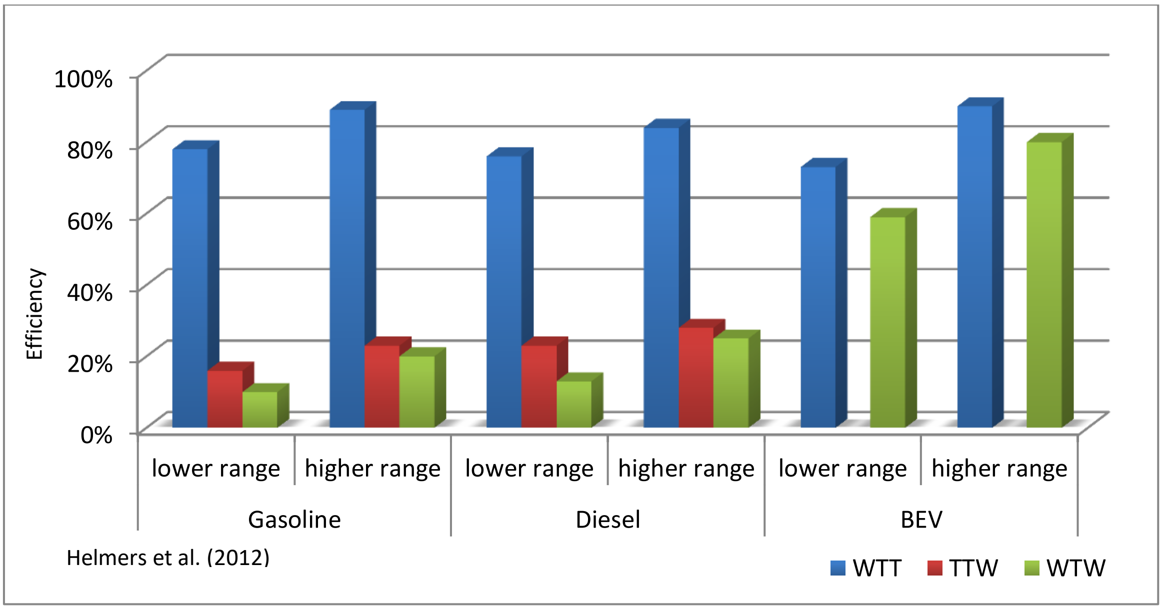


Figure 9: Efficiency of Converting Energy to Propulsion by Vehicle

It is important to note that the efficiency numbers reported by Helmers et al. (2012) are based on the same vehicle, a Smart that the authors converted from an ICEV to a BEV, and measured efficiency for both technologies under the same test conditions. Helms et al. (2010) also indicated that TTW efficiency is relatively constant for BEVs, while in the case of ICEVs the manner of driving can have great impact.

WTW Conclusion

The WTW method provide a comprehensive framework to assess the GHG impact of various propulsion technologies as they enable researches to capture a larger part of emissions relating to motion of vehicles reducing the chance for bias results. Disaggregating the method into processes relating to fuel procurement and processes relating to converting the fuel into motion allows for better identification of inefficiencies and the major sources of emissions.

The literature reviewed is consistent on the TTW efficiency measurements between BEVs and ICEVs, with the former yielding much better results. This is mainly attributed to the BEV's less complex drivetrain, which reduces the proportion of energy lost as heat. The overall WTW efficiency follows this trend, with small variations amongst gasoline and diesel, although the WTT assessment of ICEVs yields high efficiency as well. Determining the WTT efficiency of ICEVs is a very complex process yielding various results depending on the feedstock used and the manner of converting it to electricity, with the possibility of it yielding low efficiency to the extent that it makes the entire WTW efficiency of BEVs lower than that of ICEVs, although such cases are extremely rare. In addition it must be noted that the long-lived market success of ICEVs, amidst the efficiency shortcomings are attributed to the very high energy density of carbon based fuels, which is up to 20 times higher compared to Li-ion batteries (Helmers et al. 2012).

WTW emissions reported for BEVs in the literature are generally lower than those of ICEVs, but they significantly depend on the source of power used. In cases of when coal power is used to charge a BEV, their emissions fare similarly or even worse than those of ICEVs. BEVs shift almost all their emissions to the power plants, while ICEVs produce the power used for motion themselves and thus BEVs perform much better in terms of TTW emissions than ICEVs. The TTW performance of ICEVs is also influenced by driving style which is not as pronounced a case with BEVs. The sources of power must be considered when comparing the two types of vehicles on a WTT basis.

The literature on WTW reviewed in this paper excludes one major consideration when assessing WTW emissions, which is whether the type of electricity used for charging a BEV is generated by marginal or baseload power plants. This depends on the time of charging and additional grid factors. Regardless of the resource composition of a certain grid, a certain proportion of the electricity produced is generated by marginal or peak power plants, which due to the nature of their purpose are relatively inefficient and high emitting. They are employed when the demand on the grid is higher than the baseload generation can handle. Researchers argue that EVs as a new market segment as well as due to their probable charging times would mainly be charged by such plants and thus produce more emissions the ICEVs. This paper will address this in its respective section.

The WTW method does not provide absolute results. Although researchers may employ common research methodology, there are numerous factors that cannot be accounted for and numerous variables that are not constant. Therefore WTW research results should be taken with reserve and in view of the context in question. Nonetheless, they can still provide a sound basis for comparison amongst different types of propulsion. Furthermore, even though the WTW method attempts to capture as many emissions as feasible, associated with procurement of a fuel and its utilization for movement, it must be noted that there are additional considerations when assessing a vehicle's overall environmental footprint. Such aspects relate to the production of the vehicle and its disposal or recycling, in addition to the use phase, and are addressed by life cycle analysis (LCA) in order to avoid misguided comparisons amongst technologies and problem shifting.

Life Cycle Assessment

A Life Cycle Assessment (LCA) is a comprehensive and standardized methodology that allows quantification of environmental impact over the whole life cycle of a product. This includes inputs from extraction of raw materials, production of components and their assembly to the use and disposal phase. The European Commission's identified Life Cycle Assessment as the "best framework for assessing the potential environmental impacts of products" (2016). ICEVs and EVs consist of many components which are unique to their respective technologies and thus have varying environmental impacts from production. Therefore, this assessment is particularly useful when comparing environmental impact amongst the two propulsion technologies addressed in this paper, as to account for these technological differences. The importance of LCA as a tool will continue to gain significance as the use phase for both EVs and ICEVs becomes less and less carbon intensive due to efficiency improvements and cleaner feedstock.

This section will provide an overview of the LCA framework as well as present results from LCAs performed in the literature reviewed. Most literature divides the LCA of vehicles into three phases including impacts associated with production, use phase and end of life. Although the LCA attempts to account for as many inputs as possible in the production of a vehicle, there are limits on the system boundaries. Hence most LCAs exclude environmental impacts of constructing excavation machinery, transportation of raw materials and assembly infrastructure, as they are assumed to have small impact on the assessment and to be shared amongst the technologies (Nealer et al. 2015). The use phase includes results from WTW assessment but may also account for additional factors such as non-exhaust local pollutants like particulate emissions from the abrasions of break, road and tire (Van Mierlo et al. 2017). The end of life phase attempts to account for impacts associated with disposal or recycling, but as EVs are still a relatively new market segment, a big proportion of which has not reached this stage, there is still not a significant amount of real-life data reported in the literature and calculations are mainly based on assumptions.

Through its holistic approach the LCA attempts to avoid problem shifting and provide a fair comparison amongst technologies. Nonetheless, there are limitations in view of obtaining information. Information about companies' supply chain, energy use, and specific component manufacturing process cannot be obtained due to competitive secrets. In addition, there are many external factors affecting the results in all LCA phases ranging from climate and geography to human behavior. As such factors cannot be properly accounted for, researchers set assumptions on the basis of which assessments are performed and therefore LCA results cannot be taken as absolute truths, but comparative indicators that should be taken with reserves in view of their limitations.

LCA Framework

LCA is an internationally standardized methodology according to ISO 14040, which helps to quantify the environmental pressures related to goods and services, the environmental benefits, the trade-offs and areas for achieving improvements taking into account the full life-cycle of the product. It became generally accepted in the last two decades and is internationally approved and standardized (ISO 14040, ISO 14044).

The LCA procedure consists of four successive steps: the goal and scope definition, the inventory analysis, the impact assessment and the interpretation of the results. As Egede et al. (2015) point, the procedure has to be understood as an iterative process rather than one exercise. For instance intermediate results obtained from the inventory analysis, impact assessment and interpretation may require modification of the goal and scope definition.

During goal and scope definition, the questions to be answered by the study, the motivation for carrying out the study and the intended audience have to be defined (ISO 14040). The product system under study needs to be clearly described including system boundaries and functional unit, which is the quantified performance of the system. Also, a number of additional methodological details and choices have to be documented for transparency reasons.

Once the scope is defined, we know what to include in the Life Cycle Inventory (LCI). The LCI encompasses data on all environmental interventions related to a product's life cycle including raw material extraction, production, use, disposal, recycling, reuse and energy recovery, as for instance emissions to air and water, waste generation and resource consumption. The goal of the inventory analysis of the LCA is to understand and account for flows of input and output inside an observed system and to determine its interaction with the environment. The analysis may be very complex and include from individual unit processes in a supply chain, such as extraction of resources, primary and secondary production processes and transportation to hundreds of tracked substances (ISO 14040, ISO 14044).

Based on the LCI, the various inputs and outputs are grouped into impact categories allowing to perform a Life Cycle Impact Assessment (LCIA). The LCIA is the evaluation of indictors representing environmental pressures throughout a product's life cycle, such as climate change, human toxicity, acidification and resource depletion (EC 2016). In the case of vehicles, emissions are classified according to different contribution categories, then, in order to compare the various contributions they are expressed in CO_2-eq, since climate change is the focus of the assessment (p. 3, Egede et al. 2015).

Once certain results in terms of comparable units are obtained, they must be interpreted. These results are attributed to certain issues as identified in goal and scope definition, and their significance is determined, in order to identify causes, reasons and improvement potential. The results must also be checked for consistency, completeness and reliability through a sensitivity and uncertainty analysis, exploring indicators such as source of electricity or materials used in production, in order to observe the sole impact of these factors on an LCA. Only then can certain conclusions be drawn and recommendations made.

The LCA has various approaches. One is the Process Chain Analysis (PCA), which is a bottom up approach that relies on engineering data and specific information on processes from plants. This approach is very thorough and yields very precise results, however it is time consuming as well. Hence it is often simplified by establishing termination criteria which excluded processes which are less relevant from the system, but this simplification can also yield underestimated interpretation of results. Another approach is the Input-Output Analysis (IOA), which is a top down approach, focused on financial data, following money flows between economic sectors. IOA yields results that are less precise but also less case sensitive. Thus in general, IOA estimates larger impacts than the PCA, as the boundaries are extended and no process cut-off are applied (Egede et al. 2015). There are also numerous others LCA approaches scientist rely on depending on their needs and aimed level of detail.

The ISO LCA requires considerable data collection related to the product's life cycle and is generally carried out when no other studies have been conducted for a given product. Yet there is a simplified approach, in shape of a streamlined LCA, where the data collection is limited and generic data is used wherever applicable. Such streamlined assessments can only be performed if there are existing ISO LCAs that can be referenced. A further indicator used is carbon foot-printing, which assesses a product's life cycle with narrow focus on emissions that contribute to climate change. The streamlined LCA and carbon foot-printing have the advantage of a narrower focus, more time effective data collection and more definite interpretation of results, but they face an important drawback of the possibility of burden shifting, as this limitedness of data may cause overlooking of certain problems, thus allowing for possibility to solve one problem while deteriorating another. For instance products that perform well in terms of one indicator could be given preference even if they fare much worse on overall environmental impact.

In addition, some researchers implement ecological foot-printing, where the life cycle approach focuses on the effects of human activity on the natural environment of the Earth. A material flow analysis examines movements of materials either through supply chains of industry sectors or certain regions, and can be very useful for discovering issues regarding resource efficiency of systems. Life Cycle Costing, is also an economic approach that treats all costs across a products life time from purchasing to disposal, and is an excellent indicator of the adequacy of investments.

Further, Environmental Impact Assessment (EIA) is “the process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made” (JRC 2017). It is applicable mainly to large infrastructure projects like roads or airports and accompanied by Strategic Environmental Assessment (SEA) which assess the impact of new or changing policies and strategies, providing complementary information to the EIA, allowing to better asses various options resulting from plans. Bothe these assessments are required under EU legislation for projects with significant impacts on the environment (p. 19, JRC 2017).

LCA Consistency Issues

The LCA is a standardized methodology, but one which still faces many inconsistency issues. The complexity of the assessment is substantial, information availability is still very limited and system boundaries are left to the discretion of the researcher. Therefore, it is only possible to draw general conclusions about the environmental impacts of EVs. Specific questions about this issue are very challenging to answer as it is difficult to determine the situations in and conditions under which certain conclusion applies. Calculations are very complex and the results are very variable.

Nordelöf et al. (2014) performed a comprehensive review of 79 relevant studies on the LCA of EVs. This study found vary differing results, from EVs emitting a very close amount to ICEVs, some in favor of the former, others of the latter, to very large discrepancies in emissions, also where some favored one, while others favored the other technology. Further, Hawkins et al. (2012) reviewed 55 such studies, also reporting conflicting results. Both sources attribute the large discrepancies amongst results in the studies reviewed to the complexity of the product and components, difference in methodological approaches and unavailability of primary data, which is the case especially in a new and rapidly emerging market. This is also apparent considering the technological and commercial developments that occurred between the time of these studies (2013 - 2014) and today (2018), and the increase in the availability of information and understanding of technology in this field that took place, particularly keeping in mind the amount of uncertainty still existing today.

Egede et al. (2015) list the lack of transparency of the influencing factors of the LCA of EVs as one reason for inconsistency amongst various LCAs. Such influencing factors may include the electricity mix, use patterns of materials and material compositions of vehicles. The lack of transparency can be attributed to the limited access to data from the entire life cycle of an EV, because different actors are involved in various stages of the vehicle's life cycle. One entity makes it, the other is responsible for use, while someone else yet for the disposal. Thus the information is dispersed across the entire supply chain. Additionally, these phases do not happen simultaneously but in different points in time, further complicating accurate aggregation of information. Furthermore, there are issues of confidentiality where different manufacturers want to have a competitive edge and are not keen on disclosing the technologies involved, making calculations of emissions from production and assembly of parts of some vehicles impossible.

Globalization, the reduction of trade barriers and tendencies to outsource add great complexity to supply chains, which also muddle calculations, where emissions and efforts of resource extractions from various places on earth, under various technologies and environmental policies have to be taken into account, in addition to their transport, storage and packaging. Additionally, average lifetimes of EVs span around a decade, which is significant time for technological and policy changes to take place, especially in the field of electric mobility which has been and is in ever increasing focus of policy makers and manufacturers. These changes may potentially greatly influence the emission calculations.

Nonetheless, benchmarks and comparisons are important for all stakeholders, from policy makers and environmentalists to car manufacturers and consumers. So in order to be able to assess the impact of a technological change or buying trends, an ever increasing number of initiatives are undertaken with the aim to harmonize measurements and methodologies across vehicle LCAs, so as to address more specific issues rather than just make general observations. Amongst such initiative is the project E-Mobility Life Cycle Assessment Recommendations (Duce et al. 2013), as well as efforts by Hawkins et al. (2012) and Egede et al. (2015).

LCA Literature Review

This section provides a detailed overview of selected literature sources that published data on LCAs of the vehicles in focus of this paper. Until 2013, very few use phase studies have been included in an LCA, (Duce et al. 2013, Egede et al. 2015), due to lack of long-time measurements, monitoring and experience, and thus strict methodological standards addressed the vehicle production and raw material acquisition, while deriving user profiles from standardized driving cycles and thus generically calculating the associated energy consumption (Duce et al. 2013). Certain studies focus only on the production aspect of vehicles, some disaggregate production data, while others present aggregated results.

Hawkins et al. (2012), performed a thorough LCA comparison amongst BEVs and ICEVs, which became a benchmark referred to in numerous later studies up to this date. They analyzed the CO_2 emissions created by production of three identical vehicles, where one version was an ICEV the other two were EVs operating on nickel cobalt manganese (LiNCM) and lithium iron phosphate (LiFePO4) batteries. The vehicle in question was a Mercedes A-Class, assessed using a cradle to grave approach, dividing it into the production and use phase. In the production phase they relied on inventories already published by Majeau-Bettez et al. (2011), but implement a different approach when assessing the use phase, assuming the batteries to have the same lifetime as that of the vehicle, regardless of their chemistry or charge capacity, whereas Majeau-Bettez et al. (2011), as well as numerous other studies, express battery lifetime in terms of charge–discharge cycles. Hawkins et al. (2012) assumed battery capacities of 24 kWh and a 150,000 km vehicle lifetime. They found that LiNCM batteries outperform the LiFePO4 batteries in terms of global warming potential (GWP) due to their greater energy density, with a GWP impact of 87 and 95 g CO_2-eq/km respectively, placing total LCA emissions for production of EVs at around 13 and 14 tons CO_2-eq respectively. LCA emissions from the production of ICEVs was estimated to be 43 g CO_2-eq/km, totaling around 6.5 tons CO_2-eq for a 150,000 km vehicle lifetime.

A significant part of the production phase of an EV is battery production which makes up 35 - 41%. This is put into perspective when taking into account that the production of the electric engine represents 7 - 8% of the entire production process, while other powertrain components, amongst which are the inverters and battery cooling system with significant proportions of aluminum, comprise 16 - 18%.

Hawkins et al. (2012) also compared their findings to previous relevant studies and found varying results. The best case environmental impact they reported, 87 - 95 g CO_2-eq/km, was about two times as high as the GWP reported by the studies they review, including Baptista et al. (2010), Burnham et al. (2006), Samaras and Meisterling (2008) (As cited by Hawkins et al. 2012), and Notter et al. (2010). Burnham et al. (2012, as cited by Hawkins et al. 2012), report consistent CO_2 emissions from production of ICEVs with those of Hawkins et al. (2012), at 6.4 tons, but report diverging results from production of EVs equipped with LiNCM and LiFePO, whose emissions amounted to 8.6 and 8.4 tons respectively. Hawkins et al. (2012) attributes this difference to higher impacts of battery production, as they included electronic components omitted by previous studies.

Accordingly, cradle to gate battery production impacts noted in the literature they reviewed also had significant differences. Majeau-Bettez et al. (2011) reported 22 kg CO_2-eq/kg of car, while Notter et al. (2010) stated 6 kg CO_2-eq/kg of car and Samaras et al. (2008, as cited by Hawkins et al. 2012) published 9.6 kg CO_2-eq/kg of car. The discrepancies are attributed to different assumptions about energy needed for manufacturing, system boundaries and availability of primary inventory data on batteries. The cradle to gate GWP impact reported by Hawkins et al. (2012) for ICEVs, of 5 kg CO_2-eq/kg of car was in the range reported by literature sources they reviewed at the time, from 4 to 6.5 kg CO_2-eq/kg of car (Daimler AG 2005, 2007a, 2007b, 2008a, 2008b; Volkswagen AG 2008b, 2008c, as cited by Hawkins et al. 2012). This is understandable, considering that ICEV technology is long-standing, common and well researched, so industry standards are already established and detail information about all production segments is available.

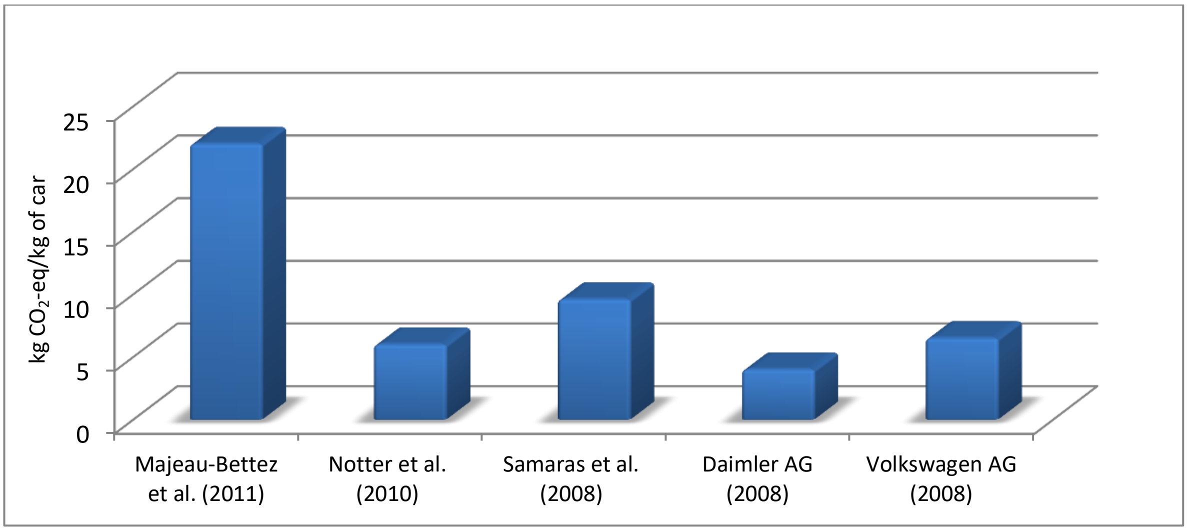


Figure 10: Cradle to Gate Battery Production Impact in kg CO_2-eq/kg of car by literature source

Considering GWP impact of the entire LCA, when measured considering the European electricity mix, the LiNCM EVs yielded GWP amounts of 197 g CO_2-eq/km, while the amount for LiFePO4 EVs was 206 g CO_2-eq/km, noting, however that their lifetime assumptions significantly increase the per kilometer impacts of the LiFePO4 relative to the LiNCM.

Another aspect significantly impacting LCA emissions is the efficiency of the vehicle in question. Hawkins et al. (2012) performed their study assuming a base case efficiency of 0.623 MJ/km as reported for the Nissan Leaf under the NEDC. This falls between the previous studies they referred to, which estimated the efficiencies to be between 0.4 MJ/km (Elgowainy et al. 2009, Shiau et al. 2009, as cited by Hawkins et al. 2012) and 0.8 MJ/km (Graham and Little 2001, Huo et al. 2010 and Parks et al. 2007, as cited by Hawkins et al. 2012). If the assumed efficiency had been 0.9 MJ/km, EVs would have a GWP footprint between that of the base case diesel and gasoline ICEVs. Likewise, if ICEVs would have fuel consumption between 40 and 50 ml/km would they would have the same GWP as the base case for EVs

Nonetheless, EVs powered by the present European electricity mix offer a 20% to 24% decrease in global warming potential (GWP) relative to gasoline vehicles and 10% to 14% relative to diesel vehicles. If the lifetime of a vehicle was assumed to be 200,000 KM, the GWP reduction attributed to EVs would be 27% - 29% when compared to gasoline ICEVs and 17 - 20 % relative to the diesel ones. Increasing the lifetime of EVs from 150,000 km to 250,000 km potentially decreases the GWP by as much as 40 g CO_2-eq/km, down to roughly 165 g CO_2-eq/km, whereas the same lifetime increase for ICEVs only decreases the GWP per kilometer by 19 g CO_2-eq/km. Accordingly, if a driving life of 100,000 km is assumed, the GWP benefits would decrease to 9 - 14% compared to gasoline vehicles, while not yielding any improvements compared to diesel.

Thus decreasing the proportion of the LCA that production comprises, namely increasing the proportion of the use phase through increasing length of kilometers driven in a vehicle's life cycle, would lead to decreasing the GWP under a European electricity mix. However this may not be always the case as the GWP of the use phase depends heavily on the electricity mix used to charge the vehicles under consideration. Hence, Hawkins et al. (2012) also performed a sensitivity analysis where they found that if wind power was the primary source of electricity generation the life cycle carbon foot print of an EV would amount to 106 g CO_2-eq/km. However, if the electricity in question was generated from the combustion of lignite the life cycle carbon footprint would be 352 g CO_2-eq/km, which is significantly worse than an ICEV in the same category. Namely, this would contribute to a 17- 27% increase when compared to gasoline and diesel powered vehicles. Charging an EV with electricity stemming from the burning of natural gas would have the same GWP impact as a diesel ICEV in 2012, and a 12% reduction compared to gasoline.

Gbegbaje-Das (2013) Performed an LCA analysis of a C-Segment passenger vehicle travelling a distance of 150,000 km during its life, on one battery, under NEDC conditions, in different scenarios, focusing on ICEVs, HEVs, PHEVs and BEVs. It focused on the C-Segment as it is a European car size classification corresponding to a “Small Family Car”, “Compact Car” or “Medium Car”, and was the most predominant in European car sales at the time of study, which was a trend the authors foresaw to continue in the future. The analysis included extraction of raw materials, production of fuels and vehicle component parts, vehicle assembly, lifetime use phase including replacement parts and fluids, as well as end of life with the cutoff point being after vehicle shredding. The scenarios considered attempt to reflect the change in technology over time and include a typical 2012 scenario which is also the base case, typical 2020, best case 2020, typical 2030 and best case 2030 scenario. The carbon intensities are assumed to be at point of consumption, while the intensities of the grids of future scenarios are based on European Commission statistical prediction, the UK Carbon Plan and the UK 2012 Draft Energy Bill.

For the ICEV as base case, namely typical 2012 scenario, they reported a total of 30.70 tons CO_2 equivalent (t CO_2-eq) produced over the vehicle's life cycle, based on fuel consumption of 5.83 l/100 km in the us phase, running on E10 petrol. For a typical 2020 scenario, and ICEV's life cycle produced 28.7 t CO_2-eq, where the EU and UK grids were 7% and 17% cleaner than in 2012 respectively, and the fuel efficiency was 5.42 l/100 km, running on E10 petrol, which has an ethanol mix yielding 60% GHG savings. In a 2020 best case, an ICEV would produce a total of 27.51 t CO_2-eq over its life, for EU and UK grids emitting 14% and 34% less carbon, consuming 5.19 l/100 km of E15 petrol, the blend of which meets 60% GHG savings. For a typical 2030 scenario the lifetime emissions would be 25.27 t CO_2-eq, the EU and UK grids would be 28 and 51% less carbon intensive, and the fuel consumption would be 4.93/100 km on E15 petrol meeting 70% GHG savings. The 2030 best case scenario would produce only 9.35 t CO_2-eq over the vehicle's life, stemming from 60 and 83% less carbon intensive EU and UK grids, respectively, and a fuel efficiency of 4.72 l/100 km burning 100% pure bioethanol that meets 70% GHG intensity savings. Across all scenarios the majority of the reductions are attributed to improved efficiency in the use phase (p. 81, Gbegbaje-Das 2013).

BEVs produce 24.46 t CO_2-eq over their life time in the base case with a 15 kWh/100 km electricity consumption, with the production phase accounting for 45% of total life time emissions. In a typical 2020 scenario they would produce 21.60 t CO_2-eq, consuming 14.7 kWh of electricity per 100 km, with the production phase accounting for 48% of total life time emissions, where the EU and UK grids are assumed to have 7% and 17% lower carbon intensities respectively, and the reduction in embodied carbon impacts of battery packs are assumed to be 10%. In the 2020 best case, an EV would produce 18.49 t CO_2-eq over its lifetime, with the production phase accounting for 53% of total life time emissions, with electricity consumption of 14.6 kWh/100 km, the EU and UK grids being 14% and 34% cleaner respectively, and the carbon impacts of battery production being reduced by 15%. In the typical 2030 scenario EVs would emit 15.74 t CO_2-eq, with the production phase accounting for 59% of total life time emissions, consuming 14.3 kWh/100 km, with the carbon reductions in the EU and UK grids being 28% and 21% respectively, while the battery pack production being the same as in the typical 2020 scenario. For the best 2030 scenario, 11.06 t CO_2-eq would be emitted over an EV's lifecycle, with the production phase accounting for 78% of total life time emissions, with consumption of 14.1 kWh/100 km, the EU and UK carbon reductions being 60% and 83% respectively and the battery pack production impact being the same as in the best 2020 scenario.

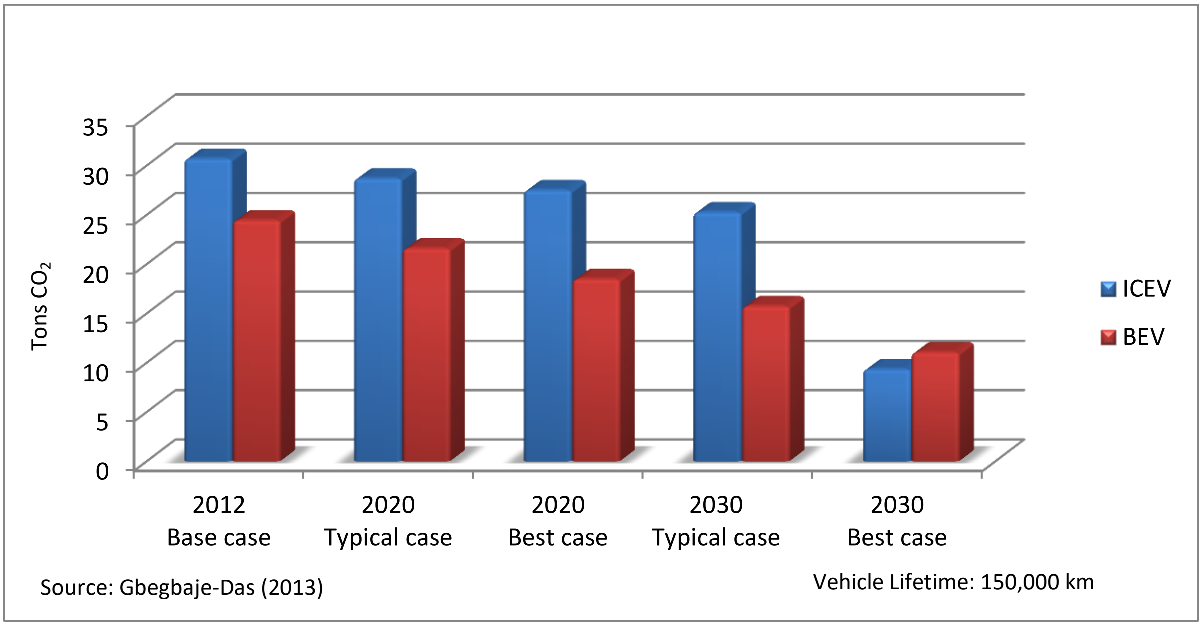


Figure 11: LCA Impact in Tons CO_2 by Future Scenarios

For BEVs, energy production required to power them comprises majority of emissions, with this proportion increasing as the scenarios progress. Of the production impact, about 50% comes from the battery, about 40% from the glider with the rest being attributed to the electric motor, power electronics and other components. On the other hand an ICEV has very low production impact and its glider accounts for 7% of the impacts. It is also interesting to note that as the scenarios progress the gap between EV's and ICEV's total emissions increases, with the exception of the final hypothetic scenario where ICEVs bur 100% bio ethanol.

The study by Gbegbaje-Das (2013) clearly indicates that the use phase is becoming an increasingly smaller contribution to a vehicle's LCA. Weather it is due to cleaner electricity mixes, more efficient vehicles or cleaner combustion fuel its impact is reducing across future predicted scenarios. Consequently, other areas of the vehicle lifetime inventory are gaining in value, with the most significant being the production phase. Thus the focus will shift towards this segment more and more, as advances in technology and production processes can bring great reductions.

Nealer et al. (2015) modeled the performance of two of the most popular BEVs available in 2014, the Nissan Leaf and the Tesla Model S, the first representing the mid-size model and the second the full size, and assessed their emissions against those of comparable ICEVs on a cradle to grave approach, taking into account vehicle production, use phase and end of life, but omitting building infrastructure for processing and assembly, and the emission from transportation of raw material in manufacturing, assuming them to be relatively similar for both vehicles. They used industry averages and data from the published literature compiled by Burnham (2012, as cited by Nealer et al. 2015). They reported their findings in terms of miles per gallon (MPG) and 26 US regions, which they divided according to their power grids.

They found that the EVs yield greater manufacturing emissions, but that this excess is offset in between 6 and 16 months of average driving. Driving an average EV in any of the region yielded less global warming emissions than an average gasoline vehicle burning 29 MPG. Moreover, an average EV caused lower global warming emissions than driving a gasoline vehicle with a consumption of 50

MPG in regions covering two-thirds of the US population. They also concluded that the overall US grid has become cleaner than 3 years prior (2012), with improvements found in 20 out of 26 regions. In certain regions even, for ICEVs to equal EVs in efficiency, 68 MPG consumption was needed (p. 12, Nealer et al. 2015), which is a rating not achieved by any conventional gasoline vehicles on the market today. This attests to the tendency of grids in developed countries to switching to renewables and that they are accompanied by significant reductions in mobility GHG emissions. Further, in support of this claim, Nealer et al. (2015) find that in a grid 80% supplied by renewables, BEV manufacturing emissions will be reduced by 25%, while 84% reductions will be seen in the use phase, assuming charging from baseload power, which would contribute to an overall reduction of 60% compared to an LCA of an EV produced and used today (Nealer et al. 2015).

Nealer et al. (2015) found that under the average US electricity grid mix, manufacturing a medium sized, middle range EV, achieving 84 miles per charge, produced 7.7 tons of CO_2-eq, which is 1 ton of CO_2-eq or 15 % more than manufacturing a comparable ICEV, which would emit 6.7 tons of CO_2-eq. Manufacturing makes up around 30% of an EV's lifetime global warming emissions, while the rest is attributed to the use phase. And it is because of the use phase however that mid-sized EVs yield life time emissions of around 28 t CO_2-eq, which is by 29 tons or 51% lower than a comparable conventional gasoline vehicle producing around 57 t CO_2-eq, under assumption of a 135 thousand miles total driving life, with the breakeven point identified at 4,900 miles, based on the sales-weighted electricity emissions of where EVs were sold in 2015. If this EV was driven in the cleanest US regions identified by the authors, it would break even within 3,700 miles, while it would take it 13,000 on the dirtiest. Battery production emissions amounted 24% of the total manufacturing emissions, but less than 8% of life time emissions.

In the case of a full-size long-range EV capable of driving 265 miles between charges, thanks to its large battery, manufacturing yielded 14.8 t CO_2-eq, 68% or 6 tons more than an ICEV, whose production emissions amount to around 8.8 t CO_2-eq. However, in this case as well, the EV produced around 48 t CO_2-eq, or 53% less emissions when considering the entire life time of 179 thousand miles, saving 54 t CO_2-eq, compared to an ICEV which yielded around 102 t CO_2-eq. The breakeven point would be reached at 19,000 miles, according to the sales-weighted electricity emissions of where EVs were sold in 2015. Driving the full-sized EV charged from the cleanest US regional grid, they would breakeven at 15,000 miles, while it would take them 39,000 miles to do so in the dirtiest. Battery manufacturing constituted 36% of total manufacturing emissions and 12% of life time emissions.

Egede et al. (2015) performed an LCA of electric vehicles composed of two different materials, where one was steel and the other aluminum, in countries with different electricity mixes: Germany, Brazil and Spain, across a distance of 100, 150 and 200 thousand kilometers, under three driving intensities scenarios: low, medium and high, treating driving behavior, desired temperature, topography and type of road. The idea behind comparing vehicles made of these different materials was to assess the performance of a vehicle made from traditional materials against that made from lightweight materials, as the reduction in vehicle weight would reduce the energy consumption in the use phase and increase the driving range without increasing the battery size. However, this aspect had a counter effect as lightweight materials are hard to come by and require more energy in the manufacturing phase than conventional materials do. Hence the case study focused on a delta analysis amongst the weight reduction of an aluminum vehicle and the CO_2-eq of the material supply of steel and aluminum. The study was performed in accordance with LCA specifications established by Das (2014).

Consequently, they found that the aluminum chassis achieves a weight reduction of 67%. However, whereas the kg CO_2-eq of a kilogram of steel is 5.7, according to Das (2011) and Ecoinvent 3.01 database (2013, as cited by Egede et al. 2015), the kg CO_2-eq/kg of aluminum is 13, according to Ehrenberger (2013) and Das (2014). They also found that the impact amongst materials does not only depend on a grid's power mix, but the energy consumption in the use phase, as well as that the higher impact of the production of aluminum eventually pays off regardless of the energy consumption per kilometer, which is increasingly evident as the vehicle life span in terms of driving range increases.

In terms of the energy mixes of the countries in focus, according to the Ecoinvent 3.01 database (2013, as cited by Egede et al. 2015), Brazil's predominantly hydro based energy mix produces relatively low CO_2 emissions, where Germany's power grid fed by a diverse mix of sources produces medium CO_2 emissions and Spain's power mix falls between these two. Hence, in Brazil the choice of steel causes lower emissions than aluminum, since usage is cleaner, even if the car is heavier and requires more energy, with the exception of a 200,000 km driving distance and a high consumption driving scenario. In Germany on the other hand, aluminum is the choice causing less emissions, as its greater environmental impact from production is offset by the savings its lighter weight causes in the use phase, with the exception of a 100,000 km life span and a low-intensity driving scenario. In Spain, nonetheless the results are very unclear. Here aluminum pays off for a driving distance of 200,000 km under any consumption scenario, but in the case of 150,000 km driving distance aluminum pays off for high consumption and whereas in the 100,000 km setting it pays off under high and medium consumption (Egede et al. 2015).

Egede et al. (2015) conclude that the external factors can influence whether a material choice pays off in terms of CO_2 emissions, but the extent to which they influence depends greatly on a country's electricity mix. Considering average values can be misleading due to the specificities of material emissions, power mixes and driving conditions. However disaggregating the various factors influencing emissions and including them in studies systematically can increase the reliability of LCAs, by reducing uncertainty and narrowing down the causes of energy consumption difference under certain scenarios. Therefore, Egede et al. (2015) have proposed a certain framework for performing LCAs which would allow policy makers, researchers, car manufacturers and car owners to make more educated decisions on their contributions towards reduction of CO_2 emissions by means of EVs in their particular countries or markets. Nonetheless, this framework could also be reduced or expanded or to encompass even more influencing variables depending on the specific needs and goals.

Ager-Wick Ellingsen et al. (2016) performed a study on EVs powered by Li-ion batteries in order to assess the effect an increase in size and range of an EV would have on lifecycle climate change potential of an EV in the European setting, as well as to compare EVs across compatible conventional vehicles. To this purpose they examined the cradle to grave GHG emissions of EVs in four different segments, focusing only on vehicle models that stated their driving range according to the NEDC. In turn they obtained curb weight in kg and the NEDC energy requirement (kWh/km) for 20 EVs, to which they paired the appropriate conventional vehicles based on vehicle weight and fuel consumption, according to research performed by Modaresi et al. (2014).

Although the energy requirements of a vehicle are affected by numerous other features in addition to mass of vehicle, for the focus of this study the authors assumed a liner regression curve, thus obtaining a slope that yields a 5.6 Wh/km increase in energy requirements per 100 kg additional weight. The 4 categories of EVs include mini car (A-segment), medium car (C-segment), large cars (D-segment), and luxury car (F-segment), choosing weights similar to existing car models. Upon the regression analysis, they determined the suitable battery sizes for each category of EVs. To calculate the driving range, the battery size was divided by NEDC energy requirement. To calculate the total EV energy requirement they assumed a 96% efficiency for the charger and 95% for the battery. Ager-Wick Ellingsen et al. (2016) compiled cradle to grave inventories for each vehicle segment by adapting and synthesizing research on EVs performed by Hawkins et al. (2012) and on Li-ion batteries performed by Dewulf et al. (2010) and Ellingsen et al. (2014). Ager-Wick Ellingsen et al. (2016) found that batteries were produces in East Asia and vehicles were produced in Germany. The original inventory was compiled based on a bill of material that the manufacturer provided. The authors assumed a vehicle lifetime of 12 years and a yearly mileage of 15,000 km, resulting in a total mileage of 180,000 km, and an average European electricity mix emitting 521 g CO_2/kWh according to Itten et al. (2014, as cited by Ager-Wick Ellingsen et al. 2016) for the use phase. In addition, a sensitivity analysis was performed considering electricity mixes with different carbon intensities.

The LCA comparison with ICEVs, including the production and use phase, was performed based on data published by Daimler and Volkswagen, for vehicles in each categorized segment that were newer than 2010. The use phase emissions (g CO_2/km) were converted to use phase impacts (g CO_2-eq/km) by multiplying the former with a conversion factor.

Ager-Wick Ellingsen et al. (2016) found that the difference between the highest and the lowest lifecycle emissions in terms of kg CO_2-eq/kg of car was 1.8 for the ICEVs and 1.7 for the EVs. When comparing equal sizes, the EVs had 20%–27% lower lifecycle impact than the ICEVs. The EVs production phase was considerably more intensive than that of ICEVs. The cradle to gate climate change potential (CCP) intensity of the EVs was 6.3–7.1 kg CO_2-eq/kg of car, whereas for the ICEVs it was 3.9–5.7 kg CO_2-eq/kg of car. The difference in the cradle to gate CCP intensity between the EVs and the ICEVs was mainly due to battery production, which caused 31%–46% of the total EV production impact, and 13%–22% of the total life cycle impact. However, ICEVs had much higher emissions in the use phase than EVs. The breakeven range for the two vehicle's emissions was between 44,000 km and 70,000 km, with the former representing the small segment and the letter the luxury. Energy losses in the battery and charger were responsible for 4.0% and 5.0%, respectively. Further, they found that the larger the EV, the sooner it made up for the higher production emissions. This is so as the heavier a vehicle is the more energy or fuel it requires to move and thus a heavier ICEV would emit more CO_2. However, this is heavily dependent on the electricity sources powering the comparable EV. Still, for both types of vehicles the use phase was responsible for much of the GHG emission, whether it was directly through fuel combustion or indirectly through electricity production. Regardless of drivetrain technology, the emissions stemming from the end of life (EOL) treatment were small compare to the emissions stemming from production and use, although EVs had a slightly higher impact due to the battery, making up 14%–23% of the total EOL treatment emissions of the EVs.

Ager-Wick Ellingsen et al. (2016) also assessed the LCA of EVs under consideration of various electricity mixes, and thus included in their research electricity based on energy from world average coal (1029 g CO_2-eq/kWh), world average natural gas (595 g CO_2-eq/kWh), and wind (21 g CO_2-eq/kWh) (Ecoinvent Centre 2010, as cited by Ager-Wick Ellingsen et al. 2016), as well as a green scenario proposed by the authors where electricity in all lifecycle phases was based on wind power (17 g CO_2-eq/kWh). Under these emission values, they found that when charging the EVs with coal-based electricity made the EV lifecycle emissions 12% – 31% higher compared to ICEVs, where EVs emissions further increased with an increase in distance driven. With regards to emissions caused by charging with electricity stemming entirely from natural gas, EVs resulted in 12% – 21% lower lifecycle impact. In the case of electricity based completely on wind, the life cycle emissions dropped to being 66% - 70% lower than their ICEV counterparts. In the author's green scenario, EVs resulted in 83 – 84% lower lifecycle impact with a production intensity of 3.2–3.3 kg CO_2-eq/kg (Ager-Wick Ellingsen et al. 2016).

It is also interesting to note that, as the use phase impact decreases so does the difference in percentages amongst EVs in the smallest and largest category, hence for the coal power the difference in emissions EVs yield compare to ICEVs between the mini and luxury category is 19%, where as in the case of wind it is 3%. This is explained by the fact that EVs are much more emission intensive in the production phase than in the use phase, and thus the smaller the impact of the use phase the smaller the absolute difference if lifecycle impact amongst the size segments. Therefore, the size and range effect decrease with the decrease of carbon intensity of an electricity mix.

Van Mierlo et al. (2017) compared LCAs of vehicles run by various propulsion technologies in Belgium including compressed natural gas (CNG), Battery Electric Vehicles (BEV), Liquid Petrol Gas (LPG), Biogas (BG), plug-in hybrid electric vehicles (PHEV), hybrid electric vehicles (HEV) and conventional diesel and petrol vehicles. As an example and context they chose the Brussels Capital region, which is the center of Belgium, as well as the capital of Europe.

They chose 1 kilometer of driving distance to be the functional unit for comparison amongst the different vehicles and assumed an average vehicle life span of 14.1 year with an annual mileage of 14,865 km, which rounds up to 210,000 km over the vehicle's life-cycle. They derived their LCAs from Van Mierlo et al. (2009), Messagie et al. (2013), Van Mierlo et al. (2013) and Messagie et al. (2014). They performed their study under the Recipe methodology of Goedkoop et al. (2008) and utilizing the Range-Base approach documented by Messagie et al. (2013) to include variation of the vehicle weight, the energy consumption and the emissions in the LCA results of the vehicles in the same category. Since the study was performed in Belgium, the authors chose to focus their testing on the small passenger car segment as it is the most represented in this country. Namely, they chose the Volkswagen Golf for the petrol and diesel versions of the test, as it is assumed to be the average conventional vehicle, and included the Nissan Leaf, Fiat Punto, Opel Ampera, Toyota Prius as vehicles in the same category, for comparison. For BEVs, lithium based batteries are considered as they are capturing the most market shares in this segment to their energy density and power characteristics.

The results of their studies indicate that BEVs charged with the Belgian average electricity mix yielded the lowest emissions. Their study ranked the remaining vehicle technologies as follows, from least to most emitting, taking into account both the LCA and WTW analysis: PHEVs, BGs, CNGs, HEVs, LPGs, Diesel and Petrol. They further found that the shares of CO_2 emissions from the manufacturing of EVs are higher than the fossil fuel vehicle, due mainly to the battery and associated electrical components. But in addition to the offset caused by the use phase, a big share of the impact of the lithium battery is balanced by the benefit of the recycling. Thus the recycling of specific EV components such as the battery pack results a big environmental benefit (Van Mierlo et al. 2017).

Amidst the much higher manufacturing emissions, taking into account baseload electricity usage, BEVs make up for this in the use phase. But here, one must keep in mind that this is strongly influenced by the source of electricity, as a BEV can be powered by a range of electricity sources including gas, coal, nuclear, and renewables such as wind, biomass and solar. On the other hand if BEVs are not powered by a grid comprised of renewables or a mix that is not mainly composed of fossil fuels, such as the Belgian, they may not contribute to emission reductions much or at all, and in some cases may even perform worse than ICEVs. Van Mierlo et al. (2017) found that a BEV powered only by coal electricity, produced under average EU conditions, has similar WTW CO_2 emissions as diesel vehicle (Van Mierlo et al. 2017). This is exemplified by the fact that in their results for BEV g CO_2-eq /km emissions vary from 2 to 175 depending on the power mix consideration. The results are calculated assuming that the average CO_2 emissions of electricity from coal, natural gas, wind and Belgian electricity mix are 885 g/kWh, 642 g/kWh, 11 g/kWh and 190 g/kWh, respectively (Messagie et al. 2014, Edwards et al. 2014). Here it should also be noted that coal electricity production technologies and efficiencies vary across the globe, producing varying levels of emissions.

Qiao et al. (2017) performed an LCA comparison amongst EVs and ICEVs produced in China, which has approximately one quarter of world vehicle production. According to their study, CO_2 emissions from production of EV range from 14.6 to 14.7 tons, which is 59% - 60% higher than the 9.2 tons of CO_2 emitted during the production of ICEVs. They state Li-ion batteries and additional components such as traction motors and electronic controller as the main reasons.

The study by Qiao et al. (2017) employs a cradle to gate system and includes material production and transformation, basic component manufacturing, special component manufacturing, batteries and attachments manufacturing and assembly. It also considers replacements of batteries, tires and fluids in the use phase. It normalizes process fuels used during vehicle production with the life cycle CO_2 emissions considered, including extraction, processing and burning. The study does not include the distribution of fuel, the use phase and vehicle disposal, as it aims to analyze CO_2 emissions from vehicle production. Also, the tiny CO_2 emissions caused by materials used in auxiliary, such as limestone, are not considered due to data availability. The study takes standard mid-size passenger cars (comparable to B-class in China) with conventional materials as reference vehicles for both EVs and ICEVs. The same standard tires are considered for both ICEVs and EVs. All kinds of fluids are considered including engine oil, brake fluid, transmission fluid, powertrain coolant, windshield fluid and adhesives.

It focuses on Li-ion batteries, LiFePO4 (LFP) and LiNiCoMnO2 (NCM), which in 2015 captured 52% and 39% of China's traction battery market respectively. It finds that CO_2 emissions from active material production are the most influential variable for both LFP and NCM batteries. (p. 6, Qiao et al. 2017) Emissions from the production of these two batteries when the results have been multiplied by the uncertainty parameters of 0.8, 1.0 and 1.2. The results range from 2,435.2 to 3,142.4 kg-CO_2 for the NCM and 2,596.3 to 3,188.5 kg-CO_2 for the LFP batteries which is quite wide, but in either case still contribute a significant proportion of EVs overall GHG emissions. Additional LCA results are presented in the figures in Appendix 1.

LCA Conclusion

As the processes and components involved in a life cycle of a vehicle are numerous and complex, different studies addressing this issue set boundaries differently. Thus the studies go into various levels of detail when performing LCAs, making comparison amongst them arbitrary. Although standards and frameworks attempting to harmonize research in this regard exist, the methodologies still differ. In addition, resource availability, production and recycling techniques and data access across the globe and industries vary. Nonetheless, general trends among studies can be observed and certain conclusions can be drawn.

All literature reviewed identifies that production of EVs produces significantly more CO_2 emissions than production of ICEVs, ranging from 30 - 100%, with the battery pack being identified as the most impactful single component of production. The use phase of the LCA of BEVs is significantly influenced by the type of electricity used for charging. Under assumptions of baseload power used for their charging, and an EU electricity mix, BEVs outperform ICEVs in the use phase to the extent that they exhibit significantly smaller overall life-time emissions. However, if BEVs were charged by electricity generated from coal, which would be the case during peak load charging or grids of certain nations even for baseload, they would produce use phase emissions comparable or worse to ICEVs, thus exhibiting significantly worse life cycle emissions. End of life emissions, due to recycling or disposal, have been identified to comprise relatively small parts of the entire LCA, even though data on them is limited as the BEV industry is still relatively young. However, improved recycling techniques would contribute to decreased production impact.

As production techniques improve and recycling develops, especially with regards to electric motor and battery components, the environmental impact of BEVs' production will decrease progressively. Therefore the use phase will constitute an ever increasing proportion of the LCA impacts. Accordingly the source of electricity used to charge BEVs will be the main determinant of their environmental impact.

Although some literature present sensitivity analysis that take into consideration electricity generated by various single sources, most consider baseload power as a base scenario when assessing use phase impacts. Thus they account for the emissions per unit of energy that would have been generated under a certain resource mix of a certain grid. However, as a new demand segment on the grid, as well as due to their most likely times of charging, BEVs would generate additional load on the grid which may not be possible to meet with the baseload capacities of current girds. Consequently, peak power plants may be employed, which mainly burn coal or natural gas, and often times use inefficient technology, therefore generating BEV use phase emissions which are significantly greater than those of ICEVs.

Electricity

As indicated by the literature, the use phase of a BEV’s lifecycle is still a significant contributor to overall life-time emissions. The environmental impact that the use phase may have is strictly dependent on the source of electricity charging the BEV. Therefore, when assessing the environmental impact of electric vehicles, special consideration must be given to the source of electricity.

Sources of Electricity

Electricity can be produced from virtually any energy source Gbegbaje-Das et al. (2013). The most utilized sources for conventional production of electricity include coal, natural gas, hydro power, crude oil and nuclear. The burning of wood, waste or other materials can also produce electricity. More recently, there was a great push towards more renewable sources including solar and wind. Newer forms of renewables are also developing, such as tidal and geothermal energy. On top of this, the methods for producing electricity from primary sources also vary with innovations constantly developing. Technologies such as combined cycle gas turbine (CCGT), integrated gasification combined cycle (IGCC) and combined heat and power (CHP), have been established for quite some time, while improvements in the efficiency of wind turbines and photovoltaic technologies are making progress currently.

Coal

Hard coal represents a major source of electricity in much of the world. Electricity from coal can be generated by direct combustion as well as coal gasification, where coal is turned into a gas through an intermediate process and then combusted for energy. According to Turconi et al. (2013), emissions from direct combustion of coal fall within the range between 750 and 1200 kg CO_2-eq/MWh, and are dependent on the recovery efficiency, which they report to be in the range from 33 to 42%. Coal gasification, achieves efficiencies of up to 52%, and produce 660 - 800 kg CO_2-eq/MWh. The energy recovery factor significantly effects the amount of emissions. Another such factor is the flue gas cleaning (FGC) system which removes pollutants from the flue gases. The effect of the flue gas system is also noted by Turconi et al. (2013), who report NO_X and SO_2 emissions to be 2 - 4 kg/MWh and 2 - 7 kg/MWh respectively, in old power plants with no or low tech FGC, whereas emissions in modern plants amount to 0.3 - 1 kg NO_X/MWh and 0.1 - 1 kg SO_2/ MWh. For coal gasification, overall emission factors were found on the order of 0.2 - 0.7 kg NO_X/MWh and 0.1 - 1 kg SO_2/MWh, with the process efficiency and an FGC system being the key aspects. Furthermore, power generated by coal produces less CO_2 emissions than was the case with a conventional modern steam turbine plant that yields an efficiency of 40 to 50% (Gbegbaje-Das et al. 2013). Additional emission reducing methods such as carbon capture and storage (CCS) are being developed, with the potential of further reducing environmental impacts of such electricity production.

Natural Gas

According to Gbegbaje-Das et al. (2013), natural gas, already extensively used for power generation, represents around 12% of the primary energy in EU-15. Even though natural gas can be burned in conventional thermal steam cycles, most new large-scale generation relies on combined cycle gas turbines (CCGT), increasing efficiency in the newest plants by as much as 58%, whereas the efficiency in a conventional plant is 33% (Treyer et al. 2013). Electricity from natural gas can also be generated in combined heat and power plants (CHP). Worldwide, 26% of electricity from natural gas is generated in CHP plants, while natural gas power plants with combined cycles made up 25 - 30 % of installed capacity in 2013.

Nuclear

Nuclear power is the cause of much controversy with strong arguments for and against it. From a CO_2 perspective it is a very clean resource, with its only emissions being associated with power plant construction and maintenance, uranium extraction, transportation and enrichment. On the other side the radioactive waste it produces has the potential to have grave consequences on the environment and human health if not disposed properly, while there is a constant risk of a catastrophic level event due to a meltdown. Although, such events are extremely rare, their effects are felt on a global scale and last many years, thus even the slightest possibility of their occurrence offsets nuclear benefits in the eyes of the population.

Hydro

Hydroelectricity currently represents by far the largest portion of Europe's renewable energy consumption (Edwards et al. 2014). It can be generated with run-off-river plants, pumped storage plants and reservoir plants, in alpine, non-alpine and tropical regions (Treyer et al. 2013). But, the growth of hydroelectricity capacity is not expected to increase, as there are not too many suitable sites left (Edwards et al. 2014). Nonetheless, hydroelectricity is fully integrated in the EU's power mix and it is also one of the cheapest sources of power. There are no direct CO_2 emissions from hydro, with the exception of plant construction and maintenance, as well as decomposition of vegetation covered by water in areas flooded as a result of damn construction. However, although almost emissions free, and regarded as renewable, hydro power severely impacts ecological habitats, causing major disturbances to plant and animal life, resulting from the damning up of rivers, causing certain areas to flood while drying others.

Wind

Wind is an unlimited resource, but the capacities for its exploitation are limited. In order to harvest wind power, large wind turbines are needed in great amounts. The only emissions associated with wind power are the construction of these turbines, their maintenance and maintenance of the grid they are connected to (Turconi et al. 2013). However, these wind farms take up a lot of land area. The area has to be adequate in terms of terrain and climate, but it also must not cause any social and ecological disturbances. Wind farms are often met with social obstruction as they influence the quality of living in an area, from deteriorating the landscape and alleged health problems caused by the currents, to disturbances for bird migration and other habitat usurpations. Nonetheless, numerous area that suit such power generations can still be found, with offshore wind farming gaining ground. Coupled with the improvements in turbine technology and energy storage, wind has much potential still to be exploited. According to Edwards et al. (2014), 5% of total electricity generation in the EU is expected to come from wind in 2030.

Solar

Solar power is being harvested to make electricity and is a technology in which much research and development has been invested over the past years. Solar radiation is converted to electricity through photovoltaic cells typically arranged on panels or laminates installed on facades, slanted roofs, flat roofs for individual or local use or in open ground layouts for large scale utilization (Treyer et al. 2013). Solar power presents an interesting challenge as well as opportunity as it can only be accumulated when the sun is shining. In household set ups with roof panels, during this period more of it is accumulated than needed for the consumption of the household. Efforts to mitigate this include, selling the excess power back to the grid and storing it in external storage units.

Wood

Wood can be burned in a simple boiler and steam turbine set, in a gasification or CCGT setup. Or black liquor can be made from waste wood and also burned. Waste material provides an opportunity for power generation either from direct combustion or through transformation to biogas and its usage in the gas grid (Edwards et al. 2014).

Emissions of Electricity Generation

In view of the different characteristics among resources and the variations in technologies for their conversion into energy, efficiency and emission levels vary widely amongst them. In addition, the power mix of a nation's grid is entirely dependent on the geography and climate, as these factors influence the availability of resources. Nonetheless, there are efficiency and emissions estimations at national, regional and global levels, which account for the proportion of each source in each grid.

According to Davis et al. (2016), in the United Kingdom in 2007, where EVs were assumed to consume 16 kWh/100 km, they would achieve a 50% reduction in emissions under the 2007 UK mix, with the potential of up to 80% reduction, in case of a low carbon mix. However, according to the Massachusetts Institute of Technology (MIT 2007), EVs would have emissions of up to 120 g CO_2/km, when powered by coal, which is very close to those of ICEVS at 130 g CO_2/km, whereas the International Energy Agency (2007), found EVs powered by coal to be even dirtier than ICEVs.

The World Wide Fund for Nature (2009) compared effects of different grid mixes on the overall CO_2 impacts of EVs against gasoline and diesel vehicles. They found that carbon intensive, mainly coal based grids as can be found in Greece or Indiana, USA, result in emissions which fall within the range of ICEVs, both diesel and gasoline. On the other side of the spectrum, in low-carbon energy grids, such as those of California and Austria, EVs exhibit emissions 70% less than comparable gasoline or diesel vehicles. Considering the average 2008 EU mix, EVs would emit 60% less than ICEVS. The average 2008 US mix would cause EV emissions to be 40% lower than those of ICEVs.

Hacker et al. (2009) also report that in case of natural gas based electricity generation, GHG emissions of electric vehicles are in the range of conventional vehicles, whereas the assumption of coal-fired energy generation leads to considerably higher values which exceed the average emissions of conventional vehicles. Helmers et al. (2012) estimated average EU grid electricity generation to emit 500 to 600 g CO_2-eq/kWh, while renewables generated around 30 g CO_2-eq/kWh.

Turconi et al. (2013) performed a review of 167 studies on the life cycle assessment of GHG emissions stemming from various power sources on a WTW basis. They found that coal emitted an average of 942.33 g CO_2-eq/kWh, with the minimum value established being 660 and the maximum 1370 g CO_2-eq/kWh. Natural gas yielded 533.17 g CO_2-eq/kWh average, with its minimum and maximum identified emissions totaling 380 and 1,000 g CO_2-eq/kWh respectively. Emissions from oil averaged at 773.8 g CO_2-eq/kWh, with a minimum of 530 and maximum of 890 g CO_2-eq/kWh. Electricity produced from nuclear power produced an average of 12.23 g CO_2-eq/kWh, with the minimum and maximum recorded values being 3.1 and 35 g CO_2-eq/kWh respectively. In the case of hydropower, the average was 8.22 g CO_2-eq/kWh, the minimum 2 and maximum 20 g CO_2-eq/kWh. Solar photovoltaic electricity generation emitted 65.05 g CO_2-eq/kWh, with the minimum recorded being 13 and maximum 190 g CO_2-eq/kWh. Wind produced average emissions 17.63 g CO_2-eq/kWh, with a minimum of 3 and a maximum of 41 g CO_2-eq/kWh, whereas biomass created average emissions of 51.05 g CO_2-eq/kWh with 1 being the minimum and 130 g CO_2-eq/kWh being the maximum.

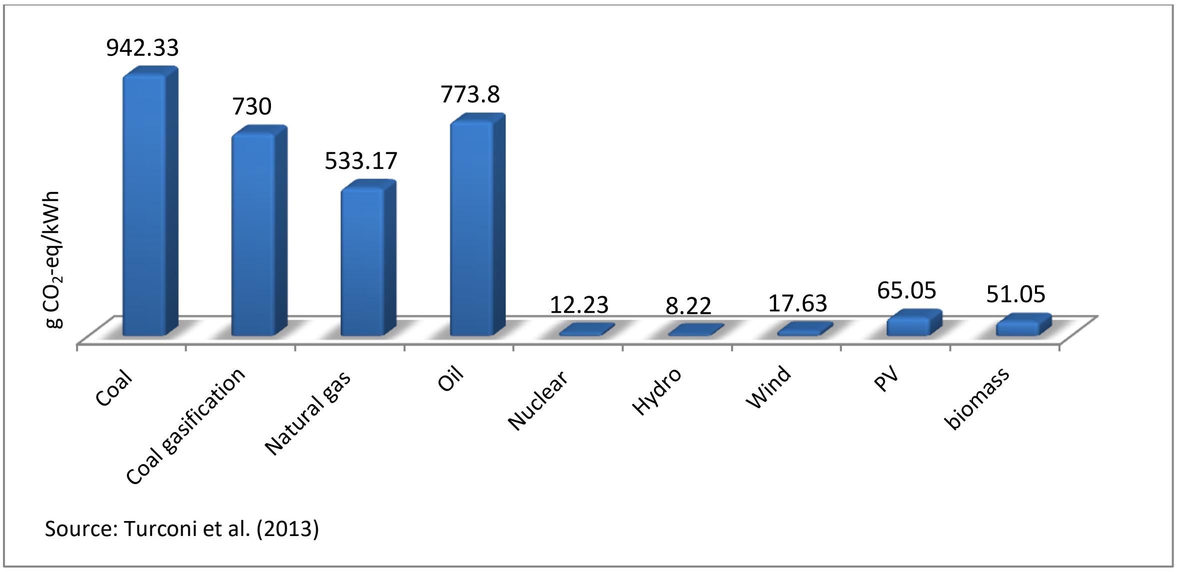


Figure 12: Emissions from Electricity Generation in g CO_2-eq/kWh by Source

Messagie et al. (2014) found that electricity generation from coal produced 885 g CO_2-eq/kWh. Electricity from natural gas emitted 642 g CO_2-eq/kWh. Wind electricity generation produced 11 g CO_2-eq/kWh, while the Belgian mix produced 190 g CO_2-eq/kWh.

Nealer et al. (2015) represented electricity made from various sources in terms of miles-per-gallon green-house-gas-equivalent (MPG_{ghg}), demonstrating how an EV being charged by a certain power source would perform in terms of fuel economy on a Well-to-Wheel assessment. To calculate MPGghg, the 2014 average sales-weighted efficiency of 0.33 kWh/mile was used and multiplied by each power source's emission factor. They found oil and coal to yield 29 MPGghg each, Natural Gas 58, Geothermal 310, Solar 350, Nuclear 2,300, Wind 2,500 and Hydro 5,100 MPGghg. These MPGghg represent electricity at the wall outlet and include emissions from power plant feedstock extraction, their combustion and power plant construction, with the latter being the only emissions stated for solar, wind, geothermal and hydro sources.

Nealer et al. (2015) divided the US into 26 regions according to the grids which supply them power. They further ranked the regions according to their MPGghg. The ranking includes "good", meaning that a typical EV driven in this region would cause global warming emissions equal to those caused by a gasoline vehicle with a fuel economy of 31 - 40 MPG. Further up the scale is "better" where EVs compare to gasoline vehicles with economies of 41 - 50 MPG, and "best" where the emissions compare to a fuel economy of more than 50 MPG, with certain BEVs in these regions going even above 100 MPGghg. To place this into perspective, an average new gasoline car purchased in the US in 2015 had a fuel economy of 29 MPG. Here one must also note however, that these rankings include the assumption of charging from baseload power, and not marginal or peaking power plants.

A positive trend is reflected in the fact that in 2014 they found 66% percent of the US population to live in regions where powering an EV produces lower global warming emissions than a gasoline car with a fuel economy of 50 MPG, which is an improvement from 2011 when the proportion of Americans living in such areas amounted to 45%. Concurrently the population living in the US regions ranked lowest by the authors according to emissions, dropped from 17 to 12% from 2011 to 2014 (Nealer et al. 2015).

It is important to note that energy considered renewable is not completely free of emissions. For instance hydroelectricity, which is categorized as the largest source of renewable energy, can create as much CO_2 equivalent emissions during early years of operation as a natural gas powered plant with the same output. This is caused by the decaying vegetable matter trapped behind certain damns, which generates CO_2 and CH_4 from aerobic and anaerobic decay, respectively. In addition, as fossil fuels account for 86.3% of all commercial energy, the energy for constructing and maintaining renewable plants will come from fossil fuels, thus producing certain emissions (Moriarty et al. 2017). Additional findings regarding emissions from electricity generation are presented in the figures in Appendix 2.

Electricity Generation Schemes

Most literature reviewed takes into account average emissions from electricity production when determining the environmental impact, which only give a rough estimation of the actual greenhouse gas emissions. It is important to note however that such estimation does not take into account the impact of the demand generated by EVs in relation to the other demand on the grid. Such interaction determines what kind of power plant would charge an EV at a given point in time.

All electricity consumed is not the same, not only in terms of the source that produces it but also in terms of function. Electricity is grouped in several different markets and each has a different control regime. Amongst them, the literature differentiates, but does not limit to, baseload power, peak power, spinning reserves and regulation. Each has a different control method, response time, duration of service, contract terms and price.

According to Kempton et al. (2005), baseload power is constantly provided by large power plants with low kWh costs, such as efficient coal plants, nuclear, natural gas or hydro. It is typically sold through long-term contracts and serves for round the clock reliable production at a low price. The power plants designated to provide baseload power typically have very large upfront fixed costs since they are built to be as efficient as the latest technology allows and to be operational for decades.

On the other hand, there is peak power, which is generated or bought only during times of day that are expected to be very demanding in terms of power consumption (Kempton et al. 2005).It serves to cushion the demand that would exceed baseload power, which occurs as a result of mass simultaneous demand from many users, such as in the evening when most people come home from work and turn on the electric devices in the house. Since peak power is required only in certain times, of peak demand, it is supplied by power plants that can be readily switched on and off, which are not required to be operational for long periods of time. These power plants are typically inefficient, but require considerably lower capital costs. The savings in infrastructure are offset by the reduction in efficiency and thus higher costs per kWh, but justified by the short time of operations.

Further, power can be supplied from so called spinning reserves, which can provide additional generating capacity very quickly upon request. The plants that provide spinning reserves are run at low speed so they are already synchronized to the grid, and consequently can provide the fastest response in case there are unplanned generation losses. Typically, they are paid for by the amount of time they are available and ready, even if no energy is actually produced, plus the amount of energy delivered if the reserve was called upon (Kempton et al. 2005).

Additionally, regulation, automatic generation control (AGC) or frequency control is used to fine tune the frequency and voltage of the grid matching generation to load demand. AGC must be under direct real time control of the grid operator, who sends signals to the generating unit, which should be able to react almost instantly, increasing or decreasing generation from the baseline level (Kempton et al. 2005). These actions are either called regulation up or regulation down, and a generator can contract to provide either of the services for a period, as they will never occur at the same time.

The kind of electricity employed depends on demand trends which are reflected in certain times a particular electricity type is deployed. Thus time is a main determinant for the type of electricity used. Van Mierlo et al. (2015) assessed the Belgian electricity grid in 2011 and the impact charging times have on emissions. They found that if charging is shifted from peak to off-peak hours, the WTT CO_2, PM, NO_X and SO_2 emissions per kilometer can be reduced by 12%, 15%, 13% and 12% respectively assuming the 2011 Belgian electricity mix.

Rangaraju et al. (2015) also assessed the impact of the time of the charging on the emissions performance of BEVs by differentiating peak (8:00 till 23:00) and off-peak (midnight till 8:00) charging in Belgium, assuming an average energy consumption of 18 kWh/100 km, based on real-time monitoring of test vehicles. Their research found that BEVs produced 36 g CO_2-eq/km when charged during the peak period, while producing 32 g CO_2-eq/km when charged during the off peak period. This trend was also true for the other pollutants associated with energy production and vehicle propulsion. Hence, the respective peak and off peak emission values were 0.012 and 0.011 g/km for particulate matter (PM); 0.031 and 0.026 g/km for nitrogen oxides (NO_X); and 0.013 and 0.011 g/km for sulfur dioxide (SO_2) (Rangaraju et al. 2015). This is so because of the varying nature amongst baseload and peak power plants. In the case of Belgium nuclear plants are mainly used for meeting the baseload, while natural gas, coal and other flexible producing units are used for filling up the fluctuating demand.

Under the assumption made by Van Mierlo et al. (2015), where a BEV has a life span of 14.1 years with driving distance of 209,470 km, charging solely during peak periods would emit 7,540,920 g CO_2-eq, whereas charging during off peak periods would emit 6,703,040 g CO_2-eq over the life time of a BEV. The 11% difference would then amount to 837,880 g CO_2-eq per vehicle that could be saved, only by capturing the adequate charging time. The yearly difference in emissions amounts to 59,424 g CO_2-eq, which alone may appear insignificant, but when scaled to the number of EVs, current and planned, in Belgium, Europe and wider, this reduction starts becoming a very significant savings potential. Moreover, if we compare the BEVs Belgium off peak scenario to the emissions for diesel of 145 g CO_2-eq/km, cited in the same study (p. 5), amounting to 30,373,150 g CO_2-eq across the vehicle's life, we get a total difference of 23,670,110 g CO_2-eq or 1,678,731 g CO_2-eq per year.

Furthermore, electricity can be viewed in terms of average and marginal. Average electricity aggregates all sources of electricity and determines its impact, such as emissions in this case on the basis of each source's grid contribution proportion. On the other hand, marginal impacts are estimated by identifying which power plants, or types of power plants, are likely to be deployed or increase their output when new electricity demand is added to the electricity grid above and beyond the demand that already exists (Nealer et al. 2015). Both types are useful in terms of policy.

In order to evaluate emissions from today's demand on grid mix and to evaluate how this mix changes over time, assessing average emissions is the appropriate approach. It treats all electricity on the grid as a shared resource and thus does not capture the short term marginal emissions impact on a grid from charging an additional EV, but it reflects changes that are reflecting non-marginal load generation in a given country. It also allows for cross temporal comparison, capturing past and future emissions data, as well as ongoing changes to the grid as a whole Nealer et al. (2015).

The majority of examples presented in this paper deal with average electricity accounting. However, numerous analyses are based on marginal emissions approaches that assess the potential impacts that the growing amounts of EV charging have on grids and accordingly emissions, including Tamayao et al. (2015), Graff Zivin et al. (2014), Elgowainy et al. (2010), and Hadley and Tsvetkova (2008). According to this literature, the marginal analysis can be divided into short and long-term approaches.

The short-term approach examines how the electricity grid responds instantaneously to a new load. Under this method, emissions from charging an EV are tied specifically to how the grid would respond to the new load, all other factors being fixed. Increased demand of electricity is met through increased generation output at a power plant that is operating at less than full output, which is typically, a natural gas or coal power plant. Hence they are considered the marginal generation sources. In contrast, sources such as nuclear, hydro, wind, and solar are very limited in their ability to vary output and cannot be considered for such purpose. Hence they provide non-marginal generation (Nealer et al. 2015). Therefore, no matter the proportion of electricity moved to renewable resources, there may still be fossil fuel power plants acting as marginal power plants, able to respond to abrupt shifts in demand of electricity. Accordingly, an EV charged on a grid with no renewables and one charged on a grid with 50% renewables may have the same emissions under a marginal emissions analysis, which would produce an environmental impact similar to or higher than that of an ICEV.

As time progresses and the numbers of EVs increase, the proportion of demand they cause will be very significant and will eventually need to be addressed through a combination of increased energy efficiency, better utilization of current sources and new electricity generation capacity. In such case, a long term marginal analysis may be needed as the short term approach only considers existing capacity. The long term approach is also known as a consequential life cycle approach. It evaluates gird responses over extended period. It estimates the effects on the grid without a new load and compares them against the effects from a new load, thus allowing researchers and policy makers to account for long-term changes such as power plant retirement, new power plant establishment and expected raises in electricity demand stemming from EVs. As it is a long term approach it is useful for policy regarding both the transportation and electricity sector.

Electricity Conversion

One additional consideration that must be taken into account when comparing emissions attributed to different sources of electricity is the manner in which they are converted to primary energy. According to Moriarty et al. (2016), it is very difficult to pinpoint the direct emissions of different renewable energy sources, as the technologies and circumstances vary greatly not only between the different energy sources but amongst the same source in different locations. This is so because the various methods of creating electricity from primary energy are not equally efficient in doing so, and hence have different efficiency coefficients for the processes involved when they are compared. For instance, Ellingsen et al. (2017) reported that EV charging under an average European electricity mix of requires 521 g CO_2/kWh at plug, and 462 g CO_2/kWh at plant.

Moriarty et al. (2017) indicate that just as ICEVs combust fuels to power a car, while EVs use electricity to give charge to a battery, so do certain power plants, as for instance nuclear or geothermal, use heat energy to generate electricity while others achieve this through movement of turbines, as would the case with hydro or wind powered plants be. Hence the conversion efficiency assumed can greatly influence the calculations of an amount of resource needed to generate a certain amount of electricity. As Moriarty et al. (2010) point, for non-thermal renewable electricity different authorities use different conversion methods. Due to this fact as well, a direct comparison amongst ICEVs and EVs or even amongst EVs being charged from different grids should be interpreted with great reserve.

The International Energy Agency (IEA 2017) converts hydro, photovoltaic cell (PV), and wind electricity on a 1:1 basis, while, British Petroleum (BP 2016) converts hydroelectricity to primary energy in the same manner as for nuclear electricity, where it takes the basis of thermal equivalence electricity in a thermal power station assuming a 38% conversion efficiency, so according to their method the energy efficiency amongst the various non-fossil sources would differ greatly. For instance if comparing a grid that uses 100% nuclear power to a grid that uses 100% hydro, the energy efficiency would be the same according to BP, while much greater in favor of hydro according to the IEA. Just as if comparing a grid using 100% hydro to a grid using 100% PV, their efficiency would be the same according to IEA, while that of hydro would be much lower according to BP. Consequently, the emission comparison interpretations amongst vehicles using different propulsion systems and grids are very arbitrary.

In view of the ever increasing tendency towards renewable energy on the global scale, if a uniform method with regards to efficiency for converting primary energy to electricity is not established amongst the scientific community, this problem could get much worse. But currently, electricity grids operate on a combination of fuels, both fossil and renewable, where the switch to non-fossil fuels occurs very gradually, still allowing leeway for the establishment of efficiency conversion standards.

Electricity Demand of EVs

The assessment on the impact of EVs on GHG emissions can not only be based on average emission factors but has to consider the interaction with the electricity market.

As Helms et al. (2010) point, electric vehicles are an additional electricity consumer that leads to the use of power plants which would not have been used otherwise. The amount of such capacity depends on several factors and determines the amount of additional EVs that can be sustained. The main factors influencing the amount of electricity that would be available for any additional consumer include the amount of total demand on the grid, the composition of the grid, the time a demand excerpted, the location of the grid and the policy governing a grid.

The total demand at a certain point in time would also give consideration to the vehicle's charging capacity, charging voltage, and the load of the connected socket. Hence, there are times when there is a high demand load on the grid with not as much electricity left over as there would be in times of low demand. Charging time directly determines whether an EV is going to use peek or baseload power. The duration of charging influences the times and intervals, when a vehicle can be charged thus influencing the type of power used for charging.

The structure of the power sector or of the grid itself significantly influences the load EVs have on that grid. Since the environmental impact of a unit of electricity consumed depends on the source of electricity and the manner in which it is made, special consideration must be given to the composition of a grid. It would determine the baseload to peak power ration, the amount of demand it could take at which time, and the emissions generated per unit of electricity and time.

With respect to the structure of a given grid, renewable energy sources are playing an ever growing part. They are highly dependent on a country's climate, geography, policy, development level and financial resources. Whereby a country's policy, development and economic situation can be prone to change, climate and geography are relatively fixed determining factors, which dictate whether wind, hydro, solar or some other form of renewable energy can be installed. The climate and geographic consideration of renewables are also the reasons why most renewable energy, with the particular exception of hydro, is so fluctuating. Additionally, certain renewables such as solar or tidal power are functions of time.

In any case, new consumers constitute additional demand that cannot be viewed independently of the other forces in play. The amount of vehicles that could be integrated into existing grids without installing additional capacity varies across the literature.

Hacker et al. (2009) report that in the case of Germany, a large scale introduction of EVs into the vehicle fleet, amounting to 50 to 100% of the entire fleet of the country, would increase the overall electricity demand by slightly over 10%. They also report that 100,000 EVs would need about 1,750 GJ or around 486 MWh of energy per day. This is about 4 times more than what was reported by Peas Lopez et al. (2009), who estimate that 6,608 EVs would require 111 MWh in one day. Hecker et al. (2009) further estimate that on the basis of their reporting, 1 million EVs, or 2% of the fleet at the time of assessment, which was also Germany's target for 2020 at that time, would require 1.77 TWh per year, which could be supported by Germany's grid. Helms et al. (2010) also agree that Germany could support up to 1 million electric vehicles, creating about 2 TWh of additional consumption, which equates to 0.3% of Germany's 2010 gross electric consumption, without any additional investments in generation. Hacker et al. (2009) estimate, that Germany's target for 2030 of 5 million EVs would need 8.85 TWh per year. Mallig et al. (2016) note that in the case of the greater Stuttgart region in Germany, increasing the number of EVs could pose some challenges to the local electrical grid when exceeding the 10% share of automobile ownership.

According to the Deutsche Gesellschaft für Sonnenenergie (2007), 10 million EVs in Germany, would constitute additional energy demand of 30 TWh, with an average carbon intensity of 650 g CO_2/kWh. The European Road Transport Research Advisory Council (2009), estimates that 1 million EVs in Germany would require 1 TWh. Hartmann et al. (2009) place this requirement at 1.77 TWh, under condition that an EV would require 14 kWh/100 km, and estimate the total additional amount for 5 million EVs with the same consumption to be 8.85 TWh. The World Wide Fund for Nature (WWF 2009), place consumption somewhat above, between 15 and 20 kWh/100 km, estimating that additional load created by 1 million EVs in Germany would be 1.5 - 2 TWh. For 10 million EVs this would amount to 18 - 24 TWh, whereas 20 million EVs would require 36 - 48 TWh additional load.

According to Eurelectric (2009), a complete shift to electric vehicles in the EU-27 would result in just a 15% increase of total electricity consumption, from 3,100 TWh to 3,570 TWh, causing 470 additional TWh. EV consumption of 18 kWh/100 km is assumed.

The UK Department of Business, Enterprise and Regulatory Reform and Department for Transport (BERR 2008, as cited by the Ricardo Media Office 2009), estimates EV consumption at 11 - 16 kWh/100 km, so that 0.5 million EVs would require 4.2 TWh, and 6 million EVs would require 31 TWh additional capacity. The Ricardo Media Office (2009) performed an analysis on the load impact of 10% EV market penetration in the United Kingdom. They found that uncontrolled domestic charging coincides with the evening peek, and would lead to only 2% or 1 GW additional load for a 10% market penetration of EVs.

A study carried out by PricewaterhouseCoopers (PWC) in 2009, funded by the Austrian Climate and Energy Fund, assumed EV market penetration of 20% of the Austrian fleet in 2009, amounting to around 1 million vehicles, expected to take place between 2020 and 2030. This study also found that the overall consumption would result in just above a 3% increase in the overall electricity consumption, assuming EVs consume 18 kWh/100 km. Further, if these EVs would be used as additional capacity, then there would be a potential to reduce overall energy consumption by 8.4 TWh or 37%, as no additional power plants and grid reinforcements would be needed to cover the extra demand. The study further concluded that there would only be need for limited adaptation of distribution networks with regards to charging points. If EVs would be introduced all over the country, 16,200 charging points would be needed, where as 2,800 points would be needed if they were to be mostly introduced in cities, with estimated investments ranging between 111 and 650 million euros (PWC 2009).

With regards to time of charge, according to an assessment performed by Hadley and Tsvetkova (2006) on the Virginia and Carolinas grids in 2006, day charging would significantly increase load, as opposed to night charging. The demand of the grid they focused on would be met by gas-fired plants during the day, while a big proportion of coal would be employed during the night. Hence the grid in focus yields cleaner day time than night time charging.

WWF (2009) found that 20 million electric vehicles, charged for 5 hours, starting at 18:00 would produce an additional demand of 60 TWh per year, with the additional load being 33,000 MW. If a faster charging scenario of 2 hours would be considered, it would result in additional load demand of up to 80,000 MW for the same amount of vehicles if started charging at the same time. They found that even if charging would be shifted to 23:00, under a load management system, there would be a new peak even higher than the day time one, going up to 100,000 MW, concluding that such load demand would pose serious problems for the power supply in terms of production and grid capacities.

Mallig et al. (2016) simulated the demand of electricity on the mobiTop model, for the Greater Stuttgart Region, Germany, which has 2.7 million inhabitants, in the long and short term scenario, for the small, midsize and large car segments, with conventional and EV engines, also considering the context of other modes of transportation. The EVs were assumed to have a battery size of 18 kWh with a range of 115 km, while it was also assumed that charging stations were always available and at home charging possible. The scenarios included the possibility of at home charging only, as well as at home and at work charging, for various EV market penetration proportions (p. 4).

For every scenario electricity consumption was lowest in the early morning and steadily increased until it peaked at 18:00, which is consistent with people returning home from work and plugging in their EVs. After this point consumption starts declining again until it reaches its lowest point early morning of the next day. The scenario with at work charging as well saw an additional peek at around 8:00, which is consistent with people arriving to work and plugging in their EVs there.

According to the literature and the examples discussed there are several important implications EVs can have on the electric grid and load demand, dependent on the time and manner of charging. Regardless of the extent of market penetration, that electricity demand for charging of electric vehicles is highly temporally and spatially concentrated, around working times and zones.

Unplanned charging increases peak demand, especially since then most charging occurs during the evening where additional load significantly increases demand load levels. Unmanaged charging can also lead to charging after every trip which further contributes to peak demand increases, especially if coupled with fast charging that requires higher capacities. Nighttime charging can ease the demand, as it uses more baseload power, but in cases of high market penetration of EVs, it can cause peaks which may be greater than in the day. Nonetheless, nighttime charging may be cleaner than day time charging in certain grids.

Increased peak demand has certain positive aspects, as in some grids it forces utilization of expensive power which may be lower in CO_2 than the base, as for instance when pumped hydro storage fulfills this role. On the other hand, increased utilization of base and medium load power plants would lead to increased competitiveness of expensive long-term power plants. Ultimately, increased load demand, especially considering higher penetration, would require additional investments in generation and grid capacity in the long run. However, load management systems could ease this transition and significantly increase market penetration of EVs as well as the utilization of renewables during their charging.

Number of EVs (in millions)	Energy Requirement (in TWh)	Source
0,5	4,2	Ricardo Media Office (2009)
1	1	ERTRAC (2009)
1	1,77	Hartmann et al. (2009)
1	1,5 - 2	WWF (2009)
5	8,85	Hartmann et al. (2009)
6	31	Ricardo Media Office (2009)
10	30	DGS (2007)
10	18 - 24	WWF (2009)
20	36 - 48	WWF (2009)

Table 2: Energy Requirements of Varying Market Penetration of EVs by source

Electricity Demand Management

As discussed in this paper, market penetration of EVs will have significant implications on the supply of electricity. The extent of EV market penetration a grid can sustain varies, depending, amongst other things, on the grid capacity, composition and planned demand, as well as policy, the kinds of EVs, charging methods, location and charging time. Eventually, as the amount of EVs increases, new generating capacity will have to be installed to meet this new demand. However, this additional demand can be managed, thus enabling a grid to sustain a much greater proportion of EVs before the need for new capacity arises. This approach can also contribute to an increased utilization of renewables, and therefore a reduction in overall CO_2 emissions.

Pecas Lopes et al. (2009) identify that a main issue with EVs is the fact that the time when they would most likely be charged is the time of peek day demand. This is so because the same factors that cause peak demand are responsible for setting the charging time. Namely, when people get home from their jobs, around 18:00 is when they are most likely going to begin the bulk of their electrical consumption, including charging their EV. This poses challenges in terms of EVs' contribution to the reduction of CO_2 emissions. They would thus contribute to the usage of peak power resulting in higher CO_2 emissions per kWh. In addition, there would be not enough capacity to support large market penetration of EVs without building additional power generating infrastructure, severely limiting the contribution EVs can have in the transportation sector.

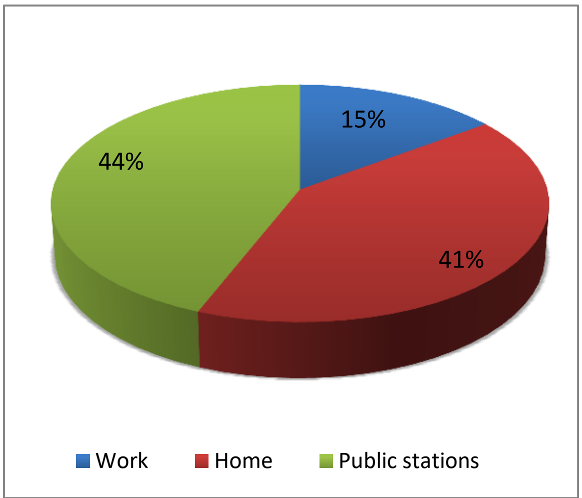


Figure 13: Survey response frequency for indicator: Main charging place of EV

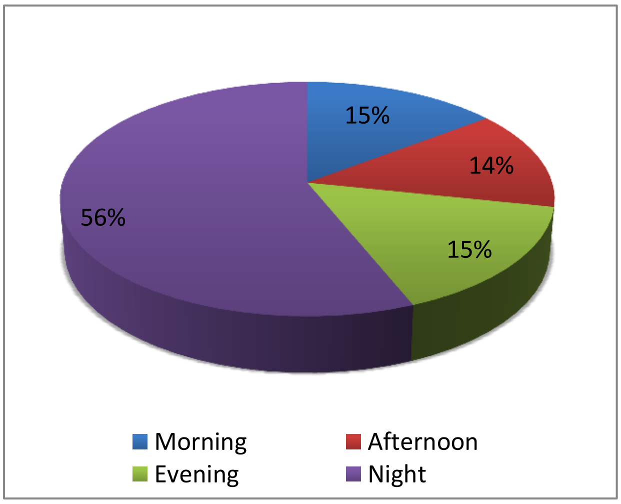


Figure 14: Survey response frequency for indicator: Main charging time of EV

This issue can be mitigated however through various methods that attempt to shift the time of charging so to exploit not only power availability, but also power that is generated by renewable sources. The methods can be as plain as consumers being disciplined and informed so that they can plug in the vehicle at the right time, or as complex as smart charging integrated with energy management systems. Amongst the institutions tackling this issues is the Institute for Energy and Environmental Research (IFEU), based in Germany, which is performing detailed modelling to study the interaction between mobility and the electricity sector since 2007. It identifies grid restrictions, emission trading, energy price elasticities and political constraints, as well as smart metering, amongst the manners of managing demand.

One way EV users could be stimulated to charge their vehicles during off peak demand or when the contribution of renewables is highest would be a dual tariff policy or a time resolved policy. Such policy is meant to be effective through charging less for electricity during certain times of day, when demand is not at its peak. This economic incentive was assumed to contribute to 25% of EV owners in Portugal switching their charging times (Pecas Lopes et al. 2009). Such policy would also need to be strongly aligned with current data on renewable generation, as to avoid increasing the contribution of coal based mid load power plants.

Such policy could stimulate night time charging, which is less emissions intensive in certain grids. It would for instance be beneficial in the case of England where, according to the Department of Business, Enterprise and Regulatory Reform and Department for Transport (2008, as cited by Ricardo Media Office 2009), mainly hydro and nuclear are employed during the night. The case in the Netherlands is similar according to the Netherlands Environmental Assessment Agency (PBL 2009), where baseload is also comprised of relatively cheap coal and nuclear power, with large nighttime wind potential, while peak power is provided by costly gas-fired power stations. In France, where majority of baseload power is nuclear, nighttime charging would bring about CO_2 emission reductions, according to the European Association for Battery Electric Vehicles (2009).

On the other hand, the literature also indicates that an increase in nighttime demand may not be so beneficial for reduction of overall CO_2 emissions, as in numerous grids night time generation is more emission intensive than during the day and even during peaks. In such grids, as is the case in Germany in 2009 according to Ilgemann, where baseload power is comprised of emission intensive lignite power plants, the efforts were to reduce this consumption. Thus such purpose of EVs would not be desired. Moreover, the WWF (2009) found that shifting charging to night time resulted in an even bigger peak than the one observed during the day.

Hence, according to the literature a plain shift to a particular time, performed by the drivers themselves may not be the most efficient way of electricity utilization. A dual tariff policy may then be prone to creating new peeks and shifting the problem temporally. Furthermore, many EV owners are constrained by factors other than price, which may limit their charging options, such as the unavailability of charging plugs at their work or sleeping patterns contrasting the less expensive times.

A much more effective method still being developed is smart charging, which allows EVs to charge at the point when electricity is coming from the least expensive and most clean source. It is based on a hierarchical control structure, where all elements connected to the grid as well as the grid's state is constantly monitored, enabling efficient management, preventing congestion and controlling voltage (Pecas Lopes et al. 2009). Practically, an EV connected to an outlet does not start charging instantaneously, but at a time when the grid load is not too high and the proportion of electricity made up from renewable sources is at its highest. According to the assessment performed in Portugal by Pecas Lopes et al. (2009), such charging strategy would provide enough economic incentives to persuade 50% of EV owners to allow such a hierarchical system control their charging. This system is superior to the dual tariff approach as it is not based on the user's will and ability to comply with it, thus one can plug an EV when sleeping and the system would charge their vehicle in the most efficient manner. However, this approach also is heavily reliant on the technology being available, so not only is a charging point required, but it must also be integrated, which may not be the case at every EV owner's place of work.

Pecas Lopes et al. (2009), note that the grid in Portugal that was focus of their study could support a maximum of 10% EV integration out of the total vehicle traffic, when no charging strategy is applied. They also conclude, that under the dual tariff system the integration limit would increase to 14% of the total vehicle fleet. In the case of smart charging, 52% of the vehicle fleet could be converted to electric and still sustained by the grid. In the maximum conversion to EVs case under smart charging, Peas Lopes et al. (2009) found that the peak load would increase by only 11%, which is not a large increase considering that 52% of vehicles in the area in question would equal to 6,608 vehicles, now converted to EVs, requiring 111 MWh in one day. Similarly, Hacker et al. (2009) report that in the case of France, 4 million vehicles could be integrated into the grid seamlessly if an adequate charging strategy was in place to avoid peak demand. Mets et al. (2011) also found that uncontrolled charging adds to the evening peek of electric power demand, while the smart charging strategy can avoid this, whereas a smart charging strategy where the vehicle can also provide power to the grid can even reduce the evening peek of electrical demand.

A smart charging strategy can be updated to serve various purposes, such as to minimize losses or maximize renewable energy usage. The concept of Smart-Metering can also be exploited in the EVs management context through onboard metering device that receives periodic energy information about prices and origins of power in regions where charging can take place. Thus smart charging can also be included into more complex integrated energy systems.

One such system is elaborated by Keiser et al. (2011), which integrates the driver, grid operator and car manufacturer. They are coordinated through a planning system, a control system and an authentication, authorization, and accounting (AAA) system. The planning system plans the charge-discharge schedule, the control system manages the interaction between the hardware components, the sensors and the planning algorithm accounting for the vehicle's and charging station's states, while the AAA system accounts consumption and supply of energy to the customer. Keiser et al. (2011) modeled the system on telecommunications technology which provides unrestricted non-discriminatory access to all parties involved.

They performed a simulation on a gasoline Mini Cooper S and electric Mini Cooper E, under planned and unplanned charging, from an energy mix of 20% nuclear and fossil energy with an emission footprint of 683,80 g CO_2/kWh and 80% wind energy with an emission fingerprint of 24,00 g CO_2/kWh. The Mini E, had an average consumption of 0.2083 kWh/km, and the simulation stretch spanned 133.28 km. The Mini S produced overall CO_2 emissions of 18,126 grams for the whole simulation. The Mini E under unplanned charging produced 4,283.53 g CO_2, while the same vehicle produced 2,064.57 g CO_2 under the planned charging system. The experiment indicates that emissions and power requirements could be reduced by about 50% under the integrated planning system, as well as allow charging when the surplus of renewables is available (Keiser et al. 2011).

One important aspect of integrated demand management is the grid side information about the power it carries at any certain point in time, such as the proportion of each source that comprises it, its price and the kinds of power plants being engaged. For instance, Germany's grid operator TransnetBW publishes real time data on the amount of electricity from each source that makes up the power mix and the load on the grid. Through such data, EV charging times could be adapted to coincide with the time when the highest proportion of renewable energy is fed to the grid. Developments in this regard, aiming at ensuring EVs are charged with an ever higher proportion of wind power are also being undertaken by the Vattenfall V1.0, Gesteuertes Laden V2.0, and Gesteuertes Laden V3.0 projects (2013).

Fraunhofer AST (2018) has a research project called eTelligence and Systemforschung ElektroMobilität (FSEM) which primarily focuses on smart grids, but also tries to further incorporate EV charging attempting to make use of renewable energy. The eTelligence project has a component called Grid Surfer dedicated primarily to this issue. The focus of this project is not only to ensure EVs are charged from sustainable energy but also to make the EVs demand response agents through V2G technology. In addition, the incorporation of charging stations through this project will also include planning, reservation, payments, taxation, battery capacity and 2-way charging possibilities. (p. 10 and 13). Power generation, energy transport and distribution are examined. The interface between power supply and vehicle is analyzed. In terms of the vehicle itself, innovative solutions for energy storage and drive technology are observed.

When scaling the number of vehicle's on a continental or global level, we can note that the current EV numbers are still far from the 10%. However, the proportion of new vehicles sold made up by EVs is rapidly growing, which is a trend that may very well continue in view of EVs marketed role in the fight against global warming. Thus, charging practices must be adjusted, not only to support an ever growing electric fleet but to reduce emissions across all sectors.

Coordinated approach through a load management systems would take into account the specificities of a grid and coordinate vehicle charging, enabling a higher integration of vehicles and proving to be a better solution in terms of emission reductions, as it aligns demand from EVs and the amount of energy produced from renewables. In addition, an increasing load on baseload power would provide financial incentive to profitably replace CO_2 intensive peak power plants which require low-capital, with capital intensive plants envisioned for continuous operation, which fare much better in terms of CO_2 emissions and other air pollutants. To push the best demand management systems and policies supporting them, involvement and will of all stakeholders is needed. Nevertheless, if EVs increasing market growth continues, a point will be reached when additional infrastructural investments in the power sector with priority given to EVs will be unavoidable.

Vehicle to Grid

The intermittent nature of renewables is a major obstacle in the way of integrating them in the power sector and replacing traditional fossil fuel power plants. Much literature including Kempton et al. (2005), Keiser et al. (2011), and Moriarty et al. (2017) identify such traits of renewables as the reason why they cannot be a reliable substitute for baseload power generation. It is difficult to integrate a source of power that is very abundant for certain periods, but virtually non-existent for the remainder of the time, such as solar and wind power. One solution for this issues would be the option to store this energy when it is abundant and use it at times when it is not. Energy storage is a complex matter that is being explored through various means. Some of the current technologies include battery packs, pumped hydrogen, hydrogen electrolysis, conversion to methane and methanol. However, most of these storage possibilities are still relatively inefficient, yielding under 50% efficiency. In addition, they are very expensive, difficult to scale up, and cause additional energy consumption and thus emissions (Energy Storage Association 2018, Seidel et al. 2016, Moriarty et al. 2017). Storing renewable energy might also increase its price for real time use, as most of it would be tied up in storage projects, making it scarce.

One way of storing energy is by using the batteries of EVs. The EVs would be plugged into the electricity grid and would charge at times when electricity from renewables is abundant. In turn, they would feed power back to the grid when demand exceeds generated supply or no renewable sources of power would be available. This is known as the Vehicle-to-Grid (V2G) concept.

Although it is not possible to pin point what electricity comes from which sources, grid operators can determine the proportion of which resources feeds into the grid at a specific time. In such manners EV charging times can be aligned with highest proportions of renewables, maximizing their utilization, enabling EVs to achieve greater CO_2 reductions in the transportation sector. The batteries can also be used in anticipation to store more energy than they need, when the proportion of renewables is high. This additional energy would be sold back to the grid in times of high load preventing peaking power plants, which are often CO_2 intensive, to be utilized. In addition, the scalability of this storage would occur with market penetration of EVs, which is taking place independently of this concept. Thus additional investments into energy storage, as well as additional energy consumption from energy storage technologies could be avoided.

There are however certain challenges to the V2G concept. The times when charging would most exploit generation of certain renewables and the time when selling electricity back to the grid would alleviate peak demand contradict with the movement of most vehicle owners, as already elaborated. Most charging would occur in the evening or night, while solar power can only be produced during the day. Under current battery capacity and driving ranges, drivers would be very limited in terms of mobility, as not to drain the battery so it can serve its grid capacity extension purpose. Moreover, the V2G approach would contradict with the concept of car-sharing, which is also making way in terms of CO_2 reductions in the traffic sector. According to Moriarty et al. (2017), at present vehicles are on the road for only 3 - 4% of the time. But the aim of car sharing is to intensify the amount of time cars are actually driven, thus reducing daytime charging and grid storage opportunities. Market penetration of EVs would also need to increase considerably in order for them to be able to provide any significant storage capacity.

Nevertheless, in a long term perspective, the V2G concept has potential to provide significant capacity reserves and to facilitate integration of renewables. This could only be achieved with an integrated electricity capacity demand planning management system that enables communication links between capacity of batteries of each vehicle, the grid operator and power suppliers. Thus charging would be adapted to the volatile nature of renewable sources, and powering the grid would be adapted to demand, eliminating additional load effect on conventional power plants (Hacker et al. 2009). According to Keiser et al. (2011), under an adequate management system, EVs could already support energy grids on a household or small local level, but with increased market penetration the size of the grid they could support would grow. Hacker et al. (2009) further note that the optimization of battery charging would also become attractive for utility companies as it would provide them a useful tool for managing the grid, especially with regards to the fluctuating supply and demand of energy.

A study performed by the Massachusetts Institute of Technology (MIT) in 2007 found that EVs can take advantage of the excess capacity generated during off-peak periods, store it and feed it to the grid again at a later time, thus balancing daily load variations. Consequently, baseload generators could increase their operation time. The Pacific Northwest National Laboratory also performed an assessment in 2007 (Kintner-Meyer et al.) where they concluded that around 85% of energy necessary to power full market penetration of cars, pickups and sports utility vehicles in the US, can be provided from transmission and distribution of electricity currently available. Thus a much larger proportion of baseload power can be utilized, which is beneficial due to a much lower cost, while the additional storage capacity of EVs can also facilitate the introduction of renewable energy, which may be beneficial for both vehicle owners and utilities. This would be especially significant for wind power, which according to MIT (2007) peaks at night, when much evening demand would be moved under a load management system.

On the other hand, Kempton et al. (2005) note that the V2G concept has been assessed in various markets and it would not be possible to provide baseload power at a competitive price. EVs, as energy storage, are constrained by the limited amount of energy they can store, short lifetime compared to conventional power plants and high costs of energy, which contradicts the nature of a baseload power generator. Nonetheless, EVs exhibit quick response time, low standby and capital costs per kW. These characteristics would make them suitable to provide peaking generation and spinning reserves. However, according to Kempton et al. (2005), as peaking duration requires 3 to 5 hours of availability, they would still need to undergo significantly more market penetration. Thus, they would be ideal for spinning reserves, as they would be paid for being plugged in and available, while incurring relatively short periods of actual generation demand.

Hacker et al. (2009), came up with a slightly different conclusion, as they find EVs adequate for spinning demands, but also for voltage regulation, emergency power and peak shaving or load levelling to power companies. They also note that, for instance in Germany, 1 million EVs could provide 14 GW of power capacity, which is 2 times more than total power available from pumped hydro storage capacities in Germany in 2009.

PWC (2009) performed an assessment on the impact of EV market penetration of 20% of the Austrian fleet in 2009, amounting to around 1 million vehicles, expected to take place between 2020 and 2030. This study found that the overall consumption would result in just above a 3% increase in the overall electricity consumption, but if these EVs would be used as additional capacity, then there would be a potential to reduce overall energy consumption by 8.4 TWh or 37%, as no additional power plants and grid reinforcements would be needed to cover the extra demand.

As EV and smart charging technology is still developing there are numerous speculation as to their potential. The literature expresses various degrees of benefits that can come about. On one hand EVs are assumed to be able to facilitate large scale introduction of renewables and support peak power demand, replacing dirty peaking power plants and causing great reductions in CO_2 emissions. On the other hand, there is much skepticism with regards to feasibility, taking into account drivers' charging patterns, the intermittent nature of renewables and technical limitations of EVs. Currently, market penetration of EVs is still low, as is the amount of electricity generated by renewables, and thus grids can absorb them as they are. However, as this proportions continue to increase, there will be a need to tackle this challenge. V2G technology accompanied by a smart charging management system have potential to contribute to this solution, but much technological advancements and EV market penetration still needs to occur.

Power Plant Emission Mitigation

Generation of power is an unavoidable necessity for our society in this day and age. Life without electricity would be unimaginable. Therefore power plants will continue to produce electricity for the foreseeable future. If the entire transportation sector switches to electric propulsion, it will create additional demand for which new electricity generation capacity will have to be built. If the transportation sector does not switch to electricity, the need for electricity will nonetheless still exist. Just as well, the transportation sector is not the only segment of society responsible for pollution and global warming. Accordingly, every sector is undertaking efforts to mitigate its associated contributions to climate change.

A switch to renewable power generation is uncertain, especially in the near future. Hence, fossil fuel power generation will continue to be the main source of electricity. Fossil fuel power plants of all kinds are exploring methods and technologies to reduce emissions. In addition to making a positive contribution to the environment, reduction of emissions can lead to economic benefits as well. By becoming more efficient in their supply chain and power generation, power plants will lower costs and increase speed of production. Further, in cases of government programs such as CO_2 permits, which are tradable on the market, a company can make a profit by emitting less as it will have more permits to sell. In addition, certain governments provide tax cuts and other benefits for the reduction of emissions.

The efforts to reduce efforts are mainly technological. As already mentioned, power plants employ more efficient production techniques, such as CCGT or CHP. Other techniques relate to cleaning the emissions produced, such as particle control systems, flue gas cleaning, denitrification, electrostatic precipitators and desulfurization system installed on some power plants (Treyer et al. 2013). One such concept, which has been given much attention in the electricity generation industry is Carbon Capture and Storage (CCS).

The concept of isolating the CO_2 produced in combustion or conversion processes and injecting it into suitable geological formations has been gaining credibility in the last few years. There are many such structures available in most areas of the globe from depleted gas and oil fields to salt domes and aquifers. CO_2 injection can also be used to enhanced and prolonged production from ageing oil and gas fields. Pilot projects are already in operation in the oil and gas industry (Treyer et al. 2013).

Carbon Capture and storage consists of separating CO_2 from other gases, compressing and liquefying it, transporting it to a site where it will be injected into suitable geological formations. Suitable sites include depleted gas and oil fields, salt domes and aquifers (Moriarty et al. 2011). Recently huge breakthroughs in the method have been achieved in Iceland, where it was established that injection of CO_2 into basaltic rock causes CO_2 to quickly turn into rock itself thus preventing its spread into the atmosphere (Sigurdur et al. 2014). Such projects are still in the pilot phases and much dispute over the effectiveness of such technology have been occurring, citing costs, excess energy requirements and spill-off negative environmental impacts as the grounds against. On the other hand, there are studies and pilot projects testifying to the success of CCS.

Therefore, although uncertain, CCS as well as other technologies are being researched and implemented. The amount of savings in emissions depends on the outcome of these technologies, but reduction in emissions are occurring. Accordingly, if significant breakthroughs occur and power generation from fossil fuels becomes significantly less carbon intensive, the shift of the transportation sector to electric propulsion would drastically reduce CO_2 emissions.

Pollution beyond CO_2

The goal of this paper is to assess the impact EVs have on climate change, and thus the focus is on Carbon Dioxide (CO_2) emissions. Emissions that contribute to global warming are converted into CO_2 equivalents, while other emissions are ignored. But these other emissions are also important consideration factors when assessing overall pollution produced by the transportation sector or any other sector. They spawn from a vehicle's supply chain as well as the use phase and have adverse impacts on human health and the environment, in addition to their contribution to global warming. This section will provide a brief overview of the types of emissions caused by the transportation sectors and some of their effects.

The types of pollution associated with transportation include the pollution emitted during the burning of fuels, the pollution associated with the production of a vehicle, the pollution associated with the extraction of resources for either production or combustion, and the pollution associated with the infrastructure necessary for the vehicles to operate including roads, garages, pumps and charging stations. With the exception of pumps and charging stations, most of the infrastructure is shared by all vehicles regardless of their propulsion technology and thus the focus of this section will be on pollution associated with the vehicles themselves.

In addition to CO_2, combustion of fuels, whether at a vehicle's tailpipe or at a power plant's chimney, produces Sulphur dioxide (SO_2), nitrogen oxides (NO_X), ammoniac (NH_3), non-methane volatile organic compounds (NMVOC) and particulate matter (PM) including dust and coal particles (EEA 2017, Van Mierlo 2017). Both, fuel feedstock and raw materials need to be extracted before they can be processed. This process depletes the earth of the extracted materials and requires energy, further contributing to the emission of the aforementioned pollutants, but it also leaves excessive disposal of mine tailings that contains Sulphur and heavy metals (McKone et al. 2001, Nordelöf et al. 2014, Van Mierlo 2017). Each of these pollutants has different characteristics in terms of lifespan, geographical dispersity and impacts. While their presence has adverse effects in general, certain combinations of these compounds lead to specific events.

The effects resulting from transportation pollutants include abiotic depletion, acidification, fossil and mineral resource depletion, local air pollution, photochemical oxidant formation, particulate matter formation, human toxicity, freshwater eutrophication, freshwater eco-toxicity, terrestrial eco-toxicity and noise (Held and Baumann 2011, Helmers et al. 2012, Hawkins et al. 2013, Egede et al. 2014, Moriarty et al. 2017, Van Mierlo et al. 2017). While certain effects, such as human toxicity, mineral depletion and freshwater eco-toxicity can be attributed to the supply chains involved in vehicle production, other effects such as terrestrial eco-toxicity, fossil depletion and GWP result from the use phase (Van Mierlo et al. 2017).

Photochemical oxidant formation refers to NOx and NMVOCs forming ozone on the ground level, which can have many adverse health and environmental effects if it occurs in densely populated urban areas. The ground level ozone is a local pollutant which is expressed in kg NMVOC equivalents (Van Mierlo et al. 2017). Particulate matter formation refers to fine dust particles found in the air emitted either directly from vehicles or created when SO_2, NO_X and NH_3 interact with the atmosphere. They are divided into PM 2.5 and PM 10 size categories, where the number indicates the maximum size of the dust particle parameter in micrometers. They are small enough to bypass a human's nasal hair and enter the lungs. Whereas PM 10 are associated with respiratory problems, the smaller PM 2.5 are linked to cancer and increased mortality (Nordelöf et al. 2014).

Human toxicity assesses harm to human health from both inherent toxicity and general source-to-dose relationship of the polluting substance. It is evaluated in terms of carcinogenic and non-carcinogenic compounds and is expressed in units of 1,4-dichlorobenzene equivalents, which is a well-known pesticide (McKone et al. 2001). In both electric vehicles (EVs) and internal combustion engine vehicles (ICEVs), the largest fraction of emissions contributing to human toxicity originates from mining for fuel feedstock and materials used in the manufacturing of a vehicle's body shell and other common parts (Van Mierlo et al. 2017). Mining wastes from nuclear, coal, copper and nickel extraction are amongst the resources that contribute to human toxicity the most (Nordelof et al. 2014).

Resource depletion is another adverse effect caused by the vehicle's production and use phase. Whereas mineral depletion results from the supply chain, fossil depletion relates to the use phase. For electric vehicles, lithium is the primary concern as it is the main component of the current battery technology (Gruber et al. 2010). However it is not the only component, hence cobalt, nickel, manganese as well as rare earth metals like neodymium are also given consideration (EC 2014). Nonetheless, as recycling develops their availability should be sustained. On the other hand, the fossil fuels used for energy generation cannot be recycling (Speirs et al. 2014) and their depletion is more worrisome, and one of the reasons renewable energy resources are being investigated.

Until recently, many countries have pursued the trend of switching from gasoline do diesel fuels as their yield better global warming potential (GWP) performance, as well as increased fuel economy. One such country is Belgium, the capital of which, Brussels, has a fleet consisting 65% of diesel and 34% or petrol vehicles (Van Mierlo et al. 2015). In 2012, Brussels' road transportation contributed to 67% of NO_X, 47% of PM 2.5 and 27% of CO_2 emissions (Willocx 2015). The daily average PM 10 limit in Brussels is set at 50 mg/m^3, but in half of its air quality measuring stations it is exceeded for 35 days during a year (Van Mierlo et al. 2017). The Brussels examples indicates the importance of addressing all pollution, rather than focusing on one factor at the expense of other. Even though CO_2 is the most responsible compound identified to contribute to global warming, other environmental and human health impacts are also worth considering.

Taking into account the environmental performance of EVs as compared to ICEVs in terms of pollutants other than CO_2, the literature is in agreement that EVs have a more intensive vehicle manufacturing phase, due to its storage battery (Notter et al. 2010, Hawkins et al. 2011, Oliveira et al. 2015, Sanfelix et al. 2015). Therefore, EVs contribute to higher human toxicity, freshwater eco-toxicity, freshwater eutrophication and metal depletion (Hawkins et al. 2012, Van Mierlo et al. 2017). Terrestrial acidification is the only impact assessed by Van Mierlo et al. (2017), where EVs fare better than ICEVs. Note should be taken that the reported findings are sensitive regarding assumptions about electricity source, use phase energy consumption, vehicle lifetime, and battery replacement schedules (Hawkins et al. 2012).

On the other hand EVs greatly outperform ICEVs in terms of local air pollution as they produce no tail pipe emissions, and all air pollution attributed to them is either caused by the vehicle production supply chain or by electrical power plants. EVs generate considerably less photochemical oxidant formation and PM than ICEVs (Van Mierlo et al. 2015). This benefits high congestion urban areas, as it shifts air pollution away from people improving their living quality (Moriarty et al. 2017). In this regard EVs also contribute positively by reducing noise (Egede et al. 2015). Nonetheless, the use phase still has a significant impact on all types of pollution for EVs and ICEVs alike.

Pollution impacts have the potential to be reduced in the production and use phase. In the production phase improvements in the mining process and waste management would lead to environmental benefits, with special contribution to human toxicity. Improved and intensified recycling mitigates resource depletion, as well as human toxicity. Expanded electrification and integration of more renewables into the grid will lead to reductions of toxic emissions in the use phase. Even though, EVs' reduction in local pollution is caused by shifting it, according to Van Mierlo et al. (2015), EVs are more energy efficient than ICEVs, thus the local pollution would not only be shifted but also slightly reduced. In addition, the shift of emissions from numerous tailpipes to several high chimneys on power plant, allows for more controlled discharge and facilitates emission management methods.

Consumer Attitudes

The primary purpose why any passenger vehicle is made is personal mobility. Cars exist to help people get from one point to another. They may be driven due to pure necessity, a way of life or simply to serve as a statement of status or style. Whatever the case, the way in which automobiles are used is completely dependent on the persons they serve. Whatever the emissions impact of any type of propulsion technology, environmental benefits can only be achieved if they are utilized in a certain manner. Therefore consumer behavior plays an essential role in a vehicle's GHG reduction potential. This includes a wide range of aspects, from vehicle ownership, across driving purposes and behavior, to charging patterns. Furthermore, their behavior is influenced by numerous factors, such as income, family status, residential location and type, work location, government subsidies, marketing, environmental awareness and education. All these considerations ultimately influence consumer uptake of EVs and thus the environmental impact this technology has.

Market penetration of EVs is a key factor that will determine their environmental contribution. As reviewed in the paper there are evidence and claims both for and against electric propulsion, when considering emissions caused when powered by different sources and charged under various schemes, as well as the impacts of production. In either case, the impact of EVs is only as significant as the amount of EVs serving for mobility and replacing conventional vehicles. Therefore consumers' perceptions and attitudes play a crucial role.

Considering the fact that the modern electric propulsion industry is still at its early stages of development, EVs have many shortcomings in relation to conventional vehicles that would deter consumers from purchasing them. Amongst the major disadvantages of EVs identified are their high price tag, limited driving range, long charging times, inadequate charging infrastructure, uncertain performance, maintenance costs and limited availability of models, as well as environmental concerns about battery and motor production (Helmers et al. 2012, Larson et al. 2014, Plötz et al. 2014, Pappas 2014, Egede et al. 2015, Ager-Wick Ellingsen et al. 2016).

As noted, the length of trips a person can travers in an electric vehicle is the main factor influencing consumer attitudes them. This depends on the driving range, availability of charging infrastructure and time it takes to charge a battery. Most EVs today can easily achieve a driving distance of up to

150 miles, while some, like the Tesla can drive up to 300 miles (Larson et al. 2014). Such range would be enough to cover the daily commutes of the great majority of users, as it is rare that someone commutes to work more than 150 miles in one day. Still it is just a fraction of the ranges of conventional vehicles, and does restrict the possibility of traveling. This problem is compounded by the fact that charging infrastructure is not available everywhere making it necessary for drivers to plan carefully their trips. In addition, very few models allow for fast charging, which takes about 20 minutes, still considerably longer than what it takes to fill up a gas tank. Most EV models need 3 - 4 hours to charge (Graham et al. 2014) , which is a great inconvenience when going on long trips.

Consumers also exhibit concerns about cost and reliability. The cost premium for an EV is $10,000-$15,000 per vehicle (Graham et al. 2014), an amount that significantly influences buying decisions. There are claims however, that this premium would be offset in the long run due to savings on fuel and maintenance, but this claims are countered by concerns about the vehicle's reliability, as there is little experience with long term ownership of EVs (Ager-Wick Ellingsen et al. 2016).

On the other hand, EVs have a certain appeal for consumers, inducing them to opt for their purchase. The main three factors making EVs attractive are environmental image, reduced fuel costs and technological innovation (Larson et al. 2014). Although there is dispute as to the environmental benefits of EVs, many consumers perceive them as being very environmentally friendly and attempt to associate with this image. Certain consumers take pride and joy in innovative technology, which EVs are a part of. Additionally, EVs offer different driving performance compared to ICEVs, such as high torque, powerful acceleration and low noise, which are aspects that certain drivers appreciate. Fuel prices are volatile and much higher than prices of electricity (Larson et al. 2014), and thus there is belief that the EVs' premiums will be offset by fuel savings. In addition certain consumers have installed photovoltaic electricity generation capacity in their households, which they may exploit for vehicle charging. It must be noted that the amount of driving needed to break even with the premium or achieve savings is variable and case dependent.

Certain governments also provide programs to facilitate the market penetration of EVs, such as subsidies, tax cuts, free charging and education (Stark et al. 2014). The effect of these programs is disputed. In the short run, they make the prospect of purchasing an EV more appealing as they significantly reduce their purchase price and cost of ownership. However, they are not sustainable, as they depend on the government's support, which may change its policy or not have as much funds in the future. In addition, such policies skew the picture about consumer's perception, thus leaving uncertainties as to how attractive this propulsion is on the grounds of its environmental and practical benefits.

To assess the extent to which the different factors identified in the literature affect the consumers' willingness to pay a premium for EVs as well as to identify trends amongst the stated factors a survey of potential consumers was performed and analyzed.

Survey Methodology

A statistical survey was performed to assess consumer attitudes about the environmental impacts of EVs and long-term money saving potential, as well as their willingness to pay a premium for EVs due to these factors. The sample included 213 participants with varying income, educational level, geographical region and age amongst other factors. A sample of the survey can found in Appendix 3. The goal of the survey was to assess the influence of demographic factors as well as perception about certain EV characteristics on the extent to which consumers perceive EVs to provide environmental benefits and money saving potential, as well as their willingness to pay a higher price tag for EVs for these reasons. To this purpose standard multiple regression analyses were performed, where the model includes 24 predictor variables. The full list of variables can be found in Appendix 4. A linear regression distribution was assumed. A stepwise multiple regression analysis was also performed in order to isolate the best combination of predictor variables. The software used was the Statistical Package for Social Sciences (SPSS) by IBM.

Survey Results

Out of the 213 persons who responded to the survey, the gender distribution was equal with 105 male and 106 female participants. The majority of participants, 76% fall within the lowest income bracket among the choices with yearly gross earnings falling between 15,000 and 30,000 euros. Most respondents, 44% stated that they had completed or were in the process of completing education at graduate level, while a significant proportion, 30% reported undergraduate studies as their level of education. 54% of participants reported currently owning a vehicle, while 78% reported that they would consider buying an EV.

In terms of extent to which participants perceive themselves to be environmentally conscious, the majority or 53% ranked themselves mid-high on the survey scale, or 4 on a scale from 1 to 5, where 1 represents the lowest extent and 5 represents the highest. In 42% of cases participants ranked themselves medium in terms of extent of technological knowledge, while a considerable proportion, 33% ranked themselves as mid-high in this regard. When scoring the perceived contribution of EVs to GHG reduction, 37% of respondents ranked it as mid-high, 27% as high and 24% as medium. The majority of participants expressed that they perceive EVs to be a long-term environmental solution to a mid-high and high extent, 36% and 27% respectively, whereas 19% perceive this to be true to a medium extent. In 37% of cases, the extent to which EVs are perceived provide long-term money saving was scored as mid-high, while it was scored as medium in 30% of cases and as high in 23% of cases. The scores for willingness to pay a premium for an EV due to the perceived long-term environmental benefits and financial savings, as well as additional survey results are presented in Appendix 5.

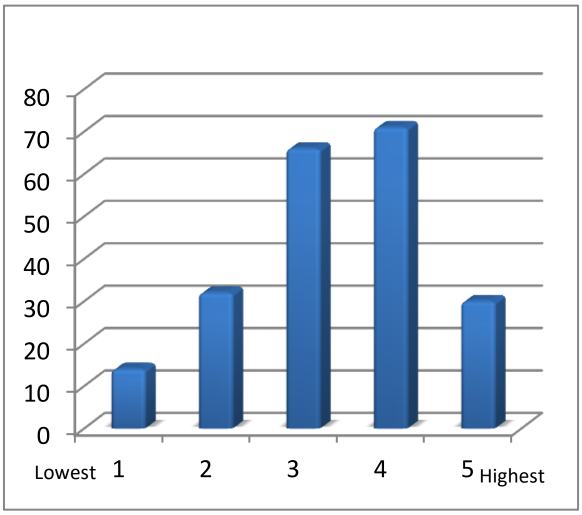


Figure 15: Survey responses for indicator: Extent of willingness to pay a premium for an EV due to perceived environmental benefits

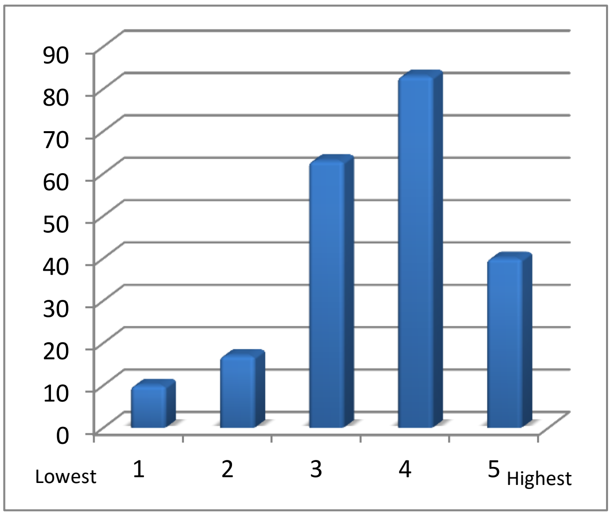


Figure 16: Survey responses for indicator: Extent of willingness to pay a premium for an EV due to perceived long-term saving potential

A standard multiple linear regression was run to determine the influence of the model and individual predictors on motivation for purchasing EVs. The regression returned an adjusted R^2 value of 0.160, with the P-value being equal to 0.001, and a standard error of 0.752. The predictor variables with a statistically significant standard Beta coefficient include the willingness to pay a premium due to perceived environmental benefits, willingness to pay a premium due to perceived long-term savings and whether a respondent would consider buying an EV, with the respective standard Beta coefficients, the significance level of these values and the part contribution of the predictors are outlined in Table 3.

Dependent Variable	**Method**	**Adjusted R^2**	**P-Value**	**Std. Error**
Motivation for buying EV	Standard	0.160	0.001	0.752
Significant Predictor Variable	**Std. Beta**	**P-Value**	**Part**	**$Part^2$**
Willingness to pay premium due to perceived environmental benefits	-0.206	0.039	-0.142	0.020
Willingness to pay premium due to perceived long-term savings	0.225	0.016	0.166	0.028
Would consider buying an EV	0.212	0.009	0.180	0.032
Would EV be primary vehicle	0.155	0.049	0.135	0.018

Table 3: Regression results for model assessing factors relevant for dependent variable: Motivation for buying EV

To determine the extent to which potential future EV consumers believe EVs contribute to reduction of GHG, a standard and a stepwise multiple linear regression was employed. In case of the former, the adjusted R^2 was equal to 0.349, with a P-value less than 0.001 and a standard error of 0.849. The statistically relevant unique predictors were found to be the extent to which EVs are perceived to be a long-term environmental solution and the extent to which it is believed that public charging infrastructure provide EVs with clean energy, with the respective standard Beta coefficients, the significance level of these values and the part contribution of the predictors outlined in Table 4. In case of a stepwise multiple linear regression, the R^2 was equal to 0.373, with a P-value less than 0.001 and a standard error of 0.833. This method narrowed the number of predictors in the model to 3, including the extent to which EVs are perceived to be a long-term environmental solution, the extent to which it is believed that public charging infrastructure provides EVs with clean energy and whether the potential consumers would consider buying an EV. The respective standard Beta coefficients, significance level of these values and the part contribution of the predictors are outlined in Table 4.

Dependent Variable	Method	Adjusted R^2	P-Value	Std. Error
Extent of perceived contribution of EVs to reduction of GHG	Standard	0.349	< 0.001	0.849
Significant Predictor Variable	**Std. Beta**	**P-Value**	**Part**	**$Part^2$**
Extent to which EVs are perceived to be a long-term environmental solution	0.337	< 0.001	0.229	0.052
Extent to which it is believed that public charging infrastructure provides EVs with clean energy	0.223	0.003	0.183	0.033
Dependent Variable	**Method**	**Adjusted R^2**	**P-Value**	**Std. Error**
Extent of perceived contribution of EVs to reduction of GHG	Stepwise	0.373	< 0.001	0.833
Included Predictor Variable	**Std. Beta**	**P-Value**	**Part**	**$Part^2$**
Extent to which EVs are perceived to be a long-term environmental solution	0.441	< 0.001	0.401	0.161
Extent to which it is believed that public charging infrastructure provides EVs with clean energy	0.240	< 0.001	0.222	0.049
Would consider buying an EV	-0.126	0.040	-0.122	0.015

Table 4: Regression results for model assessing factors relevant for dependent variable: Extent of perceived contribution of EVs to reduction of GHG

To determine the extent to which EVs are perceived to be a long-term environmental solution, a standard and a stepwise multiple linear regression was employed. In case of the former, the adjusted R^2 was equal to 0.375, with a P-value less than 0.001 and a standard error of 0.898. The statistically relevant unique predictors were found to be the extent of perceived contribution of EVs to reduction of GHG, the extent to which EVs are perceived to provide long-term money savings and the extent of willingness to pay a premium for an EV due to perceived long-term saving potential, with the respective standard Beta coefficients, the significance level of these values and the part contribution of the predictors outlined in Table 5. In case of a stepwise multiple linear regression, the R^2 was equal to 0.412, with a P-value less than 0.001 and a standard error of 0.871. This method narrowed the number of predictors in the model to 3, including all three statistically significant unique predictors from the standard method model. The respective standard Beta coefficients, significance level of these values and the part contribution of the predictors are outlined in Table 5.

Dependent Variable	Method	Adjusted R^2	P-Value	Std. Error
Extent to which EVs are perceived to be a long-term environmental solution	Standard	0.375	< 0.001	0.898
Significant Predictor Variable	**Std. Beta**	**P-Value**	**Part**	**$Part^2$**
Extent of perceived contribution of EVs to reduction of GHG	0.363	< 0.001	0.293	0.086
Extent to which EVs are perceived to provide long-term money savings	0.192	0.008	0.158	0.025
Extent of willingness to pay a premium for an EV due to perceived long-term saving potential	0.160	0.048	0.117	0.014
Dependent Variable	**Method**	**Adjusted R^2**	**P-Value**	**Std. Error**
Extent to which EVs are perceived to be a long-term environmental solution	Stepwise	0.412	< 0.001	0.871
Included Predictor Variable	**Std. Beta**	**P-Value**	**Part**	**$Part^2$**
Extent of perceived contribution of EVs to reduction of GHG	0.412	< 0.001	0.374	0.140
Extent to which EVs are perceived to provide long-term money savings	0.240	< 0.001	0.213	0.045
Extent of willingness to pay a premium for an EV due to perceived long-term saving potential	0.187	0.004	0.165	0.027

Table 5: Regression results for model assessing factors relevant for dependent variable: Extent to which EVs are perceived to be a long-term environmental solution

To determine the extent to which EVs are perceived to provide long-term money savings, a standard and a stepwise multiple linear regression was employed. In case of the former, the adjusted R^2 was equal to 0.252, with a P-value less than 0.001 and a standard error of 0.836. The statistically relevant unique predictor was found to be extent to which EVs are perceived to provide long-term money savings, with the respective standard Beta coefficient, the significance level of these value and the part contribution of the predictor outlined in Table 6. In case of a stepwise multiple linear regression, the R^2 was equal to 0.271, with a P-value less than 0.001 and a standard error of 0.825. This method narrowed the number of predictors in the model to 3, including the extent to which EVs are perceived to be a long-term environmental solution, the extent of willingness to pay a premium for an EV due to perceived long-term saving potential and whether an EV would be the primary vehicle if purchased. The respective standard Beta coefficients, significance level of these values and the part contribution of the predictors are outlined in Table 6.

Dependent Variable	Method	Adjusted R^2	P-Value	Std. Error
Extent to which EVs are perceived to provide long-term money savings	Standard	0.252	< 0.001	0.836
Significant Predictor Variable	**Std. Beta**	**P-Value**	**Part**	**$Part^2$**
Extent to which EVs are perceived to provide long-term environmental solution	0.230	0.008	0.173	0.030
Dependent Variable	**Method**	**Adjusted R^2**	**P-Value**	**Std. Error**
Extent to which EVs are perceived to provide long-term money savings	Stepwise	0.271	< 0.001	0.825
Included Predictor Variable	**Std. Beta**	**P-Value**	**Part**	**$Part^2$**
Extent to which EVs are perceived to be a long-term environmental solution	0.313	< 0.001	0.276	0.076
Extent of willingness to pay a premium for an EV due to perceived long-term saving potential	0.230	0.001	0.205	0.042
Would EV be primary vehicle	-0.158	0.019	-0.150	0.023

Table 6: Regression results for model assessing factors relevant for dependent variable: Extent to which EVs are perceived to provide long-term money savings

To determine the extent of willingness to pay a premium for an EV due to perceived environmental benefits, a standard and a stepwise multiple linear regression was employed. In case of the former, the adjusted R^2 was equal to 0.466, with a P-value less than 0.001 and a standard error of 0.789. The statistically relevant unique predictor was found to be the extent of willingness to pay a premium for an EV due to perceived long-term saving potential, with the respective standard Beta coefficients, its significance level and the part contribution of the predictor outlined in Table 7. In case of a stepwise multiple linear regression, the R^2 was equal to 0.471, with a P-value less than 0.001 and a standard error of 0.795. This method narrowed the number of predictors in the model to 6, including the extent of willingness to pay a premium for an EV due to perceived long-term saving potential, motivation for buying an EV, the extent to which it is believed that current driving range of EVs and charging infrastructure can satisfy all needs of owners, extent of environmental consciousness, current vehicle ownership and gender. The respective standard Beta coefficients, significance level of these values and the part contribution of the predictors are outlined in Table 7.

Dependent Variable	Method	Adjusted R^2	P-Value	Std. Error
Extent of willingness to pay a premium for an EV due to perceived environmental benefits	Standard	0.466	< 0.001	0.789
Significant Predictor Variable	**Std. Beta**	**P-Value**	**Part**	**Part^2**
Extent of willingness to pay a premium for an EV due to perceived long-term saving potential	0.381	< 0.001	0.301	0.091
Current vehicle ownership	0.164	0.009	0.143	0.020
Dependent Variable	**Method**	**Adjusted R^2**	**P-Value**	**Std. Error**
Extent of willingness to pay a premium for an EV due to perceived environmental benefits	Stepwise	0.471	< 0.001	0.795
Included Predictor Variable	**Std. Beta**	**P-Value**	**Part**	**Part^2**
Extent of willingness to pay a premium for an EV due to perceived long-term saving potential	0.451	0.000	0.421	0.177
Motivation for buying EV	-0.196	0.001	-0.188	0.035
Extent to which it is believed that current driving range of EVs and charging infrastructure can satisfy all needs of owners	0.220	< 0.001	0.213	0.045
Extent of environmental consciousness	0.177	0.002	0.168	0.028
Currently vehicle ownership	0.142	0.010	0.141	0.020
Gender	0.111	0.048	0.108	0.012

Table 7: Regression results for model assessing factors relevant for dependent variable: Extent of willingness to pay a premium for an EV due to perceived environmental benefits

To determine the extent of willingness to pay a premium for an EV due to perceived long-term saving potential, a standard and a stepwise multiple linear regression was employed. In case of the former, the adjusted R^2 was equal to 0.398, with a P-value less than 0.001 and a standard error of 0.790. The statistically relevant unique predictors were found to be the extent to which EVs are perceived to be a long-term environmental solution, the extent of willingness to pay a premium for an EV due to perceived environmental benefits and the extent of perceived reliability of EVs compared to ICEVs, with the respective standard Beta coefficients, their significance level and the part contribution of the predictors outlined in Table 8. In case of a stepwise multiple linear regression, the R^2 was equal to 0.429, with a P-value less than 0.001 and a standard error of 0.769. This method narrowed the number of predictors in the model to 5, including the extent of willingness to pay a premium for an EV due to perceived environmental benefits, extent to which EVs are perceived to be a long-term environmental solution, extent to which EVs are perceived to provide long-term money savings, motivation for buying an EV and extent of perceived reliability of EVs compared to ICEVs. The respective standard Beta coefficients, significance level of these values and the part contribution of the predictors are outlined in Table 8.

Dependent Variable	Method	Adjusted R^2	P-Value	Std. Error
Extent of willingness to pay a premium for an EV due to perceived long-term saving potential	Standard	0.398	< 0.001	0.790
Significant Predictor Variable	**Std. Beta**	**P-Value**	**Part**	**$Part^2$**
Extent to which EVs are perceived to be a long-term environmental solution	0.154	0.048	0.115	0.013
Extent of willingness to pay a premium for an EV due to perceived environmental benefits	0.429	< 0.001	0.319	0.102
Extent of perceived reliability of EVs compared to ICEVs	0.137	0.048	0.115	0.013
Dependent Variable	**Method**	**Adjusted R^2**	**P-Value**	**Std. Error**
Extent of willingness to pay a premium for an EV due to perceived long-term saving potential	Stepwise	0.429	< 0.001	0.769
Included Predictor Variable	**Std. Beta**	**P-Value**	**Part**	**$Part^2$**
Extent of willingness to pay a premium for an EV due to perceived environmental benefits	0.450	< 0.001	0.399	0.159
Extent to which EVs are perceived to be a long-term environmental solution	0.189	0.004	0.162	0.026
Extent to which EVs are perceived to provide long-term money savings	0.151	0.022	0.130	0.017
Motivation for buying an EV	0.150	0.010	0.145	0.021
Extent of perceived reliability of EVs compared to ICEVs	0.130	0.035	0.119	0.014

Table 8: Regression results for model assessing factors relevant for dependent variable: Extent of willingness to pay a premium for an EV due to perceived long-term saving potential

Discussion

The proposed model explains 16% of the variations in motivation for buying an EV, with a standard error of 0.752. Although statistically significant with the p-value of 0.001, which is well below the 0.05 threshold for significance, its explanatory power is limited, especially considering that it takes into account 24 independent variables and 213 observations. Nonetheless, when considering the unique contributions of the individual predictors, found to be significant and their impact relevant based on their standardized Beta coefficients and part contributions, they are in line with logical expectations, namely, that motivation to buy an EV would be influenced by the willingness to pay a premium due to perceived environmental benefits and due to perceived long-term savings, as well as by whether consumers would consider buying an EV and whether that EV would be their primary vehicle. The unique contributions of these predictors explaining the variance in motivation is 2%, 2.8%, 3.2% and 1.8% respectively.

When considering all 24 variables in the model, it explains 35% of the variance in the extent of perceived contribution of EVs to reduction of GHG, with a standard error of 0.849 and a p-value less than 0.001. The identified significant unique predictors are in line with logical expectations, as one would assume that the extent to which EVs are perceived to be a long-term environmental solution and the extent to which it is believed that public charging infrastructure provides EVs with clean energy are factors that influence the perceived contribution in reduction of GHG that EVs yield, which in case of the model, uniquely explain 5% and 3% of the variance, respectfully. Accordingly when the regression was run using the stepwise method, it included these 2 variables in the model, as well as the third variable of whether one would consider buying an EV or not. In the case of the 3-variable model, these predictors would uniquely contribute to explaining the variance in the extent of perceived contribution of EVs to reduction of GHG with 16%, 5% and 2%, respectfully. The 3-variable model would explain 37% of the variance in the dependent variable, with a standard error of 0.833 and p-value of less than 0.001.

38% of the variance in the extent to which EVs are perceived to be a long term environmental solution is explained by the model, which is statistically significant and has a standard error of 0.898. The significant predictors include the extent of perceived contribution of EVs to reduction of GHG, the extent to which EVs are perceived to provide long-term money savings and the extent of willingness to pay a premium for an EV due to perceived long-term saving potential, with a unique contribution of 7%, 3% and 1% respectively. This indicates that the perception of EVs yielding long-term environmental benefits is linked to the factors relating to the source of power charging the EVs and financial sustainability of EV ownership. When employing the stepwise method, the model includes the same three predictors, but with a higher explanatory percentage of variance, 14, 5 and 3 respectively. The 3-variable model is statistically significant and explains 41% of variance, with a standard deviation of 0.871.

In view of the results assessing influence on the extent to which EVs are perceived to provide long-term money savings, the model under the standard method is significant and explains 25% of the variance, with the standard error of 0.836, with the only significant predictor being extent to which EVs are perceived to provide a long-term environmental solution. When applying the stepwise method, the model includes 3 predictors, the extent to which EVs are perceived to be a long-term environmental solution, the extent of willingness to pay a premium for an EV due to perceived long-term saving potential and whether the EV would be the primary vehicle. The 3-variable model is significant and explains 27% of the variance. Perceived savings an EV would generate are linked to whether it would be the primary vehicle used, as the more used it is as opposed to an alternative, the more savings it can generate. Further, it is expected that if a consumer is willing the pay a premium due to future savings, he or she believes that the EV will generate savings. On the other hand, the link between the perception of long-term environmental benefits and long-term savings could be justified by consumers' perception of the life span of the vehicles, which would be constant across both considerations.

The model explains 46.6% of the variance in the extent of willingness to pay a premium for an EV due to perceived environmental benefits, with a standard error of 0.789 and it is statistically significant. Significant predictors identified included the extent of willingness to pay a premium for an EV due to perceived long-term saving potential, which could be related to the perceived lifespan of the vehicle, and current vehicle ownership, which could imply that if a person has practical experience of driving a vehicle, he or she is more aware of its environmental implications. According to the stepwise method, the model is reduced to 6 variables, including the extent of willingness to pay a premium for an EV due to perceived long-term saving potential, the motivation for buying an EV, the extent to which it is believed that current driving range of EVs and charging infrastructure can satisfy all needs of owners, the extent of environmental consciousness, currently vehicle ownership and gender. The 6-variable model is statistically significant and accounts for 47.1% of variability with a standard error of 0.795. Here too, as discussed, the predictors reflect the consumers' attitude on vehicle life span, environmental importance, practical use and sustainability, with the exception of gender, which can be open to numerous interpretations.

When considering the extent of willingness to pay a premium for an EV due to perceived long-term saving potential, the standard model is significant and explains 40% of variability with a standard error of 0.790. The identified unique predictor variables include extent to which EVs are perceived to be a long-term environmental solution, extent of willingness to pay a premium for an EV due to perceived environmental benefits and extent of perceived reliability of EVs compared to ICEVs. Although the letter has a direct link to savings, which would occur if a vehicle is reliable and no repair costs would have to be incurred, it is unexpected that the first two predictors are more closely related to environmental benefits, than to other saving related predictors. The stepwise method produces a model with 5 variables, including extent of willingness to pay a premium for an EV due to perceived environmental benefits, extent to which EVs are perceived to be a long-term environmental solution, extent to which EVs are perceived to provide long-term money savings, motivation for buying an EV, extent of perceived reliability of EVs compared to ICEVs. The 5-variable model is significant and explains 43% of variability with a standard error of 0.769. Similar to the standard method, it is unexpected that the model finds predictors relating to environment more relevant than predictors more closely associated with money saving.

The multiple linear regression model performed under the standard method and the stepwise method has the most explanatory power for the willingness to pay a premium for EVs due to their perceived long-term environmental benefits and due to their perceived long-term saving potential. The two proxies are important factors when assessing the overall contribution of EVs to reduction of GHGs, as they address one of the key issues identified to have a negative impact on EV market penetration. Namely, EVs cost more than ICEVs, and in order for them to have significant market penetration, consumers need to be willing to pay their premium. Not considering correlations to other factors, the majority of participants stated that they would be willing to pay a premium for EVs to a medium-high extent, either due to their environmental benefits or due to their long-term saving potential, which suggests that EVs would have a relatively successful market penetration according to the test sample. This conclusion counters the findings of Larson et al. (2014), who also performed a consumer survey and found that the willingness to pay a premium due to perceived savings or environmental benefits was at a low level (p. 4).

The findings that the majority of consumers ranked a government subsidy as having high influence on their decision to purchase and EV is in line with the literature reviewed, as well as the finding that the majority of consumers believe to a mi-low extent that the current charging infrastructure could satisfy their everyday needs. Somewhat deviating from the literature is the perception that the potential consumers have about the driving range of vehicles. According to the survey, the majority of consumers ranked that the current driving range of EVs would satisfy their daily needs to a medium extent, with a significant proportion giving this indicator a mid-high ranking. Nonetheless, when classifying whether the current driving range of EVs and charging infrastructure are sufficient to meet all driver needs, the majority of respondents expressed a mid-low extent of confidence in this statement, which reflects the findings from the literature.

The majority of identified significant predictors are in line with expectations as they influence the related dependent variables. However, in certain cases the expectations would have been in favor of predictors that seem to be more related to the variable in question. For instance, perceived savings would have been assumed to have more influence on willingness to a premium due to savings, than environmental predictors or gender. Furthermore, it is interesting to note that no model configuration identified certain demographic predictors such as income, driving experience, age or level of education as uniquely significant in assessing the dependent variables, which would have been assumed to be the cases prior to running the regressions.

Costs

From a practical perspective, cost is one aspect that will influence consumers' attitudes towards electric vehicles, regardless of the extent to which they are environmentally conscious or to which they believe EVs contribute to the reduction of GHG emissions. A crucial consideration in this regard is the length of time someone intends to operate a vehicle and the time span which is taken into account when calculating comparisons. The IEA (2017) puts electricity costs much lower than petrol costs per vehicle-km driven, so EVs would also have lower operating costs, particularly in Europe, where the cost of petroleum based fuels is high. Nonetheless, as Edwards et al. (2014) point out, it is difficult to determine future costs for both EVs and ICEVs, and thus to compare the potential savings. One reasons for this includes uncertainty of future innovations in the motor industry. Further, resources such as oil, natural gas, uranium, lithium and other raw materials serving as feedstock for fuel or electricity generation, or which are needed for vehicle and component manufacturing are traded on global markets, which respond to a range of pressures. Additionally some resources and technologies are subject to high taxation while for others subsidies are given, which vary in time span and extent. These factors make it difficult to accurately predict the future prices of resources, and consequently the future prices of vehicle production and operations (p. 19).

In spite of these limitations, attempts of evaluating the future costs of owning one vehicle technology as opposed to another are being made, by assuming various future scenarios, holding prices constant at current rates, attributing certain coefficients for future inflation and discounting, or through other methods. Graham et al. (2014) estimated ownership costs by looking at current gasoline prices in the United States, and making assumptions about future projections. They found that in 2014, in the US electricity was 65% cheaper than gasoline on an energy-equivalent basis, and that the projected prices of gasoline will rise much quicker than those of electricity. They also assume significantly smaller repair and maintenance costs for EVs compared to ICEVs due to the fact that EVs are made up of considerably fewer components. Therefore, Graham et al. (2014) estimate total cost of ownership of an EV in the US to be comparable and even lower than a gasoline vehicle. The costs of EV ownership are further assumed to decrease as the industry has still not matured, but the extent and pace of this process is uncertain.

When considering the cost of the vehicle itself, for instance the basic version of a 2018 Nissan Leaf starts at $29,990 (Nissan USA, 2018b) Manufacturer's Suggested Retail Price (MSRP), excluding destination and handling charges, tax, title, license and options. Considering its Nissan gasoline counterpart in the compact category, the 2018 Nissan Sentra, a basic model starts at $16,990 (Nissan USA, 2018c), while in the mid-size category, the 2018 Nissan Altima gasoline basic model starts at $23,260 (Nissan USA, 2018a).

These figures are in line with those reported by Graham et al. (2014), which cite a cost premium of $10,000 to $15,000 for an EV compared to its gasoline counterpart. The premium is attributed to the larger cost of production of EVs mainly stemming from the high price of lithium ion battery packs. Certain governments offer subsidies and tax breaks to promote EV ownership, but such benefits are non-sustainable, variable and of a short-term nature.

Country	Gasoline cost [a] USD/km	Electricity cost [b] USD/kWh	Electricity cost in USD/km for consumption of 0.165 kWh/km [c]
US	0.83	0.129	0.021
UK	1.70	0.224	0.037
Germany	1.73	0.350	0.058
Austria	1.52	0.223	0.037
Russia	0.64	0.066	0.011
Norway	2.04	0.160	0.026

a. Valev, 2018a; b. Valev, 2018b; c. Nissan, 2018b.

Table 9: Prices of Electricity and Gasoline as of 3rd quarter of 2018

The premium that a consumer would pay for a Nissan Leaf as opposed to a Nissan Sentra would amount to $13,000. Looking at just the current gasoline and electricity prices, without consideration for all additional factors such as maintenance, infrastructure costs, subsidies and future price increases, a consumer would have to drive an EV in the US for 16,070 km to generate savings equal to the premium. In the UK a driver would have to traverse 7,817 km to generate savings equal to the premium paid for owning an EV as opposed to an ICEV, while this distance would have to be 7,775 km in Germany, 8,776 km in Austria, 20,668 km in Russia and 6,455 km in Norway.

However, consideration must be given to additional costs, such as the costs of establishing personal charging infrastructure for EVs, as a significant proportion of current and potential EV owners would charge their vehicles at their home. According to Ergon Energy (2018), the cost of setting up home charging infrastructure includes the cost of circuit wiring, which they report at around $1,750, cost of outlet ranging from $100 to $2,500 depending on whether it is a standard electrical point or advanced dedicated EV charging unit, potential costs of installing additional meters, potential costs of electrical panel upgrade and potential costs of electrical service upgrade, which all vary depending on grid and electricity provider.

EV owners may also face the prospect of having to replace their battery during lifetime of their EV, in case of more intensive driving. According to the portal Inside EVs (Kane, 2018), Nissan announced new battery pack costs of $6,200 for 24 kWh, $7,600 for 30 kWh, and $7,800 for 40 kWh, while a refabricated one would cost $2,850. This would initially only be available in Japan and It is still uncertain if Nissan will deliver on this promise. If so would be the case it would represent a decreasing trend in costs of battery packs, when taking into account that in 2012, Helmers et al. (2012) reported the cost of a 14 kWh battery pack to be $5,800.

One potential for saving money through ownership of an EV might lie in V2G technology. V2G might enable owners to store electricity in their vehicles and use it at a later point in time or even sell it back to the grid. A Graham et al. (2014) estimate that through such means an EV owner might recoup $3,000 per year from a load-balancing contract with the electric utility, while incurring a onetime $1,500 cost to fit a V2G-enabled battery and charging system to a vehicle. It must be noted that such a scenario would only be true under certain assumptions, which may face numerous practical limitations, such as that it may only hold if an EV owner does not use the vehicle for purposes other than going to work.

When making a final decision on whether EVs generate enough savings through their life to offset the initial premium and possible costs of private charging infrastructure, a number of factors must be considered. Most important is the length of life of an EV, and whether the battery pack will last equally as long. It should also be noted that the exact life-time costs of maintenance of EVs are debatable, as they are still a relatively new market segment. Government subsidies and tax breaks would reduce the initial price gap and the amount of time it takes for the premium to be offset. However, government benefits to this purpose are not sustainable in the long run as they are funded by tax payers, who may not support such initiatives. Other potential scenarios such as the use of V2G technology to generate savings rely on many assumptions which are prone to practical limitations. Therefore, the topic of total cost of ownership of an EV and whether it is less than that of an ICEV is case dependent and still debatable.

Conclusion

The paper presented results from literature reviewed comparing the environmental impacts of electric vehicles to those of internal combustion engine vehicles, as well as results from a survey conducted with the aim to assess consumer perception of theses impacts and consumers' consequent willingness to pay. The environmental impact in focus was contribution to reduction of global warming, namely the reduction of greenhouse gases and therefore the main metric in focus was carbon dioxide and carbon dioxide equivalent emissions. Nonetheless, other emissions and impact were also identified. The studies reviewed employed varying methodologies, with the prevailing approaches being the Well-to-Wheel assessment and Life Cycle Assessment. Results, implications, conclusions and reasoning amongst the studies were found to be variable and dependent on numerous factors, circumstances and assumptions.

The research methodologies reviewed and vehicle emissions tests they treat are established by international regulations and standards. Yet the systems under review are complex, and determination of their boundaries are left to the discretion of the researcher, such as deciding how far up the supply chain should limits be set when determining impacts of production or fuel procurement. Data for various technologies is not uniform in terms of availability and quality, especially since modern electric propulsion is a new industry, where uniform monitoring and reporting methods are still to be established across the industry, and trade secrets are guarded for the sake of maintaining a competitive advantage. Local factors such as level of development, efficiency of electricity production, quality of transportation infrastructure, population density, climate and topography have strong influence on assessment outcomes. In view of these considerations, reserve should be taken when interpreting and comparing results across studies and technologies. They should not be taken as absolute truths, but as comparative indicators.

The main difference between EVs and ICEVs is that EVs produce no tailpipe emissions. Thus the emissions from generating energy for their propulsion are shifted from the vehicles to the power plants. This poses a challenge for comparing their environmental impacts to those of ICEVs, where fuel is combusted within the vehicle. To accurately account for their respective environmental impacts, the entire fuel provision supply chain, from resource extraction to its conversion to energy must be considered. The Well-to-Wheel approach assesses these phases, comparing the technologies more accurately and accounting for emissions of electricity generation needed to propel EVs. In addition, the different technologies require different components, manufacturing infrastructure and production processes, generating different amounts of emissions. To capture this difference, the Life Cycle Assessment is utilized, where impacts across the entire lifetime of a vehicle are considered, from extraction of raw materials for component and vehicle production, across the vehicle use phase, to recycle or disposal.

The literature is consistent on the WTW impact of ICEVs, as the conventional vehicle industry is mature and has well-established monitoring and reporting standards, where the extraction and refinement of oil into gasoline and diesel plays a minor contribution, and the bulk of emissions is generated during fuel combustion, ranging from around 100 to a bit above 200 g CO_2-eq/km for gasoline, and from about 60 to nearly 170 g CO_2-eq/km for diesel, depending on the size of vehicle. When determining the WTW impacts of EVs, consideration must be given to the sources of power generating the electricity charging the EV. In case of electricity generated by renewable sources, emissions are all but negligent, ranging from 0.6 g CO_2-eq/km attributed to electricity from hydro power charging a compact car to 11.4 g CO_2-eq/km emitted when an SUV is charged by electricity from solar power. The associated emissions stem mainly from maintenance of infrastructure.

Electricity generated by the burning of coal however can produce emissions per kilometer greater than those of ICEVs, as evident especially in the subcompact and compact vehicle categories, where ICEVs produce 101.4 and 119.7 g CO_2-eq/km, respectively, while EVs contribute to 142 and 123 g CO_2-eq/km, respectively. It is also important to consider that electricity generation from the same source may vary depending on power plant technology, and the literature identified a strong correlation between a nation's level of development and the efficiency of their power plants. National electrical grids are however supplied by several sources of power, and to calculate emissions of a mix of sources, emission coefficients are attributed to each sole source, which are then multiplied by the proportion of their respective contributions.

Special consideration must be given to the nature of the power plants in operation for a given level of demand. Baseload power supply is usually provided by a mix of capital-intensive but efficient power plants, which are intended to cover a certain estimated level of electricity demand deemed to be regular. However in cases when there is excess demand, such as daily times of peak demand or introduction of new demand segments, the marginal demand is covered by peak power plants, which are activated only then. Due to their intermittent and short operational nature, peak power plants have not incurred such extensive capital investments as their baseload counterparts, and are hence not as efficient and generally burn fossil fuels for power production, causing EVs they charge to generate higher emissions per km driven than ICEVs.

There are strong arguments that EVs would be powered by peak power plants on account that they are a new electricity demand segment and that their charging time coincides with daily demand peaks, as identified in the literature and by the performed consumer survey. On the other hand, EVs can yield over 80% efficiency when converting fuel to motion on a WTW basis, while the efficiency of ICEVs in this regard ranges from 10% to 25%. Thus there is potential for some savings in GHG emissions, even when EVs would be charged by peak power plants. Nonetheless, the amount of these savings would not be significant, especially considering their price premium, expenditures necessary for their supporting infrastructure and environmental production impacts.

Concerns about the sustainability of mass market penetration of EVs also exist, in view of the capacity of certain grids. Power plants take a long time to build and are expected to have very long operational lives. Accordingly, the amount of efficient baseload power supply is not flexible. The manner of charging plays an important role in this regard. The literature is not unanimous on the proportion of EVs that could be integrated into grids in case of uncontrolled charging. Results range from 2% to 10% of the traffic sector in a given country, without the need for additional capital investments, depending on the specific grid in question. Nonetheless even in case of the higher end of the spectrum, the integrated proportion would play an insignificant role in the reduction of GHG. However, systems such as smart charging and more complex integrated energy management systems are being developed with the aim of supporting greater integration of EVs and facilitating their utilization of cleaner power sources.

Comparing the two vehicles on a Life Cycle Assessment basis, EVs produce much more emissions during the production phase, 34% to 115% more, depending on the literature source and battery type. The majority of these emissions are attributed to the production of the lithium-ion battery pack, which can comprise up to 86% of the total production impact. All literature reviewed on this topic, finds the overall life cycle emissions of EVs up to around 50% lower than those of ICEVs, as EVs compensate for the greater production impact during the use phase, with the end of life phase constituting a very small proportion of emissions in case of both vehicle. However, the literature assumes baseload power supply when considering the use phase impacts. As the EV industry matures, production efficiency improves and recycling methods evolve, the production phase will constitute an ever smaller impact in the EV lifecycle. Therefore, much more consideration will be given to the use phase and sources of power, when assessing emissions.

In addition to carbon dioxide, emissions from vehicles and electricity production also produce compounds such as particulate matter, carbon monoxide, ozone, sulfur oxide, methane and nitrous oxide amongst else. While some of these compounds are converted to carbon dioxide equivalents to assess their impact on global warming, they are also responsible for a range of other effects including abiotic depletion, acidification, local air pollution, photochemical oxidant formation, particulate matter formation, freshwater eutrophication, freshwater eco-toxicity, terrestrial eco-toxicity and human toxicity. Certain studies found EVs to cause a higher potential for human toxicity, freshwater eco-toxicity, freshwater eutrophication, and metal depletion impacts, mainly due to the impacts associated with their production phase.

EVs shift emissions, however, from cities to power plants and thus they reduce air pollution in inhabited areas, which greatly reduces the health risks from air pollution for the people in these areas. Due to a lack of a combustion engine, EVs produce considerably less noise than ICEVs and thus further contribute to improvements in quality of life in where they replace ICEVs. Concentrating emissions to a few power plants enables easier implementation of emissions control efforts, such as filtration or carbon capture and storage.

Security of supply of certain resources would be affected by mass market penetration of EVs. On one hand, lithium-ion needed for the battery and rare earth magnets needed for some electric motors are limited resources which are concentrated in a few geographic regions. Such concentration has the potential to create dependencies and allow certain nations to use these dependencies for political leverage. On the other hand, electrifying the transportation sector would enable nations to reduce their dependency on oil, the supply of which is also concentrated.

The vehicle-to-grid concept has potential to facilitate the transition to renewables, as the additional readily available storage that EV batteries provide can help manage the intermittent nature of renewable energy sources. This concept has the potential to generate savings for drivers, as they could earn premiums from grid operators for acting as spinning reserves. However, V2G is still being developed and has many limitations, including expediting the battery aging process and limited capacity of the battery, which leaves open the issue of balancing the drivers' needs for propulsion against the grid's need for the stored electricity as the times when both are needed may coincide.

Much research and development is taking place in the field of propulsion, for ICEVs and EVs alike, and trends are evident that both technologies are becoming more efficient and less emission intensive. These trends will continue to hold, as the focus is on reducing pollution in every industry, which will impact the automotive industry in the shape of less emission intensive production processes, and especially the EV segment through less emission intensive power grids.

However, when assessing the environmental contribution of EVs, emphasis should be placed on the interconnectedness of nations, regions and grids, as to account for spillover effects and negative externalities. In some cases the demand for renewables generated by EVs may limit the availability of these renewables to other interconnected grids which will have to compensate for the loss by own production, which may generate more intensive environmental impacts than would driving an ICEV. The infrastructure required for charging of EVs also implies emissions and costs, which should be accounted for when weighing in their benefits against ICEVs.

Financial costs are one of the key factors for the success of EVs. Currently there is a considerable premium, in the range from 10,000 to 15,000 euros, limiting the uptake of EVs to wealthier consumers. On the other hand, there is potential of offsetting this premium by saving on fuel and maintenance in the long run, but the probability and extent of these savings is still uncertain.

Some governments attempt to reduce these premiums through tax breaks and subsidies, as a means of reaching carbon dioxide emission objectives in the transportation sector. In addition governments finance the infrastructure required to make EV ownership practical. As the money comes from tax payer money, there is a constant possibility of public pressure against such measures, making them not sustainable in the long term, while the question of EVs becoming less expensive due to improvements in technology and manufacturing processes is still to be determined.

Consumers are also concerned with reliability. They want to be sure that their vehicle will consistently be able to transport them to their destination, without having to worry about being stranded on the way, having to wait unreasonably long for their vehicle to charge or having to invest additional time and money for maintenance and repair. The literature reviewed, as well as the survey performed for the purpose of this paper indicate that the majority of consumers perceive environmental vehicles to be reliable and adequate to meet their daily needs. Nevertheless, a considerable number does would not agree, while the majority does not perceive EVs and the charging infrastructure to be able to meet all of their needs. Survey results also indicate that there is a medium-high willingness to pay a premium amongst consumers due to the environmental benefits of electric vehicles, which is a positive indicator about their potential market penetration.

Ultimately, there are many issues to be addressed and much technological advancement needed in this new and emerging industry if it is to play a role in the mitigation of climate change. Results of the studies performed on this topic leave the question of whether electric vehicles are the technology that will play a key role in reducing global warming still open. Whichever propulsion technology proves to be the most environmentally beneficial, every segment of society needs to engage in the effort to reduce pollution, consume smarter and create less waste, not just to stop climate change but to enable long-term sustainable life across the planet.

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Appendix 1

Figures from Literature Review on LCA

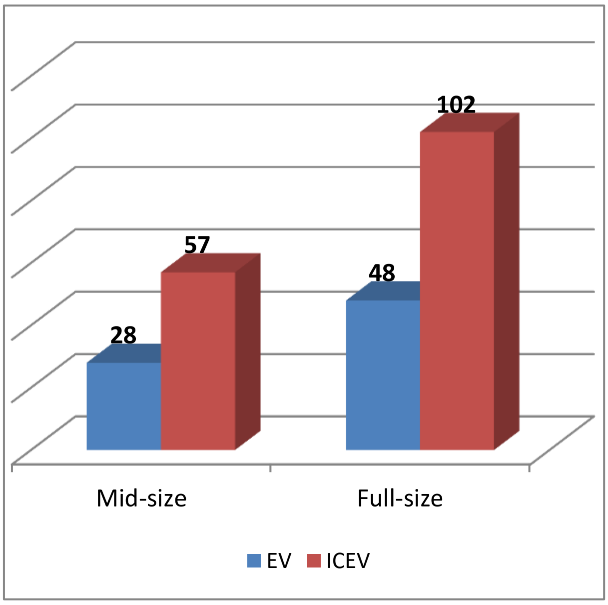

Figure 1: Total LCA emissions in Tons CO_2 by propulsion technology according to Nealer et al. (2015)

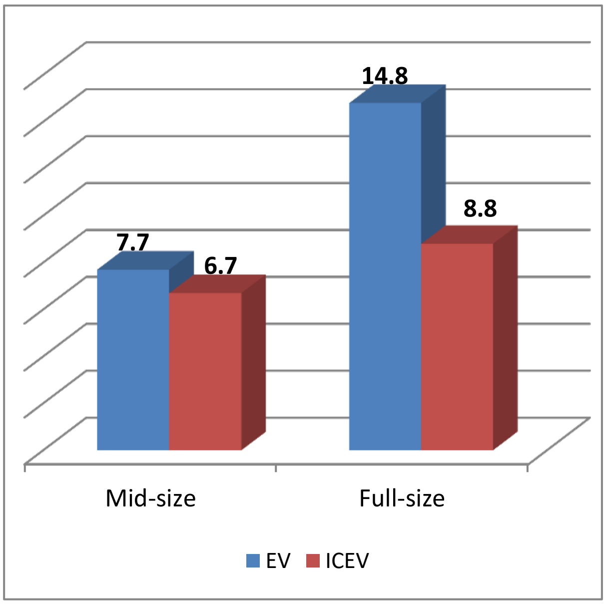

Figure 2: Production Impact in kg CO_2-eq/kg of car by propulsion technology and size according to Nealer et al. (2015)

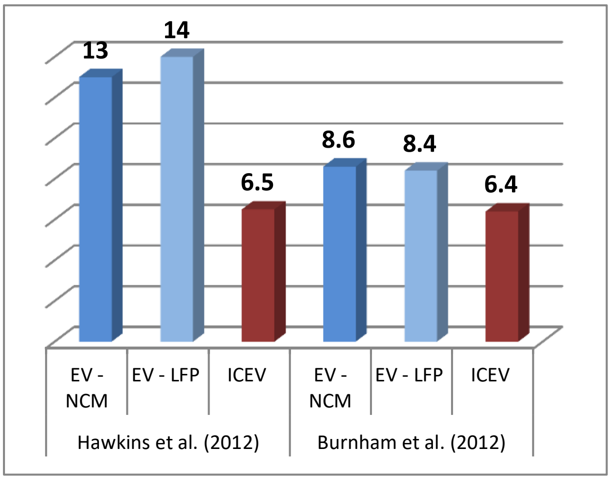

Figure 3: Comparison of Total Life Cycle Impact of Production in Tons CO_2 by vehicle and literature source

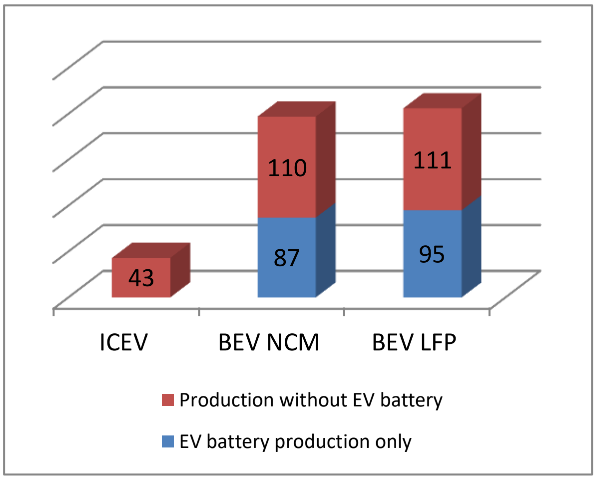

Figure 4: Impact of Production Only in g CO_2-eq/km considering the entire life time of a vehicle according to Hawkins et al. (2012)

Appendix 2

Figures from Literature Review on Emissions from Electricity Generation

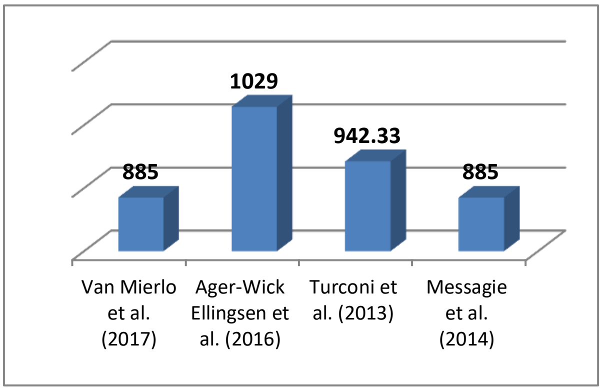

Figure 1: Emissions from Coal-Based Electricity Generation in g CO_2-eq/kWh by literature source

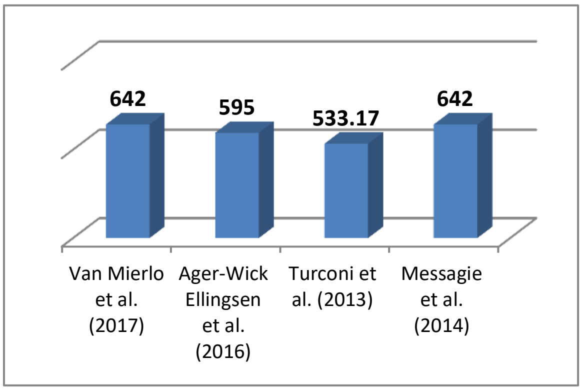

Figure 2: Emissions from Natural Gas-Based Electricity Generation in g CO_2-eq/kWh by literature source

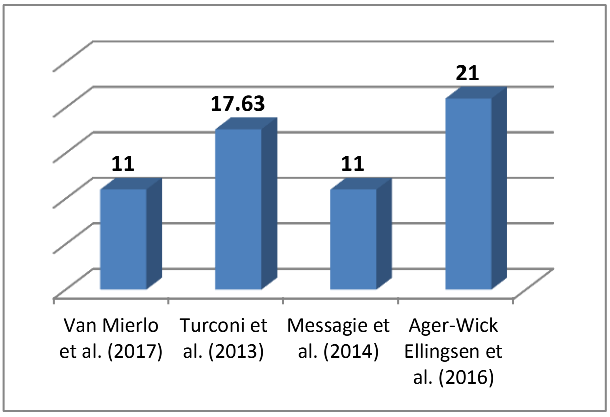

Figure 3: Emissions from Wind-Based Electricity Generation in g CO_2-eq/kWh by literature source

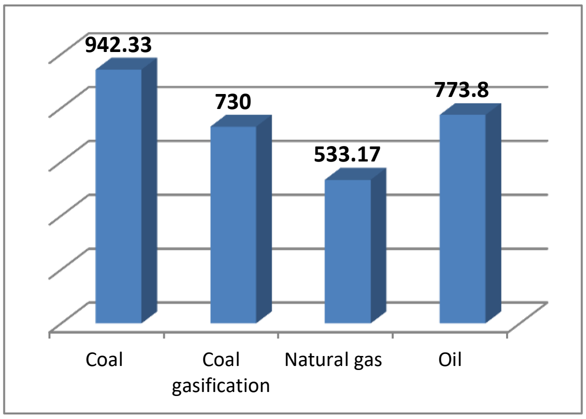

Figure 4: Emissions of Electricity Generation from Fossil Fuels in g CO_2-eq/kWh according to Turconi et al. (2013)

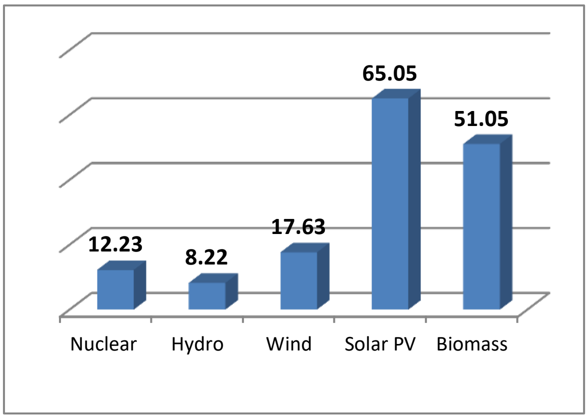

Figure 5: Emissions of Electricity Generation from Non-Fossil Fuels in g CO_2-eq/kWh according to Turconi et al. (2013)

Appendix 3

Consumer Perception Survey on Electric Vehicle Environmental Benefits

Dear Participant,

Thank you for taking the time to complete this survey about consumer insight regarding electric vehicles, conducted for the master thesis which aims to assess whether electric vehicles contribute to the reduction of CO_2 emissions, performed within the Energy and Environmental Management program of the Business Administration Masters at the University of Vienna. The survey should take about 10 minutes to complete and the participants will remain anonymous.

1. If you were to purchase an electric vehicle, what would be your primary motivation?

   1 2 3 4 5
   Not at all … Very much so

2. To what extent do you consider yourself to be environmentally conscious?

   1 2 3 4 5
   Not at all … Very much so

3. To what extent do you consider yourself to be technologically savvy?

   1 2 3 4 5
   Not at all … Very much so

4. How much do you think an electric vehicle contributes to reduction of greenhouse gases?

   1 2 3 4 5
   Not at all … Very much so

5. Do you consider electric vehicles to be a long term environmental solution?

   1 2 3 4 5
   Not at all … Very much so

6. Are you expecting to save money in the long run by owning an electric vehicle?

   1 2 3 4 5
   Not at all … Very much so

7. Would you pay a premium for an electric vehicle in contrast to a conventional vehicle, because of its environmental benefits?

   1 2 3 4 5
   Not at all … Very much so

8. Would you pay a premium for an electric vehicle in contrast to a conventional vehicle, because of its long term saving potential?

1	2	3	4	5
Not at all				Very much so

9. Would a government subsidy influence your buying decision?

1	2	3	4	5
Not at all				Very much so

10. Can current vehicle charging infrastructure enable electric vehicle owners to use their vehicle for their everyday needs?

1	2	3	4	5
Not at all				Very much so

11. To what extent to you believe public charging stations provide electric vehicles with clean energy?

1	2	3	4	5
Not at all				Very much so

12. Is the current driving range of electric vehicles enough to enable their owners to use electric vehicles for their everyday needs?

1	2	3	4	5
Not at all				Very much so

13. Is the current driving range and charging infrastructure of electric vehicles enough to enable their owners to use electric vehicles for all their needs?

1	2	3	4	5
Not at all				Very much so

14. How reliable do you perceive electric vehicles to be in comparison to conventional vehicles?

1	2	3	4	5
Not at all				Very much so

15. If you were to purchase an electric vehicle, what would the primary intended purpose for this vehicle be?

1	2	3	4	5
Not at all				Very much so

16. Where do you believe you would mainly charge your vehicle?

1	2	3	4	5
Not at all				Very much so

17. What would be the main charging time of your vehicle?

1	2	3	4	5
Not at all				Very much so

18. Do you currently own a vehicle?

1	2	3	4	5
Not at all				Very much so

19. Would you consider buying an electric vehicle?

1	2	3	4	5
Not at all				Very much so

20. If you were to buy an electric vehicle, would this be your primary vehicle?

1	2	3	4	5
Not at all				Very much so

Demographic Questions

The next section aims to collect demographic data about participants in order to assess if there is a relation between consumer demographics and perception about electric vehicles.

21. Age:
22. Gender:

Male	Female	Other

23. Driving experience (years):
24. Yearly gross (brutto) income bracket in EUR:

15,000 - 30,000	30,000 - 45,000	45,000 - 60,000	over 60,000

25. Education level:

Primary education	Secondary education (including vocational education)	Undergraduate studies (bachelor degree)	Graduate studies (master’s degree)	PhD or higher (doctoral studies including post doc)

Appendix 4

List of Variables for the Regression Analysis

Below is a list of variables used for the regression analysis performed in SPSS derived from the Consumer Perception Survey on Electric Vehicle Environmental Benefits:

1. Motivation for buying EV
2. Extent of environmental consciousness
3. Extent of technological knowledge
4. Extent of perceived contribution of EVs to reduction of GHG
5. Extent to which EVs are perceived to be a long-term environmental solution
6. Extent to which EVs are perceived to provide long-term money savings
7. Extent of willingness to pay a premium for an EV due to perceived environmental benefits
8. Extent of willingness to pay a premium for an EV due to perceived long-term saving potential
9. Extent to which a government subsidy would influence the decision to buy an EV
10. Extent to which it is believed that current charging infrastructure allows EV owners to fulfill their everyday needs
11. Extent to which it is believed that public charging stations provide EVs with clean energy
12. Extent to which it is believed that current driving range of EVs can satisfy everyday needs of owners
13. Extent to which it is believed that current driving range of EVs and charging infrastructure can satisfy all needs of owners
14. Extent of perceived reliability of EVs compared to ICEVs
15. Primary intended purpose of EV ownership
16. Main charging place of EV
17. Main charging time of EV
18. Currently vehicle ownership
19. Would consider buying an EV
20. EV as primary vehicle if purchased
21. Age
22. Gender
23. Driving experience in years
24. Yearly gross income in EUR
25. Education level

Appendix 5

Figures for Selected Results from the Consumer Perception Survey on Electric Vehicle Environmental Benefits

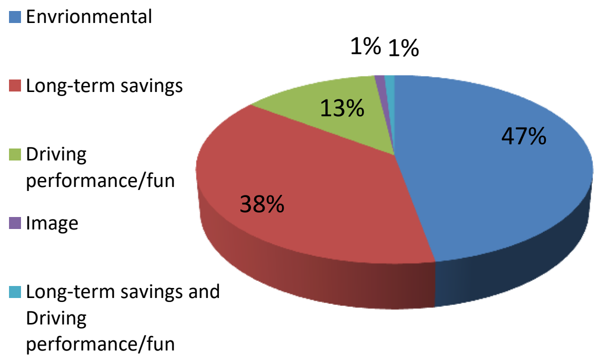

Figure 1: Motivation for buying EV

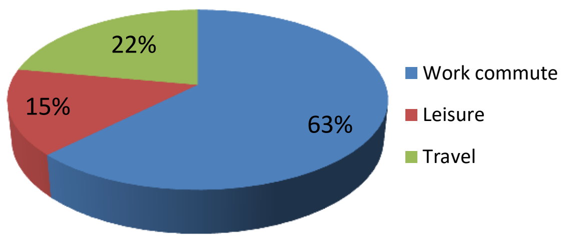

Figure 2: Primary intended purpose of EV ownership

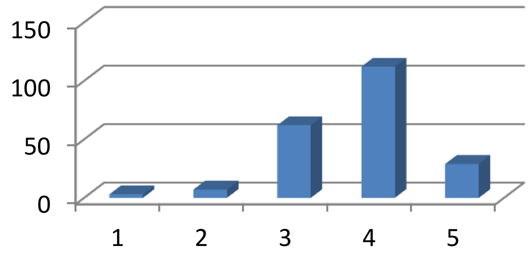

Figure 3: Extent of environmental consciousness

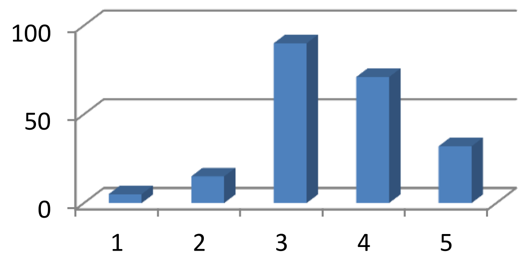

Figure 4: Extent of technological knowledge

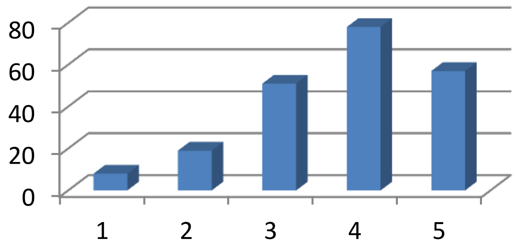

Figure 5: Extent of perceived contribution of EVs to reduction of GHG

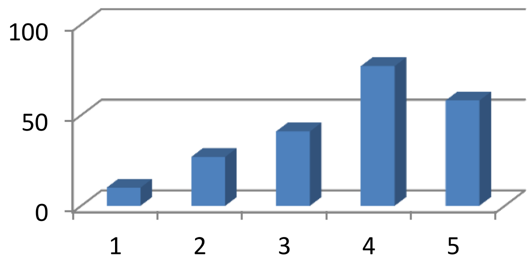

Figure 6: Extent to which EVs are perceived to be a long-term environmental solution

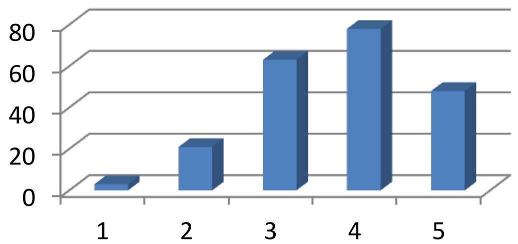

Figure 7: Extent to which EVs are perceived to provide long-term money savings

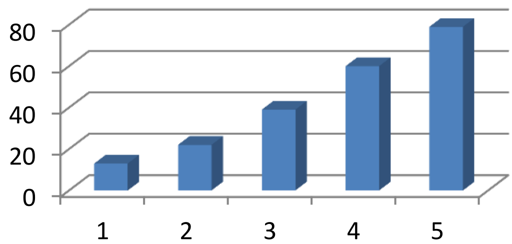

Figure 8: Extent to which a government subsidy would influence the decision to buy an EV

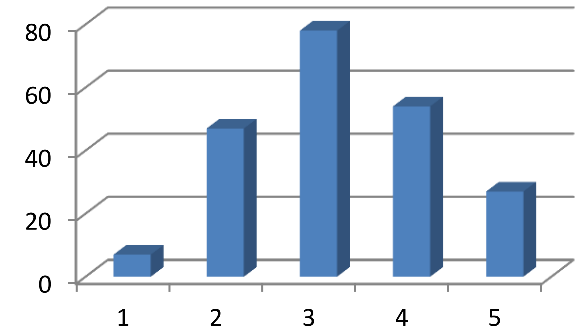

Figure 9: Extent to which it is believed that public charging stations provide EVs with clean energy

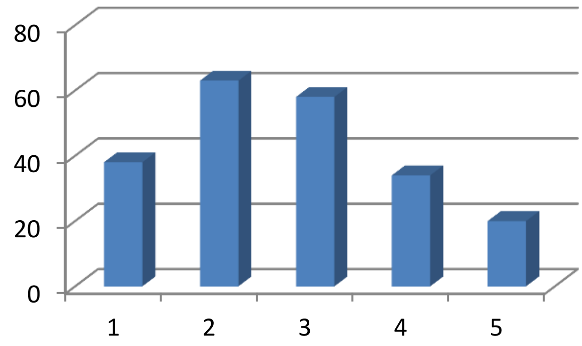

Figure 10: Extent to which it is believed that current charging infrastructure allows EV owners to fulfill their everyday needs

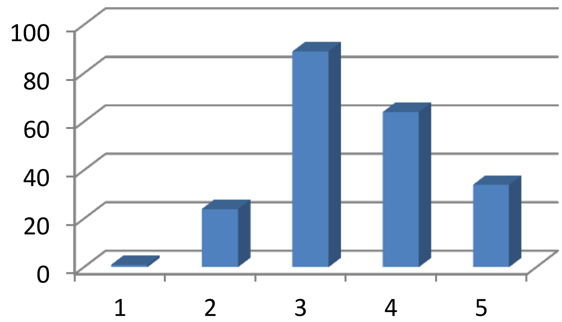

Figure 11: Extent of perceived reliability of EVs compared to ICEVs

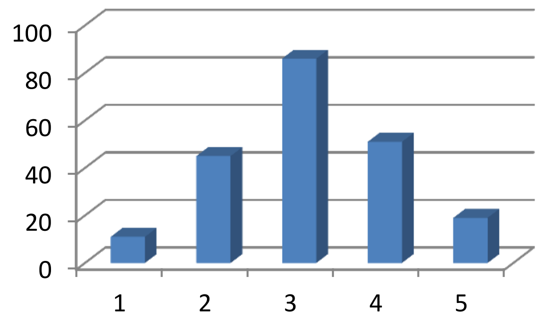

Figure 12: Extent to which it is believed that current driving range of EVs can satisfy everyday needs of owners

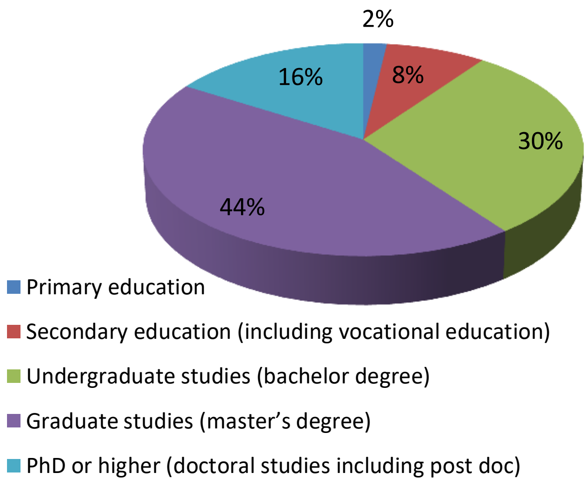

Figure 13: Education level

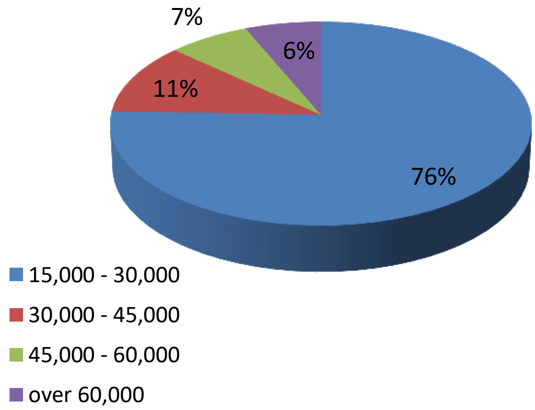

Figure 14: Yearly gross income in EUR