Life Cycle Assessment of Electric Vehicle Considering Locally Generated and Stored Energy

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ABSTRACT: The potential of electric vehicles for reducing the harmful environmental impacts of road transport in everyday conditions has to be analyzed and evaluated. If electric vehicles shall realize their potential to reduce emissions and minimize the consumption of resources, then locally generated and stored energy could increase the use of renewable energy sources. A quantitative method is necessary to determine if local energy is environmentally advantageous and, for that purpose, the life cycle assessment is a suitable method which quantifies potential environmental impacts. BS Energy is a German energy and drinking water distributor that has been expanding its business investing on new clean technologies, such as electric cars, and plans the installation of a stationary energy storage. This work carries out a detailed life cycle assessment for the local energy storage system testing several energy scenarios and taking into account the following environmental impacts: global warming, ozone depletion, photochemical smog, acidification and eutrophication. The decision of whether to prioritize one impact category over another is not always simple, as discussed in this paper.

Keywords *Electric Vehicles; Renewable Energy; Batteries; Life Cycle Assessment; Photovoltaic System*

ISBN: 978-85-92631-00-0

1. INTRODUCTION

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013) considers new evidences on climate change based on scientific analyses from observations of climate systems, theoretical studies and simulations using climate models. The atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased to unprecedented levels; carbon dioxide concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification.

Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes. The global mean surface temperature change for the period 2016–2035 relative to 1986–2005 will likely be in the range of 0.3°C to 0.7°C (IPCC, 2013) and it is virtually certain that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales as global mean temperatures increase.

Continued emissions of greenhouse gas (GHG) will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of GHG emissions.

According to the United States Environmental Protection Agency (EPA, 2016) 26% of 2014 greenhouse gas emissions in the United States come from burning fossil fuel by cars, trucks, ships, trains and planes (Figure 1). Over 90% of the fuel used for transportation is petroleum based, which includes gasoline and diesel. The transportation sector is the second largest source of greenhouse gas emissions in U.S. after electricity generation.

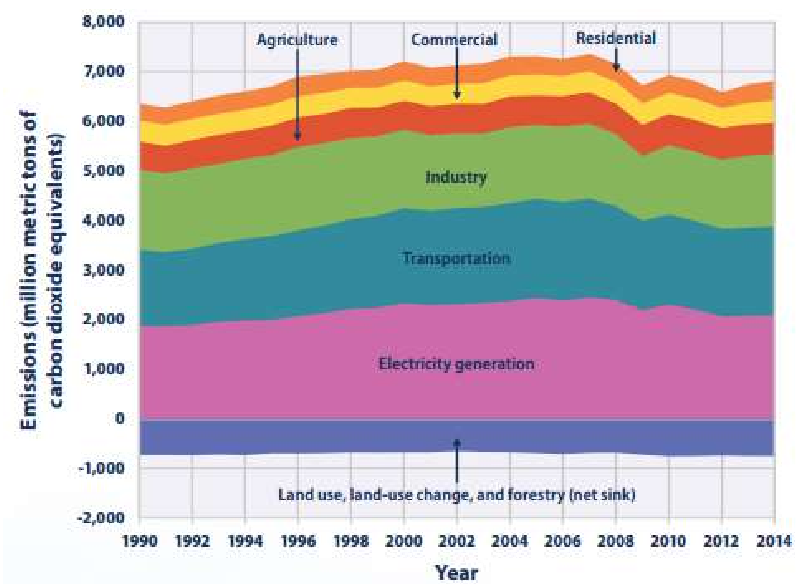

Figure 1 – U.S. Greenhouse Gas Emissions and Sinks by Economic Sector, 1990 – 2014
Source: United States Environmental Protection Agency (EPA, 2016)

ISBN: 978-85-92631-00-0

Worldwide, the transport sector accounts for about a quarter (23%) of global energy-related GHG emissions (IEA, 2015).

The Paris Agreement, announced in December 2015, clearly set the objective to limit the global average temperature increase below 2°C (UNFCCC, 2015). The ambitious GHG emissions reduction required to limit global warming to less than 2°C is unlikely to be achievable without a major contribution from the transport sector. The International Energy Agency (IEA, 2016a) indicates that the global transport sector must contribute about one-fifth of the total reduction of GHG emissions from energy use in 2050.

Electric vehicles (battery electric and plug-in hybrid electric vehicles) are seen as a major contributor to the GHG emissions reduction goal in transport, as they increase energy efficiency and reduce carbon intensity of transport energy carriers, while taking advantage of the reduction of GHG emissions in power generation and supporting the integration of variable renewable energy in the power generation mix. In a context of ever-growing urban populations, electric vehicles are also well equipped to reduce emissions of local pollutants in high-exposure areas and reduce noise levels.

Today, electric vehicles account for just a tiny fraction of the global vehicle stock (0.1% for cars). This is still not significant enough to impact the actual fuel consumption and GHG emissions from the transport sector as a whole. However, important signs of change emerged in the recent past since the year 2015 saw the global threshold of 1 million electric cars on the road exceeded (IEA, 2016b). In 2014, only about half of today's electric car stock existed and in 2005 they were still measured in hundreds.

Industry, governments and early adopters have succeeded in demonstrating that electric cars can deliver the practicality, sustainability, safety and affordability characteristics expected from them, but the electric vehicle market still requires policy support to achieve widespread adoption and deployment. Battery costs have been cut by a factor four since 2008 (IEA, 2016b) and are set to decrease further. It is important to remark that metals required for battery production is a non-renewable resource and the extraction and production are very intense energy processes.

Concerns about electric vehicle efficiency and the increase of electricity demand, still hang over industry and governments. Although advances in technology should reduce fuel usage and emissions, these improvements may be offset in the near-term by increased ownership and use.

In this respect, Life Cycle Assessment (LCA) studies contribute for the understanding on the real impacts of electric vehicles, considering the effects on the energy necessary for their charge and the storage system.

The present paper is a LCA study developed to support the Braunschweiger Versorgungs-AG & Co. KG (BS Energy, Germany) on the decision of whether to buy a stationary battery to store its photovoltaic energy generation, used for charging five electric vehicles. The main goal was to determine whether is environmentally worthy to invest in the stationary battery, considering that the vehicles could be charged straight from the photovoltaic system or from the German electricity net.

ISBN: 978-85-92631-00-0

2. LIFE CYCLE ASSESSMENT (LCA)

Life Cycle Assessment (LCA) is an environmental management technique that has its basic principles coordinated by the International Organization for Standardization (ISO). The basic idea of LCA is that all the steps involving a production system must be analyzed, making sure that all the environmental components are assessed to enable and support a decision-making. A LCA typically aims to analyze and compare different products, processes or services that fulfill the same utility (e.g., photovoltaic against nuclear power), helping to demystify some simplistic notions by calculating the environmental impact of a product or service system.

According to ISO14044 (2006), LCA consists of four phases. The first one is the goal definition, the most important phase since the depth and the breadth of LCAs can differ considerably depending on their objectives. The life cycle inventory phase (LCI) is the second step consisting of an inventory of input/output data with regard to the system being studied. It involves collection of the data necessary to meet the goals of the defined study. The life cycle impact assessment (LCIA) is the third phase whose purpose is to provide additional information to help assess a product. Life cycle interpretation is the final phase of the LCA procedure, in which the results of an LCI or an LCIA, or both, are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition.

There are cases where the goal of an LCA can be satisfied by performing only an inventory analysis and an interpretation. This is usually referred to as an LCI study. The International Standard covers two types of studies: life cycle assessment studies (LCA studies) and lifecycle inventory studies (LCI studies). LCI studies are similar to LCA studies but exclude the LCIA phase.

A variety of environmental impact indicators have been developed and more continue to be used as the LCA method evolves. The categories for indicators range from global level, such as contribution to global warming and ozone depletion, to local impacts, such as photochemical smog formation. In this research the following impact categories were considered: a) global warming - potential of contributing to climate change, measured in kgCO2eq; b) ozone depletion – potential of depleting the ozone layer, mostly by CFCs emission, measured in kgCFC-11-eq; c) photochemical smog - also known as photochemical oxidant formation or summer smog, mainly caused by solar radiation reaction with air pollutants, mostly emissions from fossil fuel combustion; d) acidification – its potential increases with the increase of sulphur (S) and nitrogen (N) in the soil and is calculated in SO2eq; e) eutrophication - marine and freshwater response to the increase of nutrients, mainly nitrogen and/or phosphates, due to human activities, such as the use of fertilizers and the disposal of sewage on water. This leads to an increase of certain organisms, such as phytoplankton, in the ecosystem. The marine eutrophication potential is calculated in kgN-eq and the freshwater eutrophication potential in kgP-eq.

Considering so many different impact categories on a single investigation may have a few disadvantages, since most of times one technical solution can be better for mitigating one environmental aspect but not another. It is difficult to find the ideal solution for all of them but it is important to emphasize that LCA provides information to support a decision, which means that it cannot be used as a substitute for a decision-making process.

ISBN: 978-85-92631-00-0

One of the main concerns is the increase of energy demand. Considering that the renewable energy market is still not big enough to meet a growth in demand, the greenhouse gas emissions may remain very high. Another important concern is related to vehicles batteries: the metals required for their production are non-renewable resources, and their extraction and production is very energy intensive.

3. CASE STUDY – BS ENERGY

BS Energy is a German energy and drinking water distributor from the city of Braunschweig. In order to meet the growing demand for a cleaner supply chain, the company has been expanding its business and investing on new clean technologies such as electric cars and different types of renewable energy.

The energy storage system consists of a stationary battery that is fed by energy from a photovoltaic power generation or from the German electricity grid (Figure 1). The photovoltaic system is a 30m^2 multi-silicon solar panel with a 10.56 kW power generation capacity. This system can feed the stationary battery as well the electric cars, whenever necessary. Since the time period considered in the study is 1 year of vehicle usage, and the solar panel life time is approximately 30 years, the environmental impact of the solar panel was divided by 30.

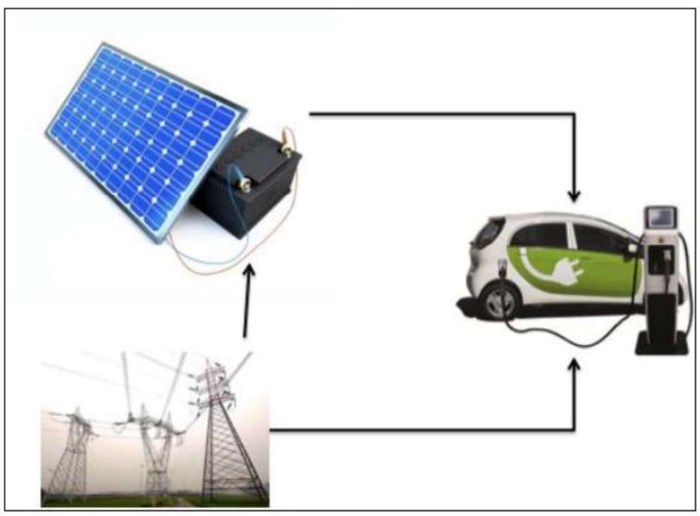

Figure 1 – Scheme of the system investigated.

The five impact categories aforementioned are analyzed for each one of the 6 scenarios studied on this work, namely:

i) BS Energy cars being charged directly from solar energy locally generated;

ii) Cars being charged by the stationary battery, which stores energy from the solar panels;

iii) Cars being charged directly with energy from the German electricity grid.

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3.1 Scenario 1 - Use of energy from the grid

The first scenario considered the energy from the grid only, which means that there is no need of local energy generation or of a special storage system.

This process includes electricity produced in the country, imports from others, transmission over aerial lines and cables, direct emissions to air, and all the electricity losses during transmission and distribution, assumed as 4% (World Bank, 2014), one of the lowest in the world. The high share of coal usage in the German electricity mix keeps emissions at high levels; the Global Warming Potential (GWP), calculated with the software Umberto Nxt, to provide energy for the 5 cars corresponds to 9.470 kg CO2-Eq.

3.2 Scenarios 2 and 3 - BS solar energy generation and electricity from the grid

Scenarios 2 and 3 admitted that the energy from the photovoltaic system was able to charge 3 and 2 vehicles, respectively. In both cases, the remaining cars were fed directly by the electricity grid. Each vehicle, traveling 50km a day, would consume about 2880 kWh a year and the total energy for the 5- vehicle fleet would reach 14,400 kWh.

Data about the solar energy production by a 10,56kWh photovoltaic system is shown in Table 1, available from 2011 to 2014. Since the time period considered in this study is just one year, the annual average production determined was 9.48MWh.

Table 1 - Solar energy production from a 10,56KW photovoltaic system
(Source: Sunny Places, 2015)

Year	Total Generation (MWh)	Monthly Average Production (KWh)	Average Oct-Feb (KWh)	Average Mar-Sept (KWh)
2011	8,87	739	252	1.087
2012	10	840	427	1.134
2013	9,44	787	335	1.109
2014	9,62	802	399	1.090
Total Average	9,48	792	353	1105

3.3 Scenarios 4, 5 and 6 – Use of stationary batteries

The battery that BS Energy intends to buy is a lithium–titanate battery, referred to as LTO in the battery industry. Due to its advanced nanotechnology, the LTO has many advantages when compared to other lithium batteries (Tian et al., 2010), such as life expectancy between 10 and 15 years. Due to its many benefits, especially high security and high stability, LTO batteries have a wide range of applications in the aerospace and military industries. The batteries will be built in Braunschweig at a driving distance of 6.7km from BS Energy. Considering that batteries will be transported by a light commercial vehicle, with an average CO2 emission of approximately 180g/km (International Council on Clean Transportation, 2014), the total emissions for this transport would be approximately 2.42kgCO2 for a round trip.

The influence of the stationary battery on the charging system was considered taking into account the following assumptions: the battery weight is 160kg and its size is 0,3m^3; when fully charged it can provide about 8kWh, which is enough energy for a 50km

ISBN: 978-85-92631-00-0

distance; each car travels around 50km per day; the internal efficiency of the battery was assumed equal to 90%.

Although the expected lifetime of a LTO battery ranges between 10 and 15 years, 3 different scenarios were herein investigated, considering 5, 10 and 15-year lifetimes, in order to better understand the influence of the battery lifetime on the LCA results.

4. LCA RESULTS

In this study the environmental impacts were investigated using the software Umberto Nxt LCA, a German tool for performing life cycle assessment with graphical modeling. Besides all the data provided by BS Energy and other open sources, the Ecoinvent database v.3 was also used, given its status as a world leader life cycle inventory data source. All the LCA results for the different scenarios, and for each impact category separately, are presented in terms of graphics (Figures 2 to 4) to facilitate the interpretation.

Figure 2 shows that the energy from the German electricity grid has a great impact in all scenarios. The GWP has its lowest value when 3 vehicles are charged by the photovoltaic system and the other 2 vehicles charged directly by the grid. The second best option is a 15-year lifetime battery combined with the photovoltaic energy and the grid. However, to be conservative, it was considered that the battery would not reach its maximum lifetime, admitting a 10-year lifetime period closer to reality. The impact between the 10-year lifetime and the 15-year lifetime batteries is not significantly different for comparison purposes. Thus, knowing that without storage, the most likely scenario for the photovoltaic system would be 2 vehicles charged by the solar energy and 3 by the grid, it is preferable to have the stationary battery system, ensuring the maximum use of solar energy.

In Figure 2 the impact of ozone depletion potential for each scenario can be also observed. The use of electricity from the grid has also a very high impact, making it necessary to ensure the maximum use of the solar energy. The photovoltaic system could be optimized by using it for charging vehicles during certain hours of the day and, if necessary, complemented by the energy stored in the battery system. Even though the battery emissions increase, it is lower when the electricity grid is used for charging a vehicle.

The photochemical smog potential, as shown in Figure 3, is also very sensitive to the use of net energy. However, in this case the battery has a greater impact than the energy provided by the grid, which means that even for the worse photovoltaic scenario it would be better to count on the photovoltaic system and the grid, without storage. However, since for charging 2 vehicles a day, the necessary average solar energy generation during one month corresponds to 480 kWh, the photovoltaic system would be able to charge 2 vehicles only between the months of March and September, when the solar generation is higher. During the other five months the photovoltaic system produces energy for charging only one vehicle and it would not be worth storing the excess energy in the battery system. If, in a future scenario, the photovoltaic system is expanded, the battery could be considered as an alternative for optimizing the use of solar energy.

The same situation can be seen for the acidification potential in Figure 3. In this case, the impact caused by the battery is even higher than that observed on the photochemical

ISBN: 978-85-92631-00-0

smog potential. In order to avoid a high acidification potential it would be important to make sure that the use of the solar energy is optimized, despite the absence of a battery.

Figure 4 shows the marine eutrophication potential for all the different scenarios. This impact category presents a similar pattern as the photochemical smog, where the storage system would not be environmentally worthy, unless the photovoltaic system is expanded. The same situation can be observed for the freshwater eutrophication potential, when the battery has also a great influence. The combination the photovoltaic system with the electricity grid is a better solution than the use of the battery system.

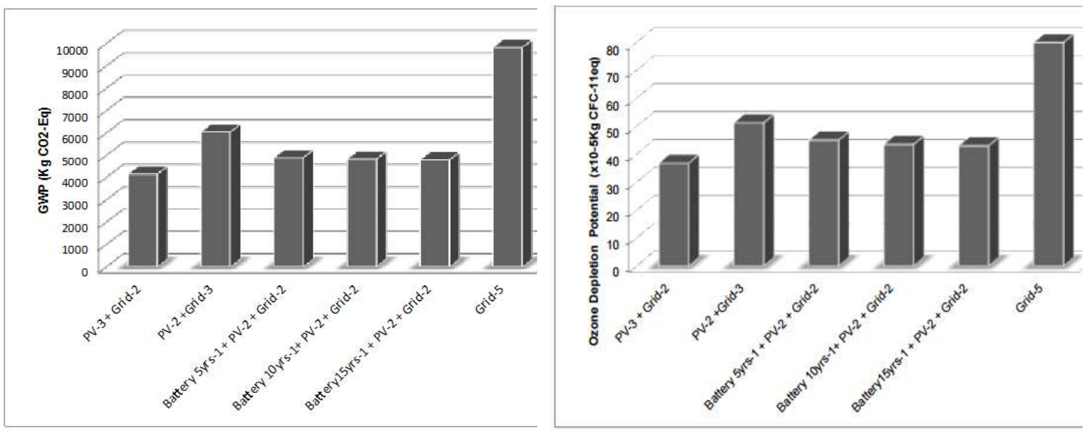

Figure 2 – GWP in kg CO2-eq (left); ozone depletion potential (x10-5kg CFC-11eq) (right)

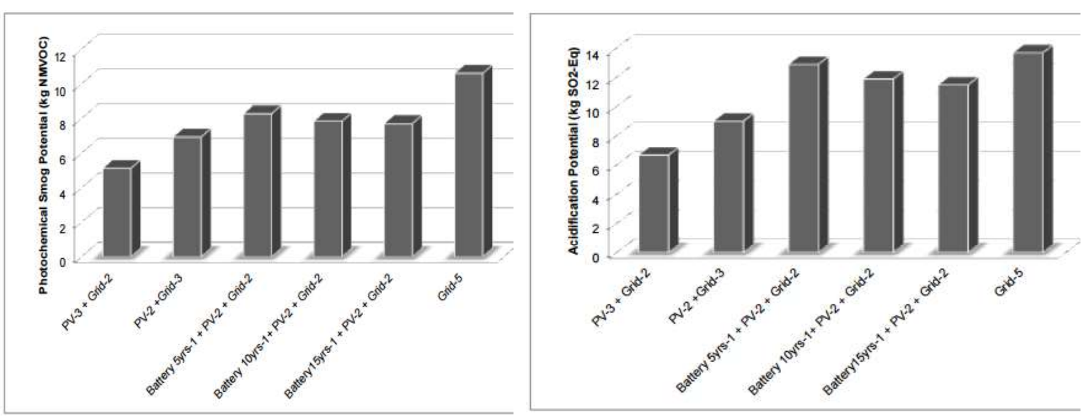

Figure 3 – Photochemical smog potential in kg NMVOC (left) and acidification potential in kg SO2-eq (right)

ISBN: 978-85-92631-00-0

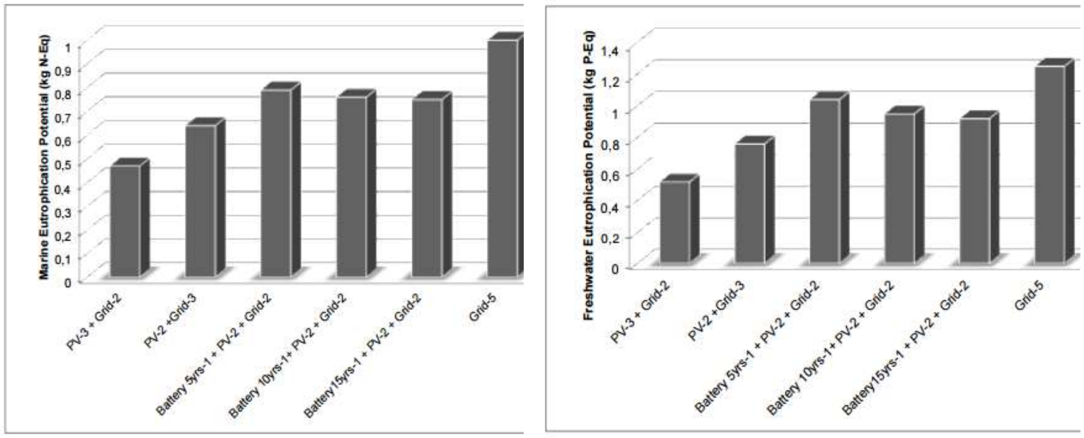

Figure 4 - Marine eutrophication potential in kg N-eq (left); freshwater eutrophication potential in kg P-eq (right)

5. CONCLUSION

Considering the current German electricity mix, the energy provided by the electricity grid has shown a greater impact than both the photovoltaic and the battery systems, with respect to the global warming and ozone depletion potentials. However, for all the scenarios examined in this work, the energy furnished by the grid is necessary to complement the energy generated by the solar panel, since the photovoltaic system provides an average of 9480 kWh per year, enough for charging only 3 out of 5 vehicles.

In some cases this combination of energy from the photovoltaic system and the electricity grid is more attractive than using energy from the battery system. This situation was observed for the following impact categories: photochemical smog potential, acidification potential and eutrophication potential (both marine and freshwater). When compared to the energy provided by the electricity grid, considering the charge of one vehicle, the 10-year lifetime battery has shown for the photochemical smog potential an impact 35% higher, for the acidification potential an impact 97% higher and for the marine and freshwater potentials the impact of the battery was 53% and 75% higher, respectively, than the environmental impact from the German electricity grid. If the battery were a Li-ion battery with a graphite anode the impact would be even greater.

Differently from the situation observed for the photochemical smog, acidification and eutrophication potentials, the energy from the grid has shown an impact 2.8 times higher than the impact of the battery on the global warming potential. When it comes to ozone depletion potential the grid also represents a much greater impact when compared to the battery, equivalent to 2.3 times higher.

The decision of whether to prioritize one impact category over another is not always simple. Even though three of the impact categories (photochemical smog, acidification potential and eutrophication potential) have shown an unfavorable scenario for the stationary battery, the priorities in relation to mitigation of environmental impacts should be considered. The global warming potential and ozone depletion potential may have greater influence on the decision making than other impact categories.

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The battery is therefore an option that should be considered to optimize the use of solar energy associated with a time schedule to charge vehicles using the photovoltaic system during periods of intense solar power generation. The photovoltaic system has shown the best environmental performance when compared to the use of the German electricity net. The possibility of expanding the local energy generation should also be considered in order to guarantee a low end of chain emissions of the vehicle fleet.

Other results would be probably obtained in countries with very high solar irradiation and the electricity net based on renewable energy such as Brazil. A similar study could stimulate the investment on local renewable energy production and on the development of electric vehicle market in the country. According to recent a document (Brazil, 2016) Brazil has a 75.5% proportion of renewable energy, compared with an average of 23,1% for the developed countries.

Germany has the target of 45% of renewable energy production by 2025. If this target is achieved the end of chain emissions would drop 15.30% which, in this study, would mean a GWP for charging one vehicle during one year decreasing to 1.670 kg CO2-eq instead of the current 1.970 kg CO2-eq. This still represents a higher impact than both the photovoltaic and the storage systems. The end of chain emissions would have to drop 51% in order to use only the grid energy as the better environmental option.

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