Design of the next-generation electric vehicle with integrated photovoltaic

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Academic year

2020-2021

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Master of Science in Electromechanical Engineering

Student at UPV enrolled in

Máster Universitario en Ingeniería Industrial

This master's thesis came about (in part) during the period in which higher education was subjected to a lockdown and protective measures to prevent the spread of the COVID-19 virus. The process of formatting, data collection, the research method and/or other scientific work the thesis involved could therefore not always be carried out in the usual manner. The reader should bear this context in mind when reading this master's thesis, and also in the event that some conclusions are taken on board.

ABSTRACT

Road vehicles account for more than 70% of the greenhouse gas (GHG) emissions of the transport sector in the European Union. This is linked to the use of fossil fuel vehicles, which is the dominant source of energy in transportation. In this regard, electric vehicles (EV) are presented as an alternative with great potential to decrease pollution rates. However, they are still in their early stages of development and thus the need to further investigate their environmental performance. This study is focused on two strategies that aim to improve EV behaviour: the use of lightweight materials in the vehicle body and the integration of photovoltaic (PV) roof, in a battery electric vehicle (BEV). These strategies have been shown in the scientific literature to potentially decrease the environmental impacts of BEV. In this light, a detailed literature review is carried out in the first part of this work. In the second part it is developed an Excel based life cycle analysis (LCA) tool to perform a comparable LCA on the next-generation electric car with PV roof and current electric car using Ecoinvent as background data.

The results obtained have proven numerically that both proposals have environmental benefits. Even though in lightweighting the specific manufacturing emissions are increased, the vehicle's lifetime emissions are diminished. With a weight reduction of 30% a 11.6% of GHG emission savings can be achieved. The integration of a solar roof will upgrade emissions by 9.4% but combined with 30% lightweighting the emissions fall by at most of 21%. These results must not be generalised as they are subjected to several limitations. They are very location dependent, the LCA performed was not a complete analysis, only emissions of the main parts were taken into account, and the calculous made for the EV energy consumption were simplified.

KEYWORDS

Battery electric vehicle, Lightweighting, Solar Car, Ecodesign, Environmental Impact, Life Cycle Assessment.

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1. INTRODUCTION

In Europe, the transportation sector accounts the 27% of the total EU-28 greenhouse gas (GHG) emissions, this implies 1,107 million tons of CO_2 equivalent were released to the atmosphere in 2017 (European Environment Agency, 2019). 72% of the emissions from transport came from road vehicles, of which passenger cars contribute 44%, light commercial vehicles 9% and heavy-duty vehicles 19%. Considering these data, investments in the automobility industry to make it more eco-friendly present as a good strategy to decrease pollution rates and achieve the targets set by governments and several international organizations in terms of sustainability.

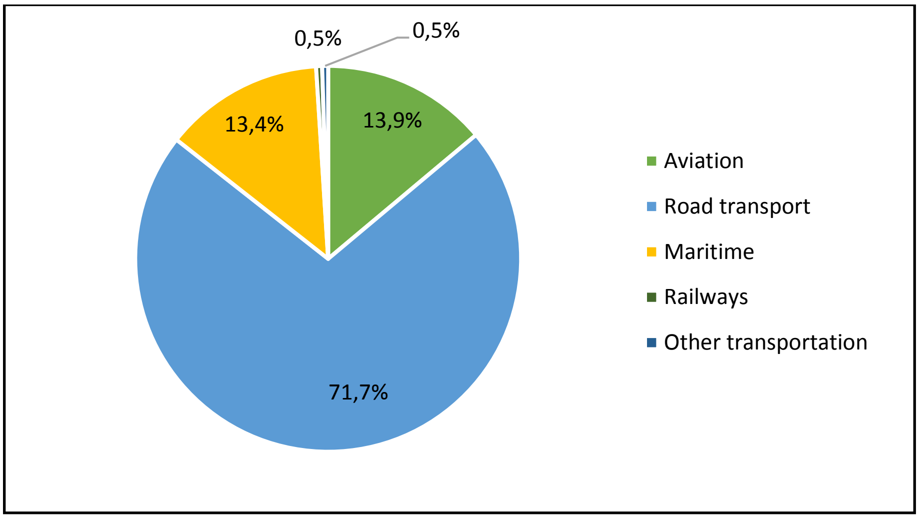

FIGURE 1. SHARE OF TRANSPORT GHG EMISSIONS. (EUROPEAN ENVIRONMENTAL AGENCY, 2019)

Transportation remains very oil-dependent, fossil fuels represent the 95% of the energy consumption in the transportation sector (European Environment Agency, 2019), especially in road transport that accounts for the 71% of the total EU consumption in 2017. In the same report it is said that even though petrol and diesel cars are the best-selling passenger vehicles, plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV) have increased their sales in a 50% in 2018. However, it only represents the 2% of the new fleet and the GHG emissions in this sector continue to grow.

In order to reverse this trend, several options are being considered. Convert from diesel to compressed natural gas (CNG) and eco-driving are two popular alternatives studied in (Li et al., 2016) that seek lower rates of GHG emissions and conservation of fuel. Other possibility that shows a great potential are electric vehicles (EV), however their environmental performance must be extensively studied as there is a debate among researchers. The fact that they do not emit tailpipe emissions may lead to the mistaken belief that they do not pollute at all; however, the production stage is particularly energy intensive. The electrified powertrain can potentially reduce GHG emissions as it has a higher efficiency contrasted to the ones used in internal combustion vehicles (ICEV), also the energy used to process and transport the fossil fuels is erased. It must be taken into account that electric vehicles emissions during the use phase are strongly dependent to the source of the electric energy that feeds the grid, they can reach their full potential in mitigating global warming when the electricity production is made from clean and renewable energy sources (RES). (Nordelöf et al., 2014)

In the past, electric cars have a limited driving range compared to internal combustion cars, nowadays that difference is becoming shorter (Høyer, 2008). While an average ICEV car offers a range of 482km the new models of passenger EV offer ranges between 200-490km (Kia, 2020) and luxury models can go beyond the 600km (Tesla, 2020). Other inconvenient of electric vehicles is the lack of charging stations and the strong dependency of a charging spot at home. For an everyday use in city this may not be a problem but when it comes to long trips by car the difficulty of finding a charging station on the way or in a new location may lead consumers to opt for a fossil fuelled vehicle. Also, EV must carry the weight of the battery, even when it is almost discharged, unlike ICEV that as fuel is consumed the weight is reduced. In addition to this, when it comes to environmental performance, the importance of the materials production and manufacturing phases enhance with the degree of electrification. In (Nordelöf et al., 2014) it is mentioned that the body in white accounts for at least the 54% of the emissions during manufacturing step.

Nonetheless the scientific literature agrees that EV are in their early stages of development and there is still a wide range for improvement. Lightweighting and solar roof are two strategies when combined could significantly reduce EV environmental impacts, especially climate change impacts.

Lightweighting is being developed on the direction of finding materials with less density than steel to substitute it in the glider. These materials could be aluminium or carbon fiber reinforced polymers (CFRP) among others, as well as the process of manufacturing steel is highly developed that of these new materials is not, therefore during this stage more energy is needed which implies a higher rate of contamination. Adding solar photovoltaic panels in the roof of the vehicle could provide a new source of energy for the battery, it can be charged while the car is parked or even when it is in motion. These two strategies together could help EV to take advantage over conventional vehicles. The use of lightweight material can compensate the extra weight of the battery and the range of the vehicle will be increased as it has extra power from the PV and less weight to carry (Raugei et al., 2015). Moreover, it will reduce the dependency from the grid and help to reduce pollution rate of EV in countries where the energy generation comes mainly from non-renewable sources.

Therefore, this study aims to upgrade the understanding of the environmental impacts of glider's lightweighting and integrated photovoltaics and suggest a set of guidelines based on life cycle assessment and ecodesing for future electric vehicles. After the literature review, contrasting benefits and drawbacks of both strategies, an EV will be modelled in Excel where the performance of the vehicle with or without lightweighting and PV panels would be studied in detail.

2. METHODOLOGY

Life Cycle Assessment (LCA) is a standardized method to evaluate the environmental performance of a product during its whole life, from cradle to grave. The requirements needed to perform a complete LCA are detailed in the ISO 14040 standard (ISO, 2006), this document explains step by step all the four phases involved in a LCA study as well as the key features and the methodological framework. LCA is a commonly used methodology in the automotive industry, it provides automakers and politicians valuable information to help them make decisions in the right direction in terms of environmental performance.

Several publications have analysed which is the correct approach to perform an automotive LCA. They all agree that there is a large variety of influencing factors, but transparency is crucial to reduce the variability of the results. These influencing considerations can be classified as external or internal to the vehicle and they may vary depending on the objective of each study. For instance, in the specific case of lightweighting with aluminium, his advantageousness changes depending on the country as a consequence of the alteration of the influencing external factors, like the kind of energy supply utilized during manufacturing and use phase. (Nordelöf et al., 2014) and (Egede et al., 2015).

2.1 LCA STAGES

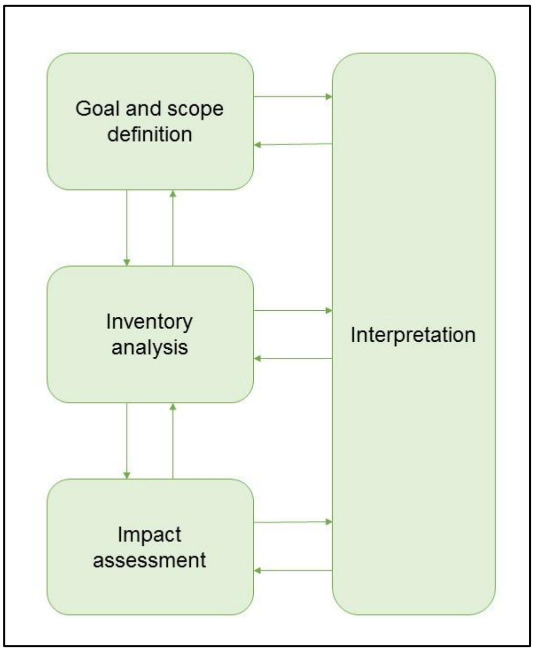

FIGURE 2. STAGES OF A LCA (SOURCE:(ISO,2006))

The first phase of an LCA is the goal and scope definition, in this initial part the reasons to carry out the study, the product system, the system boundaries and the functional unit must be clearly described. LCA studies of EV usually express concisely the scope, although the goal it is not clear enough or even completely forgotten. (Nordelöf et al., 2014)

In the life cycle inventory analysis (LCI) the inputs, the outputs, and the relations among them and with the environment are quantified through data collection or the appropriate calculous.

The life cycle impact assessment (LCIA) is based on the data provided by the inventory analysis. Impact categories and indicators must be selected and classified, then the potential impacts must be calculated relating the inventory data with the categories previously chosen. There are several methods to calculate the results due to the complexity of the environmental problems, however explaining them is out of the scope of this thesis.

The last stage is the interpretation one, it aims to relate the three previous phases and provide the audience clear conclusions in which the limitations and recommendations are explained. These statements should be based on the outputs from the impact assessment and must be in concordance with the goal and scope defined at the beginning. It is important to remark that from LCA's only potential impacts can be obtained, not actual consequences.

The reason behind the double arrows in the diagram is that these four phases should be understood as an iterative process rather than a linear path. (Egede et al., 2015) For instance, when the results of the impact assessment are obtained the goal and scope must be reviewed to check if the objectives have been met, and this may lead to changes in the goal and scope definition. (ISO, 2006)

2.2 DATABASE AND SOFTWARE

Informatic tools will facilitate the process of performing an LCA, especially in the stages of LCI and LCIA as they will support the computational part, perform uncertainty and sensitivity analyses, and could allow the user to model various impact assessment methods. There are several options available, both databases and computer programs, some free and some paid.

Nowadays, the most used software is SimaPro followed by GaBi, both are able to evaluate any type of product or process. They are private initiatives, and the cost may vary depending on the type of license. An interesting opensource alternative could be OpenLCA. In the field of databases, the Ecoinvent database is extensively used and it is the one that accounts with more datasets.

Bearing in mind what has been exposed in the previous paragraph, for this study the Ecoinvent database has been chosen to develop the model of an EV.

3. LITERATURE REVIEW

As a first step to develop the EV's model a literature review has been carried out in detail. This study is focused mainly in the GHG emissions of BEV considering lightweighting and solar roof. However, it is important to keep in mind that GHG emissions do not represent all the possible environmental impacts. For instance, human toxicity is not related with them and it could be a crucial factor when developing a new technology. An overview of the indicators considered in each study reviewed can be found in Table II of the appendix.

3.1 LIGHTWEIGHTING

For this strategy, a total of 18 research papers have been revised in detail. In total, these studies have modelled 105 different scenarios. Each study has its own different approach and assumptions, so the results obtained have had to be study one by one looking for points in common to harmonise and standardise the diverse conclusions.

Traditionally the glider is mainly made of steel, approximately 62%, which makes it interesting for lightweighting (Luk et al., 2018). Lightweighting materials more commonly studied are aluminium and carbon fiber reinforced polymers, as the glider is one of the components that shows better potential to be replaced by these kinds of materials this is where the several lightweighting strategies are applied in the literature. Most of the studies consider around a 20% reduction in the curb weight, except for (Mayyas et al., 2017) that consider a reduction of 35% with a scenario of intense aluminium. The substitution ratio is other important parameter, for the case of replacement with aluminium it varies from 0.1 till 0.8. In Table 1 there is a summary of the considerations made in each research concerning these two parameters.

Authors	**Lightweighting material**	**Substitution ratio**	**Weight reduction**
Das S.	CFRP	-	16,88%
Delogu M., Zanchi L., Dattilo C.A., Pierini M.	CFRP matrix	-	-
	Advanced hybrid materials	-	-
	Bio-composites from renewables	-	-

He D., Soo V.K., Kim H.C., Compston P., Doolan M.	CFRP	-	-
Kim H.C., Wallington T.J.	Aluminium	0.4 to 0.8	21.7%
	Magnesium	0.3 to 0.6	
Kim H.J., McMillan C., Keoleian G., Skerlos S.J.	Aluminium	0.23	-
	High Strength Steel (HSS)	0.06	-
Luk J.M., Kim H.C., De Kleine R., Wallington T.J., Maclean H.L.	Aluminium	0.73	20.8%
Mayyas A., Omar M., Hayajneh M., Mayyas A.R.	Aluminium	-	35%
	Magnesium	-	
Milovanoff A., Chul Kim H., De Kleine R., Wallington T.J., Posen I.D., MacLean H.L.	Aluminium	0.29 to 0.65	12% to 19%
Raugei M., Morrey D., Hutchinson A., Winfield P.	Aluminium	-	175kg
	Magnesium	-	214 kg
	Aluminium + CFRP	-	210 kg
	Magnesium + CFRP	-	232 kg
Sato F.E.K., Nakata T.	CFRP	-	-
	Aluminium	-	-
	Advanced HSS	-	-
Shanmugam K., Gadhamshetty V., Yadav P., Athanassiadis D., Tysklind M., Upadhyayula V.K.K.	CFRP	-	-
Tadele D., Roy P., Defersha F., Misra M., Mohanty A.K.	Talc-reinforced polypropylene (talc-PP)	-	-
	Miscanthus biochar-reinforced polypropylene (MB-PP)	-	-
Upadhyayula V.K.K., Parvatker A.G., Baroth A., Shanmugam K.	Aluminium	-	30%
	HSS	-	
Wolfram P., Tu Q., Heeren N., Pauliuk S., Hertwich E.G.	Aluminium	0.1 to 0.28	-

TABLE 1. SUBSTITUTION RATIO AND WEIGHT REDUCTION ASSUMED IN THE DOCUMENTS REVIEWED.

3.1.1 Production and manufacturing

The main drawback of lightweighting materials is the fact that their manufacturing phase is more energy intensive than that of the steel. A numeric evidence of this can be found in (H. J. Kim et al., 2010) where the emissions for primary steel are estimated to be 2.2kg CO_2-eq/kg steel and for cast and wrought aluminium are 9.72 and 9.45kg CO_2-eq/kg Al, respectively. These values correspond to a country with an electric system like the one in U.S., however if the production of this material is carried out in an intense carbon energy system, such us China, these values will increase till 3.8kg CO_2-eq/kg for steel and till 26.6kg CO_2-eq/kg for cast aluminium. Similar figures are calculated in (Wolfram et al., 2020), but most important is that the tendency is the same, steel produce less GHG emissions than aluminium and that these emissions depend on the carbon footprint of the energy supply. These values can be compared in the following table.

	Reference	Low carbon future	Current	Carbon intense system
Steel	(Kim et al, 2010)	-	2.2	3.8
	(Wolfram et al, 2020)	2.04	2.46	-
Wrought Al	(Kim et al, 2010)	-	9.45	-
	(Wolfram et al, 2020)	4.80	11.90	-
Cast Al	(Kim et al, 2010)	-	9.78	26.6
	(Wolfram et al, 2020)	4.80	11.90	-

Table 2. Comparison between the estimation made for primary metals in two studies in kg CO_2-eq/kg

Therefore, when evaluating the production of BEV with a lightened glider, compared to ICEV, not only the extra emissions from the battery and other electronic systems must be taken into account, but also the extra specific emissions from the new materials have to be added. This highlights the importance of manufacture vehicle's body in white using as clean energy as possible, by moving the factories to countries with a low-carbon electricity grid or by installing renewable energy sources in the plant area.

3.1.2 Use phase

In this stage of the EV's cycle is where the energy savings should compensate the extra emissions released during the production phase of lightweight materials. However, the results obtained in this phase depend, again, on the source of energy supply. In (Wolfram et al., 2020) is calculated that with the current energy mix the savings would be 1.2:1, this means that for each extra kg of CO_2-eq discharged during the production phase the emissions during the use phase will be decreased by 1.2 kg CO_2-eq. If the scenario is low-carbon energy supply this ratio could rise till 25:1 or even higher. (Mayyas et al., 2017) have calculated that for a reduction of 100kg in the total vehicle's weight will lead a saving of 0.85-1.4kg CO_2-eq per 100km. In (Minak et al., 2017) it is mentioned that in the case of EV a 10% of weight reduction, the vehicle's range will be increased by 13.7% and consequently this will decrease the number of battery recharges.

3.1.3 Life cycle GHG emissions

According to (Luk et al., 2017)"the use of lightweight glider is highly likely to reduce life cycle GHG emissions regardless of powertrain type", it must be taken into account that this percentage might decrease for EV due to their dependency on the emissions of the grid and the battery downsizing. Studies like (Raugei et al., 2015) more conservative results are obtained, for this case a maximum of 7% reduction of the global warming potential. Other studies, however, show more optimistic results like an 11% in (Milovanoff et al., 2019).

With the results presented in the previous paragraphs in mind, it can be concluded that, beforehand, the lightweighting strategy reports benefits in terms of EV's GHG emissions.

3.2 INTEGRATED PHOTOVOLTAICS

Integrating photovoltaic panels is other of the strategies proposed to optimize the performance of electric vehicles, the main advantages are the possibility to charge the battery while driving, less dependency on charging stations and the fact that solar will provide the vehicle with clean energy. However, there are some drawbacks, the efficiency of the photovoltaic cells remains low and the effectiveness of the system depends particularly on weather conditions.

(Khare & Bunglowala, 2020) consider that the main aspect that affects the solar car performance is the amount of solar radiation. In an ideal case the vehicle would only circulate on routes devoid of any object that could cast a shadow, however this does not come close to reality. The installed panels are subject to shadows produced by buildings and other urban equipment and to the reduction of available irradiation caused by clouds. This is considered in (Betancur et al., 2017), as the energy consumption of an EV increases with speed, they aim to set the optimal velocity to complete a race using only solar energy. They have calculated that for a cloudy day where the solar irradiance is a 60% of a sunny day the race time was increased in 2h. For the applied case of light utility EV, in (Kanz et al., 2020) they consider a shadowing factor of 30% during a lifetime of 8 years, results showed that the emissions were 0.375 $kgCO_2eq/kWh$, lower than the grid average of 0.435 $kgCO_2eq/kWh$. In the same study it is concluded that increasing the shadowing factor will increase the emissions per kWh of PV generation till they exceed the grid average, it is also settled that increasing the life of the vehicle will have benefit impacts obtaining better emission rates with higher shadowing factors.

Nowadays there are several photovoltaic technologies available in the market. In (Giannouli & Yianoulis, 2012) it is evaluated which one is the most suitable for EV, for this application it is searched the greatest efficiency possible and lightweight. The crystalline silicon panels (c-Si), the most used, present under standard conditions an efficiency of 29%, there are commercial models with an efficiency of 24%. This, in addition to their high cell packing density, makes them a relevant option for vehicular applications. Other option are the thin film solar cells which are lighter and more flexible, but their commercial efficiency is approximately 15%. At present time, the best option are c-Si panels, however thin film solar panels are still under development so in the future this decision may change. (Attia et al., 2020)

When implementing the solar roof, one of the challenges in the future is the development tools that help the driver to use the solar energy available wisely. One option could be that based on the forecast the vehicle could predict which is the best route to go to a certain point and to indicate the best parking spot to recharge the battery while parked. (Hasici6 et al., 2016) (Oosthuizen et al., 2020)

One aspect that has been missing while reading the literature review is the lack of life cycle analyses of electric vehicles with integrated photovoltaics. There are studies that analyse technical aspects like how the panel generation must be calculated (Khare & Bunglowala, 2020a), or others that perform an LCA of the photovoltaic panels only (Gerbinet et al., 2014) and the several aspects that have been presented above, however there is a generalized lack of studies which perform a comparative between conventional EV and a solar EV.

The solar vehicles started to be developed in the universities at the end of last century, they were motivated due to the several solar car races that take place every year in different parts of the world. Nowadays, some companies are developing commercial models. In table three, there could be find a comparison of their main characteristics.

Two different approaches can be distinguished when it comes to betting on the solar car, some companies are focused on trying to build a car that will work only with solar energy, these would be the ones that develop vehicles with at least 30km of PV range per day. In this category it is possible to find Lightyear One (Electric Vehicle Database, n.d.) or Aptera (Aptera

Motors Corp., 2020) that develop top-of-the-range sports models in which every detail of the vehicle is studied, from creating a design that is as aerodynamic as possible to including all possible extras in the interior. Other companies, like Squad (Squad Mobility, 2020), develop more economic solar city cars with less extras but that could be even more functional than the luxury ones.

Vehicle	Weight	Range with PV
Squad	200 kg	20km per day
Lightyear One	1300 kg	70 km per day
Sion	-	34 km per day
Toyota Prius Plug-in Hybrid Solar	1530-1550 kg (curb weight)	1000 km per year
Hyundai Sonata Hybrid	1508-1601 kg (curb weight)	≈3.2 km per day
Aptera	-	70 km per day

TABLE 3. COMPARATIVE BETWEEN THE DIFFERENT SOLAR CARS AVAILABLE IN THE MARKET

On the other hand, there are traditional manufacturers, like Toyota and Hyundai, that are developing hybrid models that only use solar energy as an extra source, but they could not be able to run only with photovoltaics. The daily extra range provided by the solar panels is 3.2km and 2.74 km for Hyundai (Hyundai Motor Company, 2020) and Toyota (Toyota Europe, n.d.) respectively. The design of these models is more similar to that of the most common ICEV and BEV today. In addition, with respect to their size, the area of solar panels included is smaller than that of the previous category.


FIGURE 3. LIGHTYEAR ONE (LEFT) AND SQUAD (RIGHT) SOLAR VEHICLES. (SOURCE: (LIGHTYEAR ONE, 2020) AND (SQUAD MOBILITY, 2020)

FIGURE 4. TOYOTA PRIUS SOLAR ROOF. (SOURCE: (TOYOTA EUROPE, N.D.))

3.3 END OF LIFE STRATEGIES

Not all the studies have considered the effects of the process involved after the use phase of the vehicle has ended. As it is explained in (Keoleian & Sullivan, 2012) the first step is dismantler the vehicle and remove the elements that can be reused or remanufactured. Then the remaining parts are sent to a shredder where the 95% of metals are recovered for recycling purposes, in contrast the non-metals parts have a lower ratio of recycling.

Regarding aluminium, as a metal, it is recycled and converted into secondary metal. The most ambitious target would be to reach a closed-loop infrastructure. It refers to "recovering wrought aluminium from vehicles and recycling it directly into secondary wrought aluminium. This currently does not occur, as all aluminium recovered from vehicles is recycled (downcycled) as cast aluminium." as (H. J. Kim et al., 2010) explained. In this same study it is exemplified that while the production of primary cast aluminium releases 9.72kg CO_2-eq/kg the production of secondary cast aluminium only emits 1.18kg CO_2-eq/kg, similar numbers are obtained for wrought aluminium, 9.45 versus 0.90kg CO_2-eq/kg.

Recycling technologies for PV panels are still quite new and there are some challenges to overcome (Contreras Lisperguer et al., 2020), although as it has been demonstrated in (Maani et al., 2020) that they have beneficial effects from an environmental point of view. In this same publication it has been found that for the crystalline silicon PV panels, the ones selected for this study, their recycling is convenient especially due to their content in silver (Ag), as it is the most expensive and with the highest GWP impact metal. Other very impactful metal is aluminium which has a high mass/m^2 ratio in c-Si panels, copper, glass and silicon are in a similar situation. The recycling of the solar panels comprises three main stages which can be more or less polluting and energy intensive depending on the methods used. The first phase is delamination, at this point the ethylene vinyl acetate (EVA) is eliminated making the rest of the panel components accessible. For c-Si panels this is considered the most critical phase, if it is done properly it is possible to recover photovoltaic cells by means of very low energetic treatments. This is followed by the material separation stage where each material is sent to the corresponding treatment. Then it comes the solar cells recovering and silicon extraction, the treatment applied depends whether the cells are damaged or not.

4. CASE STUDY

As it has been mentioned in the sections above, a Life Cycle Assessment analysis is going to be performed for the practical case of this study. It is going to be a comparative LCA between a basic battery electric vehicle and a BEV with lightweight materials in the glider and/or solar roof.

4.1 GOAL AND SCOPE

The study aims to evaluate the potential environmental impact of an electric vehicle with lightweight materials and solar roof. The modelled vehicle is a battery electric vehicle that can be recharged from the grid or thanks to the solar panels installed in the roof, due to its dimensions, it is in the segment of passenger cars. The functional unit of the process would be 1km of travel, it has been chosen because it has been considered the option that can best present the results. The car is supposed to be driven in the Spanish city of Valencia, located in the Mediterranean coast, located in figure 5. The vehicle is going to be started used in 2020 with a lifetime of 10 years and 200,000km.

FIGURE 5. MAP OF SPAIN (SOURCE: GOOGLE MAPS)

The solar panels used in the vehicle are the crystalline silicon photovoltaic ones because of their higher efficiency compared to other technologies. In addition, the fact that they are the most widely used solar panels nowadays helps to make manufacturing processes more standardised with better use of energy and resources. For the lightweighting strategy it is going to be evaluated the substitution of steel by aluminium.

In figure 6 the flow system diagram of the study can be found, the main elements included in the LCA are the PV panels and the glider, as the rest of the car's parts remain equal in all the possible scenarios studied, they were not compared. Regarding the system boundaries, in this type of study it is required to consider a crandle to grave perspective for the elements or process that are analysed. For the main materials of the glider, steel and aluminum, the recycled techniques reviewed in the bibliography are considered, as it has been described they can make a point between which of both materials has a better environmental performance. In the study only the production of aluminum and stell is going to be considered even though the glider has a percentage of other materials. As it has been demonstrated in (Luk et al., 2018) the amount of these other materials used in the body in white is the same for both, the base case and the lightweighting cases. Also ,due to their big impact, the emissions of the battery manufacturing are included. Emissions of other less representative parts of the vehicle are excluded from the manufacturing and end of life stage, these could be the vehicle interior or tires and wheels, among others.

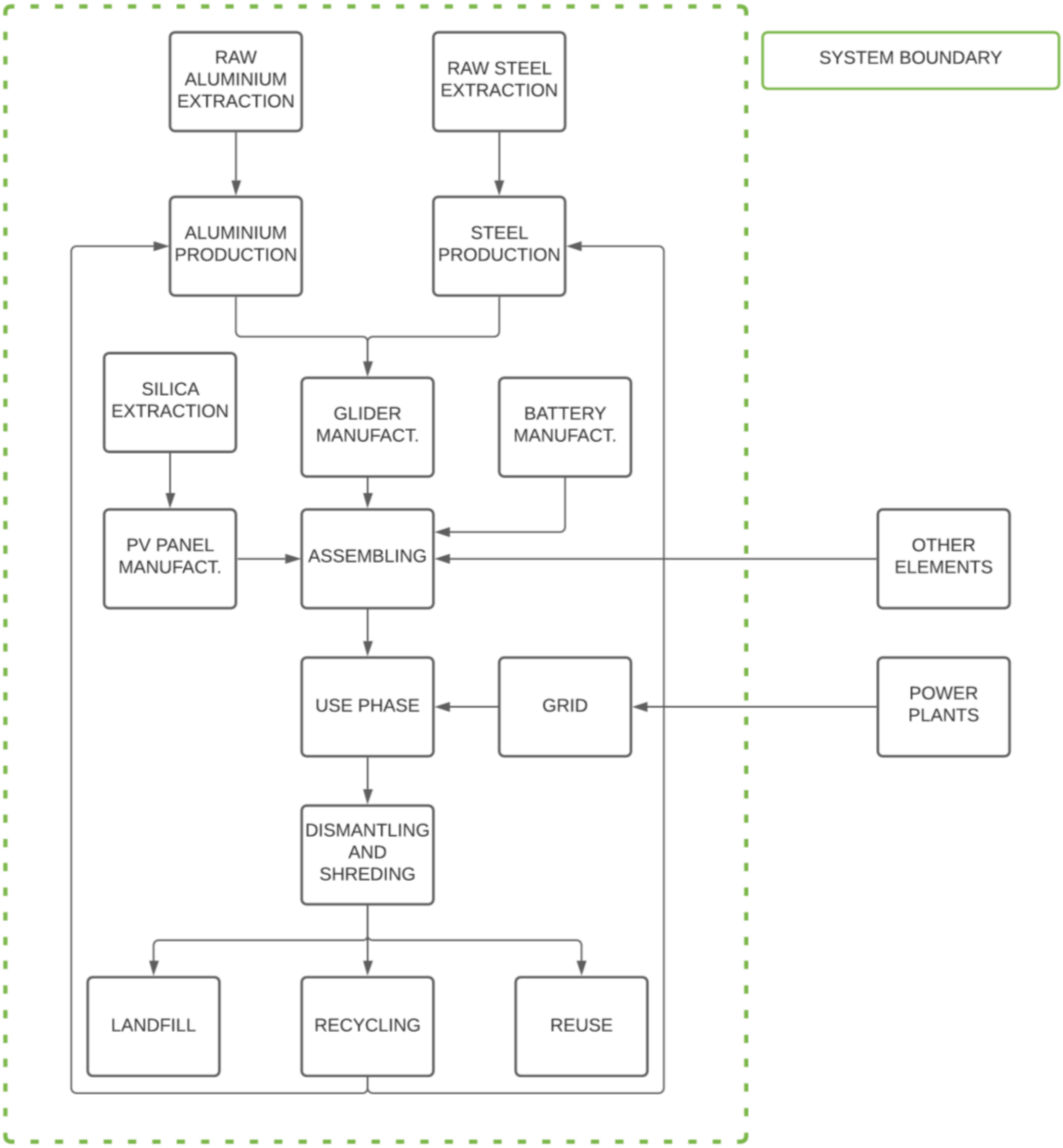

FIGURE 6. SIMPLIFIED PROCESS DIAGRAM FLOW (SOURCE: OWN DEVELOPMENT)

4.2 LIFE CYCLE INVENTORY

In this phase the environmental performance of every component in every stage is going to be quantified, careful data collection has been carried out.

There are going to be considered five scenarios combining the different alternatives, they are summarized in table 3. In the "Base case" scenario the calculations are made for a traditional EV, then in "Lightweighting", "Optimistic lightweighting" and "Intense lightweighting" the effect of different levels of glider mass reduction are considered. In the fifth scenario, "Solar roof" it is evaluated the benefit that only PV integration can bring. In the last scenario "Solar roof + lightweighting" it is evaluated the performance of both strategies when combined.

	Scenario	Lightweighted %	PV panels
1	Base case	0%	NO
2	Lightweighting	10%	NO
3	Optimistic lightweighting	20%	NO
4	Intense lightweighting	30%	NO
5	Solar roof	0%	YES
6	Solar roof + lightweighting	30%	YES

TABLE 4. DIFFERENT SCENARIOS PROPOSED

The base case has been assumed with the weight and dimensions of a general electric vehicle; these values are taken from the literature. For the glider, the general weight breakdown of each material has been obtained from (Luk et al., 2018b). For the battery it has not been selected a specific model, but it has been decided to use values that represent the market average nowadays. While reading (H. C. Kim et al., 2016) and (Ambrose & Kendall, 2016) it is clear that there is a wide variety of possible configurations, in this case it has been chosen a 30kWh LFP battery with an energy density of 0.08kWh/kg.

4.2.1 PRODUCTION STAGE

In this section the process of mining extraction, treatment and glider assembly are going to be analysed. The dataset obtained from the Ecoinvent 3.6 database represent the global market process including raw material extraction, manufacturing, and transportation from production plants to the market. The values of CO_2 emissions per kilogram of material show higher pollution rates for aluminium compared to steel, for the steel the polluting quota is 4,472kg CO_2 eq/kg steel and for the cast and wrought aluminium is 9,815 and 13,092kg CO_2 eq/kg Al, respectively. These values differ slightly from the ones proposed in (Wolfram et al., 2020) and (H. J. Kim et al., 2010) however they are in the same order of magnitude. With this information it is calculated the total amount of kilograms of CO_2 per vehicle released during the production phase of the glider, as explained in the previous section four cases of glider are going to be modelled, conventional steel intense scenario (base case scenario) and with 10%, 20% or 30% of glider lightweighting. For the emissions released during the battery production it has been assumed a value of 140 kg CO_2eq/kWh as it is calculated in (H. C. Kim et al., 2016) for the specific case of a Li-ion battery for EV.

For the photovoltaic panel manufacturing process there are no numbers available in the database, for this reason a value has been chosen from the literature review. As explained in section *3.2 Integrated photovoltaics* the most suitable technology for automotive application is the crystalline silicon photovoltaic panels. For this technology in (Pu et al., 2021) the carbon emission factor for a photovoltaic system is estimated in 2,2677kg CO_2 eq/Wp.

The watts peak (Wp) refers to the capacity of the system, this property is calculated by multiplying the number of panels by the nominal power of each one. The installed capacity is the maximum output that could, theoretically, be obtained from the system without taking into account any losses or efficiencies.

The emissions released during the manufacturing phase of other parts of the vehicle such us the powertrain are not included in this study as these elements remain invariant among the scenarios proposed and do not account for a large percentage in the emissions of an EV.

4.2.2 Use stage

Among the literature reviewed the lifetime of the vehicles studied vary from 150.000km (Delogu et al., 2017), (Raugei et al., 2015) and (Choma & Ugaya, 2017) to more than 300.000km in (Mayyas et al., 2017). In the following graph the lifetime considered in each study is represented, the ones that appear twice is because they have modelled scenarios with different lifetimes. The average of this reports is 212.514km, therefore for this study a value of 200.000km driven for 10 years has been chosen.

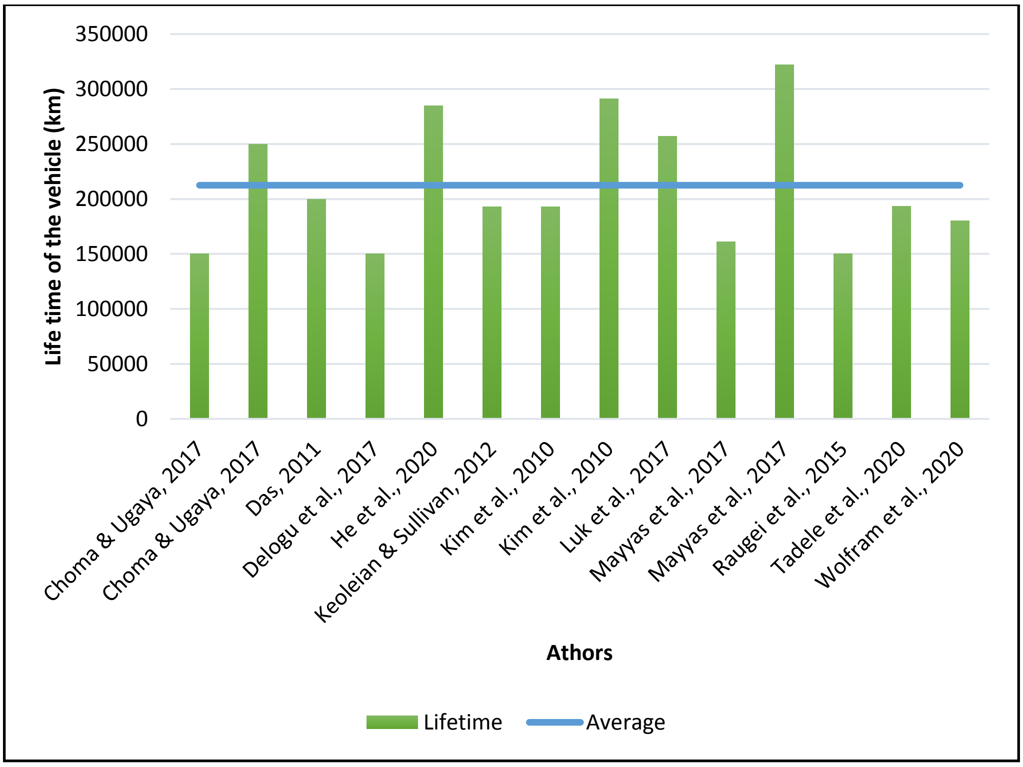

FIGURE 7. COMPARATIVE OF LIFETIMES CONSIDERED. (SOURCE: OWN DEVELOPMENT)

4.2.2.1 VEHICLE'S ENERGY CONSUMPTION

To calculate the vehicle's energy consumption there are standardized driving cycles where vehicles should be tested. On of them is the New European Driving Cycle (NEDC), it was used for homologation testes in the European Union. NEDC was approved for light-duty vehicles and it has continuously periods of low acceleration and deceleration, however it is not considered a good indicator of a vehicle's actual consumption as it does not represent real driving patterns (Barlow et al., 2009). Because of this and the fact that it was outdated, NEDC was substituted by the World Harmonized Light-duty Vehicles Test Procedure (WLTP). This test overcomes constraints of NEDC and obtains more realistic values for the energy consumption and CO_2 emissions (Pavlovic et al., 2018). In table 5 there can be found the main differences between the two driving cycles.

However, the main issue to be studied here is the effect that lightweighting has on vehicle's consumption rather than developing a very accurate and realistic model of vehicle's energy utilization. Therefore, it has been decided to develop a simple calculating model taking the WLTP data as input.

	NEDC	WLTP
Time	20 minutes	30 minutes
Distance	11.03 km	23.25km
Driving type	66% urban 34% non-urban	52% urban 48% non-urban
Average speed	33.6 km/h	46.5km/h
Idling time	23.7%	12.6%
Max. acceleration	1.04 m/s^2	1.67m/s^2
Min. deceleration	-1.39 m/s^2	-1.5 m/s^2

TABLE 5. MAIN DIFFERENCES BETWEEN NEDC AND WLTP

The methodology used to calculate the energy consumption of the vehicle is based in (Abousleiman & Rawashdeh ., 2015). In the first place it is needed to calculate the consumption due to the vehicle's mass dynamics as it is showed in the following equations.

$$\sum F = F_{roll} + F_{grade} + F_{air} + F_{acc} \quad (1)$$

$$F_{roll} = M * g * fr \quad (2)$$

$$F_{grade} = M * g * i \quad (3)$$

$$F_{air} = \frac{1}{2} * \rho_a * C_D * A_f * (v + v_{wind})^2 \quad (4)$$

$$F_{acc} = M * \delta * a \quad (5)$$

In equation (2) the rolling resistance force is calculated, it represents the force necessary to overcome the friction between the road and the tires. F_{grade} refers to the force needed by the car to climb a hill (positive value) or to descend it (negative value). Equation (4) express the resistance existing between the car and the air, the velocity of the wind can be positive or negative whether it has the same direction of the vehicle or not. The force required during the acceleration period is considered in equation (5). These four forces added together result in the value of the minimum force required to move a vehicle, whether electric or not. If the summatory is multiplied by the velocity it is obtained the power in watts needed.

In Table 7 it can be found the values of the different parameters considered for the equations 1 to 5, most of these values are obtained from (Abousleiman & Rawashdeh., 2015) where the energy consumption of an EV is modelled and contrasted with real life measurements. One factor that has been omitted is the wind speed, a value of zero has been used on the equations. Wind speed is known by its variability, it has been considered use the average wind speed of Valencia however as it is obtained from the meteorological data of the city it has been measured at 10m high which do no match the high for cars, 0.7m in WLTP. Also as explained in (Ligterink et al., 2015) not only the speed of the wind matters, but the direction also affects. Compared to a one way trip in a net trip, go and return, the wind influence on the whole route is less. So due to its complexity it has been assumed as there is no wind.

Description	Symbol	Value	Unit
Aerodynamic Drag Coefficient	Cd	0,25	-
Frontal Area	Af	2,25	m2
Rolling Resistance Coefficient	fr	0,005	-
Vehicle Mass	M	variable	kg
Gravitational Acceleration	g	9,8	m/s2
Air Mass Density	ρa	1,275	kg/m3
Rotational Inertia Factor	δ	1	-
Regenerative Braking Factor	α	0,5	-
Road grade	i	variable	-
Vehicle speed	v	variable	m/s
Wind speed	vwind	variable	m/s
Auxiliary Load	Aux_load	300	W

TABLE 6. VEHICLE'S PARAMETERS USED TO CALCULATE ITS ENERGY CONSUMPTION

Electric vehicles account with a regenerative braking power system which allows the vehicle to recover energy while going downhill or when the driver steps in the brake. In both cases kinetic energy is converted in chemical energy stored in the battery. It is assumed a regenerative braking factor of 0,5 as due to mechanical efficiencies not all the energy available is actually recovered in the battery. The energy recovered from this system is deducted from the total energy demand of the car as it is energy incoming in the battery.

The auxiliary load factor (Aux_load) includes all other expenses that a car has and that are not directly related to its movement. An example of these consumptions would be all the extra electronics needed by the car and the air conditioning system.

To obtain the net force utilized by the vehicle it is added the value of dynamic load obtained from *F (eq. 1)* and *Aux_load* and subtracted the energy from the braking recovery system.

4.2.2.2 SOLAR ENERGY

The global solar horizontal irradiation data has been obtained from the European Commission's tool "Photovoltaic Geographical Information System" (PVGIS). This informatic tool allows the user to search for a location and download the irradiation data, among other functions, from 2005 till 2016. For this model, the average of this period has been chosen as it is considered to be a representative sample. Also, as this data is the monthly global horizontal irradiation other meteorological factors like the clearness index and the rainy days are included.

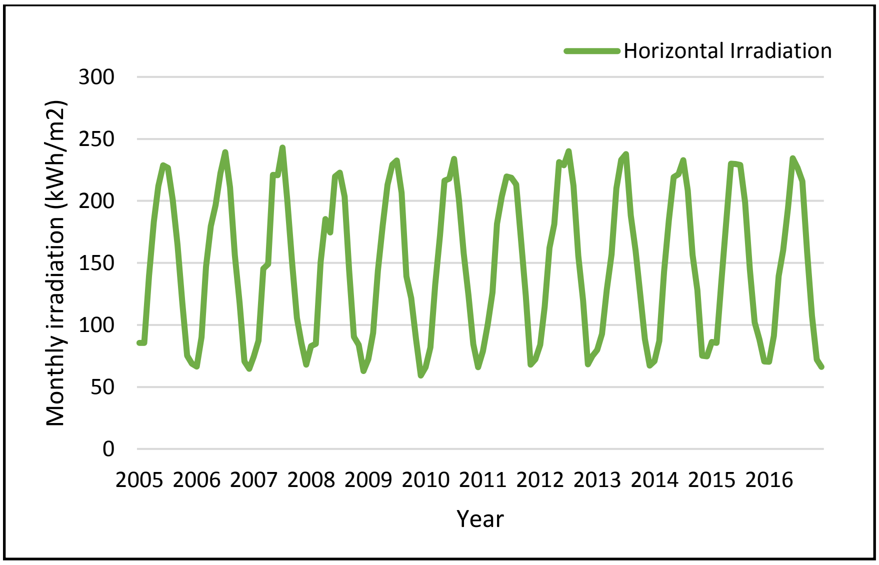

FIGURE 8. MONTHLY GLOBAL SOLAR IRRADIATION. (SOURCE: OWN DEVELOPMENT)

(Khare & Bunglowala, 2020) highlights the need to use the equations for a tilted panel when the car is climbing a slope. This is something feasible to be calculated for a specific route as it is that case but not for all the use that is given throughout its life. In this study the PV panels are modelled as horizontal ones during its whole life. This assumption is also supported by the fact that Valencia is a very flat city with hardly any slopes.

The solar panel selected is the SPR-A430-COM model from SunPower made of monocrystalline silicon solar cells, this model has been chosen due to its higher efficiency compared to the other commercial options. It presents a panel efficiency of 22.2% and a nominal power of 450W, the rest of the panel characteristics can be found in the following table.

Parameter	Value
Nominal power (Pnom)	450W
Panel efficiency	22.2%
Rated voltage (Vmpp)	44.0V
Max. System Voltage	1500 V

Max. Series Fuse	20A
Power Temp. Coef.	-0.29%/ºC
Degradation	0.2%/year
Temperature	-40ºC to 85ºC

TABLE 7. CHARACTERISTIC OF THE PV PANEL

The energy produced by the solar panel cannot be supplied directly to the electrical motors, it must go through several devices that add losses to the system. It is needed a charge controller, it monitors the state of the battery, gives protection against overcharging, prevents from unwanted discharging and it has embedded the MPPT. The maximum power point tracker (MPPT) allows the panel to operate as close as possible to the optimum point, the conditions to which the panel is subjected are constantly changing, therefore the optimum operating point also changes. In the following figure it can be found the block diagram of the proposed design.

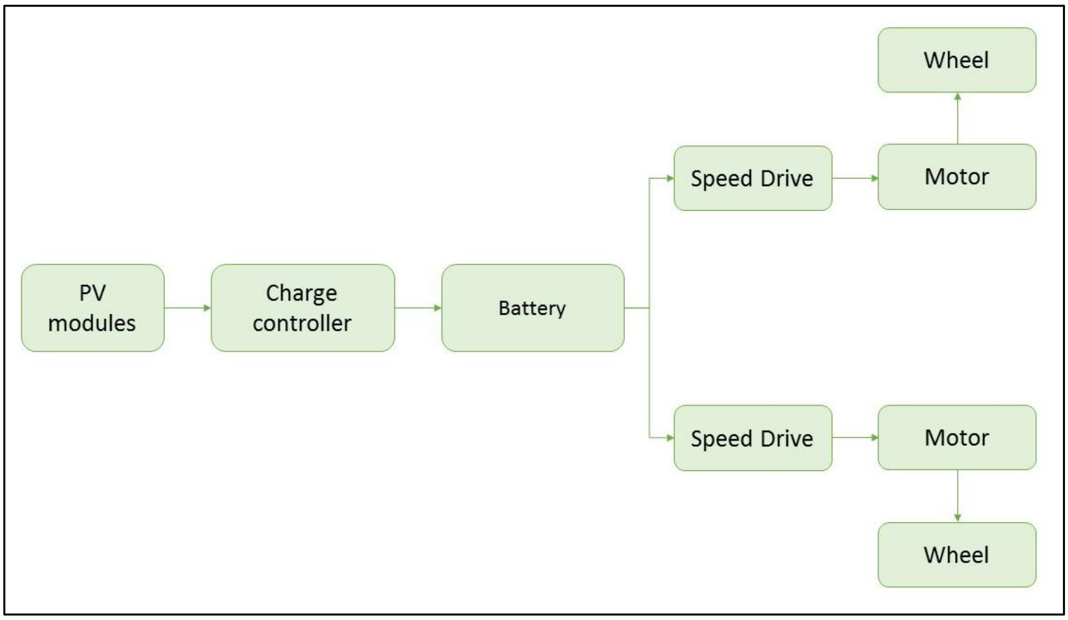

FIGURE 9. BLOCK DIAGRAM OF THE PHOTOVOLTAIC INTEGRATION. (SOURCE: OWN DEVELOPMENT)

4.2.2.3 ENERGY FROM THE GRID

To calculate indirect emissions of the electricity consumption from the grid, data has been taken from the official website of the Spanish electric system operator: "Red Eléctrica de España" (REE). In their webpage it is possible to look up the monthly emissions rates of the national system since 1997. For this study it has been considered the average emissions of the last ten years, since 2009 till 2019, 2020 have not been considered due to the special situation derived from the pandemic. As it can be read in table 9 the highest polluting rates are reached in the months from June till November.

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	**Average**
January	0,30	0,19	0,20	0,31	0,20	0,16	0,27	0,19	0,29	0,22	0,22	**0,23**
February	0,25	0,18	0,23	0,30	0,18	0,09	0,19	0,14	0,23	0,24	0,21	**0,20**
March	0,27	0,14	0,22	0,29	0,12	0,10	0,17	0,13	0,16	0,11	0,13	**0,17**
April	0,23	0,15	0,21	0,20	0,11	0,11	0,21	0,10	0,17	0,14	0,14	**0,16**
May	0,25	0,17	0,26	0,26	0,17	0,21	0,20	0,12	0,26	0,20	0,14	**0,20**
June	0,28	0,20	0,25	0,32	0,19	0,31	0,32	0,18	0,30	0,21	0,17	**0,25**
July	0,31	0,24	0,29	0,30	0,29	0,30	0,33	0,24	0,29	0,25	0,19	**0,28**
August	0,25	0,25	0,29	0,30	0,27	0,31	0,31	0,23	0,25	0,25	0,18	**0,26**
September	0,29	0,28	0,33	0,27	0,29	0,34	0,30	0,29	0,25	0,29	0,17	**0,28**
October	0,29	0,22	0,31	0,28	0,28	0,28	0,29	0,30	0,30	0,25	0,19	**0,27**
November	0,23	0,20	0,28	0,27	0,19	0,22	0,30	0,31	0,33	0,28	0,14	**0,25**
December	0,21	0,20	0,26	0,24	0,28	0,24	0,30	0,33	0,26	0,23	0,11	**0,24**

TABLE 8. MONTHLY GRID EMISSIONS IN TONCO2EQ/MWH.

4.2.3 END OF LIFE STAGE

For this stage of the life cycle, no data are available in Ecoinvent dataset, hence the values used have been extracted from the literature available.

Several studies do not include the emissions related with the end of life and recycling process for the glider's materials like (Patella et al., 2019). In this case the data provided in (Ambrose et al., 2020) is going to be used, a value of 0,994 gCO_2 eq/km for the end-of-life process of electric vehicles. As it is described in (Raugei et al., 2015) according to de European legislation for steel it is supposed an 85% of open-loop recycling and 15% to landfills, for the aluminium, this ratio is 75% of open-loop recycling and 25% landfilling. As the emissions of the manufacturing stage are calculated with values for primarily production, the potential savings of recycled materials in that stage are calculated now and added at the end as negative emissions.

For the battery, no end-of-life treatment emissions or recycling savings are considered. Even though battery recycling brings environmental benefits (Nordelöf et al., 2014), there is a lack of a robust recycling system for batteries (Heelan et al., 2016) . New researches call for second use of EV batteries in stationary energy storages so the benefits of this will not impact the EV market (Ahmadi et al., 2017). In this same study the end of life processing represents only 3% of the battery life cycle emissions so they are despised here.

For the photovoltaic panel's retirement, the data used has been obtained from (Pu et al., 2020). The emissions in this stage correspond with the energy used in recycling and destruction, they are calculated with equation (6) where EF_{re} is the CO_2 emission factor, in this case it is 0.3330 $kgCO_2$ eq/kWh and RC is the retirement capacity in Wp.

$$Emissions = EF_{re} * RC \quad (6)$$

5. RESULTS

5.1 MANUFACTURING STAGE

As it has been explained in the previous sections, the manufacturing process of the lightweighting material, aluminium, is more polluting than the steel process. As a consequence, the specific emissions, measured in $kgCO_2eq/kg$ of glider, increase as the lightweighting percentage increases, this prediction is represented in figure 10 by the green vertical bars. This graph also shows the total emissions during the manufacture of a complete glider, however, these emissions do not follow the same pattern as the specific ones. For every 10% reduction in weight, specific emissions increase by 12% linearly. By contrast, the total emissions are increased for the 10% weight reduction but for the cases of 20% and 30% they fall drastically. This non-linear behaviour is due to the fact that emissions are calculated per kilogram of material, for the first case of lightening the increase in emissions is greater than the reduction in weight but for the two following cases, although specific emissions continue to increase, the reduction in mass is large enough so that in total emissions also begin to decrease.

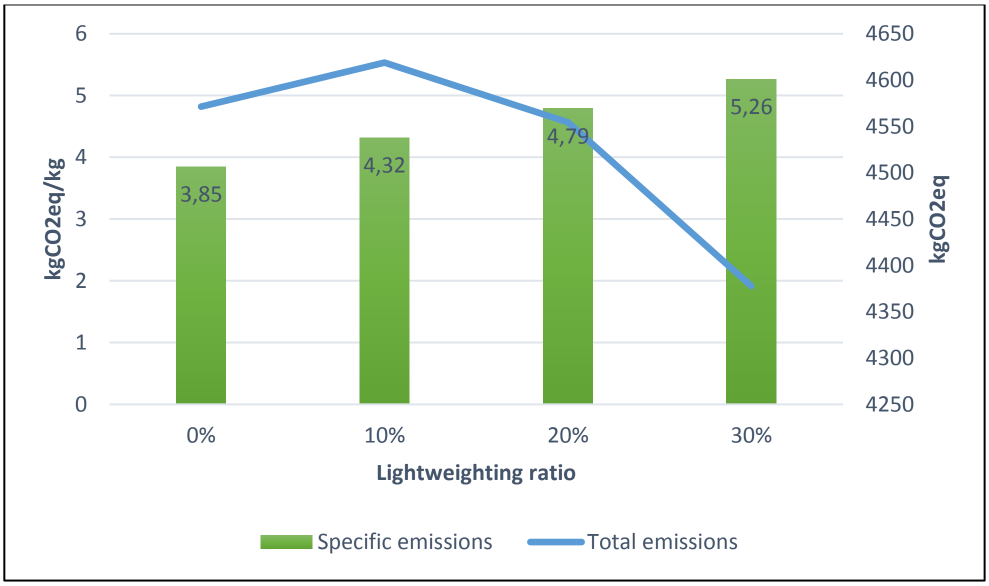

FIGURE 10. EMISSIONS DURING MANUFACTURING STAGE. (SOURCE: OWN DEVELOPMENT)

5.2 USE STAGE

This is the phase where most GHG are emitted, and it is where the benefits of lightweighting and solar panels are obtained. Compared to the base case all the strategies proposed show beneficial results. For its complete lifetime, as weight is reduced so are emissions during this stage. For a 10% of lightweighting there is a 6% of savings, for a 20% the savings are 12% and for a 30% the emissions are decreased in a 18%.

In the following graph it is represented the daily maximum energy and range that can be obtained only with the photovoltaic source in the fifth scenario (without lightweighting), as expected the most profitable months are during end of spring and summer. These months are also the ones with the highest irradiation values, which is consistent with the results obtained. In the graph it is represented the maximum energy that can be obtained, this means that these results correspond with a model with no shade from buildings or similar objects, the shadowing factor is zero. The maximum values are obtained for the months of June and July, where there are more than 13km of extra range. The months of May and August also obtain values above 12km. The minimum is in the month of December where this range hardly reaches 4km, the yearly average is 8.94km.

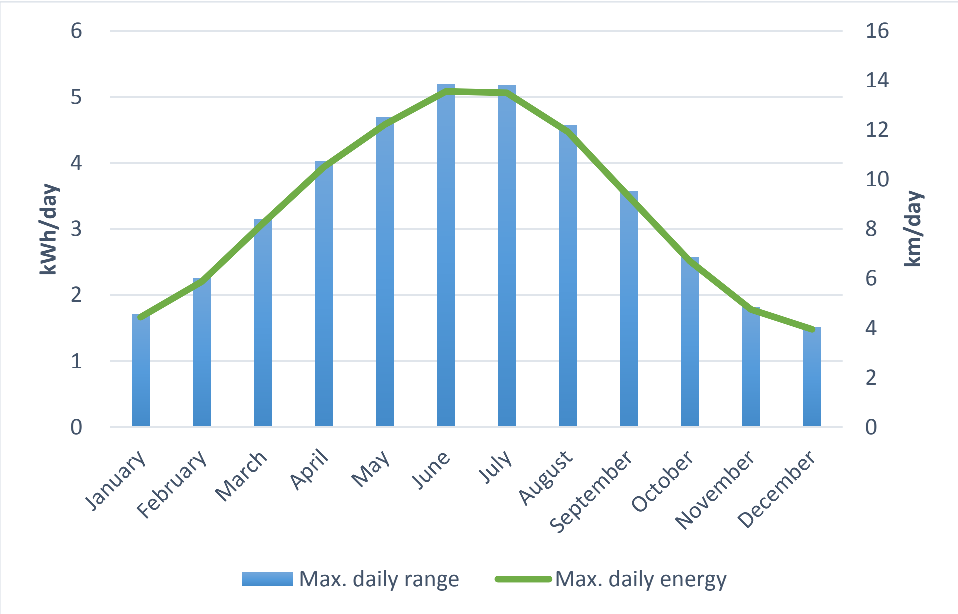

FIGURE 11. MAXIMUM ENERGY AND RANGE OBTAINED FOR THE 5TH SCENARIO (SOURCE: OWN DEVELOPMENT)

For the sixth scenario where the solar roof is combined with 30% lightweighting there is an improvement of 22% in the solar range each month. This means that during June and July the solar contribution grows till more than 16km and in December it is reached 4.92km, again these results are for a zero-shadowing factor and the comparison between the 5th and the 6th scenarios is represented in figure 12.

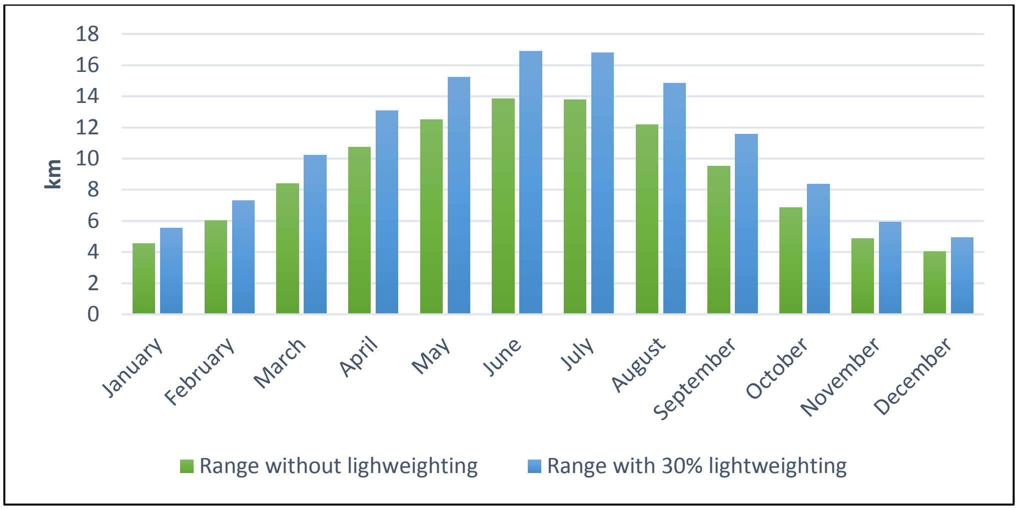

FIGURE 12. COMPARISON OF SOLAR AUTONOMY BETWEEN THE 5TH AND 6TH SCENARIOS. (SOURCE: OWN DEVELOPMENT)

In figure 13 the emissions associated with a 30km trip are represented, the lightweighting ratio is 30% and the shadowing factor. It has been chosen a trip of 30km because 70% of the cars run less than 30km per day on average (Institute of Electrical and Electronics Engineers, n.d. 2019), therefore in this case it is intended to represent the daily route of most cars. Also, the estimate of a 30% shadowing factor is intended to approach real driving conditions (Kanz et al., 2020). As it can be observed the addition of solar panels is especially profitable during the summer months, although all months show enhancements when adding the solar roof. During the months of July and June, photovoltaic energy attains a reduction in emission's rate around a 64%, the biggest decrease achievable throughout the year. These months have such margin of improvement since during those months, compared to the rest of the year, the global solar radiation is higher as well as the emissions from the network, which leads to a great improvement with the incorporation of solar panels. May and August also show an upgrading around 59%. The lowest rate is presented in December where the reduction is around 30%, the yearly average improvement with integrated photovoltaics is 48%. It is interesting to compare the months of November and June, without the solar roof their emissions are quite similar but emission's deployment when adding the PV panels is higher in June thanks to the higher radiation levels.

It must be taken into account that these percentages of improvement will decrease when extending the duration of the trip, while the emissions without PV will rise proportionally the emissions with PV will rise at higher rates because of the fact that the energy from the panels remains the same and it will mean a lower percentage. For the complete use stage (200,000km) reduction in emissions are a 16% for only solar roof and a 34% when combined with 30% of lightweighting.

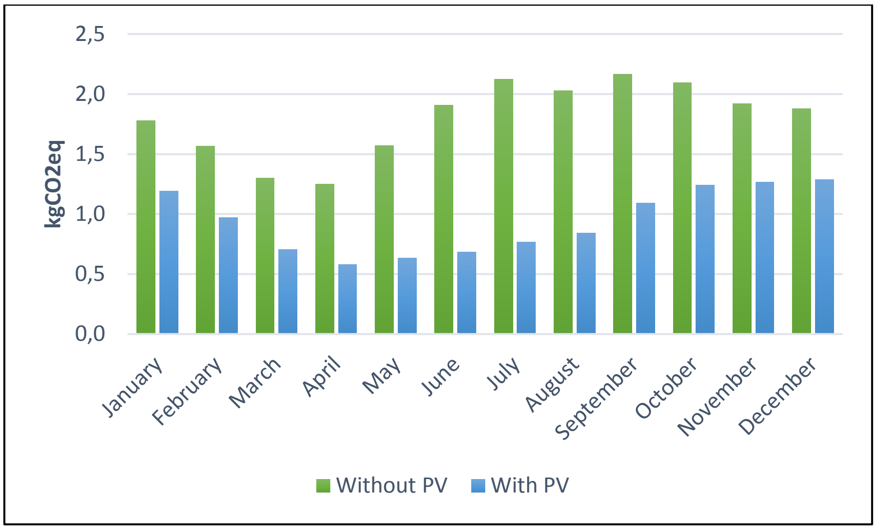

Figure 13. Emissions during a trip of 30km. (source: own development)

5.3 END OF LIFE

All the process related with the end of life dismantling and transportation to landfills or recycling plants of the EV only suppose 0.5kgCO2eq. in total accounting with the PV panels. However, what can really bring a difference is the introduction of recycling materials in the manufacturing process of the glider. With the recycling rates discussed in section 4.2.3 and the manufacturing values from 2.3 savings around 30% in the emission rate of the glider manufacturing can be achieved. Moreover, this percentage is increased with lightweighting, the specific reduction for aluminium is higher than that one for the steel.

5.4 LIFE CYCLE

As explained before, for the life cycle calculous the battery has been also taken into account. Therefore, in this part of the analysis five stages can be distinguished: battery manufacturing, glider manufacturing, use phase, end of life treatment and recycling.

In figure 14 it can be analysed the percentage of emissions that each stage represents in the vehicle's life cycle. The use phase accounts for the highest percentage, it varies from 57% in the base case till 46% in the solar roof + lightweighting scenario. The percentage of emissions corresponding to the glider's manufacturing phase increases when optimisation strategies are implemented even though they are lower in these cases, this is due to the fact that emissions in the use phase are reduced at a higher ratio. The battery production stage suffers a similar evolution, as the total emissions are the same for all cases the percentage it represents increases as less consumption is achieved during the use phase. The share represented by the emissions corresponding to the EoL processes is minimal, reaching a maximum of 3% when the PV panels are integrated.

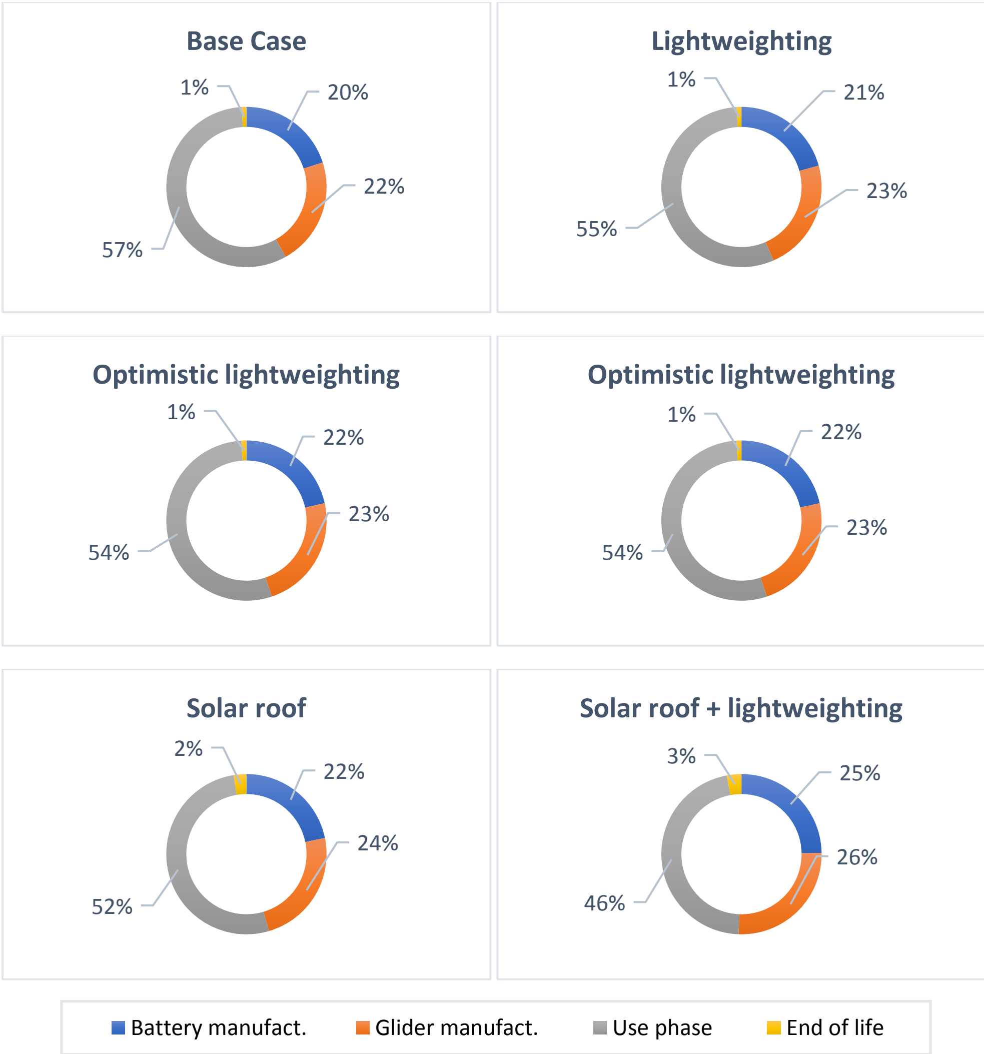

FIGURE 14. NORMALIZED RESULTS FOR EMISSIONS IN EACH STAGE. (SOURCE: OWN DEVELOPMENT)

In figure 15 the total emissions accounted by each scenario per km are represented. As expected, the worst results are obtained for the first scenario, the base case without any improvement strategy, and the best when both strategies are combined, scenario 6, where results are improved by 21%. Only lightweighting can provide an upgrade up to 11.6% with a lightweighting ratio of 30%, for the 10% of weight reduction 6% is the maximum. On the other hand, with only solar roof the maximum benefit is an improvement of 9.4% and it still has a great margin of improvement. The efficiency of this technology is expected to increase with time, other possibility is to add more square meters of photovoltaic panels, if the roof is not enough, they could also be installed in the bonnet and the boot. Also, it must be taken into account the potential savings of recycling, it could reduce emissions 15% and 17% for the first and sixth scenarios respectively,

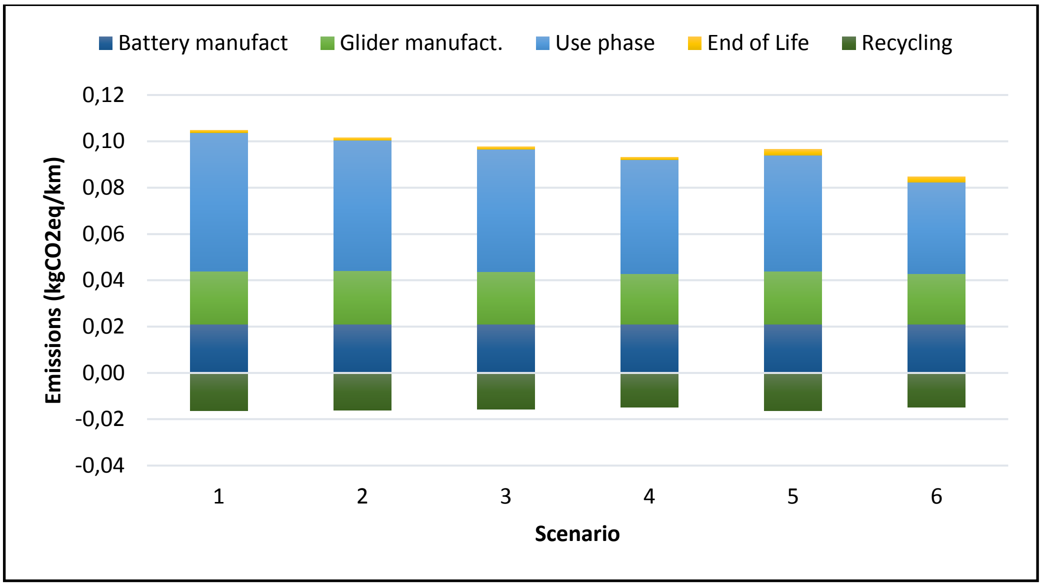

FIGURE 15. LIFETIME EMISSIONS. (SOURCE: OWN DEVELOPMENT)

In conclusion it can be said that both strategies have fulfilled their initial purpose, to reduce life cycle emissions of an electric vehicle. As it would be expected from reading the literature, the best results are obtained when both strategies are combined at the same time. Similarly, it has been demonstrated that when these strategies are applied the percentage that represents the use phase emissions is reduced in favour of that of the production phase. In the next chapter these results are going to be discussed and compared with the literature.

6. DISCUSSION

As it has been demonstrated conventional EV still have room for improvement in terms of environmental performance. Lightweighting EV glider reduce vehicle's energy consumption during the use phase and therefore GHG emissions are also decreased, however during the manufacturing stage modern materials like aluminium are more energy intense. Solar roof shows great potential not only from an environmental point of view, but it also helps to overcome some of the disadvantages of EV at large. It is conductive to increase the independence of electric cars from the grid and it provides the driver more freedom by increasing vehicle's range.

It has been verified the beneficial impact of lightweighting, however as mentioned in (Minak et al., 2017) there is a limit to reducing the weight since the stability and safety of the vehicle must first be ensured. To ensure stability the vehicle must have its centre of gravity near the ground and it must be heavy enough so that in case of adverse wind conditions the driving and the car are not affected. For this reason, it has to be analysed in detail the technical feasibility of reaching a 30% of mass reduction with aluminium, this rate of weight reduction has only been considered in two of the studies reviewed: (Upadhyayula et al., 2019) and (Mayyas et al., 2017).

Comparing the results obtained here with the ones reviewed in the literature they have the same order of magnitude. In (Raugei et al., 2015) for a weight reduction of 175kg using aluminium it is concluded that it should not be expected to have a reduction in global warming potential of more than 7%. The reduction assumed in that paper is between the 10% and 20% simulated in this study, for that scenarios the reductions obtained in were 3.6% and 7.4% respectively. As can be seen, the 7% of (Raugei et al., 2015) is between the two values obtained here. In (Milovanoff et al., 2019) for a weight reduction of 19% in 2030 in an aluminium intense scenario the reduction achieved is 5.6%, well below the results obtained here. However, this study and the one presented here are very different, they study lightweighting from the perspective of the total U.S. fleet which includes all kind of powertrains, not only EV. In (Luk et al., 2017) a reduction of 250kg in vehicle's glider which means a mass reduction of 20% the total life cycle emissions were decreased an 11%. In this case the difference might be caused because they use GREET and the values they take for the component production emissions in the aluminium are lower than the values considered here based on Ecoinvent.

As it has been explained in section 3.2 solar cars were born in races that each year take place all over the world, for this reason most of the studies were focused on vehicles that satisfy the needs for this kind of events but this model's characteristics and that one's of passenger cars do not look alike. These competition cars are usually designed to carry only one passenger and to maximise lightweighting, in (Minak et al., 2017) the vehicle proposed weighted 206.45kg which is less than one sixth of the weight of the vehicle modelled here, even in the *Intense lightweighting scenario*. In (Farooq et al., 2014) they objective is to design an economical solar car for developing countries and the proposal only weights 150kg and has an autonomy of 35-40km provided by a battery that can be charged by only one solar panel with a surface of 1.16m^2. In (Alnunu et al., 2012) they model a solar car with 6m^2 of Mono Crystalline Si panels, that were able to provide and independency of at least 25km which is the length of the race where they participate.

Study	**Weight (kg)**	**Photovoltaic technology**	**Efficiency**	**Surface (m^2)**	**Range (km)**
Present work	1371- 1728	Mono Crystalline Si	22.2%	4.06	3-10
(Alnunu et al., 2012)	140	Mono Crystalline Si	12%	6	25
(Farooq et al., 2014)	150	Poly Crystalline Si	-	1.16	35-40
(Minak et al., 2017)	206.45	-	-	4.55	100

TABLE 9. COMPARISON WITH LITERATURE'S SOLAR VEHICLES

As can be seen in the tables above, in the literature longer ranges can be achieved, even with a smaller surface of photovoltaic cells and/or lower efficiency. This is mainly due to the difference in weight, the kinetic force required to move the car is the most demanding term in the total energy consumption and it is heavily influenced by the vehicle's weight. This positions vehicle's mass as a critical factor in the design of solar cars, this reinforces the results of the present study, which shows that the number of kilometres of autonomy obtained thanks to solar energy increases when the weight of the vehicle decreases.

Considering the results obtained, it can be said that both strategies, lightweighting and solar roof, bring environmental benefits to electric vehicles. Therefore, manufacturers should opt to incorporate these strategies into their future designs, moreover as they begin to be more adopted, the potentially savings are even greater since with standardisation these processes are optimised and pollute less.

7. LIMITATIONS

An important caveat that should be considered is that rapid improvement in process or systems efficiency or the development of new and unpredictable technology have not been considered in this paper. Also, the long-term trend is to decarbonise the electricity system so that emissions associated with the grid will be lower and lower over the years.

While interpreting the results explained in the past sections it is important to keep in mind what is inside the system boundary in this case. To calculate the emissions in the manufacturing phase it has only been taken into account the glider and the battery as they are considered to contribute the most, in contrast, for the energy consumption of the vehicle in order to obtain a more realistic value the weight of the powertrain has been considered as well.

The quality of the data used may have a great influence on results. For the manufacturing stage the data used comes from Ecoinvent dataset where all the process and transportation emissions are considered. However, for the case of manufacturing with recycled materials the manufacturing emissions and percentages have been obtained from literature where the reference dates from year 2000 and these values may have varied to these days. Also, it is assumed a close-loop scenario so the potential profits of recycling are deducted from the total emissions and eventually it might not be the case as the recycling materials might be sent to other industries. Also, the data available refers to the general values of the industry but no specific data have been found for Spain.

Another aspect that has been missed during the literature review is the lack of clarity in the emission values used in the investigations. In many cases, the goal and scope are explained, as well as the system boundaries, but then the results are directly presented. These results are presented either in tonnes of CO_2 equivalent per km or kg or in percentage when comparing several technologies. These results are very useful and valuable, but the fact that they do not specify the base data considered limits their use as a source of inputs for the model developed here.

The model was developed for a vehicle operating in the Spanish city of Valencia where the solar radiation is high compared to the rest of Europe. This means that a vehicle of the same characteristics operating in other locations where the average solar radiation is lower, the benefits obtained from the PV panels will also be lower and it would be necessary to study if the addition of the panels compensates or not. Therefore, the results obtained here are only applicable for locations with similar weather conditions and can not be extended to any location.

Results obtained are highly dependent on the assumptions made while modelling. One of these assumptions was no to include the secondary mass reductions derived from lightweighting, weight reduction may not only influence the required energy to run it may also allow downsize other parts of the vehicle. For example, to cover the same range the lightened vehicle needs less energy than the conventional one, therefore in order to maintain the same autonomy, a lighter and smaller battery would be required, and this change would, again, have an impact on the energy consumption of the vehicle. In EV a mass reduction of 10% can improve vehicle's range by 13.7% (H. C. Kim & Wallington, 2013).

Also, it has been assumed a lifetime of 200,000km so a higher lifetime will reduce the vehicle's manufacturing emissions per kilometre(Luk et al., 2018) thanks to the fact that it has been assumed that the BEV's powertrain and battery do not suffer any deterioration over time. As showed in (Wolfram et al., 2020) and (Abousleiman & Rawashdeh ., 2015) the life cycle emissions of vehicles are very sensitive to the lifetime considered.

In the use phase simulation, there are a lot of variables that have been assumed and that can change depending on the case. The term of auxiliary loads covers all the energy required for heating or air conditioning the cab or the battery and all other electronic devices in a vehicle which require electricity to operate that are not related to making the vehicle move. This term has been considered constant for simplicity's sake, but in some studies such as (Hu et al., 2017) it is calculated by integrating as indoor and outdoor conditions vary, so the value obtained would be more accurate.

Other parameter influencing EV's performance is the personal driving style of each one, if a driver knows how an electric car works and wants to take the most of it, eco-driving strategies can be adopted and he or she can reduce energy consumption during a trip. In (Braun & Rid, 2017) it is exposed that the eco-driving behaviours have critical influence in energy consumption of EV, they are especially effective in congested traffic conditions. An in-depth review of this topic can be found in (Wolfram et al., 2020). Other factors have not been considered are: the possible deterioration of systems over the years, different road types and different lifetimes.

Results obtained for the use phase are critically dependent on the energy supply system, if the country in question has a very carbon intense electric grid, it could be the case that emissions from the production phase are higher than the savings made in the use phase, in that case lightweighting would be a counterproductive strategy (Institute of Electrical and Electronics Engineers, n.d.). In this same study it is mentioned that if only renewable energy sources are used to recharge the vehicle, the emissions caused by the production process would represent three quarters of the total.

Regarding the energy obtained from the PV system, in this case the calculations made were very simplified compared to how complex the calculations can be if it is taken into account that the surface of the ceiling is more the section of a sphere than a 2D plane, which is how it has been calculated in this study. Even if a more realistic 3D model is wanted to be developed there would be problems with the irradiance data as these have been measured to calculate with 2D panels. The solution proposed in (Haghdadi et al., 2012) to measure the curvature of the roof was a curve factor that would be a value less than 1 and that would lower as the curvature is increased. Also, the string mismatching caused by partial shading must be considered in this case with the shadowing factor, its effect can be diminished by increasing the number of strings. Other solution for mismatching proposed in (Choma & Ugaya, 2017; Shanmugam et al., 2019; Tadele et al., 2020 and Upadhyayula et al., 2019) is the development of new maximum power point (MPP) techniques in the controller.

Another limitation of this study is the fact that a specific tool for this type of analysis, such as SimaPro or OpenLCA, has not been used to perform the LCA. Microsoft Excel has been used instead thus attention has only been focused on a single environmental performance indicator, which in this case is CO_2 emissions released to the atmosphere. If more sophisticated tools had been available, in the same analysis, other environmental indicators could have been assessed. Examples of this can be found in (Choma & Ugaya, 2017) where they also evaluate categories like ozone depletion potential, human toxicity, or acidification potential. Some of these barometers may be critical in the future development and improvement of the materials and technologies analysed in this study. However, these issues are outside the scope of the project.

8. CONCLUSIONS

Road transport is responsible for more than 70% of GHG emissions from the transport sector in the European Union. Therefore, if the environmental objectives imposed by the European institutions are to be achieved, decarbonise passenger cars is a good strategy for achieving these goals. There are several alternatives under investigation, but electric cars are profiled as the most effective option from an environmental point of view. (Choma & Ugaya, 2017)

This paper evaluates two strategies that aim to improve the environmental performance of electric cars: glider lightweighting and integration of photovoltaic panels on the roof. In the case of lightweighting, the bibliography review revealed that investigations are being carried out in the direction of reducing the use of steel in vehicle's body in white and replacing it with less dense materials such as aluminium or CFRP. The principal drawback of these materials is that their manufacturing stage is more polluting than that of steel, however these extra emissions and more are supposed to be saved during vehicle's use phase. For the installation of the solar panels the only extra emissions are those obtained during the manufacturing process and end of life management, in addition it is necessary to add the balance of the system components.

By obtaining the emissions data from the Ecoinvent dataset or from the literature, an excel model based on the LCA methodology has been developed in which different scenarios with and without lightweighting and/or solar panels are evaluated. I absence of other ecodesing strategies lightweighting and integrated photovoltaics have demonstrated in the model that they can upgrade the environmental performance of EV, both simultaneously and separately. The maximum saving was obtained for the case in which the use of photovoltaic panels is combined with 30% lightweighting, a 21% reduction in CO_2 emissions was predicted. Applying only lightweighting or solar roof, the maximum savings were 11.6% and 9.4% respectively. Although these values should not be applied lightly in other situations and the limitations of this study should always be kept in mind, the effectiveness of both measures is clear even if their rate of improvement may vary from case to case.

In summary, it has been demonstrated that the strategies of lightweighting and addition of a solar roof to electric vehicles bring environmental benefits and this must encourage laboratories and vehicle's manufacturers to continue investigating in these research lines. This is still a technology in its early stages of development and further research is needed to develop more efficient systems and processes. Despite the good results obtained here, it should not be forgotten that electric cars can only reach their full potential when the electricity grids are fully supplied by renewable energy sources.

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10. APPENDIX

I. Glossary of the main impact categories analysed in the literature.
II. Impact categories analysed in each study.
III. Data sheet of the photovoltaic panel selected.

I. Glossary of the main impact categories analysed in the literature.

Abbr.	**Impact category**	**Unit**
ADP	Abiotic Depletion Potential	kg Sb-eq.
AP	Acidification Potential	mol H^+ eq. or kg SO_2-eq.
CED	Cumulative Energy Demand	GJ
EP	Eutrophication Potential	kg Phosphate-eq.
FDP	Fossil Depletion potential	kg oil-eq.
FEP	Fresh Water Eutrophication Potential	hg P-eq.
GHG -E	Greenhouse Gas Emissions	kg CO_2-eq.
GWP	Global Warming Potential	kg CO_2-eq.
HTP	Human Toxicity Potential	CTU_h or kg 1-4 DB eq.
MDP	Metal Depletion Potential	Kg Fe eq.
MEP	Marine Aquatic Ecotoxicity	%
ODP	Ozone Depletion Potential	kg R11-eq.
PED	Primary Energy Demand	GJ
PMFP	Particulate Matter Formation	kg $PM_{2.5}$-eq.
PO	Photochemical Oxidation	
POFP	Photochemical Ozone Formation Potential	kg Ethene-eq. or kg NMVOC

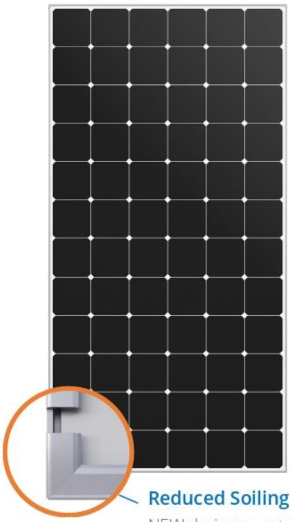
II. Impact categories analysed in each study.

	ADP	AP	CED	EP	FDP	FEP	GHG-E	GWP	HTP	MDP	MEP	ODP	PED	PMFP	PO	POFP
(Choma & Ugaya, 2017)	X	X		X		X		X	X		X	X			X	
(Delogu et al., 2017)	X			X				X			X	X				X
(He et al., 2020)													X			
(Keoleian & Sullivan, 2012)							X						x			
(H. J. Kim et al., 2010)							X									
(Luk et al., 2017)							X									
(Mayyas et al., 2017)							X									
(Milovanoff et al., 2019)							X									
(Raugei et al., 2015)		X	X					X	X							
(Shanmugam et al., 2019)		X	X			X		X	X			X		X		X
(Tadele et al., 2020)		X		X	X			X				X				
(Upadhyayula et al., 2019)		X			X	X		X	X	X		X		X		X

III. Data sheet of the photovoltaic panel selected.

A SERIES

SUNPOWER®



Reduced Soiling
NEW drainage notch improves performance

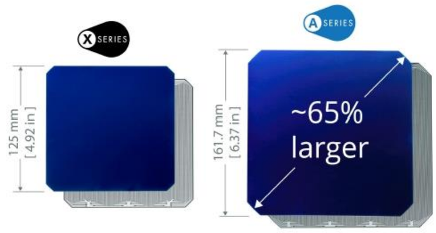
430–450 W Commercial A-Series Panels

SunPower® Maxeon® Technology

SunPower® Maxeon® cell-based panels maximize energy production and savings by combining industry-leading power, efficiency, and durability with the best power, product, and service warranty in the industry.[1,2]

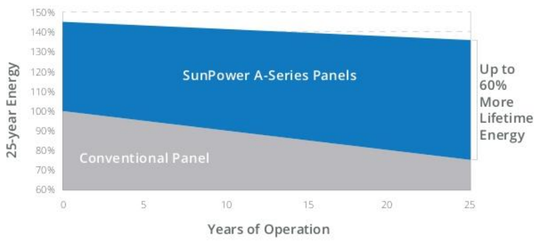
Highest Power Density Available

SunPower's new Maxeon® Gen 5 cell is 65% larger than prior generations, delivering the most powerful cell and highest efficiency panel in commercial solar. The result is more power per square meter than any commercially available solar.[1]



Maximum Lifetime Energy and Savings

Designed to deliver up to 60% more energy from the same space over the first 25 years in real-world conditions like partial shade and high temperatures.[1]



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BETTER PRODUCT · BETTER WARRANTY
25-yr SunPower Complete Confidence

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Fundamentally Different.
And Better.

- Most efficient cell in commercial solar[2]
- Delivers unmatched reliability[3]
- Patented solid metal foundation prevents breakage and corrosion

As sustainable as the energy it produces.

- Achieved the #1 ranking on the Silicon Valley Toxics Coalition's Solar Scorecard for 3 years running
- SunPower modules can contribute to your business's LEED certification[4]

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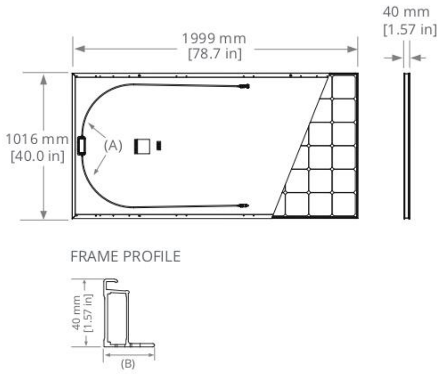
430–450 W Commercial A-Series Panels

Electrical Data	SPR-A430-COM	SPR-A440-COM	SPR-A450-COM
Nominal Power (Pnom)[5]	430 W	440 W	450 W
Power Tolerance	+5/0%	+5/0%	+5/0%
Panel Efficiency	21.2%	21.7%	22.2%
Rated Voltage (Vmpp)	42.7 V	43.4 V	44.0 V
Rated Current (Impp)	10.1 A	10.2 A	10.2 A
Open-Circuit Voltage (Voc)	51.2 V	51.6 V	51.9 V
Short-Circuit Current (Isc)	10.9 A	10.9 A	11.0 A
Max. System Voltage		1500 V UL	
Maximum Series Fuse		20 A	
Power Temp Coef.		−0.29% / ° C	
Voltage Temp Coef.		−136 mV / ° C	
Current Temp Coef.		5.7 mA / ° C	

Operating Condition And Mechanical Data	
Temperature	−40° F to +185° F (−40° C to +85° C)
Impact Resistance	1 inch (25 mm) diameter hail at 52 mph (23 m/s)
Appearance	Class A
Solar Cells	72 Monocrystalline IBC cells
Tempered Glass	High-transmission tempered anti-reflective
Junction Box	IP-68, TE (PV4S)
Weight	47.7 lbs (21.6 kg)
Max. Load	Wind: 75 psf, 3500 Pa, 357 kg/m² front & back Snow: 125 psf, 6000 Pa, 612 kg/m² front
Frame	Class 2 silver anodized

Tests And Certifications	
Standard Tests	UL1703
Quality Management Certs	ISO 9001:2015, ISO 14001:2015
EHS Compliance	OHSAS 18001:2007, lead free, Recycle Scheme
Ammonia Test	IEC 62716 (Pending)
Desert Test	MIL-STD-810G (Pending)
Salt Spray Test	IEC 61701 (maximum severity) (Pending)
PID Test	1500 V: IEC 62804
Available Listings	UL, CEC



(A) Cable Length: 1320 mm +/-10 mm [52 in +/-0.4 in]
(B) Long Side: 32 mm [1.3 in]
Short Side: 24 mm [0.9 in]

Please read the safety and installation guide.

1 SunPower 450 W, 22.2% efficient, compared to a Conventional Panel on same-sized arrays (310 W, 16% efficient, approx. 2.0 m²), 4.9% more energy per watt (based on PVSyst pan files for avg US climate), 0.5%/yr slower degradation rate (Jordan, et. al. "Robust PV Degradation Methodology and Application." PVSC 2018).
2 Based on search of datasheet values from websites of top 20 manufacturers per IHS, as of January 2019.
3 #1 rank in "Fraunhofer PV Durability Initiative for Solar Modules: Part 3". PVTech Power Magazine, 2015. Campeau, Z. et al. "SunPower Module Degradation Rate," SunPower white paper, 2013.
4 A-Series panels additionally contribute to LEED Materials and Resources credit categories.
5 Standard Test Conditions (1000 W/m² irradiance, AM 1.5, 25° C). NREL calibration Standard: SOMS current, LACCS FF and Voltage.

See www.sunpower.com/company for more reference information.
For more details, see extended datasheet: www.sunpower.com/solar-resources.
Specifications included in this datasheet are subject to change without notice.

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