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Life cycle assessment of electric vehicle charging infrastructure: systematic literature review and development of an life cycle inventory database

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Table of contents

Abbreviations and acronyms

CO_2	Carbon Dioxide
GWP	Global Warming Potential
LCA	Life Cycle Assessment
EV	Electric vehicle
PG	Plug-in charger
CP	Charging point or charger
CF	Carbon footprint/Impact on climate change

Introduction

Electric vehicles are a key technology to decarbonise road transport, a sector that accounts for around 15% of global emissions. Some major economic players such as China, the United States or Europe are seeing a drastic increase in the number of electric vehicles. In 2023, 18% of global vehicle sales were electric vehicles. This increase is due in particular to the commitment of governments to the transition to an electric fleet. (“Outlook for Electric Vehicle Charging Infrastructure – Global EV Outlook 2024 – Analysis,” n.d.)

With the aim of decarbonizing the transportation sector, which accounts for over 40% of annual greenhouse gas emissions in Quebec, Quebec’s government has set goals to electrify the vehicle fleet. One of the objectives is to encourage the purchase and use of electric cars to reach 2 million electric vehicles by 2030. As one of the main obstacles to buying an electric vehicle is the lack of charging infrastructure to deliver energy, Quebec intends to deploy electric vehicle charging stations on a large scale by 2030. (“Stratégie québécoise sur la recharge de véhicules électriques - Québec investit un demi-milliard de dollars et prévoit implanter plus de 116 000 bornes de recharge publiques d’ici 2030,” n.d.)

However, just like electric vehicles, charging infrastructures, particularly the charging point directly connected to the vehicle, use metals such as copper or aluminium that may be costly for the environment. Since 2000, some scientific studies have been carried out to quantify the impact of specific charging stations on climate change. These studies, which vary in date, come from different countries and study charging stations that are sometimes manufacturer-specific.

This report is intended to present, compare and analyze the methods and results of these studies in order to understand better the environmental impact of the deployment of charging stations in Quebec.

First, a summary of the various electric vehicle charging technologies will be presented. Second, a literature review will be conducted on the life cycle assessments of chargin infrasturcture. The literature review methodology will be presented. The results of the various studies will then be compared and criticized. In order to quantify the impact of some of these charging stations with more recent data and a harmonized LCA methodology, the charging stations will be finally re-modeled with ecoinvent v3.X and the software XX, and the results of their impact on various indicators will be studied, with a static and a prospective approach.

1. Literature review

1.1 General information on charging technologies for electric vehicles

The EV charger or charging station is an essential part of the electrical energy supply chain for an electric vehicle (EV). They form the link between the electrical grid and the vehicle to be recharged using power electronics. A difference can be made between a charger and a charging station: a charger (or charging point) is a single unit that can charge one vehicle at a time whereas a charging station can charge two or more vehicles at the same time.

Usually, the charging station are categorized into 3 categories that could be named "charging ways". They characterize the way energy is transferred from the chargers to the EV (Mastoi et al. 2022)as shown in *Figure 1* :

- Conductive charging like plug-in technologies: a cable connects the charging station to the car;
- Inductive charging which uses electromagnetic induction between two coils, one in the car and the other one in the road surface for example. It recharges vehicles as they drive;
- Battery swap which consists of replacing the old battery with a full one.

The last option is very costly, as it requires several batteries for different car models and the inductive way of charging is still under development. Thus, as the only option that is really used in practice is plug-in technology, this report focuses on this one.

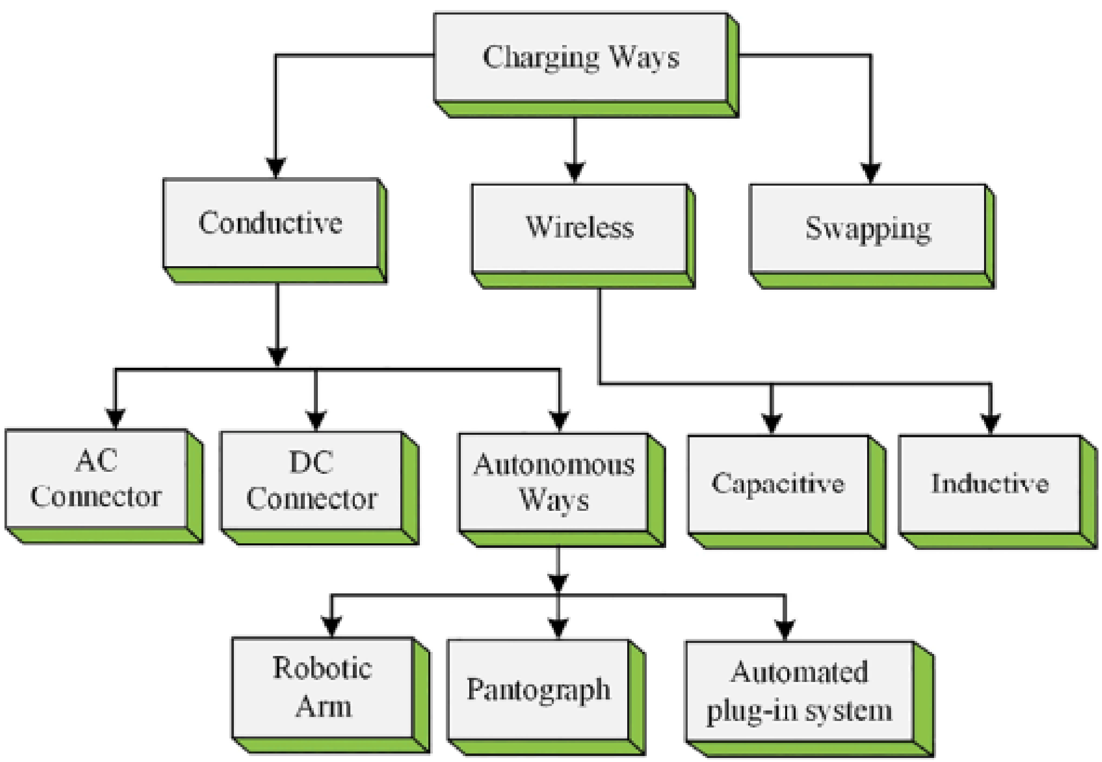


Figure 1 – Different charging ways (Mutarraf et al. 2022)

Furthermore, for wired charging, two charging modes can be distinguished for vehicles(Mutarraf et al. 2022) : Alternating Current (AC) and Direct Current (DC) which characterizes the type of current leaving the chargers. Indeed, the battery needs to be refilled with DC and the grid supplies AC current, so a converter is needed to convert this energy from AC to DC. In the case of on-board charging (AC), the converter is located in the vehicle and in the case of off-board charging (DC), the converter is located in the charger *(Figure 2*).

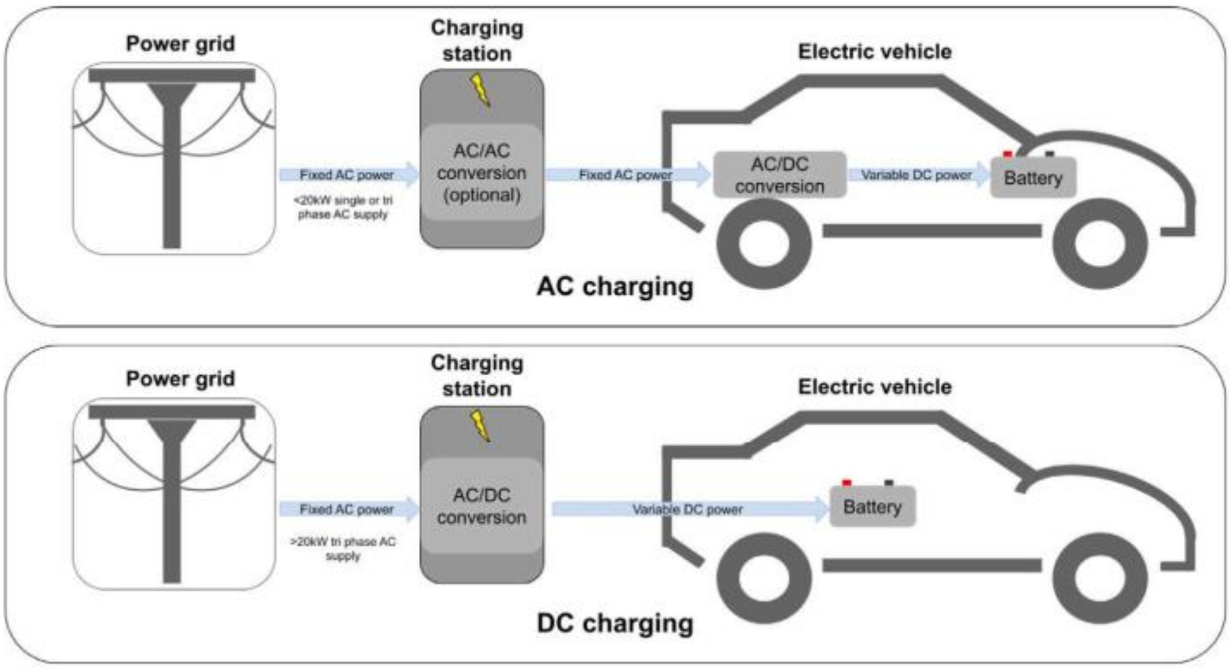


Figure 2 – Charging modes (Metais et al. 2022)

Depending on the connected network, its voltage and frequency, but also the charging station's components, the Automotive Engineers' Electrical Energy Research Institute (SAE) and the International Electrotechnical Commission (IEC) have established standards called “levels” characterizing charging stations. Each level has a different power rate and therefore a different charging time, depending on the type of battery, and each level meets different needs. (Savari et al. 2023)

	Level 1	**Level 2**	**Level 3**
Charging mode	AC	AC	DC
Voltage (V)	120 US 230 EU	240 US 400 EU	208-600
Power rate (kW)	1,3 – 2,4	3 - 19	25 - 350
Charging speed (time for 40 km for light vehicle	Slow (8h)	Semi-fast (1-3h)	Fast (<30 min)
Usual place	Home	Private/public	Public
One main advantage	Universally compatible so economically	Fast charging	The fastest charging

One main drawback	Very long charging time	Specific installation required so costly

Table 1 – Type of plug-in chargers (Mutarraf et al. 2022)

1.2 Methodology of literature review

Following this brief review of recharging ways, a literature review of the Life Cycle Assessments (LCA) on charging infrastructure published in the scientific literature was conducted. Indeed, one of the best-known methods for determining the potential environmental impacts of objects or services is the life cycle assessment method standardized by ISO 14040 and 14044 standards (ISO14040 and ISO14044) So, in order to observe whether the environmental impact of charging infrastructure for electric vehicle has been studied in the scientific literature, this literature review was conducted by selecting several parameters : keywords to access documents on the subject, databases of documents to search and relevant information collected to compare studies.

<u>Step 1 : Definition of keywords</u>

The keywords used for the search included a combination of synonyms and extensions of the terms : “Environmental impact” (“Life Cycle Assessment”, “LCA”, “Carbon footprint”) and “Electric vehicle Charging infrastructure” (“charging point”, “charging station”).

<u>Step 2 : Selection of databases and documents</u>

An online search was performed in Google Scholar and Science Direct: after entering the keywords in the main database, the filters for file types were set to “Articles”. Additionally, references in the identified literature were used to find new documents.

For the collected articles, reading titles and abstracts enables us to exclude articles that were not relevant enough to the stated topic.

Finally, articles are classified by charging method and energy source.

<u>Step 3 : information collected from each article</u>

For each article, information required for a critical literature review of LCAs was collected where available (*Table 2 and 3*), including :

- General information on the article: first author, publication date and title ;
- General information on the systems studied and their key parameters: charging method, charging mode, power, efficiency, weight, lifespan, location of study ;
- LCA parameters:
    - The functional unit that defines the service or object whose impact is being measured;
    - The impact method and indicators;
    - The foreground and background databases used and the data collection period;
    - System boundaries that could include raw materials stage(the production of materials needed for the final product), manufacturing stage (including assembly and packaging and eventually the plant infrastructure and equipment operation), installation stage (the transport of the finished product from the manufacturing site to the distribution center), use stage (electricity

supplied to EV), maintenance stage and the end-of-life stage (disposal of the product at the end of its service life) ;

- Information on the availability of the list of materials. This information is used among other things to determine whether the study is reproducible;
- Finally, the main conclusions and any additional analysis made in the study.

Nº	1st Author - Publication date	Type of vehicle	System studied	Charging method	Charging mode (assumed)	FU	Reproducible LCIs	LCIA method	GWP method	Indicators	Foreground database
1	Zhao - 2021	Bus	electric bus charging stations (Tritium BEV charging Model Veefil dual cable) into existing bus depots	Plug-in (PG)	Level 3 (Fast DC)	unit mass of GHG per unit of energy/material production kgCO2e/kWh or kgCO2e/kg	Yes	N/A	N/A	GWP	locally charging station in Australia
2	Nansai - 2001	Light vehicle	charging equipment Level 2 which consists of charger, battery and stand from 1 factory located at Kyoto city	PG and Wireless power transfer (WPT)	Level 2 (AC)	N/A: All charging stations in the country	Yes	N/A	Input-output table	Flow indicators: CO2, SOx, Nox and CO (air pollutants emissions)	current charging station in Japan
3	Zhang - 2019	Light vehicle	4 main types of chargers for EV in China: --> Home charger --> Public AC charger --> Public DC charger --> Public mix charger	PG	--> Level 1 --> Level 2 --> Level 3	per kW of electricity used by one mid-size passenger	Yes	N/A	N/A	GWP100	12 leading manufacturers (70% of market) and EVCIPA
4	Lucas - 2012	Light vehicle	Whole infrastructure --> Home charger: AC --> Normal charger: AC --> Quick charger: AC and DC Product from EFACEC	PG	--> Level 1 --> Level 2 --> Level 3	MJ	Yes	IPCC 2013	IPCC 2013	GWP100	leading manufacturer of charging stations in Portugal (EFACEC)
5	Zhang - 2017	Light vehicle	2 different topologies: --> inductive charging system --> conductive non isolated charging system 3 different level's power rate 3,7 kW, 22 and 50 Kw. Each charging system is equipped with a charger and charging equipment (EVSE)	PG and WPT	--> Level 1 --> Level 2 --> Level 3	1 kWh of electricity delivered to the battery from the vehicle	No	ReCipe	IPCC 2013	--> Climate change (GWP) --> Ozone depletion --> Human toxicity --> Metal depletion	N/A
6	Kabus - 2020	Light vehicle	On-board and off-board charging systems (manufacturers: ABB, EVTEC, Stercom, etc...)	PG	--> Level 2 --> Level 3	1 kWh	Yes ?	ReCipe 2016	IPCC 2013	All impact categories	manufacturers (ABB, EVTEC, Stercom, Bnetza)
7	Bi-2015	Bus	plug-in (model based on a 2013 chevrolet Vol charger) and wireless charging (in develpment for Wireless charging)	PG and WPT	N/A	providing transit services for Ann Arbor and Ypsilanti area for 12 years with 67 buses, equivalent to 48,034,407 vehicle kilometers in total	Yes ?	IPCC 2013	IPCC 2013	GWP100	WPT under development at the University of Michigan-Dearborn PG based on a 2013 Chevrolet Volt charger whose components were estimated and their weights were measured

Table 2 (1/3) – Information on LCAS focused on plug-in chargers and grid-connected technologies [A]

Nº	Background database	Data collection period	Global reach	Power (kW)	Charging time (h)	Efficiency in use phase	charging point's weight (kg)	Lifespan (years)	List of materials	List of components	Cumulative energy demand (CED)	Location
1	GREET 2019	2018	China	350	3h	98,50%	260 kg for user unit, 220 for control unit, 700 kg for Power unit and 200 kg for cables	12y	Yes	yes	No	Sydney, Australia
2	Tables of reference in Japan	N/A	N/A	N/A	3h	N/A	300 kg without the storage battery	N/A	Yes	yes	No	Japan
3	CAS RCEES 2014	2014/2017	China	--> 7 to 40 --> 7 to 40 --> 60 to 360 --> 60 to 360	--> 8h --> 3 to 8h --> 30 min --> 30 min	Between 85 and 95%	--> 14 kg --> 33 kg --> 235 kg --> 249 kg	--> 8y --> 8y --> 12y --> 12y	Yes	yes	Yes	China
4	GEMIS, GREET (2008)	2004/2005/2006	Worldwide but not present in Canada	--> between 3 and 7,4 --> between 3,7 and 22 --> 43 and 50	--> 8h --> 5 to 8h --> 15 to 30 min	N/A	--> 11 kg --> 1255 kg --> 3250 kg	--> 15y --> 6y --> 12y	Yes	No	Yes	Portugal
5	Ecoinvent V.2.0	N/A	N/A	--> 3,7 --> 22 --> 50	N/A	--> For conductive charging system, from charging pole to charger is 91%, 90% and 88% for 3.7 Kw. 22 Kw and 50 Kw, from charger to battery is 90%. --> from charging pole to charger is 83%, 82% and 80% for different power level and from charger to battery is 90%.	N/A	14y	No	yes without weights	No	Belgium
6	Ecoinvent 3.4	2013	worldwide companies	--> AC : 22 --> DC : 50	N/A	90 to 95%	N/A	10y	No	yes	No	Germany
7	Ecoinvent v2.2, data of technologies from special models	2013-2015	worldwide company	60	N/A	90%	N/A	24y	No	yes	Yes	Michigan

Table 2 (2/3) – Information on LCAS focused on plug-in chargers and grid-connected technologies [A]

Nº	System boudaries	Raw materials extraction	Manufacturing	Transportation	Installation	Use	Maintenance	End-of-life	Main conclusions	Sensitivity analysis/Other studies
1	cradle-to-grave	x	x	x	x	x	Negligible	x	1) The operation phase dependent on the electricity grix-mixes carbon intensity contributes the most greenhouse, gas emissions (98,8%) followed by production (0,69%) 2) Transitioning the existing transport could reduce the impact on climate change if the electricity used to charge the buses is generated from low carbon-intensive sources (renewable energy)	Yes : - different charging scenario - more renewable grid mix - net zero emissions by 2050
2	cradle-to-gate		x	x	x				1) The production phase is dominant (92%) in the total emissions of CO2, SOx and CO. The transport represent 20% of emissions of Nox 2) Advantage of EV compared to Gasoline Vehicle (GV) for CO2, NOx and CO but not SOx	Yes : - addition of the contribution of the charging infrastructure to the life cycle emissions of the EV comparison of the life-cycle of GV
3	cradle-to-grave	x	x			x		x	1) Considering the mix and the ratio of vehicles per charger, the home charger has the lowest GWP followed by public AC and public DC and then public mix (due to larger material consumption and electricity loss) 2) The GWP of a single charger accounts for 1,89% of GWP of Evs but according to scenarios, it could reach 5,36% in 2040 3) It is recommanded to consider enrivironmental burdens of different charger types and encourage the use of home and public AC chargers	Yes : - electricity mix - ratio of vehicle and charger quantities
4	cradle-to-grave		x				x	x	1) Energy supply infrastructures are more carbon and energetic intensive than gas or diesel supply infrastructures 2) The contribution in overall vehicle LCA does not exceed 8%	Yes : - Monte Carlo analysis with lifetime, service rate (number of EV/charger), materials quantities - variation fo service rate
5	cradle-to-grave	x	x			x		x	1) The environmental performance depends on efficiency and electricity production 2) The amount of copper and numbers of charging pole are key factors affected environment	Yes : - efficiency of the charging point
6	cradle-to-gate		x	x		x			1) The manufacturing has the highest contribution to environmental impacts of the production phase 2) The filter could be identified as main polluters for all power levels 3) DC system causes less environmental impact than AC system	Yes : - degree of utilization - efficiency - ratio of charging at home/non-public charging
7	cradle-to-grave	x	x			x		lack of data	Wireless charging consumes less energy and emits less	Yes several

Table 2 (3/3) – Information on LCAS focused on plug-in chargers and grid-connected technologies [A]

N°	1st Author - Publication date	Type of vehicle	System studied	Charging method	Charging mode (assumed)	FU	Reproductible LCIs	LCIA method	Indicators	Foreground database	Background database	Data collection period	Global reach	Power (kW)	Charging time (h)	Efficiency in use phase	charging point's weight (kg)	Lifespan (years)
8	Konrad - 2022	N/A	Mobile Hydrogen powersupply : hydrogen fuel cell supplied from HP with High voltage battery	PG	Level 2 (AC and DC)	1 kW	No	N/A	GWP100	N/A	GEMIS, GREET2 and ProBas	N/A	in research/progess	20 kW	N/A	Various	1500 kg	10y
9	Cheikh-Mohamad - 2021	Light vehicle	PV-powered charging station	PG	Level 2 (AC)	one item	No	Bilan Carbone de l'Ademe	GWP30	Estimation from process of databases	Ecoinvent	N/A	in research/progess	between 2,3 and 22 kW	N/A	N/A	N/A	10y
10	Marmiroli - 2019	Light and heavy vehicles	e-road developped by Polito	WPT	Level 3 (DC)	1 km of lane	Yes	IPCC 2013	GWP100	data from Polito and tests	Ecoinvent V3.3	N/A	in research/progess	50 (Light vehicle) or 100 (trucks)	N/A	depends on the vehicle	N/A	20y
11	Balieu - 2019	Light and heavy vehicles	e-road (pantograph, Conductive rail from elways technology, e road from Polito)	WPT	DC	1 km of lane	Yes	N/A	Impact categories	regional data	N/A	N/A	in research/progess	N/A	N/A	N/A	N/A	20y

Table 3 (1/2) – Information on LCAS focused on other technologies [A]

N°	List of materials	Cumulative energy demand (CED)	Location	System boudaries	Raw materials extraction	Manufacturing	Transportation	Installation	Use	Maintenance	End-of-life
8	Yes	Yes	Australia	cradle-to-grave	x	x	x		x		x
9	No	No	France	cradle-to-grave		x	x	x	x	x	x
10	Yes	Yes	Susa, Italie	cradle-to-grave		x				x	
11	Yes	No	Sweden	cradle-to-gate		x			x	x	x

Table 3 (2/2) – Information on LCAS focused on other technologies [A]

NB : N/A means "Not found"

1.3 General notes on papers found

We found 11 articles assessing the life-cycle environmental impacts of charging infrastructures, focusing on the technology at the end of the chain that supplies energy to the vehicle and other papers reuse the impact of these 11 papers. Of these articles, 7 (numbers 1 to 7) or 64% of the total number of papers study chargers with a plug-in technology connected to power grid, 2 (number 8 and 9) or 18% others study mobile technologies powered by renewable energy and finally the remaining 3 (number 10 and 11) or 27% focus on inductive charging. These last 5 papers will therefore be excluded from the critical review because these technologies are highly specific and under development.

The first study dates to 2001 and since 2010 studies on the subject have multiplied, as many countries seek to deploy charging infrastructures (figure 3).

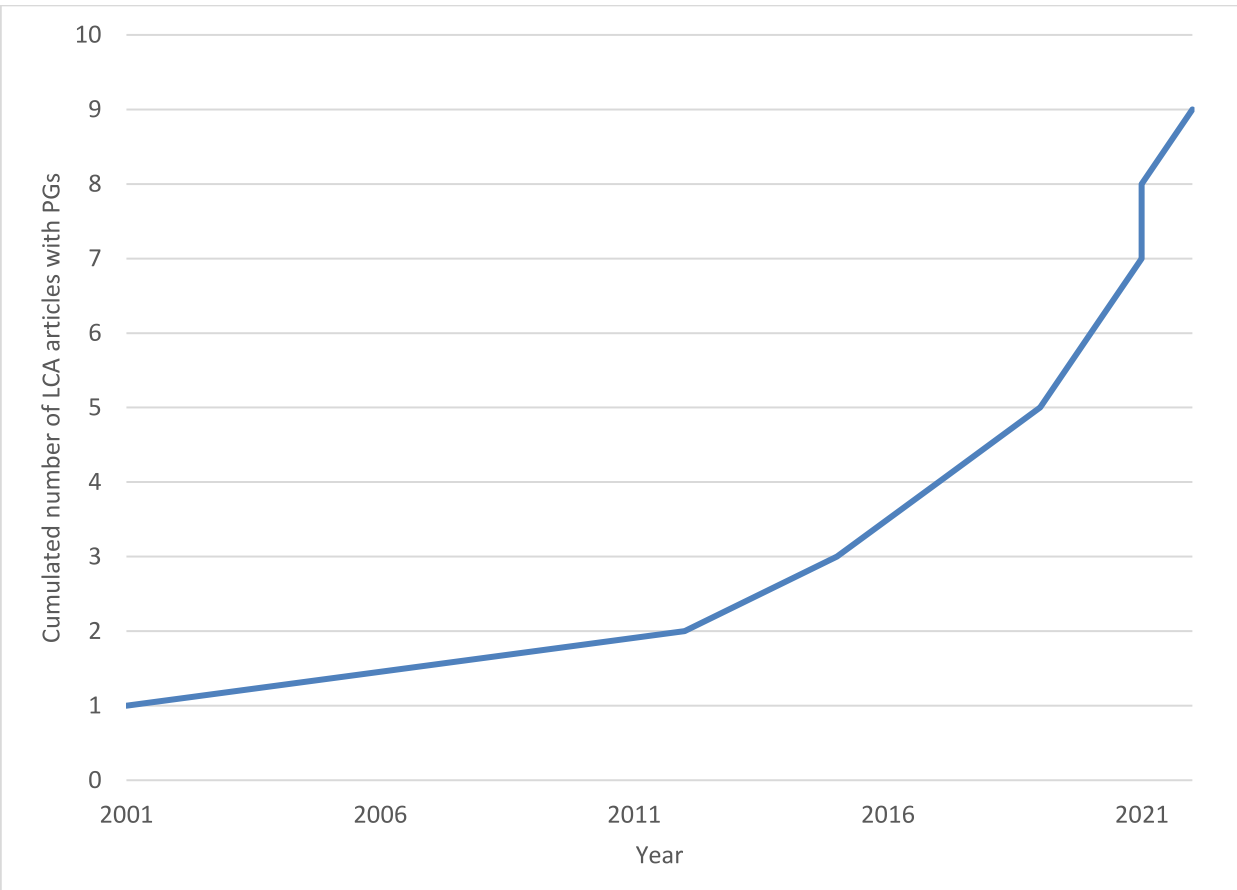


Figure 3 – Cumulated number of LCA articles with PGs primary inventories [A]

Other major differences between charging stations studied are worth noting:

- Not all papers deal with the same type of charging points: 15 chargers are studied from different levels: 20% are level 1, 33% level 2 and 47% level 3.Moreover 29% are for buses (number 1 and 7) and 71% for light vehicles so a distinction must be made between level 3 for light vehicles and level 3 for buses;
- Not all studies have the same Functional Unit (FU): 57% have studied the impact of 1 charger

recharging a vehicle, while 43% have taken 1 kWh delivered by the charger as a reference. Calculations have been made to put the results on the same functional unit using information given in the studies.

Reference	DOC 1	DOC 2	DOC 3	DOC 4	DOC 5	DOC 6	DOC 7
Information about calculations for a FU of 1 charger	given	given	Assuming a loss electricity of 10% and using the total electricity loss given during the life of the charger	given	28 000 kWh used during the whole life of charging station and the battery has an efficiency of 90%	10% of utilization rate (time of use during a day)	given
Information about calculations for a FU of 1 kWh provided by the charger	2600 charging cycle of a battery of 324 kWh	Assuming 100 000 km travelled during the vehicule's life and 126 000 EV for 4200 charging stands	given	150 000 km for each 2 269 vehicles assuming a consumption of 21 kWh/100 km	given	given	Assuming 1 cycle/day of charging a battery of 324 kWh

Table 4 – Assumptions for calculations in a same functional unit

- Not all papers cover the entire product life cycle: 71% of the papers study the chargers from cradle to grave, including manufacturing, use and end-of-life and 29% study chargers from cradle to gate, excepting end-of-life and sometimes use stage. However, some studies mixed present impacts between end-of-life and manufacturing.
- Regarding impact methods: 29% of studies use Recipe, 29% use IPCC2013 and 43% do not specify the impact method used.

1.4 Analysis of comparison of results in the studies

1.4.1 Results of impact on climate change of 1 charger during its whole life (for chargers considering the use stage)

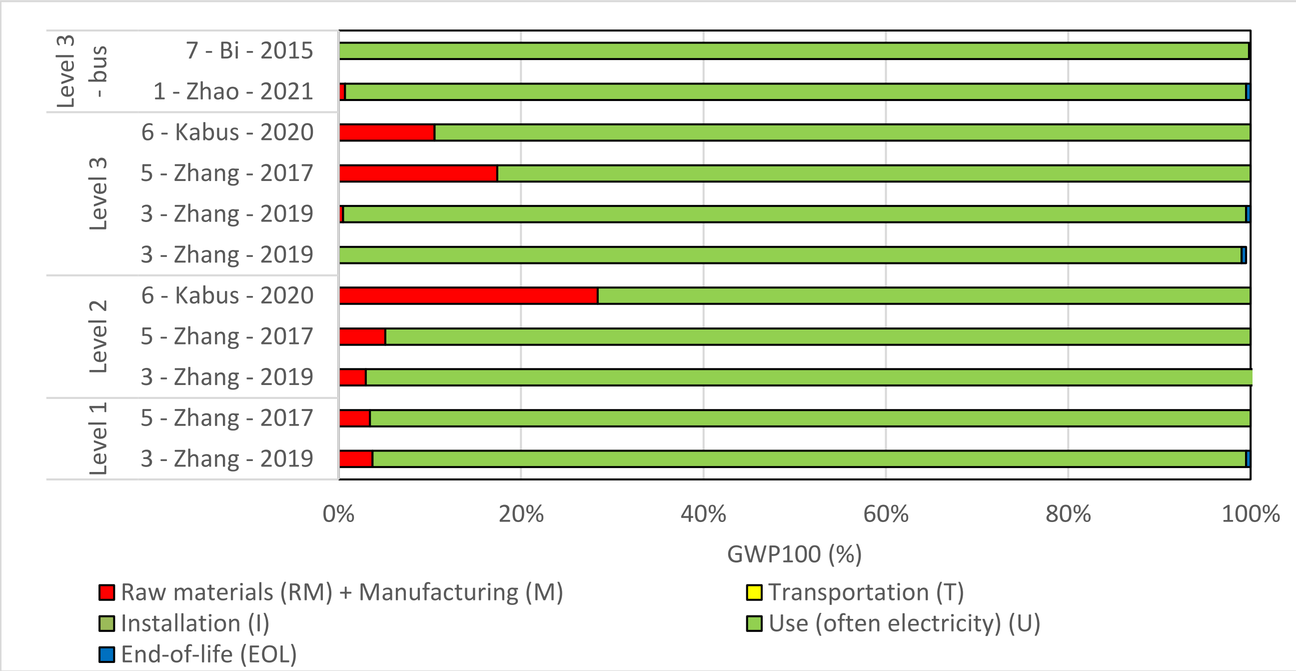


Figure 4 – Impact on climate change of 1 charger [A]

<u>Observation 1</u> : Impact of electricity delivered

Generally, the charger itself has a negligible impact compared to the impact of the electricity delivered over its lifetime (*Figure 4*). The impact of the electricity delivered represents more than 80 to 90% of its total impact over its entire life cycle. This is why many studies do not focus on this component of the chain such as Lucas's study (Lucas, Alexandra Silva, and Costa Neto 2012), which shows that the impact of infrastructure accounts for less than 10% of the total impact of driving one km with an electric vehicle.

1.4.2 Results of impact on climate change of manufacturing stage for both FU

As not all systems took into account all stages of the charging point's life cycle, we can only compare the manufacturing stage (often confused with the raw-materials stage) taken into account by all studies. Both functional units (1 charger or 1kWh delivered by charger) are studied *Figures 5 and 6*.

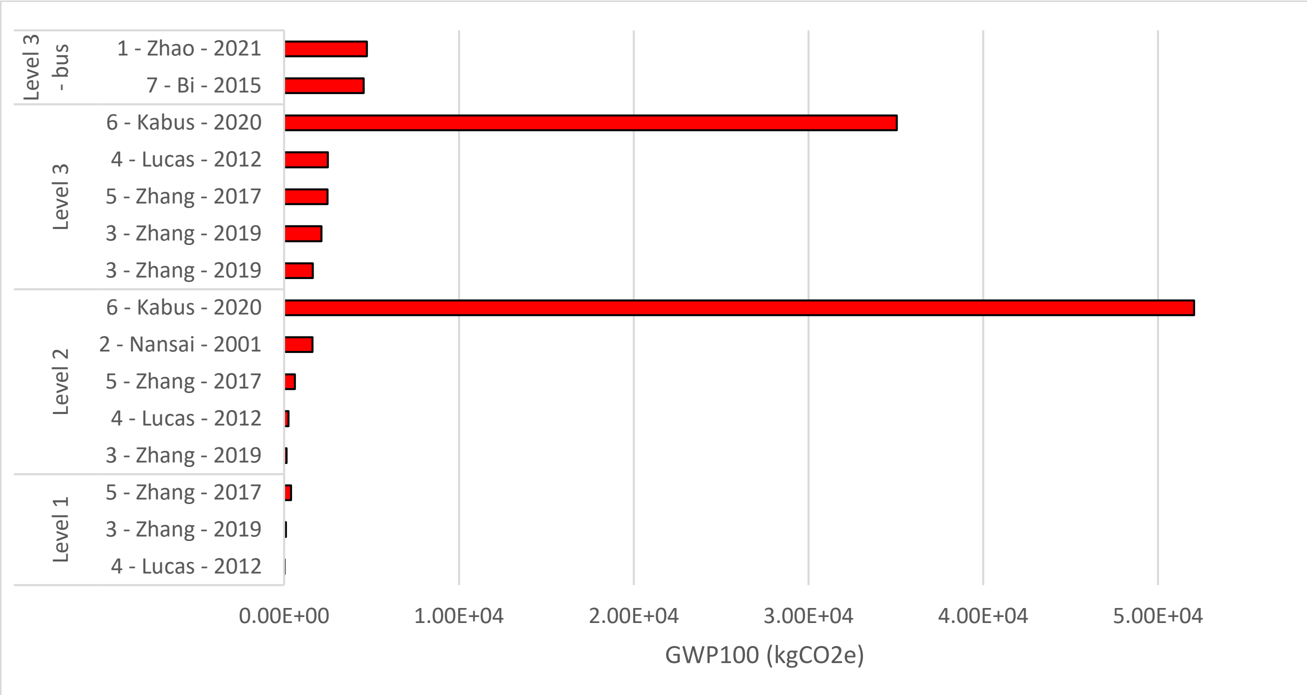


Figure 5 – Impact on climate change of 1 charger (only manufacturing stage) [A]

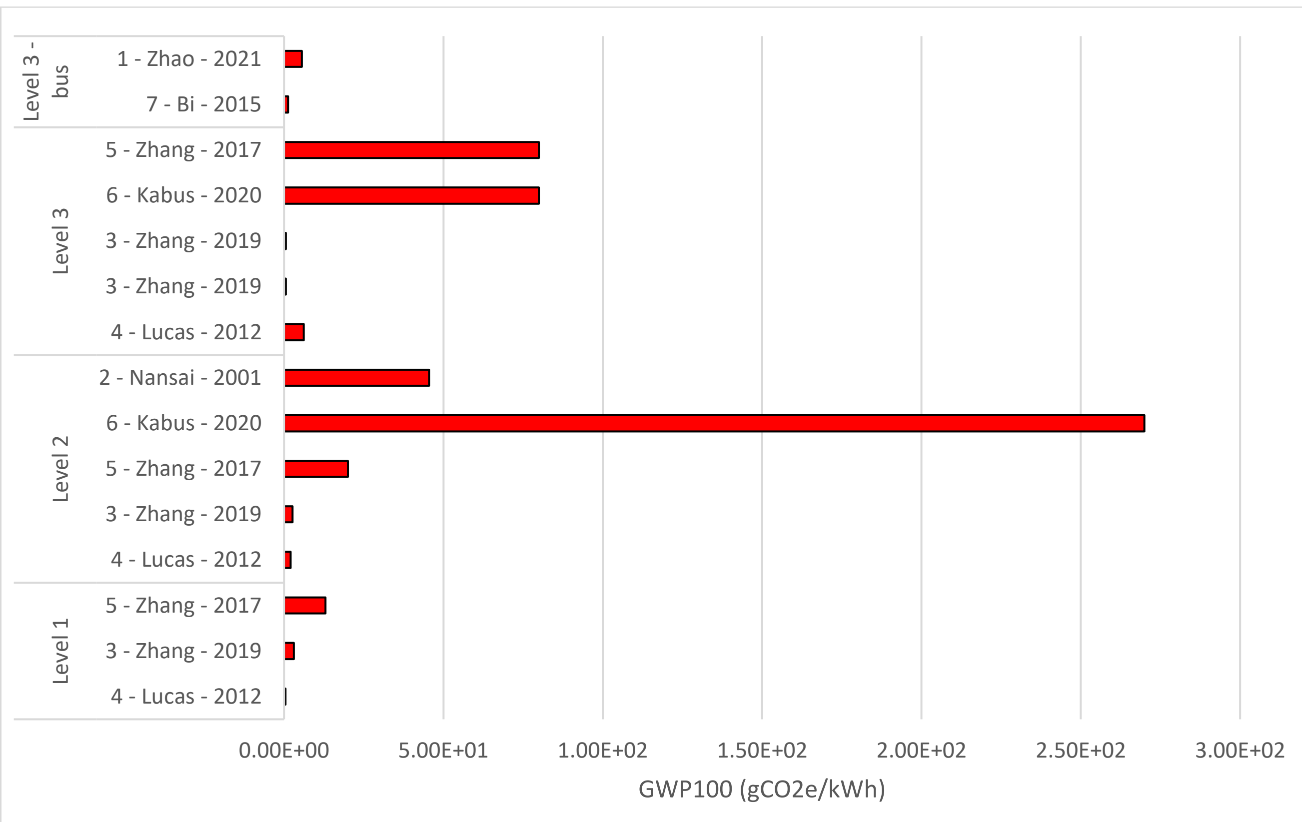


Figure 6 – Impact on climate change of 1 kWh delivered by chargers (only manufacturing stage) [A]

<u>Observation 2 :</u> Significant differences in impact between chargers on the same level

For each technology level, the impact to climate change, whatever the functional unit is, are highly variable with significative deviations sometimes exceeding 100% of the average. Taking the functional unit of 1 kWh, the differences are even greater. This can be explained by the fact that chargers have very different lifetimes and energy quantities within the same level.

Looking at the impact averages (*Figures 7 and 8*), we can nevertheless draw a few conclusions.

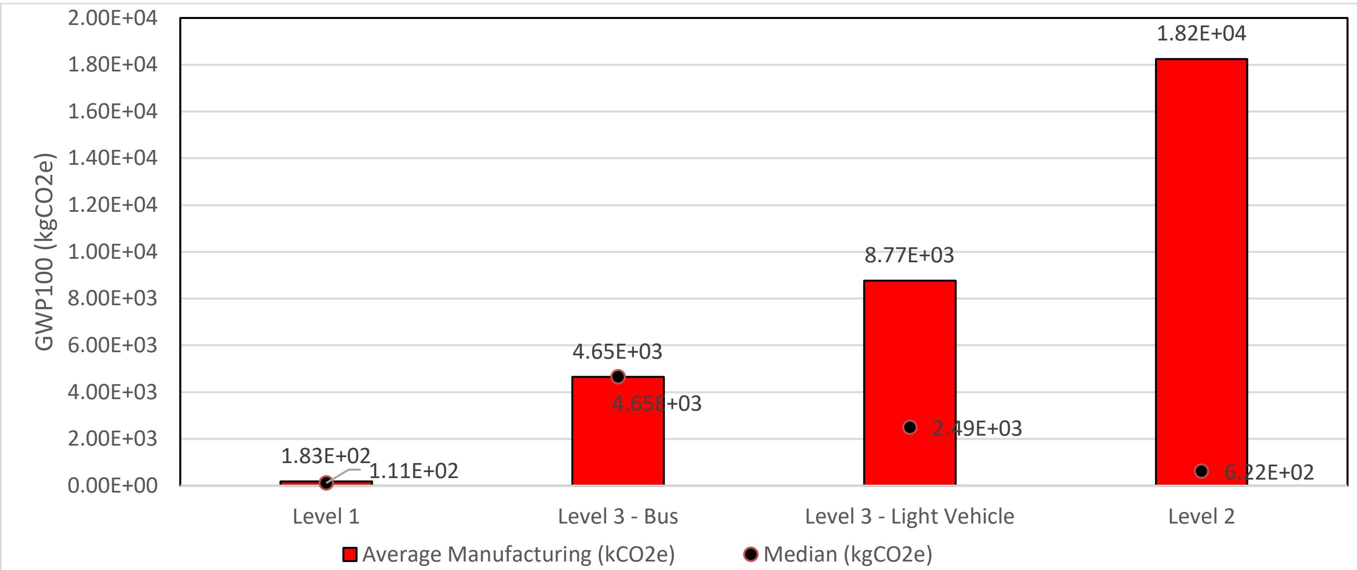


Figure 7 – Average Impact on climate change of 1 charger (only manufacturing stage) [A]

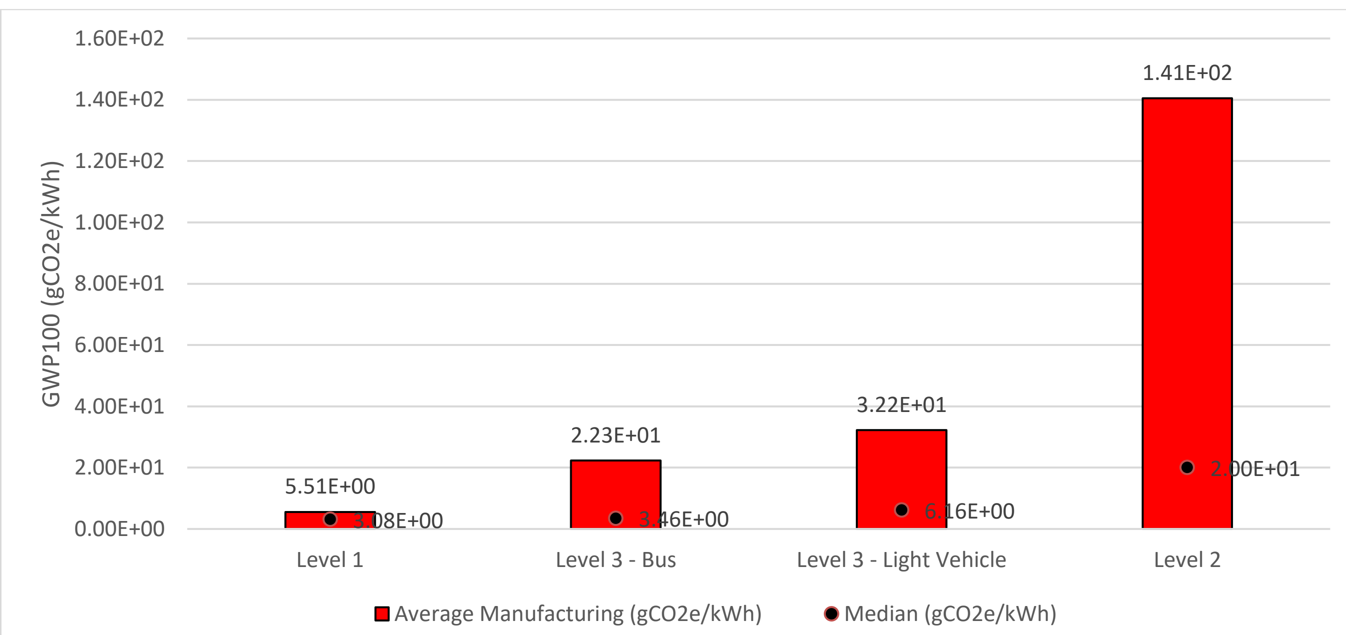


Figure 8 – Average Impact on climate change of 1 kWh delivered by chargers (only manufacturing stage)

[A]

<u>Observation 3</u> : Ranking levels according to impact

The average impact of level 1 is lower than the average impact of the other levels. It represents only 25% of the impact of level 2, which seems to have the greatest impact, considering the FU of 1 charger. Likewise, Level 3 has half the impact of level 2. These overall results appear to be consistent with the conclusions of some studies (Kabus et al. 2020) but not consistent with other studies which rank level 2 as less impacting than level 3 (Zhan Zhang et al. 2019; Zening Zhang et al. 2017) which is the case if we consider medians rather than means.

When we consider the functional unit of 1 kWh delivered by chargers, level 1 is always the least impacting, but here the average and median rankings show level 2 to be the most impacting, ahead of level 3.

We can also note that the bus charger always has less impact than level 3 charger for light vehicles, which may be surprising given the quantity of materials used for charging station for bus.

1.5 Gaps and limitations of previous LCAs

The studies of charging stations display very significant discrepancies in impacts. Nevertheless, for each level, we can have a range of values for the impacts on climate change (*Table 5*).

	for 1 kWh delivered (gCO2e/kWh)		for 1 charger (kgCO2e)	
Charging mode	**MIN**	**MAX**	**MIN**	**MAX**
Level 1	4,47E-01	1,30E+01	3,40E+01	4,04E+02
Level 3 - Bus	1,30E+00	5,62E+00	4,56E+03	4,74E+03
Level 3 - Light Vehicle	5,55E-01	8,00E+01	1,65E+03	3,51E+04
Level 2	2,05E+00	2,70E+02	1,46E+02	5,21E+04

Table 5 – Maximum and minimum impacts on climate change for 1 charger of 1 kWh delivered by chargers [A]

These significant discrepancies can be due to different causes: the studies do not use the same functional unit, the same background databases, the same system boundaries, and/or the same impact methods, which complicates the comparison.

In addition, studies have been carried out on different charging points models at different dates, which do not have the same lifespan or deliver the same amount of energy.

For a better comparison, the LCAs will be reproduced from the inventories of materials or components given in the studies, and compared using the same database, the same functional unit and the same impact method.

2. Reproduction and methodological harmonization of chargers' LCA

2.1 Reproduction of chargers' inventories

To fill the gaps identified in the previous section and better understand the variability of impacts on climate change related to the production of chargers, we reproduce these chargers LCA models with the collected inventories. Not all studies have detailed inventories and are therefore reproducible (*Table 6*).

Reference	DOC 1 [Zhao – 2021]	DOC 2 [Nansai – 2001]	DOC 3 [Zhang – 2019]	DOC 4 [Lucas – 2012]	DOC 5 [Zhang – 2017]	DOC 6 [Kabus– 2020]	DOC 7 [Bi – 2015]
Information collected	Materials of charger	Materials of charger	Materials of charger	Materials of charger	Partial list of components so not reproductible	Partial list of components so not reproductible	List of components

Table 6 – Type of inventory given in studies

NB : an update of materials in study 4 bis

Thus, the first 4 articles gave their inventories of chargers' materials, enabling us to observe the average weight of chargers and the types of materials most present in these chargers.

Type of charger	Number of chargers	Average weight	MIN	MAX
Level 1	**2**	13	11	14
Level 2	**4**	528	28	1255
Level 3	**4**	1250	248	3350
Level 3 - bus	**1**	1380	1380	1380

Table 7 – Average weight of chargers by level [A]

A first observation on *Table 7* is that the level 1 charger is on average lighter than the level 2, which is consistent because the level 1 requires fewer components than the level 2, since it plugs into a domestic socket. Moreover, the level 2 is lighter than the level 3.

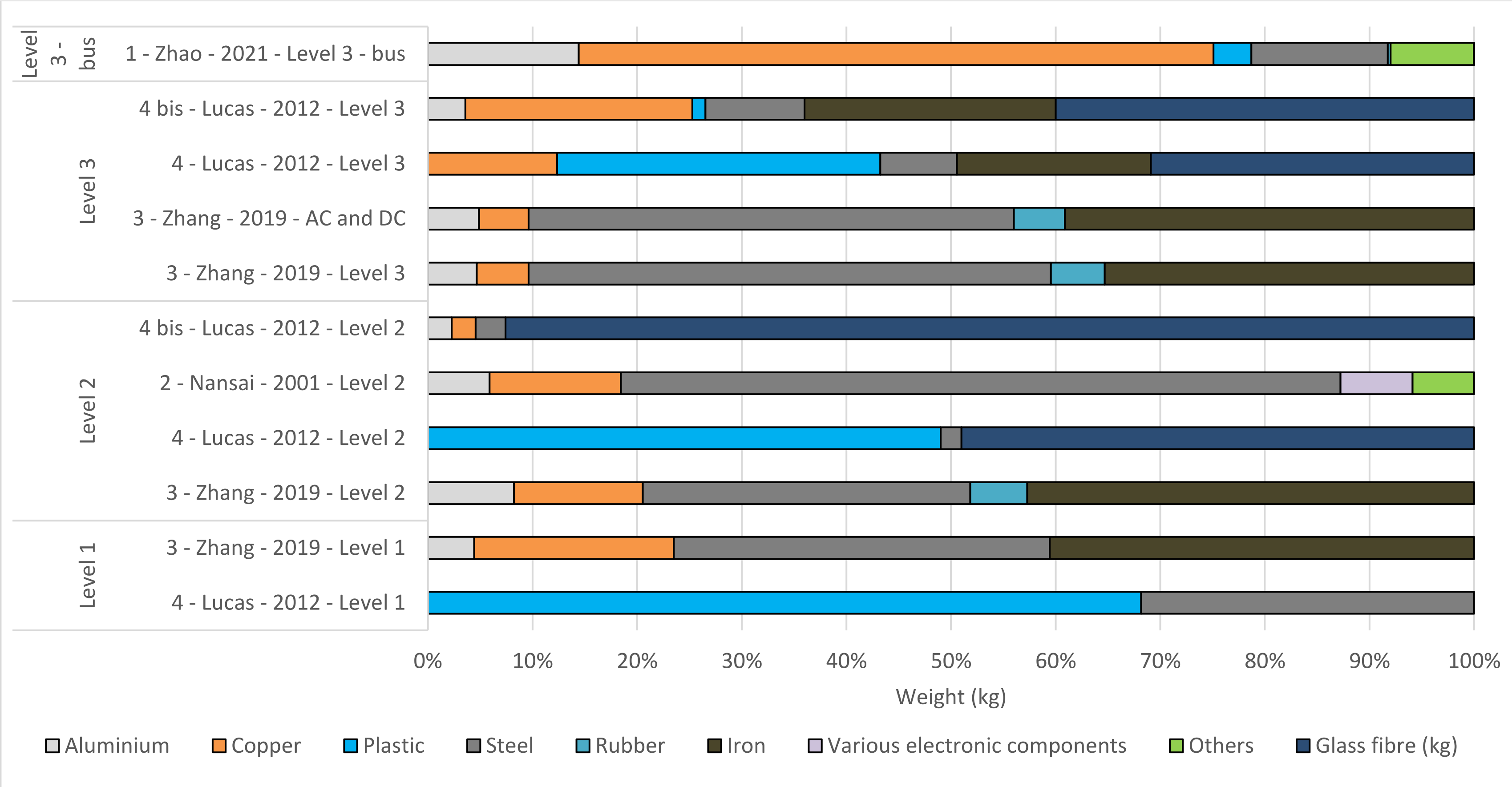


Figure 9 – Materials in chargers by level [A]

The mass share of each specific material in each charger does not seem to depend on the level.

The materials used in chargers are the same as those traditionally used for electronic components : copper for the connection wires, representing on average 14% of the weight of the chargers, iron and steel in large quantities (18% and 27% of the average total weight respectively), as well as the materials required for the enclosure surrounding the electronic components or the chargers, such as PVC plastic, glass fibre or aluminum.

Among these materials, steel, copper and aluminum generally have a fairly high footprint per kilogram: more than 10kgCO2e per 1 kg of aluminium for example.

Only one reproducible study, (Bi et al. 2015), refers to charging station components. The level 3 component chain for the bus is then as follows.

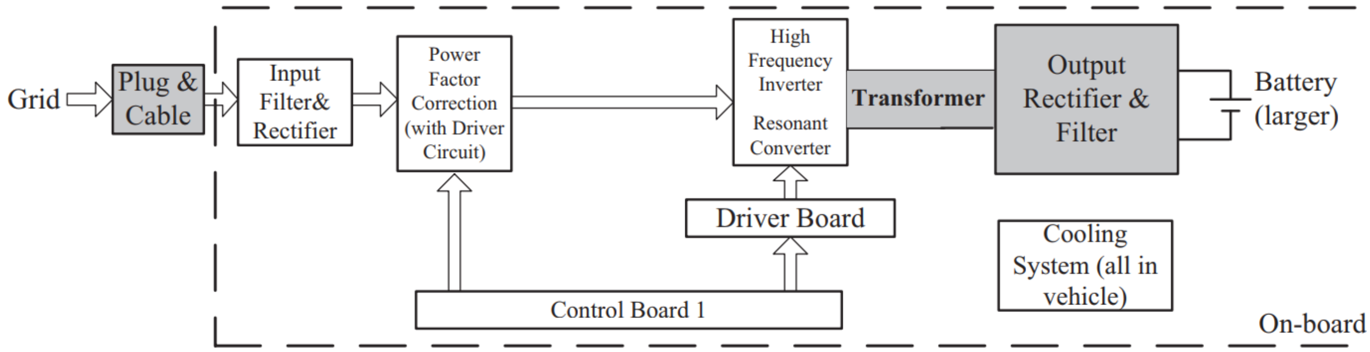


Figure 10 – Components of charger for level 3 bus in study 7 [Bi - 2015]

These components (*Figure 10 and Table 8*) are common to the chargers of other level 2 and 3 studies (Zening Zhang et al. 2017; Kabus et al. 2020).

Thus, the main components of EV chargers are the power supply (which transforms electrical power from the grid and contains transformer, rectifier and control circuit), the plugs and the control board (which manages the charging process). The electronic components found in these components are inductors, diodes, capacitors, resistors, printed circuit board or connectors.

DOC 7	Main function
Input filter (in input filter & rectifier)	Limit high frequency oscillations
Power factor correction	Reduce loss of power
Rectifier (in input filter & rectifier)	Convert AC current to DC
High frequency inverter	Convert AC current to DC
Transformer	Transfer energy from one circuit to another
Output rectifier and filter	Convert DC voltage to another
Cooling system	Keep the temperature of the structure
Plug and cable	Connect charger to EV and grid
Driver board	Serve as interface between the input connections and display panel
Control board	Serve as main printed circuit board

Table 8 – Main functions of components identified [A]

2.2 Methodology to reproduce chargers' LCA

The aim of this reproduction is to standardize the LCA methodology for better comparison, so the following parameters have been set:

- Functional unit: the impact of 1 charger is considered at first and then the impact of 1 kWh delivered by chargers recharging 1 vehicle is considered. This functional unit better reflects the charger's main function, and it considers only the impact of charger, not the impact of power grid infrastructure;

- Databases used: EcoInvent 3.8 to compare reproductions with study models, EcoInvent 3.10 to have more recent impact values of chargers and then EcoInvent 3.9.1 to calculate impacts under different future global warming scenarios with the premise module ;
- Impact methods used: Most studies use IPCC2013, we also use IPCC to compare reproductions and studies and then Impact World +, a method developed by the CIRAIG;
- Indicators studied: Most studies focus on the climate change indicator which is most relevant to the general public. We will also focus on this indicator;
- Materials and components used to reproduce the chargers will also be standardized, using materials from global markets;
- Quantity of energy delivered over its lifetime, efficiency and lifespan of chargers have also been standardized by level.

Brightway and Activity-Browser tools were used for this modelling.

Only the manufacturing stage was considered at first, then the use stage was also taken into account. This choice was made in order to be able to compare the results of the reproductions with those of studies.

2.2.1 Standardization of materials

Materials have been standardized, *Table 9* summarizes the list of common materials from global markets usually chosen for the reproduction of chargers in EcoInvent :

Name	Product	Activity
ABS/Glass	glass fibre	market for glass fibre
Aluminium	aluminium, wrought alloy	market for aluminium, wrought alloy
Concrete	concrete block	market for concrete block
Copper	copper, cathode	market for copper, cathode
Electronic components	electronic component, passive, unspecified	market for electronic component, passive, unspecified
Iron	iron ore, crude ore, 46% Fe	market for iron ore, crude ore, 46% Fe
Plastic	polyvinylchloride, suspension polymerised	market for polyvinylchloride, suspension polymerised
Rubber	synthetic rubber	market for synthetic rubber
Steel	steel, chromium steel 18/8	market for steel, chromium steel 18/8

Table 9 – Mapping of paper's materials inventories and ecoinvent processes in reproduction [A]

2.2.2 Standardization of key parameters

Chargers' lifespan and efficiency have been standardized for each level by taking the average life and efficiency of chargers from studies (*Table 10*).

	Power (kW)	Lifespan (year)	Efficiency
Level 1	1,85	12,33	91%
Level 2	7,25	9,50	90%
Level 3	84,22	12,00	89%
Level 3 - bus	150,0	12,0	99%

Table 10 – Lifespan and efficiency of chargers [B]

Moreover, the power chosen for level 1 corresponds to the average value of the maximum and minimum powers found in level 1. For levels 2 and 3, data from the Circuit Eectrique charging stations, representing one of the largest operators of charging stations in Quebec, were studied. Level 2 and 3 power ratings were determined by averaging the power ratings of the Circuit Electrique charging stations. [B] For the bus, the power of Société des Transports de Montréal (STM) buses was chosen. STM operates buses in Montreal.

Another key parameter for calculating the energy delivered by the charging station, and therefore its impact per kWh of energy delivered, is the utilization rate, that is the time during which the charger is used during the day out of the total time of the day.

To calculate these utilization rates, several assumptions were made using the Quebec context. One of them is that light-vehicle users travel an average of 40 km/day to get to work and for their personal activities, for example ("Durée et lieux de recharge d'une auto électrique.," n.d.). Considering the average consumption of electric cars (21 kWh/100 km) in Quebec [E], the energy required each day is 8 kWh.

Depending on the efficiency and power of chargers, it is then possible to deduce charging times.

Charging point	Charging time (h) for 1 EV	Time (min)	Hydroquebec values
Level 1	5,02	301,03	> 8h
Level 2	1,29	77,24	Between 1 and 3h
Level 3	0,11	6,70	Between 8 and 15 min

Table 11 – Charging time for 1 EV by level [B]

These values (*Table 11*) are lower than those given by Circuit Electrique : our assumption is that the company took vehicle consumption values around 30 kWh/100 km, which corresponds to a significant increase in actual consumption, even when the consumption is affected by wear and tear on the car or weather phenomena [E]("Durée et lieux de recharge d'une auto électrique.," n.d.).

Finally, assuming that 90% of users have a home charging system that they use 80% of the time ("Stratégie québécoise sur la recharge de véhicules électriques - Québec investit un demi-milliard de dollars et prévoit implanter plus de 116 000 bornes de recharge publiques d'ici 2030," n.d.), it is possible to find utilization rates for each level by considering the number of level 2 and 3 charging stations in Quebec and the number of cars in Quebec that need to be recharged.

In the same way, for buses, an average number of kilometers per day was determined using STM figures. Then, taking into account 1 charger per bus, the utilization rate was calculated.

With all these key parameters, we find the total energy delivered for each level over its lifetime (*Table 12*).

General hypothesis by level	Utilization rate (time used)	Energy delivered (kWh)	*Deviation of energy*
Level 1	**17%**	**3,34E+04**	*30%*
Level 2	**38%**	**2,31E+05**	*165%*
Level 3	**3%**	**2,94E+05**	*80%*
Level 3 - bus	**9%**	**1,45E+06**	*33%*

Table 12 – Charging time for 1 EV by level [B]

The deviation from the average energy calculated in the studies is very different, but this is not surprising as we have taken a particular context of use linked to Quebec. The chargers of the studies and reproductions will therefore be compared in detail on the functional unit of 1 charger.

2.3 Comparison between impacts of chargers in studies and in reproduction

Using the IPCC method and the Ecoinvent 3.8 database, we obtain the following results *Table 13*.

GWP100 (kgCO2e) in studies	GWP100 (kgCO2e) in reproduction choosing the revelant IPCC	*Difference between reproduction and results in studies*
4,74E+03	1,07E+04	*125%*
1,63E+03	2,97E+03	*83%*
2,13E+03	6,22E+02	*-71%*
1,11E+02	4,15E+01	*-63%*
1,46E+02	9,68E+01	*-34%*
1,65E+03	6,22E+02	*-62%*
3,40E+01	2,52E+01	*-26%*
2,50E+02	3,21E+02	*28%*
2,50E+03	2,49E+03	*-1%*
4,56E+03	7,71E+02	*-83%*

Table 13 – Results of reproduction and comparison with studies [C]

As the studies were carried out at different dates, and the most commonly used indicator and impact method are the GWP100a with the IPCC method, we can compare the results of reproduction with the most likely used impact method and the results of the studies.

The differences in impacts between studies and reproductions are quite significant, which may be due to the lack of precise data used by the studies. The difference varies between 3% and 110%, taking the values of the studies as a reference. It is difficult to draw conclusions from these results.

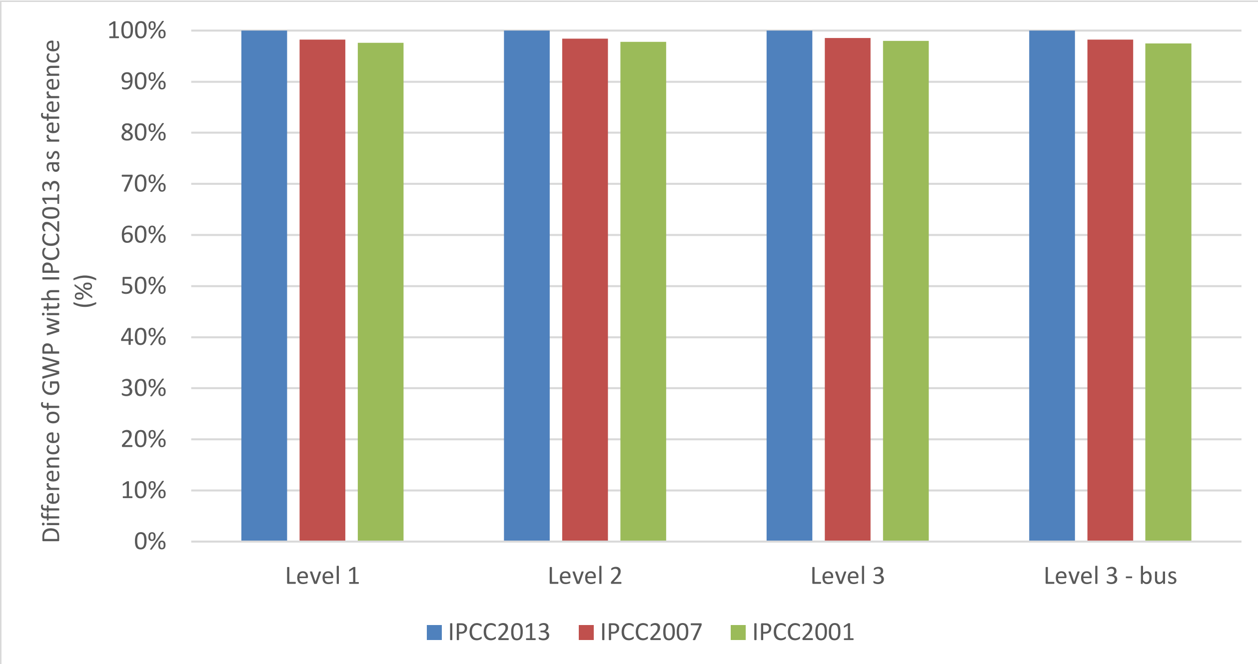


Figure 11 – Differences of impacts on climate change of chargers (considering GWP100 from IPCC 2013 as a reference) [C]

If we compare the consequence of the impact methods (*Figure 11*), we also note that impact on climate change varied slightly by less than 3% between IPCC 2001 or IPCC2007 and 2013. The version do not change considerably the results so we will use the last version of this impact method.

However, if we change some materials, for example by replacing "steel chromium" with "steel low alloyed", also used in power electronics, the impact may vary by 40%, given the large amount of iron in the chargers [E]. In addition to the uncertainties surrounding the materials chosen for modeling in the studies, method-related differences add further uncertainties to the reproduction results.

2.4 Impact on different indicators

2.4.1 Indicators chosen

However, by changing the impact method and using more recent databases such as EcoInvent 3.10, we can still compare the average impacts of different indicators, such as:

- Impact on climate change or carbon footprint: measuring the quantity of greenhouse gases (in kgCO2e) emitted that will disrupt the Earth's radiation balance and thus lead to global warming;
- Impact on ecosystem quality: measuring the increase in the disappearance of marine, aquatic or terrestrial species linked to emissions of toxic substances into water, air and soil (in PDF.m^2.year that means potentially disappeared fraction of species in 1 m^2 in a year) ;
- non renewable energy resources (in MJ deprived) or water use (in m^3 world eq deprived) : linked to the impact of the competition between different users of the resource.
- Impact on human health: measuring for example the impact of emissions of fine particles on

the increase in diseases and thus on the number of years of life in poor health for humans (in DALY : disability adjusted life years) ;

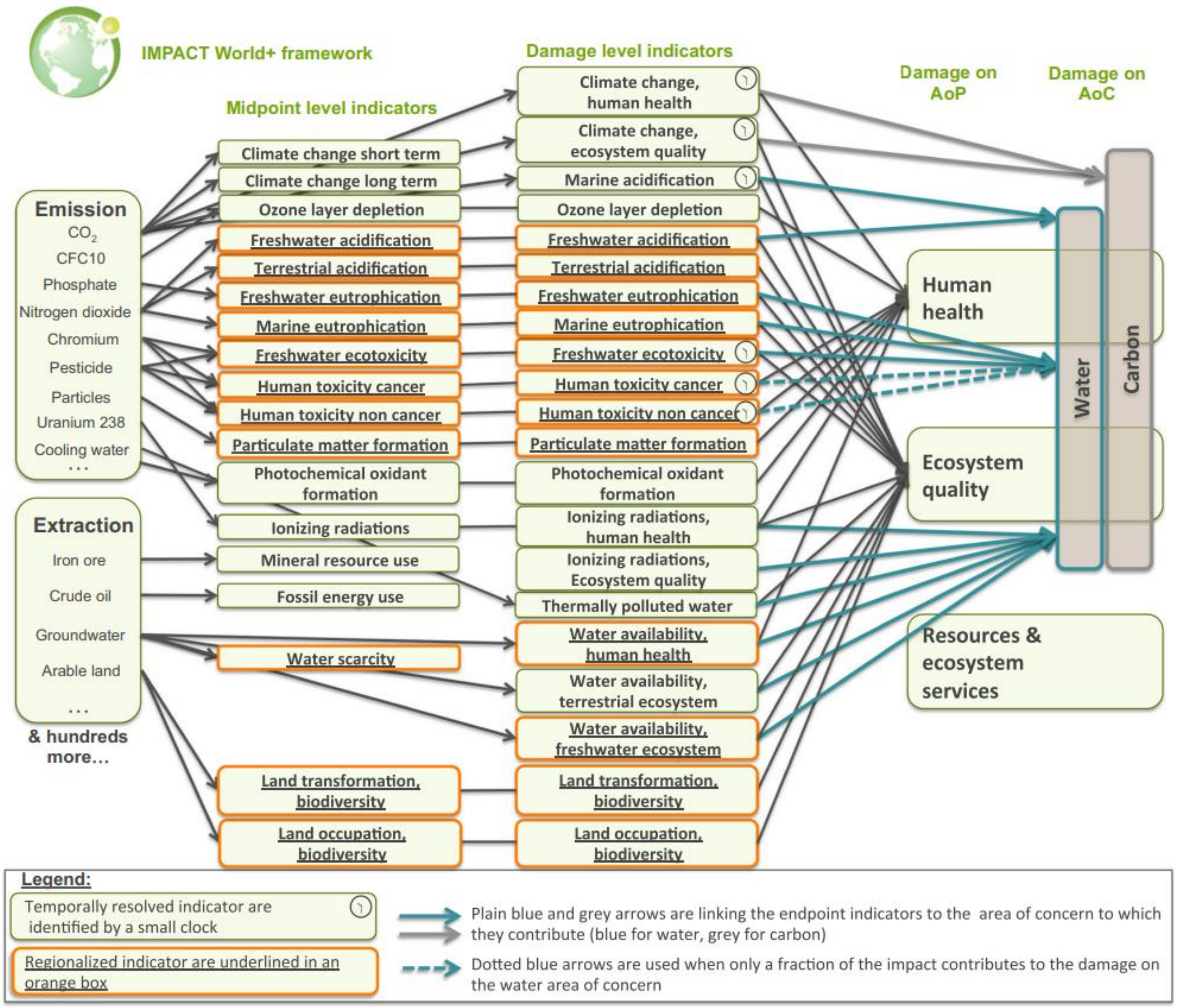
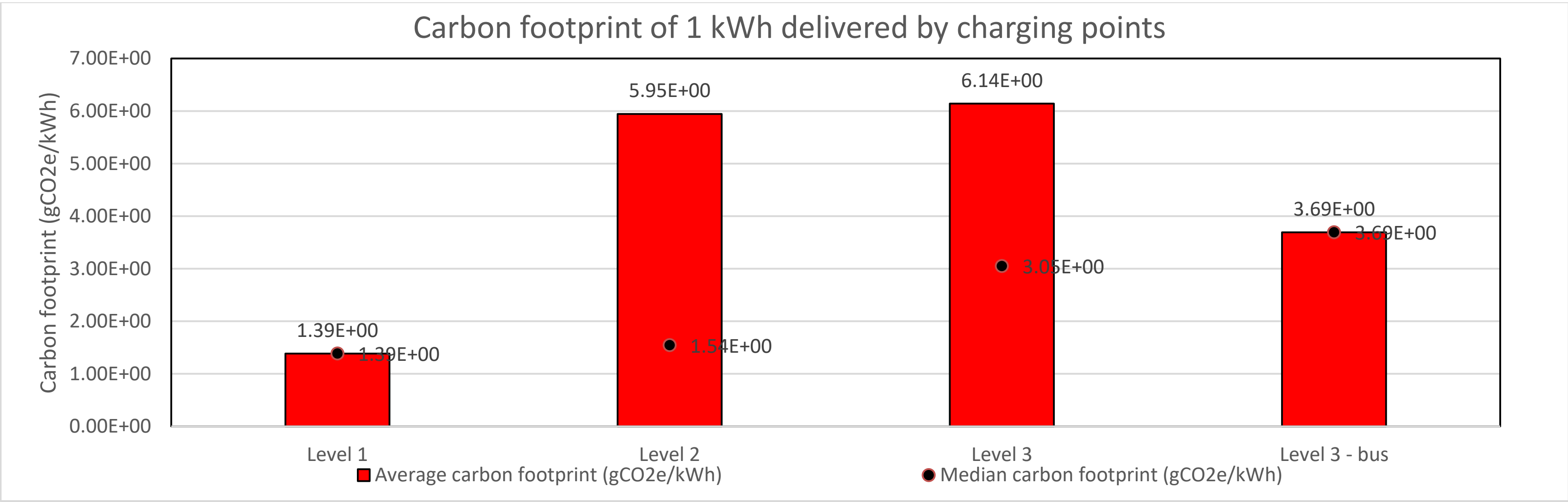
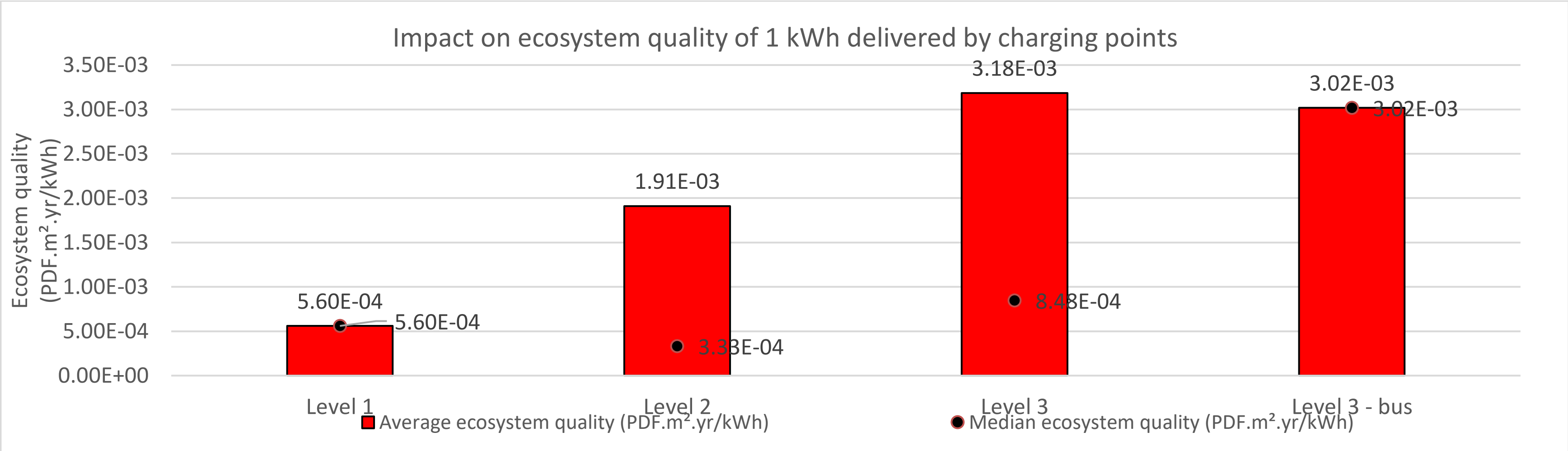


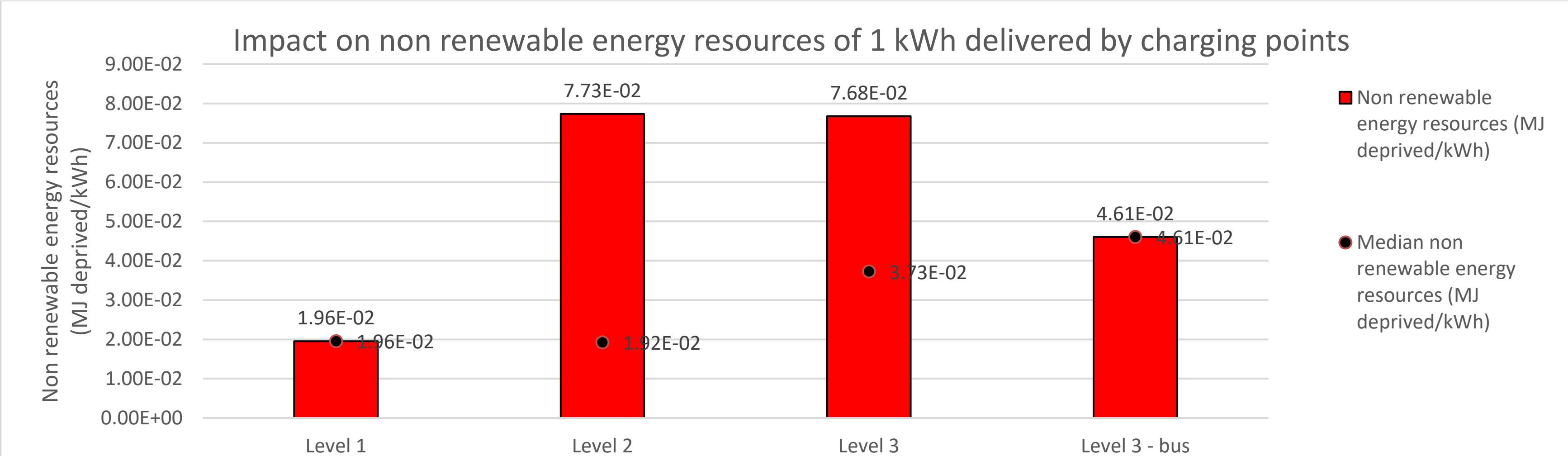
Figure 12 – Impact world+ framework [7]

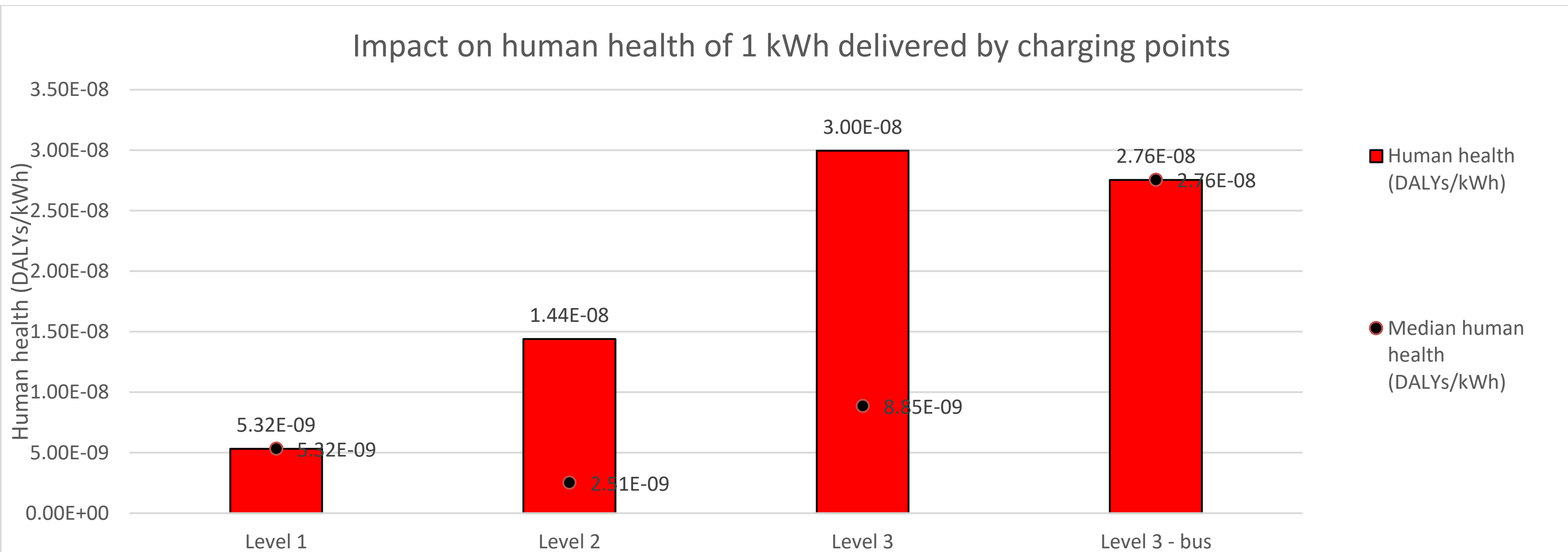
2.4.2 Results

To compare charging points against each other on these indicators, the functional unit chosen is 1kWh delivered by the chargers (*Figure 13*).






Impact on non renewable energy resources of 1 kWh delivered by charging points
Non renewable energy resources (MJ deprived/kWh)
9.00E-02
8.00E-02
7.00E-02
6.00E-02
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
1.96E-02
1.96E-02
7.73E-02
1.92E-02
7.68E-02
3.73E-02
4.61E-02
4.61E-02
Level 1
Level 2
Level 3
Level 3 - bus
Non renewable energy resources (MJ deprived/kWh)
Median non renewable energy resources (MJ deprived/kWh)


Impact on human health of 1 kWh delivered by charging points
Human health (DALYs/kWh)
3.50E-08
3.00E-08
2.50E-08
2.00E-08
1.50E-08
1.00E-08
5.00E-09
0.00E+00
5.32E-09
5.32E-09
1.44E-08
2.51E-09
3.00E-08
8.85E-09
2.76E-08
2.76E-08
Level 1
Level 2
Level 3
Level 3 - bus
Human health (DALYs/kWh)
Median human health (DALYs/kWh)

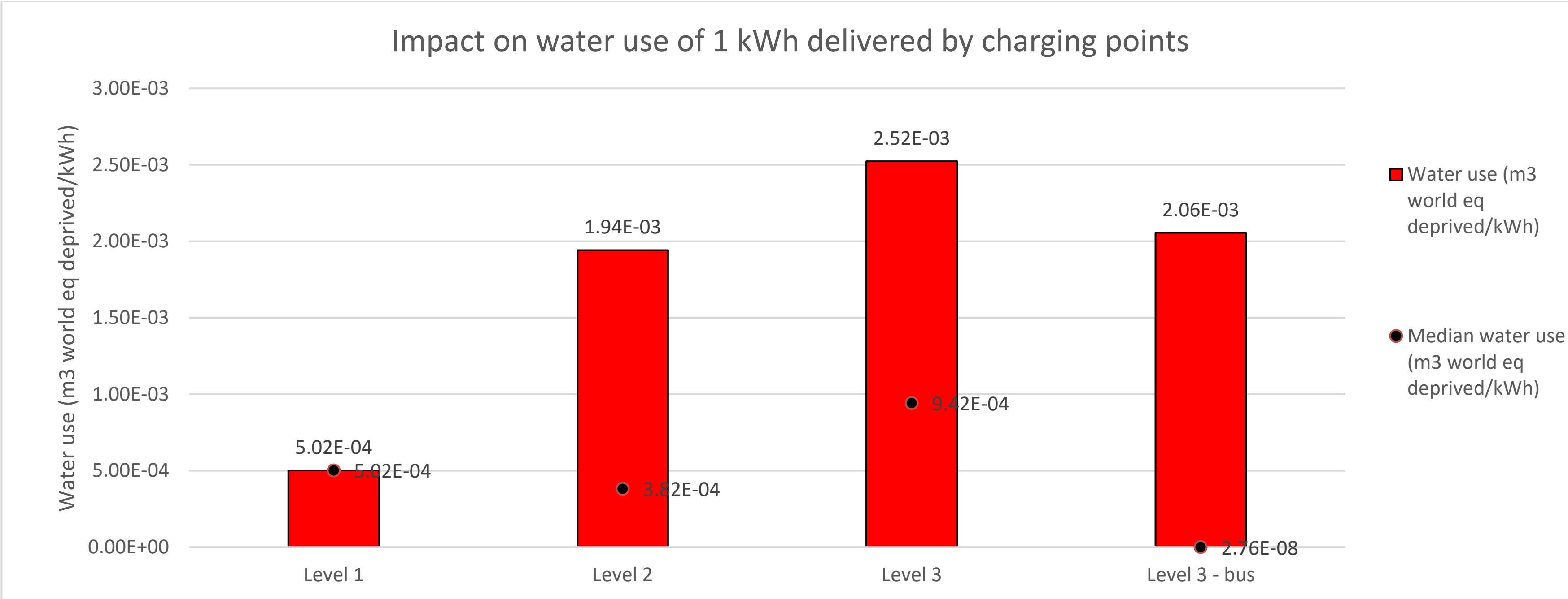


Figure 13 – Impact on indicators of 1 kWh delivered by chargers [C]

First of all, we can observe that for all indicators, the level 1 has less impact than level 2, which has less impact than level 3 for light vehicles in the Quebec context with the corresponding utilization rates. Charging point level 1 represents only a quarter of the impact of the level 3.

Furthermore, level 2 and 3 deliver same quantity of energy considering this utilization rate but the level 3 seems to have more impact than level 2 on all indicators.

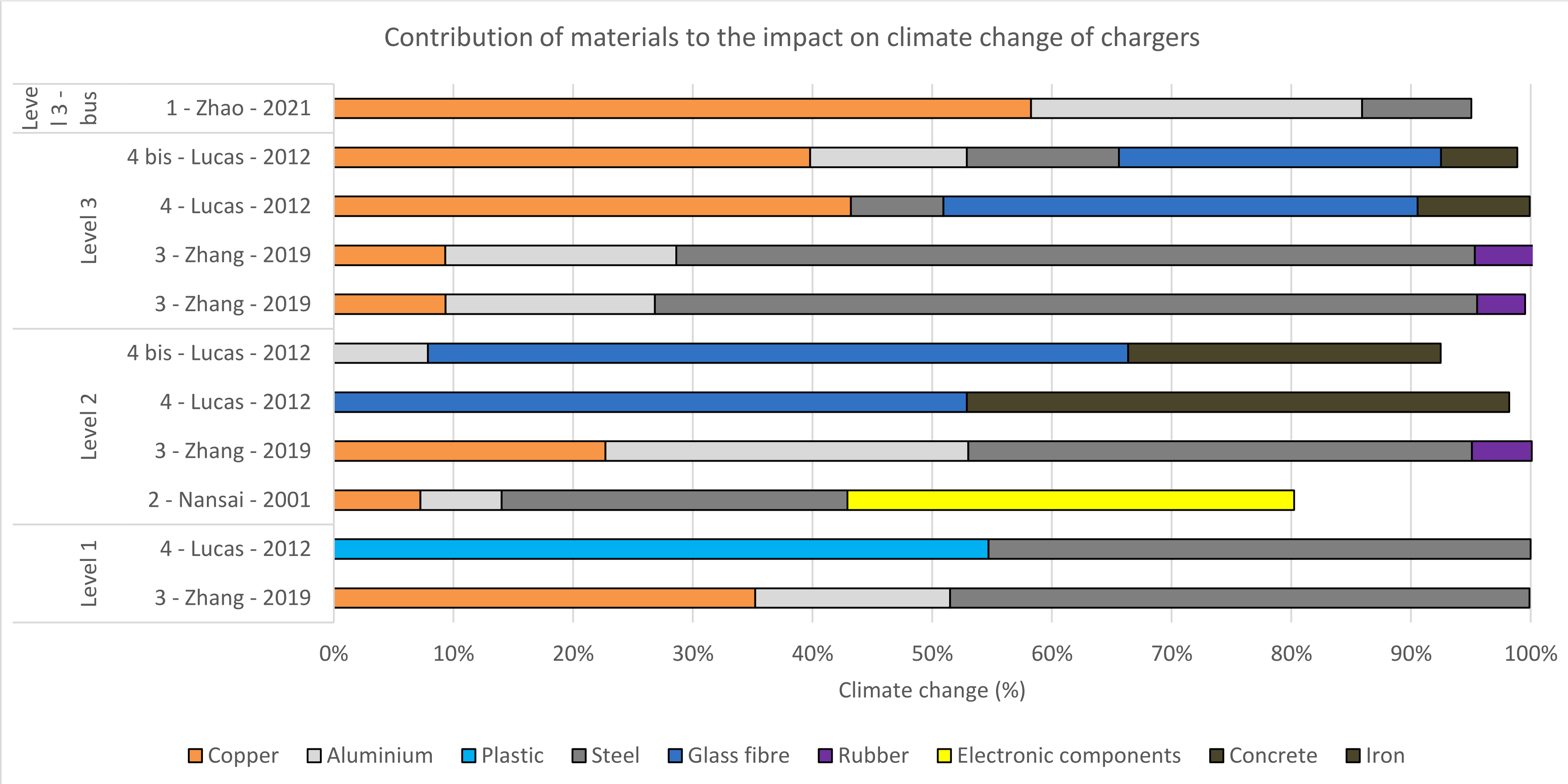


Figure 14 – Contribution of materials to impact on climate change of chargers [C]

In fact, electronic components, copper and aluminium have a major impact on all these indicators as they require highly polluting extraction notably. The steel being very present in chargers also has a great impact.

Considering the components in chargers, electronic components are the main contributors ahead of infrastructure or cables which is consistent with studies. (Zening Zhang et al. 2017; Kabus et al. 2020).

Nevertheless, these results are not entirely reliable, as once again the standard deviation of impact values around the mean is very high, reaching 70% for some indicators but we obtain a range of impact values for each category and level (*Table 14*).

	Carbon footprint (kgCO2e)		Ecosystem quality (PDF.m^2.yr)		Non renewable energy resources (MJ deprived)		Human health (DALYs)		Water use (m3 world eq deprived)	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Level 1	3,96E+04	5,32E+04	6,45E+00	3,10E+01	6,34E+02	6,76E+02	5,37E-05	3,02E-04	5,37E-05	3,02E-04
Level 2	1,08E+05	3,65E+06	4,68E+01	1,20E+03	1,32E+03	4,77E+04	4,45E-04	8,94E-03	4,45E-04	8,94E-03
Level 3	8,98E+05	3,63E+06	2,50E+02	2,31E+03	1,10E+04	4,59E+04	2,60E-03	2,12E-02	2,60E-03	2,12E-02
Level 3 - bus	6,20E+05	1,01E+07	1,18E+02	8,61E+03	8,07E+03	1,25E+05	7,29E-04	7,90E-02	7,29E-04	7,90E-02

Table 14 – Range of values of indicators for each level [C]

3. Discussion

3.1 Data quality analysis

As mentioned above, studies data are not systematically given and accurate. In addition, the charger models studied are models distributed in certain countries over a certain period. Also, the chargers studied are not necessarily representative of the chargers that are installed or could be installed in the future in Quebec.

The pedigree approach (*Table 15*) provides a rough approximation of the uncertainties associated with study data. It takes into account the reliability of inventory data, their completeness and also geographic, temporal and technological correlation of chargers between the chargers in studies and the charger in Quebec.(Weidema and Wesnæs 1996) [8]

N°	1	2	3	4	5	6	7
Reliability	4	4	2	2	?	2	3
Completeness	5	5	5	5	5	5	5
Temporal correlation	2	5	3	5	3	4	4
Geographical correlation	3	4	3	2	?	1	2
Technological correlation	4	4	3	4	?	2	4

Table 15 – Pedigree matrix of studies [A]

In our case, the charger in study 6 (Kabus et al. 2020) whose data come from major global manufacturers such as ABB, and whose data date is more recent, is more representative of charger models currently being deployed in Montreal. The results of the study would therefore be more representative of the results that would be possible with chargers in Quebec and should therefore be given greater consideration.

3.2 Sensitivity analysis

Some parameters used in the modeling are subject to a certain degree of uncertainty. We have already observed the influence of the choice of materials on the results, but in our study, there is also an uncertainty about the utilization rate, which has been calculated in a Quebec context.

In a sensitivity analysis, we will vary this utilization rate and observe the variation in the impact on climate change of 1 kWh delivered by chargers. Secondly, for specific utilization rates, we can observe the variation in the impact of 1 kWh delivered by chargers in the future by choosing scenarios thanks to premise (Sacchi et al. 2022)[9].

Finally, as mentioned above, the electricity delivered has the greatest impact, when considering the entire charger life cycle, so it is relevant to observe the impact of both, the manufacturing and use stages, on climate change.

3.2.1 Sensitivity analysis on utilization rate

By varying the utilization rate of the chargers, we can vary the electricity delivered over its lifetime, and thus the life-cycle impact of the charger per kWh delivered. We consider arbitrarily an utilization rate varying between 10 and 90% for each charger. This range has been chosen because it reflects the wide reality of charger use (*Figure 15*).

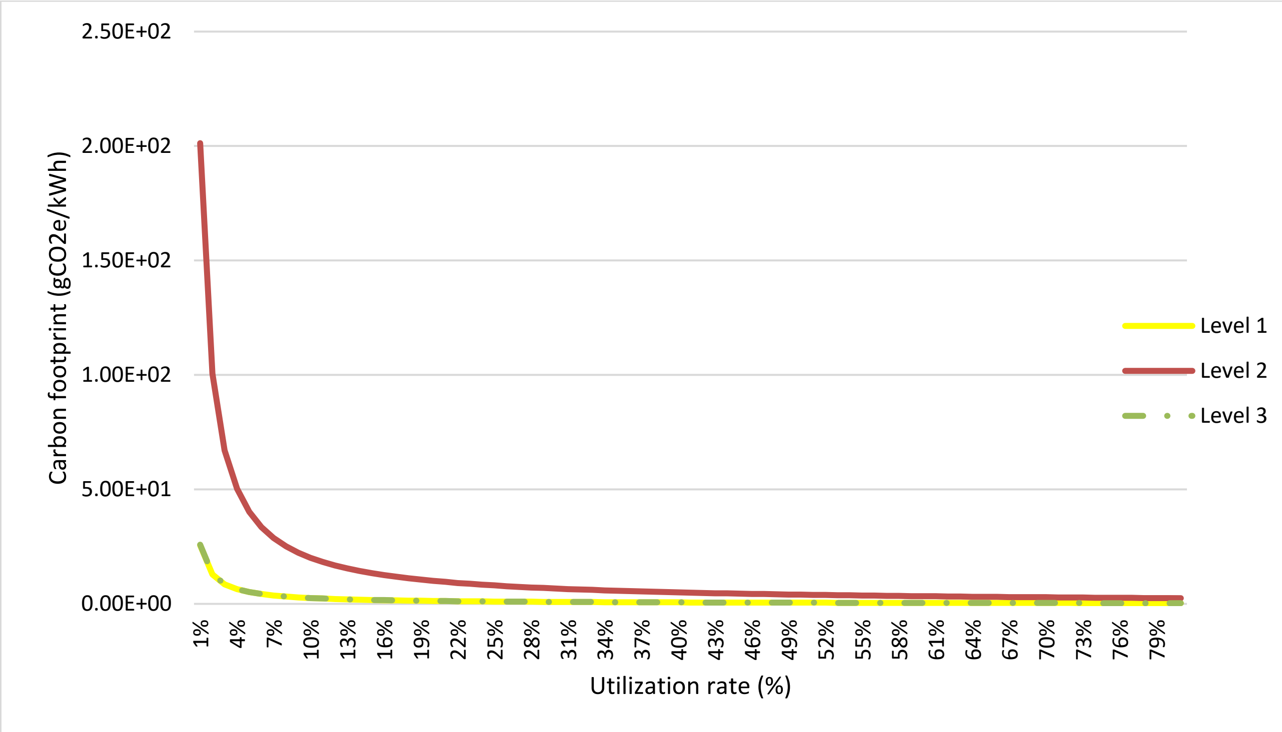


Figure 15– Evolution of carbon footprint considering different utilization rates [C]

For each level, we find a hyperbola representing inverse functions. Also, the higher the number of hours of use, the smaller the carbon footprint of the charger lifecycle per kWh delivered.

The impact of the level 1 and level 3 chargers is almost equal surprisingly. The difference between the impact of level 3 and level 1 is 2% for an utilization rate of 10%, and this difference decreases for higher utilization rates. Indeed, the impact of level 1 is 44 times less than that of level 3, but the quantity of electricity delivered by level 3 is also 44 times greater than the electricity delivered by level 1.

However, it is worth noting that our analysis does not change the lifetime of the charger whereas the more the charger is used, the shorter its lifespan.

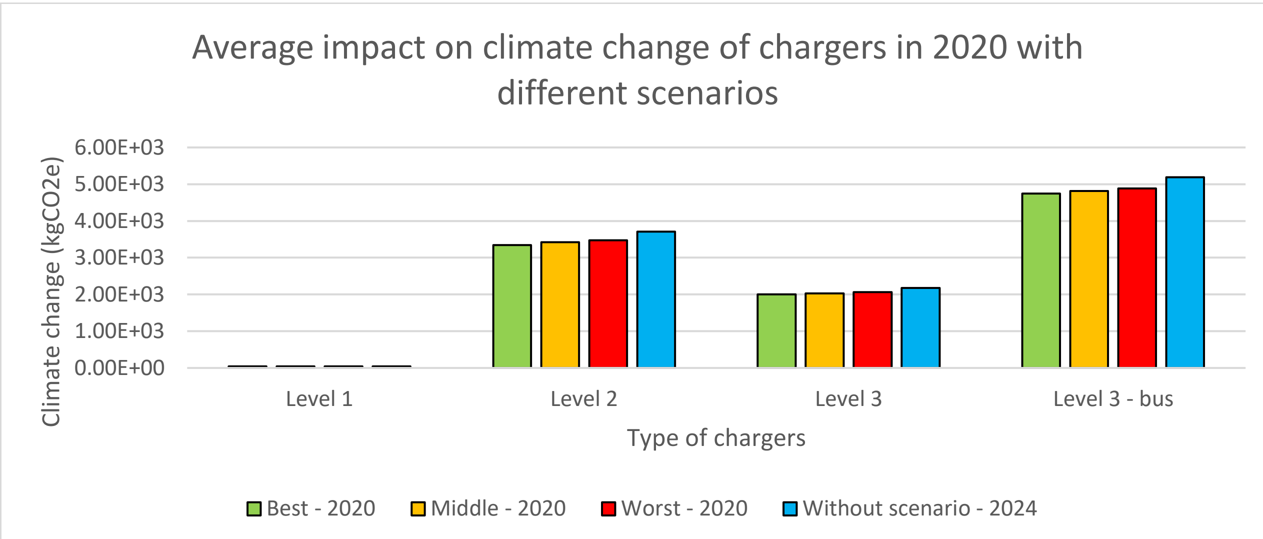
3.2.2 Sensitivity analysis on scenarios in the future

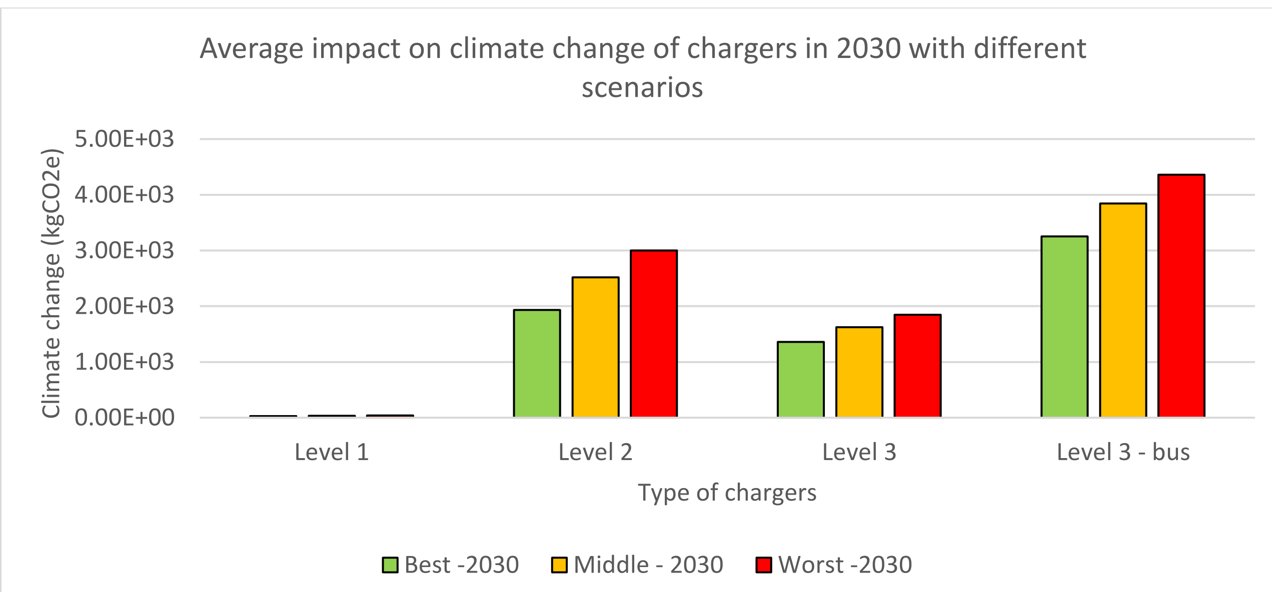
Depending on the climate actions taken to combat climate change, the impact of materials, largely due to the impact of the electricity used to shape them, could change between now and 2030 and 2050 and so do the impact of chargers.

In this section, we will analyze the variations in the impact on climate change of the 3 levels for light vehicles according to 3 different scenarios:

- A scenario limiting global warming to 4,5 degrees above 1990 in a world that emphasizes economic growth driven by competitive markets, innovation and consumerism: called “worst scenario” (besides the fact worse scenarios exist);

- A scenario limiting global warming to 3,3 degrees above 1990 but also in a world that emphasizes economic growth driven by competitive markets, innovation and consumerism : called here “middle scenario” ;
- A scenario limiting global warming to 1.5? degrees above 1990 in a world that shifts toward a more sustainable path (reducing resource and energy consumption, emphasing well-being rather than consumption), respecting the Paris agreement, called “best scenario”.





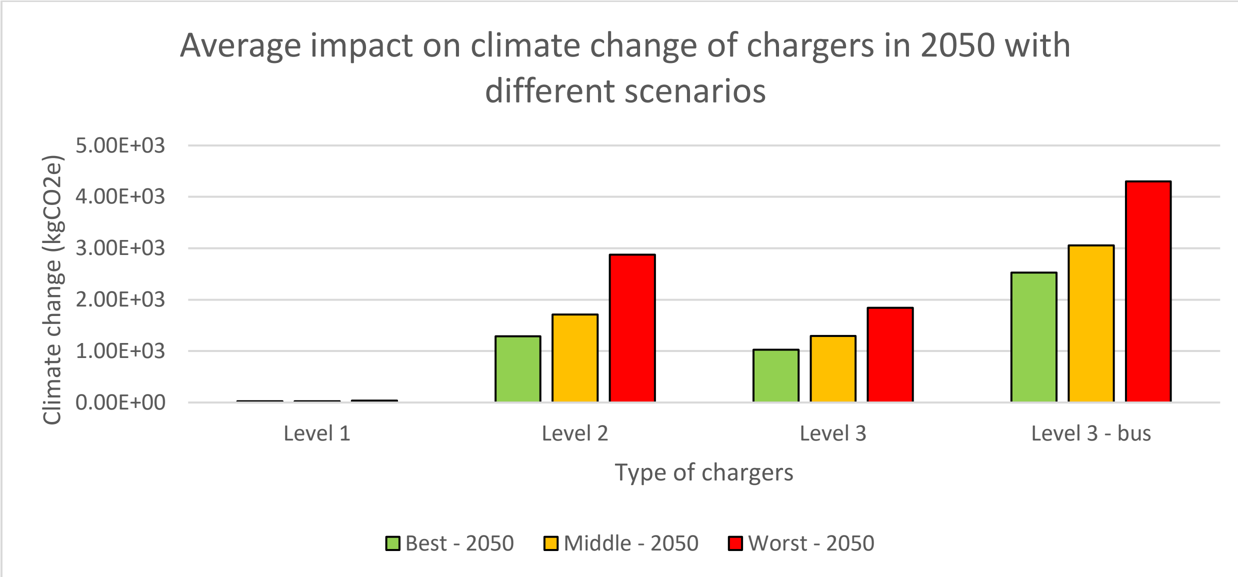
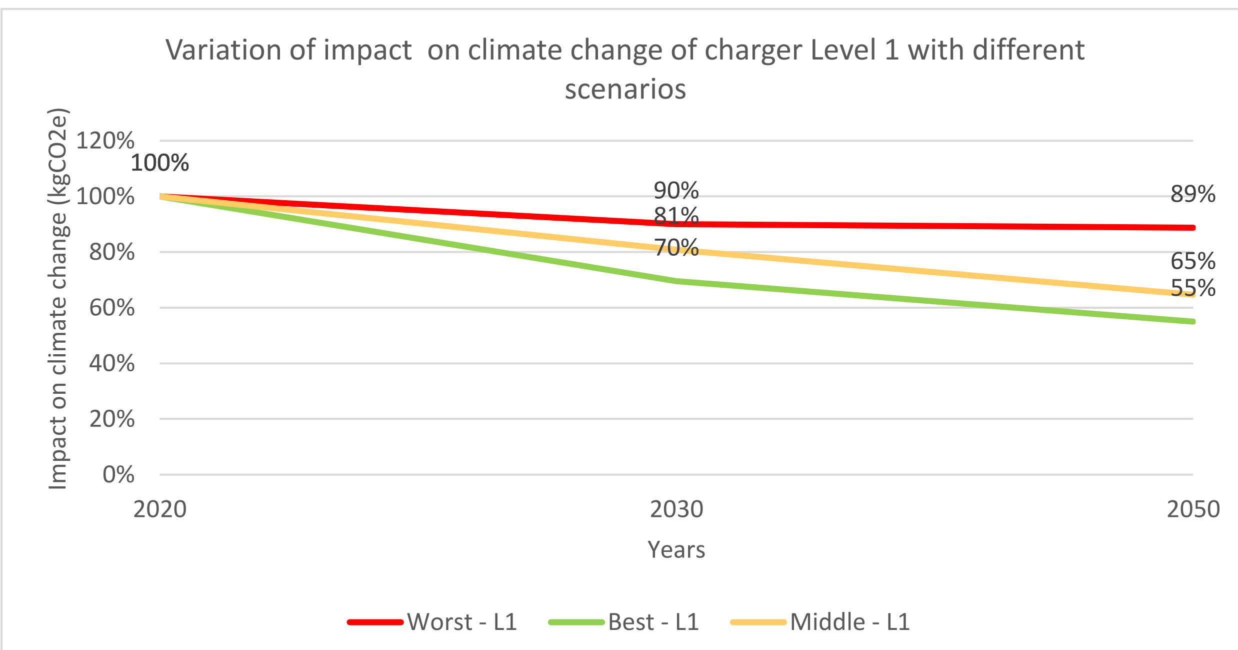
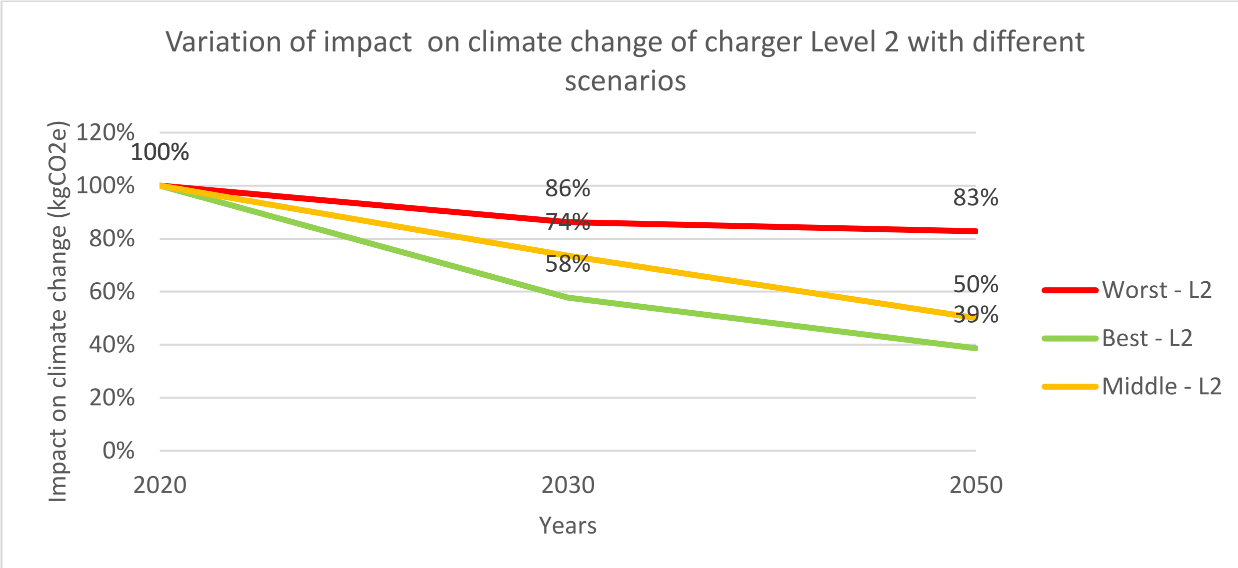


Figure 16 – Average impact on climate change of chargers with different scenarios [C]





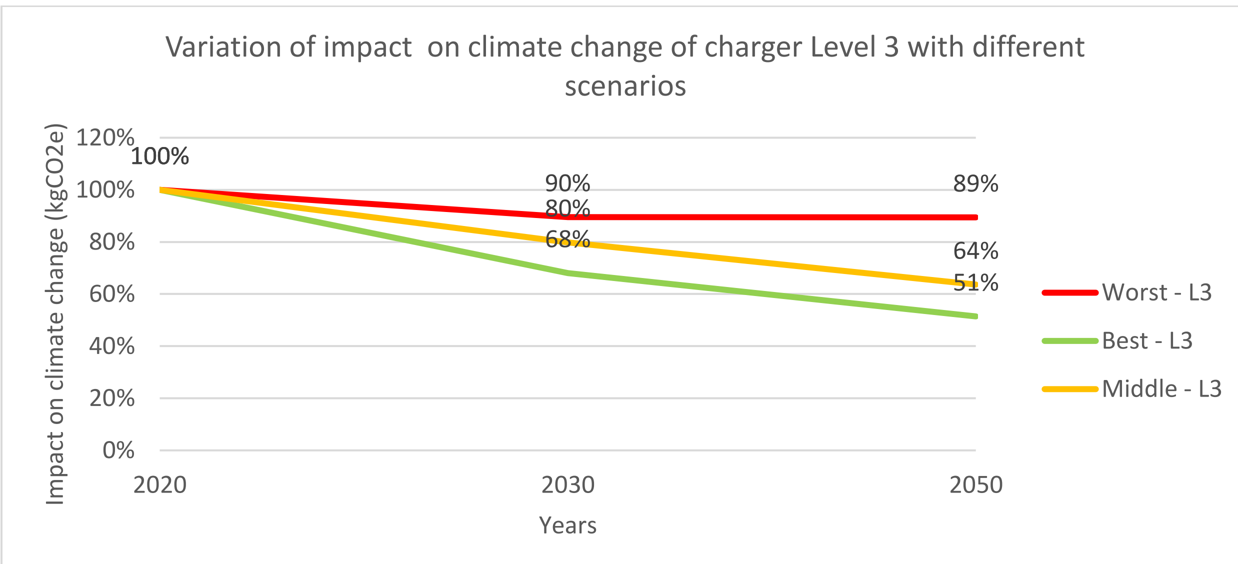


Figure 17 – Variation of impact on climate change of chargers with different scenarios [C]

A first observation is that the impact on climate change of chargers decreases for all scenarios (*Figure 17*). The lower the temperature targeted by the scenario, the greater the decrease. This result is consistent with the fact that metals will be decarbonized at different speeds depending on the scenario. Copper, for example, has its carbon footprint reduced by 20% in the worst scenario and by 60% in the best scenario (*Figure 18*). The materials carbon footprint is largely linked to energy, which is increasingly decarbonized depending on the scenario.

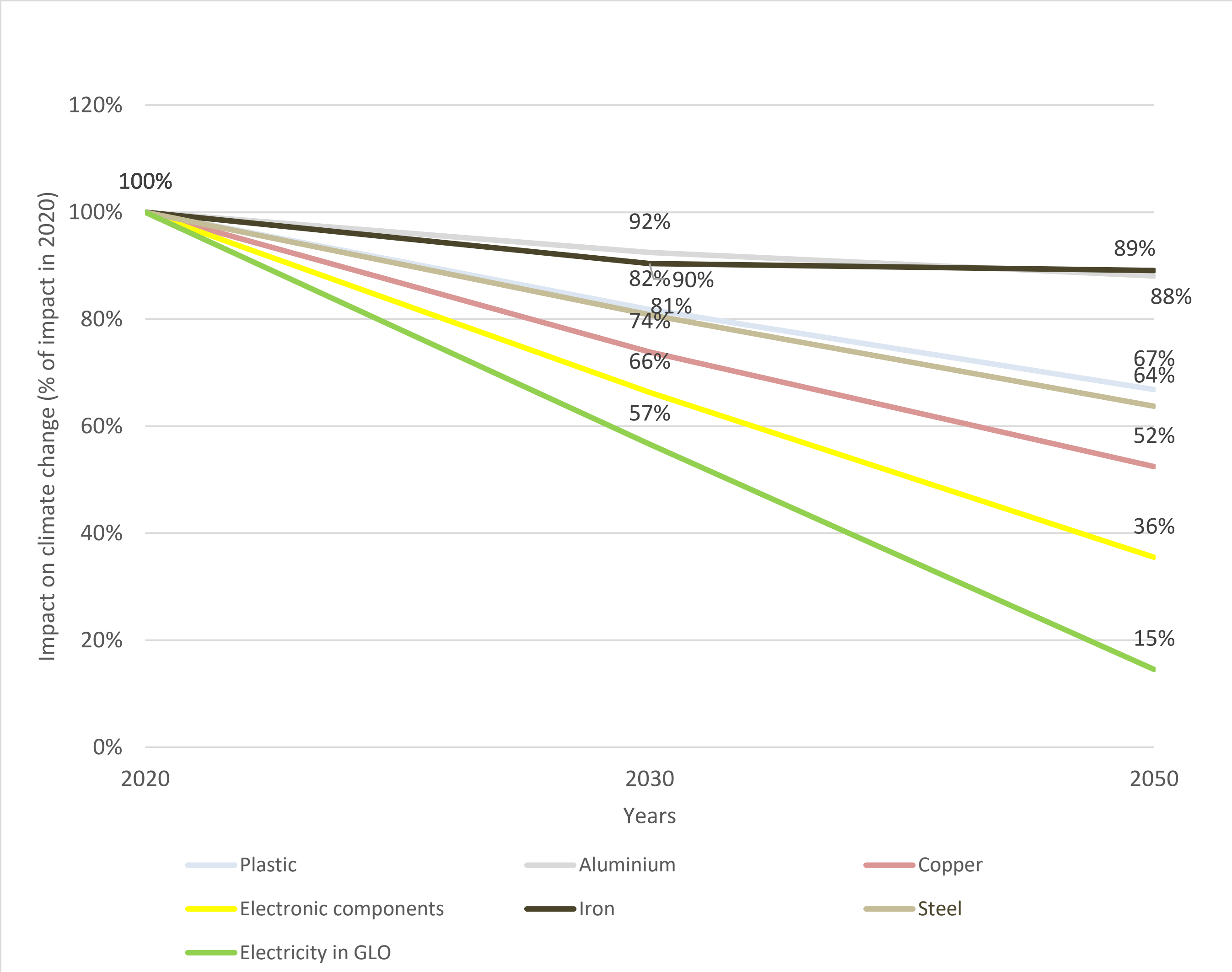


Figure 18 – Variation of impact of 1 kg of materials or impact of 1 kWh with middle scenario [C]

However, a calculation of current footprints using the same database shows that the impact is 5% larger than the impact with the worst scenario in 2020.

3.2.3 Sensitivity analysis on country using the chargers

The reason why the materials footprint is decreasing, is because it is easier to decarbonize electricity than metal use. We have already observed that the electricity stage is the most important, so it may be interesting to evaluate the impact of 1kWh delivered by the chargers used in different locations over time according to different usage rates with a specific scenario like the middle scenario and considering the manufacturing and the use stage.

In our case, we will examine the impact of use on the global market (GLO) with global electricity and on the Quebec market with largely decarbonized electricity from Quebec. Quebec electricity is less carbon-intensive than electricity from GLO in the ecoInvent database, but this difference varies with different scenarios (*Figure 19*).

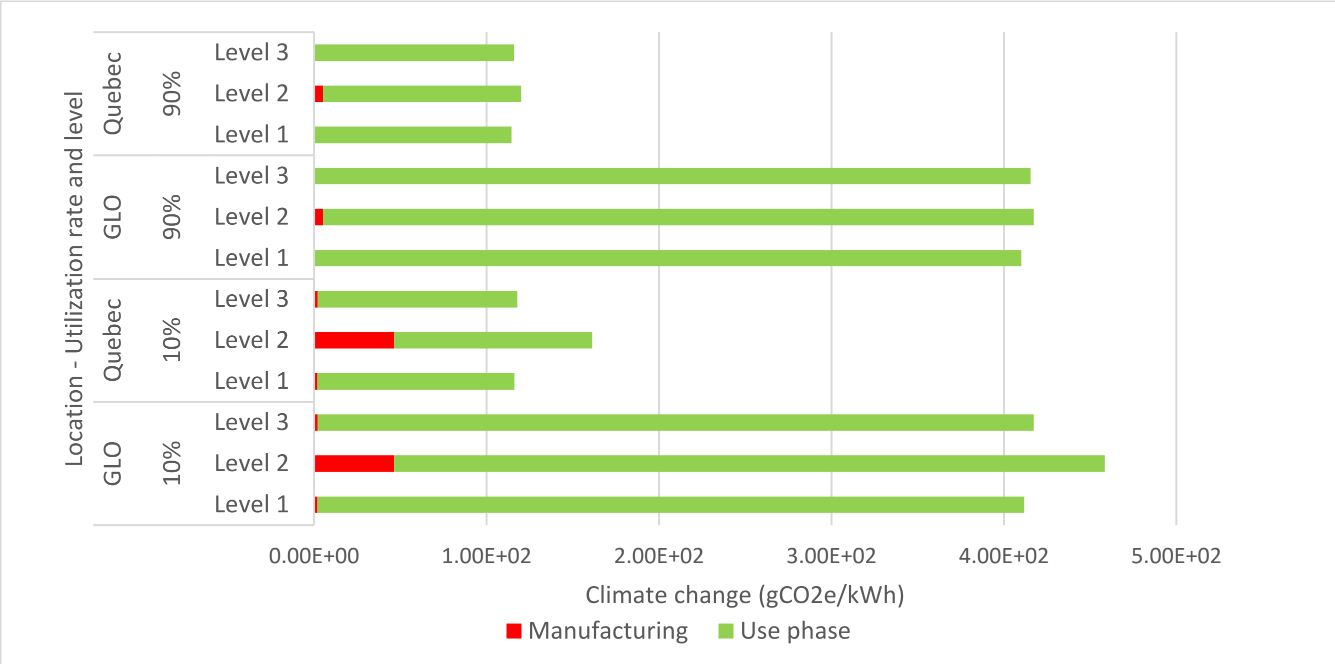


Figure 19 – Variation of impact on climate change of 1 kWh delivered by chargers in 2030 with middle scenario in different locations and utilization rates [C]

Level 1 still has the least impact, whatever the chosen parameters and level 2 still has the greatest impact, but the differences is not very significant, they are less than 30% for the middle stage for example

For chargers 1 and 3, use remains systematically the most impacting stage, accounting for over 98% of impacts. For charger 2, on the other hand, the manufacturing stage sometimes accounts for 30% of the total impact for a utilization rate of 10%. And for all of them, as the utilization rate increases, the impact of this manufacturing relative to the impact of use decreases.

Since Quebec electricity has less impact and the manufacturing stage always has the same impact for a specific utilization rate, the total impact of Quebec charging stations for an utilization rate is reduced by about 3.5.

Thus, decarbonizing the electricity used by the chargers seems to be one of the major actions to be taken to reduce the impact of the chargers on this part of its life cycle.

4. Conclusions

The aim of this study was to compare the life cycle impact of charging infrastructure from published scientific literature, and to reproduce LCAs using the literature inventories, in order to quantify the impact of charging infrastructure with a harmonized LCA methodology. Charging infrastructure has been little studied, as its use stage carbon footprint, linked to the impact of electricity, is more important than the impact from its production stage.

We found 7 scientific articles on conventional charging infrastructure, from level 1 to level 3 technologies. The analysis of the studies shows significant differences of impact on climate change of manufacturing stage in each of the levels due to the different choices made for the realization of the LCA (charger specific to a time and place, functional unit, database, impact method, etc). However, for each level, the studies provide a range of carbon footprint values, and we see that level 1 is less impacting than the others and should therefore be preferred considering a functional unit of 1 charger. A reproduction of these chargers showed that level 1 had less impact on several other indicators like damage to ecosystem quality or to human health.

On the other hand, the impact of level 3 seems greater than that of level 2, considering the functional unit of 1 charger because level 3 uses more materials, which are the same between all levels. However, on a functional unit of 1 kWh delivered, level 2 chargin points have the greatest impact, because for the same rate of use, level 3 delivers way more energy.

For all chargers, a sensitivity analysis showed that the higher the utilization rate, the less polluting the charger, considering 1 kWh delivered as the FU. Furthermore, if we consider an electric car that consumes 20 kWh/100 km and has a lifespan of 150,000 km, the car's impact for 1 kWh is 1.20 kgCO2e/kWh, or more than 94% of the total impact if we take energy and recharging into account. The impact of the chargers is therefore negligible, as shown in our literature review (Lucas, Alexandra Silva, and Costa Neto 2012).

Finally, this study focused on the manufacturing stage, but this latter is less impactful than the use stage of the e-vehicle, and it is therefore easier and more important to decarbonize the energy delivered to reduce the impact of the use stage than the manufacturing stage, which depends more on energy to produce materials. Nevertheless, the electricity network being less challenging to decarbonize than other sectors involved in the life cycle of the charging points, for instance metal production, the contribution of charging points to the life cycle impact of e-mobility could become an important stake in the future.

In the future, as the LCA studies on charging points are a little dated, it may be interesting to carry out LCAs on chargers currently manufactured by major manufacturers, to have more representative and accurate inventories and quantify the impact of current chargers on the market.

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6. Additional documents

[A] 1 - Literature review about LCA on chargers

[B] 2 - Data about chargers

[C] 3 – Reproduction of chargers

[D] 5 – Calculs on EV consumption