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A Strategic Sustainability Analysis of Electric Vehicles in EU Today and Towards 2050

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***Abstract*—**Ambitions within the EU for moving towards sustainable transport include major emission reductions for fossil fuel road vehicles, especially for buses, trucks, and cars. The electric driveline seems to be an attractive solution for such development. This study first applied the Framework for Strategic Sustainable Development to compare sustainability effects of today's fossil fuel vehicles with electric vehicles that have batteries or hydrogen fuel cells. The study then addressed a scenario were electric vehicles might be in majority in Europe by 2050. The methodology called Strategic Lifecycle Assessment was first used, were each life cycle phase was assessed for violations against sustainability principles. This indicates where further analysis could be done in order to quantify the magnitude of each violation, and later to create alternative strategies and actions that lead towards sustainability. A Life Cycle Assessment of combustion engine cars, plug-in hybrid cars, battery electric cars and hydrogen fuel cell cars was then conducted to compare and quantify environmental impacts. The authors found major violations of sustainability principles like use of fossil fuels, which contribute to the increase of emission related impacts such as climate change, acidification, eutrophication, ozone depletion, and particulate matters. Other violations were found, such as use of scarce materials for batteries and fuel cells, and also for most life cycle phases for all vehicles when using fossil fuel vehicles for mining, production and transport. Still, the studied current battery and hydrogen fuel cell cars have less severe violations than fossil fuel cars. The life cycle assessment revealed that fossil fuel cars have overall considerably higher environmental impacts compared to electric cars as long as the latter are powered by renewable electricity. By 2050, there will likely be even more sustainable alternatives than the studied electric vehicles when the EU electricity mix mainly should stem from renewable sources, batteries should be recycled, fuel cells should be a mature technology for use in vehicles (containing no scarce materials), and electric drivelines should have replaced combustion engines in other sectors. An uncertainty for fuel cells in 2050 is whether the production of hydrogen will have had time to switch to renewable resources. If so, that would contribute even more to a sustainable development. Except for being adopted in the GreenCharge roadmap, the authors suggest that the results can contribute to planning in the upcoming decades for a sustainable increase of EVs in Europe, and potentially serve as an inspiration for other smaller or larger regions. Further studies could map the environmental effects in LCA further, and include other road vehicles to get a more precise perception of how much they could affect sustainable development.

***Keywords*—**Strategic, electric vehicles, fuel cell, LCA, sustainability.

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I. Introduction

A. Road Traffic and Sustainability

THE current road traffic within Europe contributes to a good living standard through enabling transporting people and goods, but it also contributes to sustainability related problems. Accidents cost society money, which in the EU-15 countries in 2004 exceeded 180 T€ [1], and cost the Swedish society about 2T€ in 2005 [2]. Road traffic has also negative consequences on people's health due to emissions. Within the EU-24 countries in 2010, OECD indicate that the road transport share of the economic cost of health impact from ambient air pollution, including morbidities, was about 550 T€ [3]. Further on, these vehicle related emissions also contribute to the greenhouse gas (GHG) effect, acidification, eutrophication, ozone depletion, and particulate matters [4]. Governments within the EU and the European Parliament have therefore realized the importance of sustainable development and have recently set goals like reducing GHG emissions with at least 40% by 2030 and 80% by 2050 [5].

To meet emission targets, electric vehicles (EVs) are suggested by several organizations as a solution due to zero emissions when used in traffic [6]-[8], but there might be some implications that has to be accounted for in order to achieve a sustainable development of road transport. There has been several studies using Life Cycle Assessment (LCA) to measure and compare environmental impact of different vehicle systems [9]-[13], but none of them were combined with a strategic sustainability assessment that could avoid sub-optimizations that might cause problems for other societal sectors or people outside the EU. Research within the GreenCharge project aims at finding a roadmap for how a large-scale introduction of EVs in southeast of Sweden can be done in a sustainable way to contribute to the Swedish national emission goals; fossil fuel independent vehicle fleet by 2030 and GHG neutral society by 2050. The research team within GreenCharge has included Strategic Life Cycle Assessment of buses and cars in previous studies [4], [14], but have not made further LCA studies for different car types, nor included the fuel cell concept. For these reasons, there seems to be a need for analyzing strategic sustainability implications within the whole life cycle of EVs before taking further steps towards a large scale-up of EVs within the EU.

B. Research for Strategic Sustainable Development

Research within the GreenCharge project uses the Framework for Strategic Sustainable Development (FSSD) [15], which can guide any organization, system, or societal sector towards a sustainable future. The FSSD comprises the five levels 'system', 'success', 'strategic', 'actions', and 'tools', and has been used for successful development of several business cases for companies and sustainable development societal sectors such as transport [4], [16]-[18]. A principled definition of sustainability is included at the success level of the FSSD. It acts as a filter for any system, action, or strategy that would like to develop towards and exist in a sustainable future. The social part of the definition is currently being further elaborated [19], but in this study we have used this version:

"In a sustainable society, nature is not subject to systematically increasing…

I …concentrations of substances extracted from the Earth's crust,

II …concentrations of substances produced by society,

III …degradation by physical means, and, in that society…

IV ...people are not subject to conditions that systematically undermine their capacity to meet their needs."

C. Purpose of the Study

The purpose of this study was to widen the already existing systems perspective of research in the GreenCharge project by analyzing sustainability effects of a large scale-up of EVs in Europe, also including trucks. Battery Electric Vehicles (BEVs) are already today a more sustainable option in the south-east of Sweden if charged by new renewable electricity [4]. However, the new Hydrogen Fuel Cell Electric Vehicle (HFCEV) technology seems to be an interesting sustainable solution when powered by new renewable energy [9]. This study compared these solutions with today's dominating technology Internal Combustion Engine Vehicles (ICEVs), and used the same methodology as the GreenCharge study in 2014 (Fig. 1), but without Life Cycle Costing (LCC). The study then discusses how a development of BEVs and HFCEVs could follow a sustainable development that contributes to European (road) transport targets [7]:

- 60% reduction of transport emissions.
- No conventional fuelled cars within cities by 2050 and 50% reduction by 2030.
- A 50% shift of medium distance intercity passenger and freight journeys from road to rail and waterborne transport by 2050, and 30% by 2030.

EU has also set a target for renewably sourced energy to at least 55% by 2050, which includes an increase of renewable electricity to 64-95% [20]. This will, for example, guide the share of renewable electricity for EV charging and production of hydrogen in Europe.

This study had these main system boundaries and assumptions:

- Europe as a geographical area set the energy system boundary.
- EV represents vehicles with electric driveline including different combinations of onboard energy storages, such as batteries or fuel cells.
- Focus on energy carriers and driveline technology that differ from each other.
- Electricity for BEV-charging and hydrogen production are based on wind power generated electricity and current EU-27 electricity mix in Europe, meanwhile the 2050-scenario are based on EU energy targets for 2050.
- Vehicles and electricity are produced in Europe, but subsystems, such as motors, batteries, fuel cells, along with fossil fuels and hydrogen, might be produced elsewhere.

II. Methods

A. Strategic Life Cycle Approach towards Sustainability

With the sustainability principles (Section I-B) in focus, the GreenCharge research study from 2014 [4] about energy carriers for public transport buses in southeast of Sweden used an iterative Strategic Life Cycle Approach from the tools level of FSSD. This approach started with a Strategic Life Cycle Assessment (SLCA) [21], [22] that identified the most important high-level sustainability challenges within each life cycle phase in order to guide necessary decisions and activities. Then, if needed, complementary analyses were suggested, such as LCA [23], and/or LCC as illustrated in Fig. 1. The focus in this study, though, is on SLCA and LCA, and LCC is excluded.

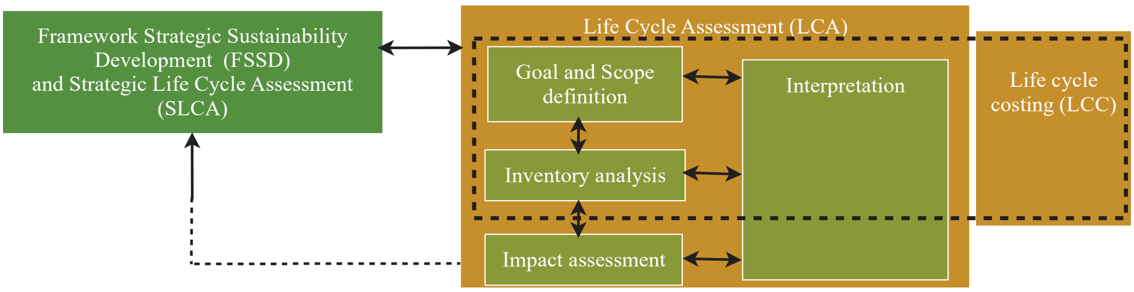

Fig. 1 The GreenCharge Iterative Strategic Life Cycle Approach that Uses SLCA to Scope an Integrated LCA and LCC analysis [4]

B. Strategic Life Cycle Assessments for Road Vehicles

The SLCA in this study compared ICEVs with vehicles that had an electric driveline with batteries powered by, or fuel cells produced with, wind-generated electricity. The results displayed in a table format could within each life cycle contain more than one reason for violation of each SP, and further described in text format and could result in a breakdown of activities included in each life cycle phase. The color-coding contained a scale from 'neutral' to 'slightly negative' and 'negative' to indicate the magnitude of the effect from each violation. The LCA verified some of the results in SLCA by partially quantifying identified 'hot-spots' in different life cycle phases. This study identified these most important links between SLCA and LCA for cars by using ReCiPe (H) mid- and endpoint (v1.08) environmental impacts categories.

C. Life Cycle Assessments for Cars

Life Cycle Assessment (LCA) is in this study used to quantify the environmental impacts by ICEVs, Plug-In Hybrid Electric Vehicles (PHEVs), BEVs, HFCEVs, and has followed the ISO standard 14040 [23].

1. Prerequisites for the LCA

The LCA within this study was designed this way:

- The LCA software SimaPro 8.05 with the Ecoinvent 3 database was used to compare current environmental impacts of cars, with a focus on strategic sustainability indicators and climate change. An independent LCA consultancy [24] has verified the LCA model and results.
- The functional unit was travelled car kilometers.
- The total travelled distance for the cars were 150000 km.
- The cars were modeled to be comparable by size. ICEV cars weigh about 1200 kg (i.e. VW Golf), while PHEV cars (i.e. VW Golf GTE and Toyota Prius) and BEV cars (i.e. Nissan Leaf) weigh about 1500 kg.
- The cars could be produced worldwide, but used and scrapped in Europe.
- All cars met the Euro 5 emission limits.
- The PHEVs were modeled as ICEVs with an extra electric drivetrain and battery that allows 25-50 km ranges on only electricity. The share of fuel consumption and electricity use were defined by the European NEDC test cycle and collected from vehicle data [25], [26].
- The European Recycling Directive [27] states that 95% of the car (in weight) shall be recycled. The disposal scenario therefore assumed that 5% of the car (in weight) is disposed as landfill. The disposal scenario in SimaPro and Ecoinvent 3 for passenger cars has been used for ICEVs, and the battery disposal scenario together with the electric drivetrain has replaced the engine disposal scenario for BEVs, and it has been added for PHEVs.
- The results were divided into environmental effect categories according to the ReCiPe method [28] version 1.08 for environmental impact assessment.
- The uncertainty analysis was done via 1000 Monte Carlo runs in SimaPro and used 95% confidence interval.

2. LCA Process Description

The LCA study started with a comparative LCA where ICEVs powered by Biogas, Petrol and E85 (ethanol 85% and Petrol 15%), PHEV type 'Golf GTE' powered by wind-generated electricity, and BEVs powered by EU-27 electricity mix and wind-generated electricity were analyzed for each environmental impact category. A HFCEV car model was not found in SimaPro and could not be modeled for this study due to time restrictions. A comparison was instead made with data gathered from another study [11] that compared HFCEVs and BEVs via the environmental impact assessment CML2000 method. In that study, the HFCEVs were powered by hydrogen from electrolyzed wind-generated electricity. Moreover, a third analysis clarified in which of the life-cycle phases ('Extraction to Distribution', 'Use' or 'Disposal') the environmental impacts had occurred. That analysis also included ICEVs powered by CNG, Diesel, and a PHEV type 'Prius' powered by wind-generated electricity, and a BEV powered by Swedish electricity mix, to include more commonly used vehicles. As the electricity grid in Sweden is connected to the European electricity grid, the BEV powered by Swedish electricity mix includes a small share of marginal electricity that is produced in Europe. An uncertainty analysis was also performed for this third life cycle phase study. The uncertainty results were aggregated for all three phases.

III. Results

A. Strategic Life Cycle Assessment of Current ICEV, BEV, and HFCEV Systems

The Strategic Life Cycle Assessment (SLCA) revealed sustainability implications of today's situation with Internal Combustion Engine Vehicles (ICEVs), Battery Electric Vehicles (BEVs) and Hydrogen Fuel Cell Electric Vehicles (HFCEVs). The results were divided into sections for each sustainability principle (SP) and the main identified SP effects were commented on in the tables and the text.

1. Assessment against Sustainability Principle 1

As displayed in Table I, SP1 is violated when substances like heavy metals are extracted from the earth's lithosphere and spread at a rate that increase their concentrations in the biosphere. This is also valid for fossil fuels needed for combustion in vehicles and energy production in many life cycle phases for this study. This creates a lot of local and global emissions that, for example, increase global warming, acidification, eutrophication, ozone depletion, and particulate matters [4], [29]. Emissions from fossil fuel vehicles are slightly different in the use phase since the regulations are different for working equipment and factories than for road vehicles, but the emissions still violate SP1 since they increase in the biosphere. An EV driveline, on the other hand, contains fewer components and subsystems than an ICEV driveline and uses much less oil in the motoring concept. Still, electricity and hydrogen produced from fossil resources, which are the most common production method today, violates SP1 in both 'Extraction' and 'Production'.

2. Assessment against Sustainability Principle 2

As displayed in Table II, violation of SP2 primarily occurs when burning fossil fuels causing emissions of NO_X, as Nitrogen stems from the air. NO_X emissions from both combustion in vehicles and production of energy contribute to Acidification and Eutrophication [4], [29]. There might also be other man-made compounds that violate SP2 involved in the numerous life cycles of the compared energy carriers.

TABLE I
SP1 STRATEGIC LIFE CYCLE ASSESSMENT COMPARING CURRENT ALTERNATIVE VEHICLE SYSTEMS

Life cycle phase	SP1 effects by ICEV powered by fossil fuels	SP1 effects by BEV powered by wind-generated electricity	SP1 effects by HFCEV powered by hydrogen produced from renewable fuels and wind electricity
Extraction	Emissions from fossil fuel usage. Heavy metals in components and processes. Oil leakages, gas flaring.	Emissions from fossil fuel usage. Heavy metals in components and processes.	Emissions from fossil fuel usage. Heavy metals in components and processes.
Production	Emissions from fossil fuel usage. Heavy metals for components and production. Oil leakages, gas flaring.	Emissions from fossil fuel usage. Heavy metals for components and production. Less components in the driveline*	Small emissions from fossil fuel usage. Heavy metals for components and production. Less components in the driveline*
Distribution	Emissions from truck transports of infrastructure systems, vehicles, and transport of fuel	Emissions from truck transports of infrastructure systems and vehicles.	Emissions from truck transports of infrastructure systems, vehicles, and transport of fuel
Use	Heavy metals in maintenance. Emissions from maintenance transport. Combustion emissions. Fuel leaks at accidents.	Heavy metals in maintenance. Emissions from maintenance transport.	Heavy metals in maintenance. Emissions from maintenance transport.
Waste	No full recycling of heavy metals and other materials related to SP1	No full recycling of heavy metals and other materials related to SP1	No full recycling of heavy metals and other materials related to SP1

*A contribution to sustainable development Legend: Negative Slightly Negative Neutral

TABLE II
SP2 STRATEGIC LIFE CYCLE ASSESSMENT COMPARING CURRENT ALTERNATIVE VEHICLE SYSTEMS

Life cycle phase	SP2 effects by ICEV powered by fossil fuels	SP2 effects by BEV powered by wind-generated electricity	SP2 effects by HFCEV powered by hydrogen produced from renewable fuels and wind electricity
Extraction	NO_X emissions from combustion.	NO_X emissions from combustion.	NO_X emissions from combustion.
Production	NO_X emissions from combustion. POP and Dioxin emissions.	NO_X emissions from combustion. POP and Dioxin emissions.	NO_X emissions from combustion. POP and Dioxin emissions.
Distribution	NO_X emissions from truck transports of infrastructure systems and vehicles.	NO_X emissions from truck transports of infrastructure systems and vehicles.	NO_X emissions from truck transports of infrastructure systems and vehicles.
Use	NO_X emissions from truck transports of infrastructure systems and maintenance vehicles. NO_X emissions from the vehicle's engine.	NO_X emissions from truck transports of infrastructure systems and vehicles.	NO_X emissions from truck transports of infrastructure systems and vehicles.
Waste	No full recycling of compounds related to SP2	No full recycling of compounds related to SP2	No full recycling of compounds related to SP2

Legend: Negative Slightly Negative Neutral

3. Assessment against Sustainability Principle 3

Surface extraction, e.g. open pit mining, is a violation of SP3 if it leads to a systematic degradation of nature by physical means (Table III). The open pit mining might also lead to extinction of species or natural habitats. Mining also leads to leakages of hazardous compounds to nature, potentially destroying soil and ground water, especially by using tailing ponds for waste treatment. SP3 implies that over-harvesting, mismanagement, displacement, or other forms of physical manipulation must not systematically degrade natural systems. Infrastructure for distribution of fossil fuels via pipelines and electricity via power grids prevents use of productive surfaces. Some non-recycled materials contribute to the increase of landfills.

TABLE III
SP3 STRATEGIC LIFE CYCLE ASSESSMENT COMPARING CURRENT ALTERNATIVE VEHICLE SYSTEMS

Life cycle phase	SP3 effects by ICEV powered by fossil fuels	SP3 effects by BEV powered by wind-generated electricity	SP3 effects by HFCEV powered by hydrogen produced from renewable fuels and wind electricity
Extraction	Open pit mining of oil, metals and other resources	Open pit mining of metals for batteries and other resources	Open pit mining of metals for fuel cells and other resources
Production	Contamination of ground at refineries		
Distribution	Land use for roads and pipelines. Some contamination of ground at accidents.	Land use for roads and power grids.	Land use for roads and pipelines
Use	Land use for roads	Land use for roads	Land use for roads
Waste	Non-recycled materials to landfill	Non-recycled materials to landfill	Non-recycled materials to landfill

Legend: Negative Slightly Negative Neutral

4. Assessment against Sustainability Principle 4

Many conflicts are rooted in the control of natural resources such as oil. Effects of these conflicts prevent some people (e.g. that are wounded, having their property destroyed, or become refugees) from meeting their basic human needs. As displayed in Table IV, another implication is the scarce metal recovery in some countries that exposes people, animals and nature to hazardous materials and emissions [30]. SP4 is violated when fossil fuels from the earth's lithosphere are extracted as they might be limiting, at least within a century and maybe even sooner [31], and therefore might not be available for future generations, Lithium in batteries can be seen as a scarce metal [32], [33], and a study from 2012 [34] concluded that "*The presently known lithium resources excluding the ocean will only be exhausted this century if large scale use of predominantly BEV sized batteries comes into play, or if batteries are not recycled.*". Platinum used in fuel cells (and catalytic converters) is even more scarce, and a study in 2013 [35] concluded that "*…the introduction of FCVs may lead to a faster depletion of platinum resources, although even without their introduction these resources are expected to deplete before the end of the century.*". Another scarce metal in vehicles is Copper [36].

The increased demand for renewable and locally produced energy in Europe and also local recycling facilities for EV drivetrains can increase the job market in Europe [20]. This could increase the possibilities for today's poor people without a job to get one and increase their chances to meet their basic human needs.

TABLE IV
SP4 Strategic Life Cycle Assessment Comparing Current Alternative Vehicle Systems

Life cycle phase	SP4 effects by ICEV powered by fossil fuels	SP4 effects by BEV powered by wind-generated electricity	SP4 effects by HFCEV powered by hydrogen produced from renewable fuels and wind electricity
Extraction	Use of scarce resources as Platinum. Open pit mining causes negative health effects and forces people to move.	Use of scarce resources as Lithium. Open pit mining causes negative health effects and forces people to move.	Use of scarce resources as Platinum. Open pit mining causes negative health effects and forces people to move.
Production	Negative health effects from emissions related to fossil fuel use and vehicle production. Harmful job conditions at some sub-suppliers.	Negative health effects from emissions related to vehicle production. Harmful job conditions at some sub-suppliers.	Negative health effects from emissions related to vehicle production. Harmful job conditions at some sub-suppliers.
Distribution	Health effects from transport emissions.	Health effects from transport emissions.	Health effects from transport emissions.
Use	Negative health effects from emissions related to fossil fuel use	Negative health effects from emissions related to fossil fuel use during maintenance.	Negative health effects from emissions related to fossil fuel use during maintenance.
Waste	Harmful working conditions in some countries.	Harmful working conditions in some countries. Can create local job opportunities*	Harmful working conditions in some countries. Can create local job opportunities*

*A contribution to sustainable development   Legend: Negative | Slightly Negative | Neutral

B. Indicators Linking Ecological Sustainability and Life Cycle Analysis

The strategic life cycle assessment revealed particular sustainability challenges that here will be linked to indicators that are quantifiable in LCA.

For **SP1-2**, systematic increasing concentrations in nature of substances links to environmental effect categories:

- Combustion of fossil fuels increases CO_2 emissions, which links to 'Climate Change' and 'Fossil depletion'.
- Non-recycling of heavy metals such as Lead, Cobalt, Nickel, Mercury, etc, links to 'Metal depletion' category.
- Combustion of Sulphur in fossil fuels creates SO_2 emissions, which links to 'Acidification' and 'Particulate Matter' categories.
- Use of Phosphates for fertilization links to 'Eutrophication' category.
- Combustion of air and fuels creates NO_X emissions, which links to 'Acidification', 'Eutrophication', 'Particulate matter' and 'Photochemical oxidants'.
- Release of toxic substances such as POP and Dioxins links to 'Ecotoxicity'- and 'Human toxicity' categories.

For **SP3**, systematic degradation of nature by physical means, such as open pit mining, landfills and slash-and-burn, links to 'Land use' categories.

SP4 defines social sustainability and is violated when people are systematically hindered to meet their basic human needs. Typical examples are the use of scarce resources such as fossil oil, Lithium and Platinum and these links to depletion effect categories. Negative health effects, exemplified by emissions from combustion of fuels and radiation exposure links to 'Human toxicity' and 'Ionizing Radiation'.

All of the impact categories in LCA have thereby linkage to the SPs and could quantify parts of the SLCA in this study.

C. Life Cycle Assessment of ICEV, BEV, and HFCEV Cars

This study made a Life Cycle Analysis that resulted in a comparison of environmental impacts by ICEV, PHEV and BEV cars, and revealed that (Fig. 2):

– ICEV cars powered by biogas and E85 have about 50% less climate change impact, and overall less (but not for all categories) environmental impact than petrol cars,
– PHEV cars have 30% higher climate change impact, and overall higher environmental impact than BEV cars powered by electricity from the EU-27 grid,
– BEV cars powered by electricity from EU-27 electricity grid have less life cycle climate change impact, and overall less life cycle environmental impact than ICEV cars powered by petrol, and
– BEV cars powered by electricity from the EU-27 grid have 50% higher climate change impact and overall higher life cycle environmental impact than BEVs powered by electricity generated from wind turbines.

According to Fig. 3 and [11], a HFCEV car has less life cycle environmental impact in five out of ten impact categories than a BEV powered by wind-generated electricity. However, the BEV has about 30% less climate change impact.

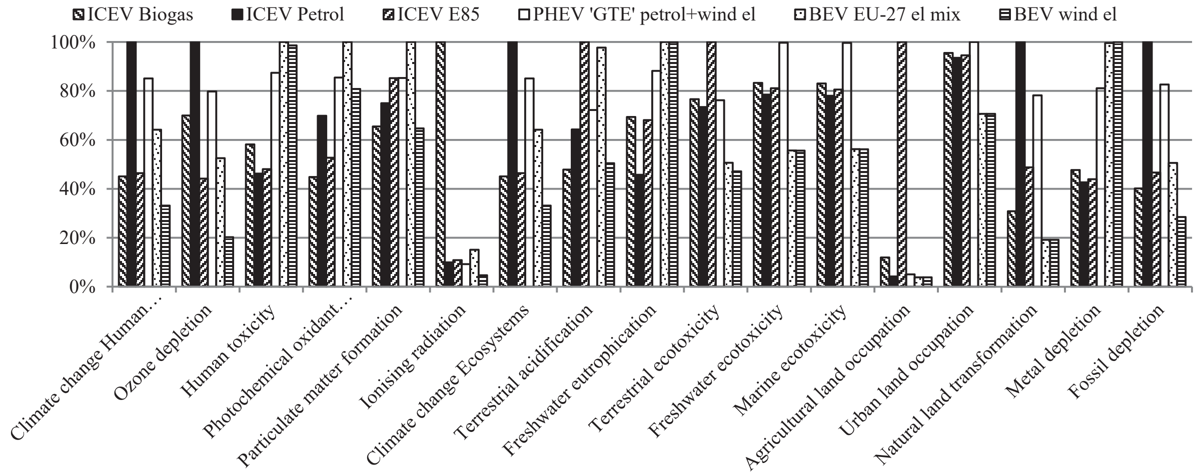

Fig. 2 Life Cycle environmental impacts of ICEV, PHEV and BEV cars by ReCiPe endpoint (H) v1.12 characterization

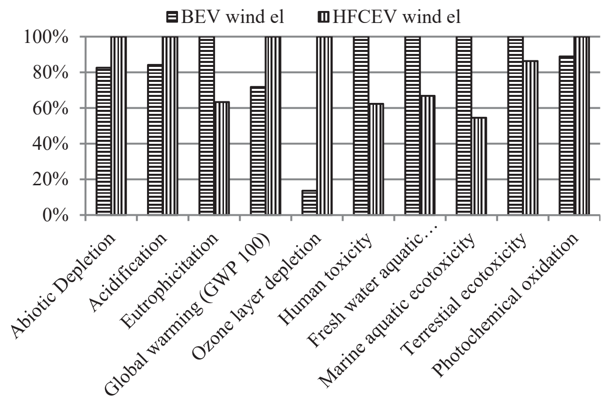

Fig. 3 Life Cycle environmental impacts of BEV and HFCEV cars by CML2000 characterization. Developed from [11]

More detailed patterns emerge when grouping the life cycles phases into Extraction-to-Distribution (E-D), Use, and Disposal (Fig. 4). For climate change, this includes that:

- Contrary to impacts for cars powered mostly by fossil fuels, most impacts occurs in the E-D phase for BEVs powered by wind-generated electricity or Swedish electricity mix. The production of energy carriers is included in the use phase, giving higher impact on 'Natural Land Occupation' for BEVs powered by wind-generated electricity than for BEVs powered by the Swedish electricity mix.
- The PHEVs have high impacts in the use phase, assuming an electric drive share from 21-45%, in line with the NEDC drive cycle [25], [26]. This could be lowered down to BEV levels by a larger electricity share.
- The E-D phase impacts are similar for BEVs, PHEVs, and ICEVs, because all vehicles are similar. BEVs has about 20% higher impacts than for ICEVs in the E-D phase.
- A deeper analysis of the results shows that the production of battery represents about 12% and the powertrain about 14% of the BEV impacts.
- The uncertainty analysis (and Fig. 4) showed that 95% of the included results are close to the mean value, with a standard deviation between 8 and 15.

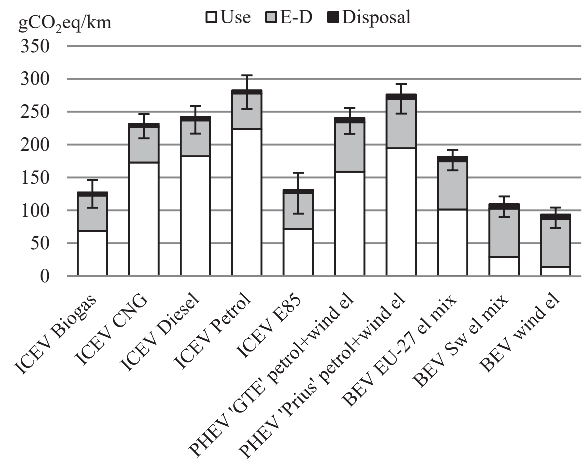

Fig. 4 Climate Change impact from different cars life cycle phases 'Extraction to Distribution' (E-D), 'Use', and 'Disposal' within the 95% confidence interval, according to ReCiPe midpoint (H) v1.12

D.Key Improvements for BEV and HFCEV towards 2050 and a Sustainable Future

Research within the GreenCharge project has suggested a vision for EV systems in a sustainable society, which could be applied for any region or even the whole European Union [37]. This vision complies with the SPs and includes technologies like smart electric grids, BEVs and HFCEVs, but also flexible use of other future sustainable energy carriers, renewably sourced electricity and fuels (e.g. hydrogen), and renewable and recycled resources. In line with that vision, the Strategic Life Cycle Assessment results on the current situation for ICEV, BEV and HFCEV indicate some current main sustainability challenges for EVs:

i. Use of scarce metals in batteries and fuel cells.
ii. Emissions and leakages from mining of materials.

iii. The share of fossil fuels in the energy mix for production and distribution of motoring systems and energy carriers.

These and the other identified sustainability challenges and violations (Section III-A) have to be dealt with in order to reach towards sustainable EV systems within Europe.

1. Energy for Sustainable Development of EV Systems

It is preferable from a sustainability point of view that all energy for electric drivelines, and production of these, as well as the energy carriers, are produced from flow-based resources such as wind, sun, geothermal, waves, and running water. These also need to be managed in a sustainable manner. The EU goals for 2050 do not fully meet these requirements, but are in line with such development and some organizations claims that it is possible to at least reach the sustainability requirements for energy [6]. By that year, renewable fuels, such as biodiesel, could replace the extensive use of fossil fuels for mining equipment. There is also a great possibility to introduce an electric driveline that uses fuel cell technologies, in line with EV-solutions for trucks.

2. Batteries for Sustainable Development of EV Systems

Recycling of batteries is today possible to 80%, and that could solve the Lithium scarcity for this century if it will be made mandatory to recycle batteries before 2050, while assuming that battery capacity in each BEV is about 35kWh [34]. That battery capacity would allow an average electric car (e.g. Nissan Leaf) of today to range 20-30 km. Recycling would also reduce the need for mined materials.

3. Fuel Cells for Sustainable Development of EV Systems

Platinum is possible to recycle at about the same rate as Lithium in batteries. Although Lithium reserves might be sustained by thorough recycling of batteries, the use of Platinum in fuel cells eventually has to be substituted by other materials to maintain a stable supply for other purposes than energy storage in vehicles [35], [38]. Today's SP1 violations for hydrogen could be neutralized if future production would stem from more sustainable resources, e.g. water and sunlight.

IV. Discussion

A. Main Message

This comparative strategic sustainability study used Strategic Life Cycle Assessment (SLCA) and Life Cycle Assessment (LCA) to analyze sustainability effects and quantify environmental impacts in each life cycle phase for road vehicles in Europe today, and in a future scenario derived from current EU goals for 2050. The study compared Internal Combustion Engine Vehicles (ICEV) powered by fossil fuel, and Electric Vehicles (EVs) powered by batteries or hydrogen fuel cells. The study found that:

– EVs powered by battery or fuel cells have less sustainability violations than ICEVs powered by fossil fuels
– current main sustainability violations by EVs are (i) the use of scarce metals in batteries and fuel cells, (ii) emissions and leakages from mining and of materials, (iii) the share of fossil fuels in the energy mix for production and distribution of motoring systems and energy carriers
– possibilities for a sustainable development of EVs depend on the development of some main sustainability implications (i-iii). Violation (i) can be reduced due to increased recycling of batteries, but platinum has to be replaced in fuel cells. Violation (ii) can be reduced if recycling is developed for all substances violating the SPs, and when mining and transport are powered by fossil-free energy. Violation (iii) can be reduced if the EU 2050 energy goals will be fulfilled, but hydrogen still needs to be produced from renewable sources.

B. Critical Assessment

The study is moderate about possible future technological changes, and the results can be inaccurate if the future vehicles or production of energy carriers will be very different.

Only cars have been analyzed in the LCA, but based on the results in previous studies [4], the results for buses and trucks are not expected to make any big differences for the conclusions of the study.

The LCA does not account for future marginal electricity, which likely will have a more positive effect regarding electricity supply for EVs, as the marginal electricity of today that is based on fossil fuels is likely to be phased out. However, the expected sustainability improvement of marginal electricity is covered in the projection towards 2050 and a sustainable future (Section III-D).

Results from LCA could have been analyzed in more detail to discover the amount of use of certain rare metals like Lithium and Platinum, but the authors suggest that would not have changed the conclusions of this study.

Technologies to capture or eliminate emissions from ICEVs or blending in a great share of renewable fuel could be favorable to a sustainable development of ICEVs, but the study results point towards that such measures would rather decrease the sustainability related impacts with ICEVs than fade them out.

C. Comparison with Other Studies

Previous GreenCharge research studies have mapped sustainability effects caused by bus and car transport through SLCA. The study from 2013 about energy carriers for buses [4] included also an LCA. The Business Model study for cars [4], [14], mapped costs and CO2 emissions over the lifecycle but did not contain a full LCA, nor any data for HFCEVs. As a contrast, this new study provides a broader perspective by including all road vehicles in the SLCA and an up-to-date LCA analysis with low uncertainty including the whole car.

Several other LCA studies have included BEVs with different sourced electricity, and a few have also included HFCEVs [9]-[12], [39]. The results of these studies are comparable to LCA results in this study, and the differences are related to prerequisites and assumptions. For example, Reis and colleagues [10] have used a well-to-wheel approach that traditionally excludes for example the production of vehicles and the disposal phase, which gives much lower impact than the LCA within this study. Another example is the study by Bartolozzi and colleagues [11] that provided this study with information about HFCEVs based on CML2000 environmental impact assessment, instead of the ReCiPe methodology that has been used in this study. None of the LCA studies [9]-[12], [39] has, like this new study, been done from a strategic sustainability perspective with an SLCA. This means that this new study reduces the risk for making sub-optimizations that might create problems for other societal sectors or people outside the EU.

D. Conclusions and Further Work

This study identified sustainability effects and quantified environmental impacts from current road vehicles, and projected how battery and hydrogen fuel cell EVs can contribute towards EU goals for 2050 and a sustainable future. Except for being adopted in the upcoming GreenCharge roadmap for fossil free personal road transport, the authors suggest that the results can contribute to planning in the upcoming decades for a sustainable increase in numbers of EVs in Europe, and potentially serve as an inspiration for other smaller or larger regions.

Further studies could map the environmental effects in LCA more systematically with the latest advances of the principles for social sustainability. Such thorough LCA mapping could also include other road vehicles to get a more precise perception of their effect on sustainable development.

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