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Life Cycle Assessment of Electric Vehicles – The Influence of Regional Aspects and Future Renewable Energy Targets

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Summary

Electric vehicles are seen as a promising strategy to achieve a significant reduction in road transport originated emissions. The environmental performance of electric vehicles depends on multiple parameters. Together with the production of the battery system, the impact generated from the electricity generation is one the most significant drivers of the ecological footprint of an electric vehicle. Auxiliary systems like heating and air conditioning, which are directly related to the ambient temperature, significantly affect the energy consumed by the vehicle in the use phase. Parallel to the rise of incentives to foster the market development, most countries strive towards increasing the share of renewable energy sources in their electricity mix. This paper presents a concept to consider the influence of regional ambient temperature and electricity mixes in life cycle assessment (LCA) and visualizes the potential environmental impact of electric vehicles (EV). Additionally, the implementation of future renewable energy targets into the environmental assessment is considered. The results are presented in LCA world maps, enabling a comparison of the regions where EV or conventional internal combustion engine vehicles (ICEV) perform environmentally better. The LCA world maps are presented for the current and the year of 2030 situation.

Keywords: environment, emissions, EV (electric vehicle), LCA (Life Cycle Assessment), renewable

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1 Introduction

Transportation is responsible for 22% of the global anthropogenic greenhouse gas emissions, 75% of which is caused by the road transportation sector [1]. A widespread penetration of electric vehicles is expected to decrease the transport related emissions. Many countries are adopting e-mobility as their strategy and setting policies and incentives in order to enhance the deployment of EV [2]. The environmental impact of EV in the use phase correlates to the energy consumption. The energy consumption depends on the user behavior and local influencing factors. Unlike the conventional internal combustion engine vehicles (ICEV), EV can not utilize waste heat to heat the vehicle cabinet. Hence in addition to the energy demand of drive train that runs the vehicle, auxiliary energy demand used for heating and cooling systems can have a considerable impact on total energy demand. The intensity of auxiliary systems use is closely influenced by the ambient temperature and user behavior. In addition, the generation of electricity used to charge the battery has an important influence on the overall results. Depending on the electricity sources (e.g. renewable or non-renewable); the environmental performance of EV may vary drastically [3], [4]. Therefore, regional aspects such as local climate and electricity mix should be considered for a robust environmental evaluation of EV.

In addition to the e-mobility targets, countries are setting renewable energy targets in order to reduce their emissions [5]. Increasing the share of renewables in electricity generation may provide a momentum to the emission reduction potential of e-mobility. The energy and mobility policies are strongly linked to each other since the electricity is a key issue in the entire life cycle of EV. Figure 1 summarizes the relationship between regional, technosphere and policy levels. Regional level expresses the parameters to consider in LCA of EV in a local context. Technosphere level shows the life cycle stages of EV, where policy level shows mobility and energy policies in relation to the life cycle stages of EV. These interdependencies require a stringent synchronization to achieve a successful implementation strategy. To provide a holistic understanding of these interdependencies the paper addresses the following questions: i) Do EV perform environmentally better than ICEV under each regional context? ii) Are the future renewable energy targets realistic enough to make EV advantageous all over the world? iii) How can the environmental trade-offs be visualized, so that the decision makers perceive the correct messages?

The paper uses the LCA methodology to assess the environmental impacts of EV. Although LCA is a widely adopted methodology for environmental assessment of product and production systems, it is criticized not to reflect the influence of regional aspects [6]. A concept is introduced that integrates local climate conditions, local electricity mixes as well as a technique for modeling the future electricity inventories. Advanced visualization techniques, which is a vital part of the presented concept, aims to achieve an understanding of the results from a systems perspective and derive policies for future vehicle engineering.

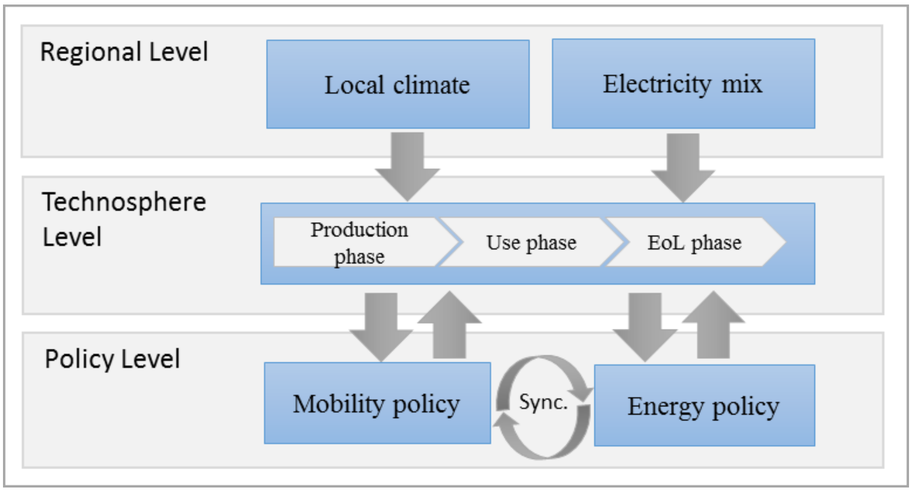

Figure 1: Interactions between different information levels

2 Life Cycle Assessment of Electric Vehicles and the Effect of Regional Ambient Temperatures

The growing interest in EV is driven by the general hypothesis that EV bring important opportunities to reduce the environmental impact of the transportation sector. The environmental impact assessment of EV requires a careful study since the life cycle stages are influenced by a large set of factors. Egede and the colleagues highlight the influencing aspects which have to be considered in an LCA of electric vehicles [7] and similarly Faria and the colleagues discuss the impact of user behavior and the electricity mix on the results [8]. Research from Hawkins and colleagues [9] presents an exhaustive review of the literature available on the LCA for electric vehicles. As they conclude, most of the life cycle inventories for the production phase of EV in the literature lack transparency. In addition, they argue that the assumptions done regarding the modeling of electricity mix, driving patterns, and end of life scenarios are often inconsistent or not appropriate, which makes it difficult to compare the environmental effects of EV compared to those of ICEV. In their research, they propose a system boundary in order to perform the environmental assessments of EV. Their system boundary considers the complete production processes of the EV including components, as well as the material extraction stages. For the use phase, the authors suggest that the driving and charging patterns should be considered, as well as the vehicle's maintenance and the replacement of parts. The generation of energy together with the consideration of specific infrastructure required are also included within their analysis framework. However, their study does not point out local climate aspects as an important issue to consider in the use phase of an electric vehicle. A similar framework was proposed within the guidelines for the evaluation of environmental impacts of electric vehicles (eLCAr Project) [10]. The eLCAr guidelines provide recommendations on how to proceed with the application of the LCA methodology for the analysis of EV. Complementary to the similar frameworks available to evaluate the impact of EVs, the eLCAr guidelines include guidelines to consider the effects of local climate on the energy consumption of electric vehicles. The research from Nealer and colleagues [11] presents as well a review of recent LCA studies for EV. The review looks at the most sensitive assumptions done within the considered studies. Regarding the analysis of the use phase, four groups of assumptions are identified: i) vehicle lifetime, ii) driving behavior, iii) electricity generation and iv) vehicle weight. In general, the research on LCA for EV is focused on the development of transparent and complete life cycle inventories for the production phase of the vehicle and its components. In this regard, research from Hawkins and colleagues [12] and Del Duce and colleagues [13] present detailed inventories for the production phase of the vehicle. Majeau-Bettez and colleagues [14], Ellingsen and colleagues [15] and Dunn and colleagues [16] present detailed inventories for the production of the traction batteries. The approach from Sullivan and colleagues [17] proposes a model to estimate life cycle inventories for the production of parts and components of the vehicles. Although not exhaustively analyzed, the effect of ambient temperature is also identified as an important aspect to be considered when analyzing the environmental effects of EV. Regarding this matter, Horrein and colleagues [18] developed a model to estimate the impact of cabin heating on the range of an electric vehicle using a real driving cycle. In their research, they find that the electrical range of an EV can be reduced by a 30% due to the heating system. Kambly and colleagues [19] propose a model to estimate the energy consumption of the Heating, Ventilating and Air Conditioning (HVAC) system of an EV. Their model considers local weather, solar loads, driving behavior and an estimation of the regional passenger fleet population in the U.S.. Further research from Kambly and colleagues [20] applies the model developed to estimate how the range of an EV differs depending on the time of the day in which the trip takes place and the location. As an example, they estimate losses in the electric range of around 23% for the case of Arizona. Egede [4] presents a concept for the evaluation of environmental impacts arisen from the use phase of an EV which integrates use patterns and regional patterns such as climate and the local electricity mix. The effect on range reduction to the life cycle environmental impacts of the vehicle is not considered. A similar approach is followed by Yuksel and Michalek [21]. In their research, they characterize the energy consumption of an EV considering local climate for many regions in the U.S.. Additionally, they consider local electricity mixes based on marginal emissions factors estimated for all of the eight National American Electric Reliability Corporation (NERC) regions. As an example, they find out that the spectrum of the CO_2-equivalence emissions per kilometer ranges between approximately 65 g/km and 210 g/km.

3 Concept for Environmental Assessment of Electric Vehicles

Life Cycle Assessment (LCA) is a method that accounts for the energy, the resources consumed, and the emissions produced by a product system throughout its entire life. LCA is adopted to compare the environmental impacts of electric and conventional vehicles; however, reflecting the influence of regional aspects (such as climate or local electricity mix) or the prospective analysis (the influence of the increasing share of renewables in electricity generation) may be challenging in LCA method. Egede [4] presents an approach to consider regional and user related factors. The proposed concept adopts Egede's approach and combines it with country specific regional energy targets and local electricity inventories in order to reflect the situation in the future. Therefore, it enables to assess the environmental performance of EV on a regional level (consideration of climate and local electricity mixes). Besides regional aspects, the influence of future renewable energy targets on a country level is also considered for a comparison of EV with ICEV.

3.1 Methodology

Use patterns (when and how the vehicle is used), regional aspects (local electricity mix, ambient temperature), and utilization of heating and cooling systems (related to the ambient temperature and use patterns) have a high impact on the overall environmental assessment of EV. The intensity of use of these auxiliaries has a direct influence on the total energy demand of EV. The methodology presented here calculates regional energy demand (considering auxiliary energy demand based on local ambient temperature and integrates it with country based electricity inventories. Figure 2 shows an overview how different aspects are linked into the LCA method.

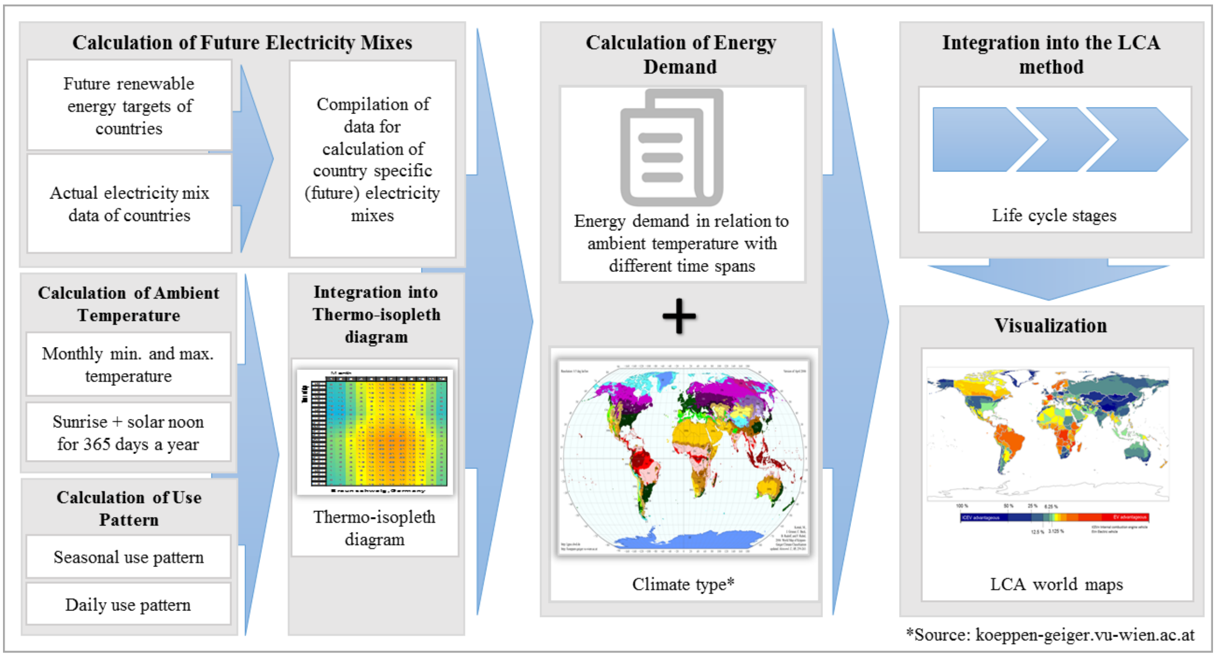

Figure 2: Approach to consider regional aspects and future renewable energy targets

Use patterns express how and when the vehicle is used. Journeys are defined according to driving purposes, like commuting daily to work or driving for business requirements such as delivery or maintenance. Seasonal patterns describe whether the vehicle is driven evenly each month or just in a specific period of the year. In the presented case, the scenario of a "commuter" with "even use" during the year as presented in [4] is adopted for the calculations. The "commuter" pattern includes two longer drives per day, to and from the workplace, one in the morning and one in the evening. The influence of varying user types is not discussed within this paper.

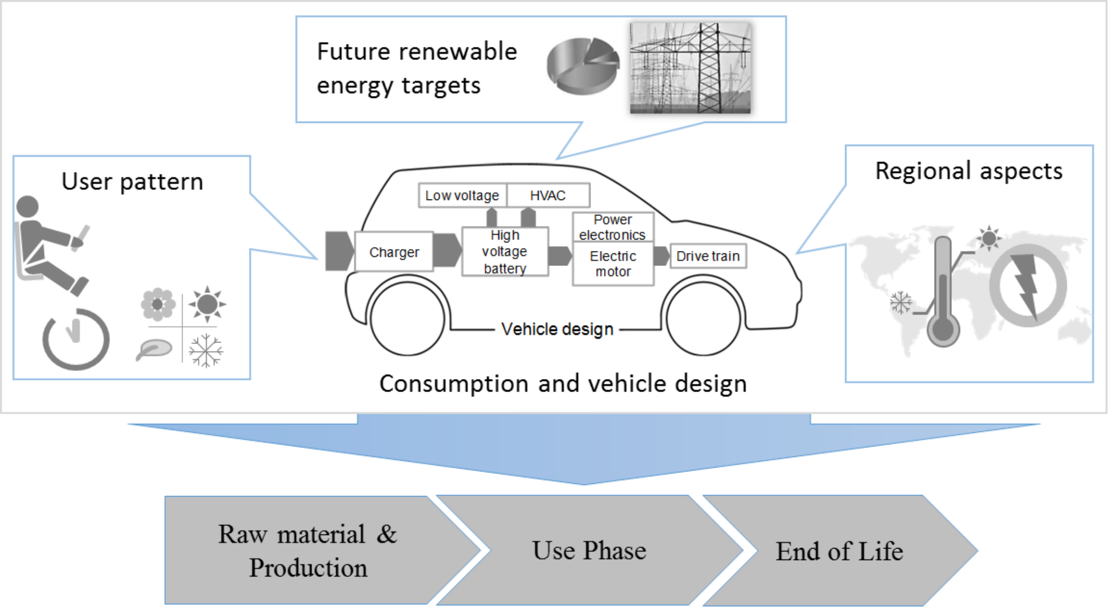

Figure 3: System description

Regional conditions build the basis for both the ambient temperature and the electricity mix. Climate categories and Thermo-isopleth diagrams are used together with the Köppen classification of climates [22]. Isopleth diagrams are created using the daily minimum and maximum temperatures and average time of sunrise and solar noon. The differences in the northern and southern hemisphere are also considered. The co-utilization of these methods enables us to link the ambient temperature with use patterns. Defining temperature values for each grid point that exist on the world map, the power demand for heating and cooling purposes according to eLCAr guidelines are calculated for each temperature range [23]. World Bank Data on electricity generation is adopted to find the country-specific electricity mixes [24]. Ecoinvent Database (Ecoinvent 3.1) is used to build the background system inventory [25]. The inventory data for the end-of-life (EoL) and production stages of electric and conventional vehicles (processes including the production of the vehicle, engine/motor, battery, and powertrain) are adopted from Hawkins et al. [12]. 150.000 km of total driving distance is assumed for the use phase energy demand calculations. A broad range of environmental impact categories is evaluated within the concept. Climate Change is displayed within the scope of this paper. Figure 3 displays an overview of system model as adopted from Egede [4].

3.2 Integration of renewable energy targets

As a further development of the concept presented in [4], an inventory modeling approach is developed to calculate the country specific future electricity mixes based on their future renewable energy targets. This approach enables to evaluate the impacts with the future electricity mixes and compare them with the current situation. The share of electricity generation from renewable energy sources and related targets, which are set by countries, is adopted as published in the REN21 Global Status Report [5] and the future renewable shares of country specific electricity mixes are calculated based on these target values. REN21 is a network comprised of 700 experts in the area of renewable energy, energy access, and energy efficiency. The report is the world most referenced report on the global renewable energy market. The report includes 92% of GDP, 95% of the world population and covers 148 countries. Figure 4 shows the decision tree used for the calculation of future electricity mixes.

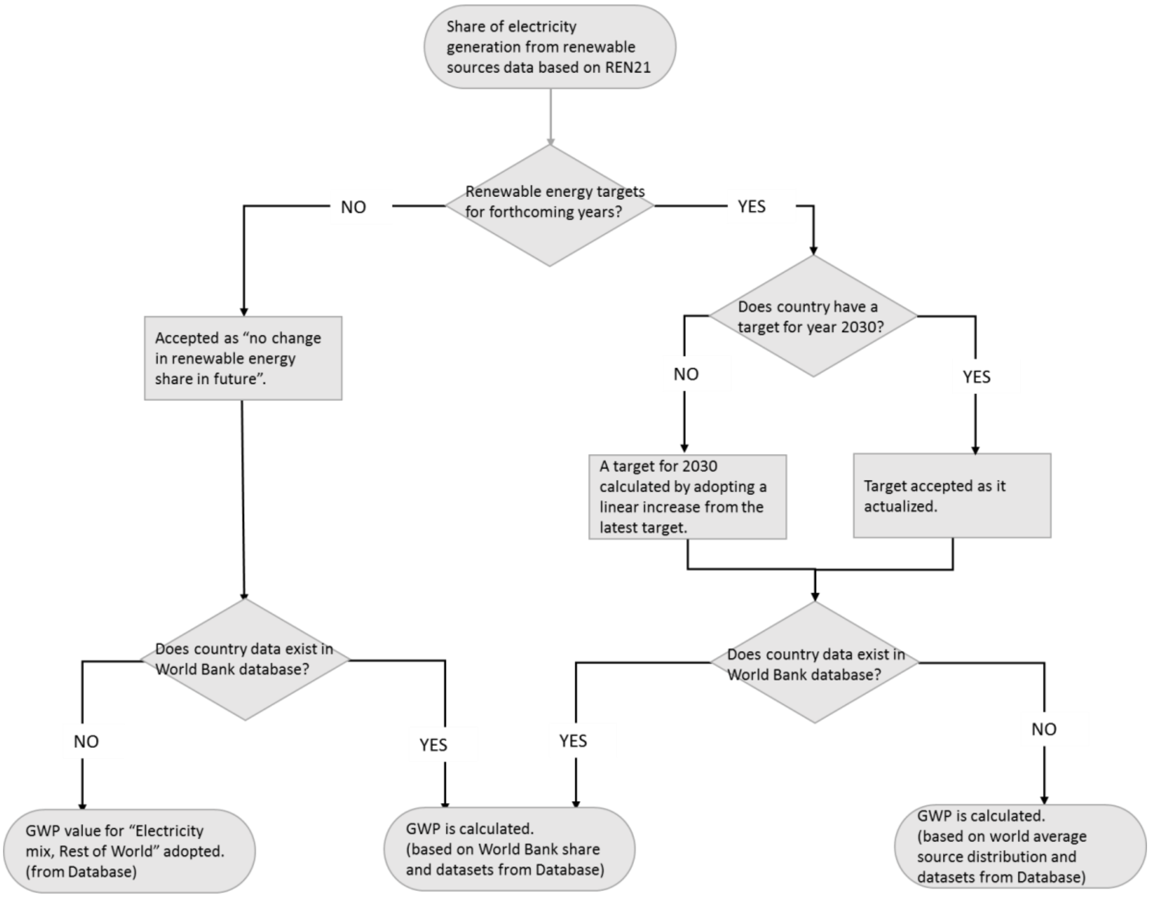

Figure 4: Decision tree for calculation of future electricity mixes

The REN21 report provides a list, expressing the share of electricity generation from renewable sources for countries with the actual shares and the target values. Depending on whether the country declares a target for forthcoming years, a decision tree is formed to calculate the future electricity shares (Figure 4). The countries declaration for the existing renewable shares (as declared in the REN21 report) is set as a starting point for calculation of the actual status (the year 2015). When a country does not declare any actual share, then data is accepted as in the World Bank databank. As many countries set a renewable energy target for 2030, this year is set for comparison with the actual values. The targets are taken as they are actualized for calculation of the future electricity mixes (the year 2030). If the country does not have a target value for 2030, but for another forthcoming year (2020, 2050 etc.), then the linear increase within target years are accepted and a renewable energy target interpolated or extrapolated in order to set a value for the year 2030. Just an exception for China and United States is made since they have investments through renewable energy but do not set any electricity share targets on a national level. The target share for the final energy from renewable sources (20%) is taken as electricity share target for China as given in the REN21 report. An average value of declared targets as in the report is calculated for the United States (35%) since there are targets only on states level but not on the national level. Electricity generation sources are taken as in World Bank database (the share of wind, solar, biomass or hydro in renewables or the share of coal, oil, nuclear in non-renewables) and no change in these ratios is considered. Adopting the World Bank ratios, Global Warming Potential (GWP) value -in kg CO_2 equivalent- per kWh is calculated with the Ecoinvent database [25]. In the next step, the country-specific future electricity shares are integrated with power demand for heating and cooling purposes. The environmental impacts with future renewable energy shares are then calculated and visualized. No future change in electricity mix is accepted for those countries, which do not have a renewable energy target. Similar to the other countries with target, electricity generation sources share are adopted from World Bank and the GWP is calculated based on these shares, using data sets from Ecoinvent. The “Ecoinvent - electricity mix, Rest of World” GWP dataset is used for the countries, which have no targets and are not listed in World Bank database.

The assumptions below are accepted during the calculation of the country-specific future electricity shares:

- If a country has no target, no change in electricity mixes is foreseen. For such countries, the GWP value based on World Bank share data is calculated utilizing Ecoinvent inventories for electricity generation.
- If a country has a target but no target year, this target is assumed to be reached in 2030.
- If a country has a target, but this target is below the actual share of renewables, the projection for 2030 equals the share of 2015.
- If a country set a target, but electricity generation sources based on the World Bank database is unknown, then an average value for source distribution is used for calculations.

Besides these assumptions in the country-specific future electricity mix calculations, no improvements in infrastructure or in current fossil/renewable energy technologies are considered. Also, no rise in average temperature due to global warming is considered. The possible improvements in vehicle or battery technologies in future years are neglected. These aspects are further discussed in section 5.

3.3 Visualization

To visualize the results LCA worldmaps are used. A color coding is employed to perceive the results [4]. The edges of the color scale express the maximum comparative performance. The highest value of the impact category is set to 100%. An uneven distribution is selected in the areas close to zero. The degradation of each color level represents a 50% reduction from each category to the next, so that a distinguishable presentation and a detailed analysis is possible (e.g. 100 % → 50 % → 25 %, etc.). The scales from green to blue point out the zones, where driving a conventional vehicle instead of an electric vehicle is advantageous in terms of environmental impacts. The deeper the blue is, the higher the advantage (left side of the color bar). The same rule applies for EV. The colors from yellow to dark red express the EV advantageous zones. The deeper the red is, the higher the advantage of EV is (right side of the color bar).

4 Results and Policy Implications

This chapter highlights the results, utilizing the previously described concept. Figure 5 displays the baseline scenario showing a comparison of EV with ICEV using the electricity mix of the year 2015. This scenario is planned to reflect the actual status. China, Kazakhstan, and Mongolia are examples for good comparative performance, where ICEV perform better from an environmental perspective. On the contrary, EV perform better in comparison to ICEV in France, Norway, and Sweden. As expressed in the previous section, an uneven distribution is used in color categories to make the small differences noticeable by the human eye. The light green and yellow colors represent the countries where a distinct comparison is not possible. These areas represent a minor difference in EV or ICEV advantageous zones, therefore an absolute decision for such countries is not made. In such countries both EV and ICEV can be advantageous, like southern African countries or Mexico. Middle African and Latin countries perform towards the EV-advantageous edge, while Russia and Australia perform towards the ICEV advantageous side according to the actual (2015) scenario. It should be noted that both the country-specific electricity mixes and the climate influence the results. The countries with multiple colors are the ones with different climate zones within the country. Different ambient temperatures result in different heating and cooling demands. Canada, United States, Mexico, Turkey are among the countries with different climate zones, therefore different impact levels are shown. The significant impact of climate variations underlines that the background system with the influencing factors has a vital effect on the results of LCA for the studied case.

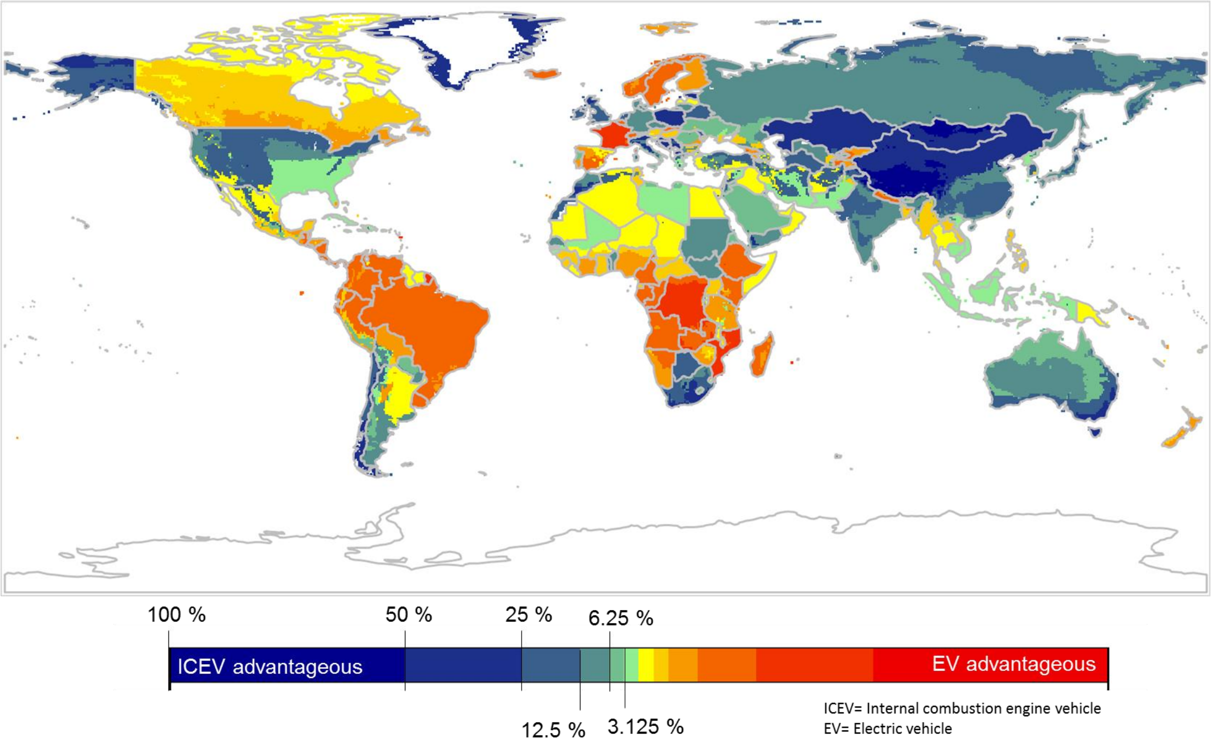

Figure 5: LCA map for climate change (actual local electricity mix (2015), "Commuter" with "even use" scenario)

Applying the methodology for calculation of future electricity mixes, LCA maps can be created to visualize the situation in the year 2030. The comparative maps for the years 2015 and 2030 are shown in Figure 6. The projected LCA world maps for the year 2030 show a shift towards an EV advantageous state compared to the year 2015. The increased share of renewable energy sources in electricity generation is reflected based on the REN21 report as described in the methodology. Policies towards the increase of renewable energy generation contribute to lower the emissions from EV. Figure 6 presents a zoom into the geographies where the leading countries in e-mobility are located. One region of interest is Asia, with a current EV stock of over 800,000, more than three-quarters sold in China. An other region of interest is Europe with a current stock of over 500,000 electric vehicles. Major markets are Norway and the Netherlands with over 100,000 vehicles each. While Norway shows a larger share in Battery electric vehicles (BEV), where as about three-quarters of EV in the Netherlands [26].

India introduced policy support mechanisms for deployment of EV and aims to have 0.3 million EV at 2020 [2] and sets a target of 40% for renewable energy in electricity mix for the year 2030. The LCA world map shows that India shifts towards EV advantageous state due to its renewable energy targets. A different situation can be seen in China. China sets major investments to increase the renewable energy share in electricity mix and is the leading country in e-mobility worldwide [26]. However, the renewable energy target (20%) is not sufficient for a shift to the EV beneficial state, and just a slight improvement according to the LCA maps is observed. Japan is constantly increasing the share of EV in its fleet with around 150,000 vehicles in the market. Its target (to 20% from 12.20%) for increasing the share of renewables outperforms the current situation with large shares of coal and nuclear energy. Thus, the usage of EV is likely to be beneficial in the time horizon of 2030.

A detailed comparison shows that European countries do not experience a significant change. Germany is an exception with its targets of renewable energy provision of 55-60% by 2035 and 80% by 2050. Although France has a target of increasing its share on renewables from 20% to 40% until the year of 2030, it turns to dark orange from red color in the future scenario. This change is directly related to the nuclear energy share in the country. Nordic countries, which have the highest EV shares on the roads, keep their status and perform EV-advantageous for both today and the 2030 scenario. Spain keeps its EV-advantageous state in the year of 2030, even though it does not declare any aggressive renewable targets according to REN report [5]. Further improvements towards the advantageousness of EV can be observed for Ireland, Italy, and Greece. While the share of EV is well below the European average in these markets, the set targets for the share of renewable energy are in favor for an environmentally sound shift towards EV. A country already experiencing a relevant EV share in its fleet is the Netherlands. The applied concept shows a shift towards an advantageousness of EV in this market.

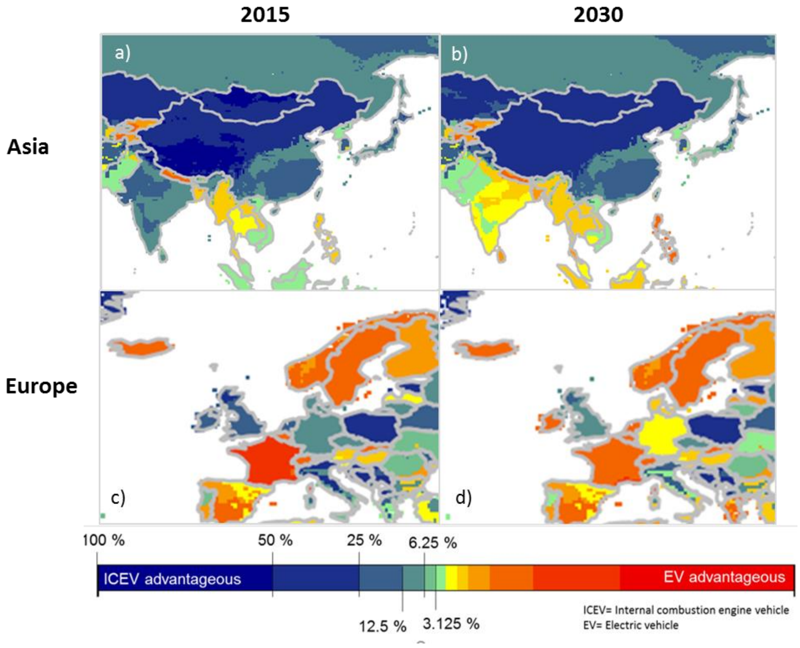

Figure 6: LCA world maps for selected countries (Climate Change, "Commuter" with "even use" scenario)
a) Asia in 2015, b) Asia in 2030, c) Europe in 2015, d) Europe in 2030

5 Discussion

The global electric vehicle stock has exceeded the 2 million thresholds in 2016. On one side, the Paris Declaration publishes a deployment scenario with 100 million electric vehicles on the roads in the year 2030 [2]. On the other side, the countries which lead in e-mobility as China, the United States, Japan, the Netherlands, and Norway set targets and introduce assertive policies to enhance the deployment of EV. The current trend points out an increased deployment of electric vehicles. But do they really environmentally perform better than conventional vehicles? It is an open question yet to be answered with the consideration of underlying influence factors that may have a dramatic impact on the answer. The concept introduced in this paper chases this answer. The LCA world maps aim to deliver inputs in order to evaluate the advantages and disadvantages of electric vehicles. Nevertheless, the methodology shows shortcomings needing to be addressed in future research.

France has a target of 40% of renewables (20% increase from current state) for 2030 and also set a target of 6% of EV stock for 2020. However, it shows a withdrawal according to the LCA world maps. This comedown is a result of the decrease in nuclear power. The advantage of EV drops down in France case due to the low global warming potential per kWh for nuclear power. While this result might be true for global warming potential impacts, the situation might change for other environmental impact categories. Thus all relevant environmental impacts resulting from local energy production have to be considered in future studies, e.g. discussed in [27].

One drawback of the presented concept is related to the assumptions made in modeling future electricity mixes. The targets set by the countries are accepted as they are going to actualize and the countries continue investing in renewable energy until the year of 2030. Hence, the results display an optimistic overview where the countries commit their statements and enhance their renewable energy share in electricity mixes. Another assumption is no rebound effect considered as a response to the increase in renewable energy production. The increased share of renewables may reduce the demand for fossil fuels and as a response, fossil fuel prices may drop down. Decreased oil prices may create a global rebound effect which may cancel out the advantages of increasing renewable usage. No improvement in current energy generation technologies or in distribution infrastructure is considered. In addition to these assumptions, the vehicle and the battery technology is also accepted as it is and no further estimation about the improvement of these technologies are considered.

Towards increasing the level of detail in modeling and thus further developing the results, different aspects need to be addressed in the further development of the presented methodology. One very important factor is an increase in the level of detail when modeling the energy shares. Electricity grids are not necessarily limited to political borders as assumed in the presented concept. Furthermore, local electricity mixes change over short time horizons and external impacts, e.g. weather conditions. A higher resolution and incorporation of more parameters in modeling the electricity grid would enable a more detailed view on the reduction potential of EV based mobility. In addition, a higher degree of detail in modeling the observed vehicle technologies in the foreground system could improve the capabilities of the methodology to support product design, technology planning as well as the design of service systems.

6 Conclusion

A concept is introduced integrating the regional aspects and the country-specific future electricity mixes into the LCA methodology. The comparison of electric vehicles and internal combustion engine vehicles are conducted using the concept introduced and the grid-specific results are displayed on LCA world maps. The LCA world maps allow presenting the complex results in one single map and make them available for discussions.

The LCA world maps underline the importance that local climate has to be considered for environmental assessment of EV. The countries with multiple colors display that even in one country climate specific results are derived. Besides the influence of the climate, the maps reveal indications for the synchronization of energy and e-mobility policies. On one side energy, when generated from clean resources, plays a role in mitigation transport-born emissions through e-mobility. On the other hand, electric vehicles, when driven in locations with high auxiliary demand and charged with electricity generated from fossil fuels, create additional environmental impacts. Therefore, setting e-mobility targets for reducing GHG emissions without improving the renewable energy share in electricity mix can even create a converse effect. The scenario for the year 2030 displays an improvement through EV advantageous states. However, for many countries (e.g. China), a dramatic change is not projected until 2030. This means that the increasing market shares of EV will not lead to lower overall emissions resulting from vehicle use. A push for EV might not make sense at the moment and or new technologies, e.g. for HVAC of vehicles need to be developed. This means that there is still a long way to make EV environmentally meaningful in each country.

While the concept provides a framework for including climate conditions and current as well as future electricity mixes in the comparison of ICEV and EV, there are several potentials for further development. The most prominent being the modeling of energy provision, e.g. taking into account a higher resolution and boundaries of specific energy grids. This could enable as well a consequential modeling of the energy usage of EV to the overall energy provision. Another starting point for further development would be the increase of detail in vehicle and fleet modeling, as specific market situations are not adequately reflected in the current approach.

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