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A Sustainable Development Analysis for a Market Penetration Scenario of Electric Vehicles with Range Extenders in the Stuttgart Metropolitan Area

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Abstract

The EVREST (Electric Vehicle with Range Extender as a Sustainable Technology) project is a transnational European Project carried out in the framework of the ERA-NET Electromobility+ call, including partners from Germany, France and Austria and was finished in 2015. The main idea of this project is to study how Electric Vehicles with a Range Extender (EREV), a small internal combustion engine, could match the different usage patterns and what would be the impact of such a solution. Electric vehicles with a range extender would not be limited to urban trips. Occasional long distance trips would be possible and people living in low density areas could also be concerned. Electric vehicles with range extender are expected to be an effective solution to cope with pollutant and noise emissions in urban areas and the demanded vehicle range by the potential users. The approach in EVREST takes into account the users´ mobility needs collected in user surveys. A methodology to virtually design a set of possible EREVs that fulfil the requirements in terms of range and performance has been carried out. Concerning the environmental study a Life Cycle Assessment, that considers both the production and use phase of the proposed EREVs and of the reference vehicles - gasoline (internal combustion engine vehicles - ICEV) and Battery Electric Vehicles (BEV) - has been conducted. For a more global evaluation and market projection at horizon 2025, a set of indicators for the development of the implementation scenarios was developed based on a car purchase decision model. Simulations of these scenarios to define the impacts on mobility and grid are conducted using a microscopic description (mobiTopp model) of cars and users in the Stuttgart metropolitan area as well as a simulated grid with the PERSEUSNET-TS model. The mobiTopp simulation results show EREVs are used rather similar to conventional vehicles and have a different use profile than BEVs. Technical, environmental, and social assessments were done within the project and the results fed the Sustainable Development Analysis (SDA). Following the principle of a multi-criteria analysis, indicators and their contribution towards a sustainable development were determined. The sustainable development analysis includes indicators of economic (energy consumption, employment effects), social (traffic safety, mobility cost) and ecological aspects (noise, global warming, primary energy from non-renewable resources, acidification potential, eutrophication potential, photochemical ozone creation potential). Especially in the field of economic aspects (energy consumption, employment) there are significant differences between the reference scenario and the implementation scenario.

The “green” reputation of electric mobility is not clearly reflected, as manufacturing BEVs and EREVs cause greater environmental pollution than producing conventional cars. In terms of social aspects there are hardly any noticeable differences between the scenarios and only small differences for the indicator mobility cost. However, the overall SDA indicator shows a positive contribution towards sustainability.

Keywords: Electric vehicles, Electromobility, Range extender, Sustainable development analysis.

Introduction

Thanks to advances in battery technology on the one side, and to an increasing interest of people and stakeholders in the development of sustainable transport solutions on the other side, Battery Electric Vehicles (BEVs) have recorded some improvement in their performances over the last 10 years. However, the BEV market penetration is still weak because of different drawbacks – in particular, the high purchase price and the limited range. Moreover, the range announced by BEV manufacturers is often too optimistic since it corresponds to nominal driving conditions. The actual range depends on several parameters and could be much lower in some use conditions, such as extreme temperatures, high speed operations and aggressive driving and charging patterns. This range limitation and variation is a real problem for potential customers and could lead to a psychological barrier to BEV purchase intentions (Franke et al., 2012).

In the same time, European statistics seem to indicate that a large proportion of the daily trips are far below the maximum range announced by BEVs constructors, customers prefer higher ranges than they actual need for everyday travel. For example, Bunzeck et al. (2011) examined the daily travel distances of 1,899 respondents in eight European countries and found that, on average, 86% of the respondents travel less than 100 km a day. Nevertheless, respondents prefer an average range of 308 km.

The Extended Range Electric Vehicle (EREV) is one possible solution to cope with some of the BEV limitations. In this solution, a second energy source is added to the vehicle in order to improve its range and to make sure that the user reaches his destination in case of battery failure. This source, which is called a Range Extender (RE), is usually based on a small Internal Combustion Engine (ICE) associated to an electric generator (as the optional RE of the recently launched BMW i3). This allows smaller batteries (i.e. lower costs) and higher ranges with shorter “recharging” times. However, the sizing of the combustion engine and battery is crucial in order to provide an attractive offer to vehicle users with advantages in range and costs compared to internal combustion engine vehicles (ICEV) and BEV.

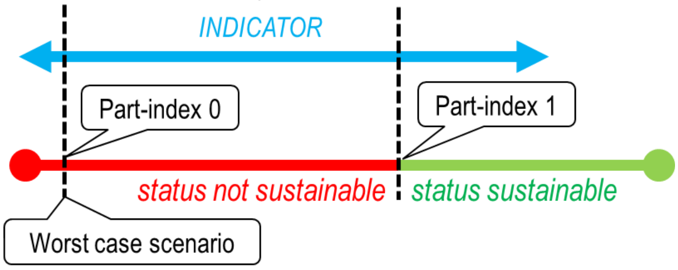
Such a promising technology that is expected to fit with most of the users’ needs has to be assessed and compared to other possible solutions. Most of the previous studies about EREVs focus on one aspect only, such as technical solutions (e.g. range, noise, pollution, heating). A global approach that also includes, besides technical aspects, economical aspects, environmental aspects and psychological aspects is currently missing.

Methodology

Sustainability in the sense of resource consumption - respectively more specific in the sense of environmental protection - was defined from the World Commission on Employment & Development in the year 1987 (Brundtland-Report), where sustainable development is a “development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World commission, 1987). Additional to this definition, the Rio Conference (1992) for Environment and Development of the United Nations (UNCED) expressed the three corner stone's of interest, in between sustainability needs to be placed: ecology, economy and social society. In that sense, the idea of sustainable development is an optimization concept.

Based on that definition, a sustainable development analysis (SDA) is a methodology to analyze the contribution of the proposed solutions for the sustainable development in a specific area - in the case of the EVREST project the greater Stuttgart region - based on sociological, economic and ecological aspects. Following the principle of a multi-criteria analysis, indicators and their contribution towards a sustainable development have to be determined using values between 0 (worst case for a sustainable development in the study area) and 1 (existing sustainable development in the study area) (part-index), see Figure 1. A synthesis of all indicators leads to the assessment of the overall contribution for a sustainable development with a sustainable development index.

Figure 1. *Relation between Value of an Indicator and its Contribution towards Sustainability*



Different scenarios for the introduction of electric mobility can be compared. This allows deriving recommendations on the implementation process and the framework conditions.

The main work steps of the SDA are:

1. Definition of the scenarios and the relevant time horizon,
2. Definition of criteria for the SDA and collection of indicators,
3. Definition of objectives (upper and lower limit) and the shape of the value function,
4. Determination of the quantitative effects for each scenario and transferring the values according to the standardized value,
5. Weighting of the different single indicators and synthesis of partial indices to an index for sustainable development.

Scenarios and Time Horizon

For the greater Stuttgart region four future scenarios (year 2025) of electromobility are defined. They correspond to the scenarios developed in a market share prognosis, Trigui et al. (2015) and are documented in Table 1:

The "most likely" scenario and the scenarios "low" and "high" which refer to a pessimistic respectively optimistic assessment of the future development of electromobility. Additionally, they are compared to a hypothetical scenario "without" – that means, without any electric EVs (BEVs, EREVs) as reference scenario. For each of these scenarios the contribution to a sustainable development is calculated.

Table 1. *Overview of the Scenario Specifications*

	Scenario 0 ("without")	**Scenario 1 ("low")**	**Scenario 2 ("medium")**	**Scenario 3 ("high")**
Share of EREV & BEV on the car fleet	0% BEV & 0% EREV	1% BEV & 5% EREV	1% BEV & 7% EREV	2% BEV & 12% EREV
Different car segments of the EREV fleet	-	26% small 67 % middle 7% large	26% small 67 % middle 7% large	26% small 67 % middle 7% large
Recharging possible	-	At home	At home	At home & at work
Charging performance	-	3.7 kW	3.7 kW	3.7 kW

Indicators and Objectives

According to the principle of sustainability, the indicators used for the SDA consider the three fields of a sustainable development (i.e. economic aspects, ecological, social aspects). The indicators were selected with regard to the data produced as output in the different work packages of the EVREST-project and were enriched by further statistical data (Table 2).

Economic Aspects

The energy consumption during the operation of vehicles is based on the car mileage travelled per year in the greater Stuttgart region (for different types of propulsion: BEV, EREV, Diesel, and Gasoline) and the belonging energy consumption of these vehicle types in 2025 which is an outcome of the model used in the EVREST-project. For the lower limit of the utility function the energy consumption rate for private cars from the year 2010 with car mileage of the year 2025 is used. This refers to a not sustainable situation. The upper limit of 100% sustainability is defined as a 25%-reduction of the energy consumption. This assumption is based on an extrapolation of EC-targets in the Energy Efficiency Plan (2011) setting a target for 2020 of saving 20% of its primary energy consumption compared to projections.

Another indicator of economic aspects is the employment effect. This is expressed in additional work places that can be traced back to additional investments due to the implementation of electric mobility. For this indicator it is assumed that the employment effects will occur in the whole province of Baden-Württemberg. The additional person-years of employment are correlating with the additional welfare by a certain factor expressed in person-year per €. If dividing the additional person-years of employment through the number of years, the mean number of additional annual full time working places can be calculated and subtracted from the present missing working places in the city that enables to calculate the new unemployment rate. In the scenario "without" no additional work places will be generated compared to the other scenarios, in which additional investments costs lead to a higher rate of working population. The lower limit is set to 20% of unemployment in the province whereas 100% sustainable would be a full employment in the region and therefore defined as sustainable.

Ecological Aspects

Noise reduction is seen as a big advantage of EVs. It depends on the driving speed and the car fleet on the road. In parallel, the question arises whether or not the number of accidents increases due to the reduced warning which signalizes an oncoming vehicle (see indicator traffic safety). However, there are no specific data on this issue. The indicator for the SDA is expressed in the number of disturbed persons due to road traffic noise; the lower limit of the utility function is defined as all of the inhabitants in the study area are disturbed, the upper limit equals no one is disturbed. The part indices of sustainability for each scenario are calculated using the car mileage per year of fossil fuel vehicles and the share of disturbed persons in the city of Stuttgart (>50db(A) day-evening-night noise index over 24hrs, Stadtklima Stuttgart, 2010). For the change of persons disturbed by traffic noise the following approach is used (Sammer & Wernsperger, 1994):

$$\Delta PN[\%] = 37.5 * (\log_{10}(ckm_{low/mostlikely/high}) - \log_{10}(ckm_{wo}))$$

ΔPN [%] = *percentage change of persons disturbed by road traffic noise between scenarios "with" and "low" / "most likely" / "high" [%]*
ckm [km] = *car-kilometres (fossil fuel vehicles) in the scenario "low" / "most likely" / "high"*
ckmwo [km] = *car-kilometres (fossil fuel vehicles) in the scenario "without"*

The approach described above follows the assumptions that traffic noise is mainly a problem in the urban area (city of Stuttgart), the number of disturbed persons in 2009 will stay constant otherwise until 2025, EREVs drive in electric mode in the urban area due to shorter trips and lower velocities, and all of the EVs cause no noise pollution > 50 db(A) in city of Stuttgart.

Another ecological indicator is global warming (mainly related to CO_2 emissions). The CO_2 emissions due to car traffic are calculated using the car mileage per type of vehicle simulated for each scenario in 2025 and the CO_2 emissions per km per type of vehicle. The lower limit of utility function (0% sustainable) is defined as an emission rate for private cars (year 2010) with a car mileage of 2025. As upper limit (100% sustainable) the EU white paper target for 2050 is used, which includes a CO_2 reduction of 60% (European Commission, 2011).

When assessing the ecological impacts of EVs also environmental pollutions have to be considered stemming from manufacturing EVs. The indicator primary energy from non-renewable resources describes the energy consumption for production and maintenance. The input for the calculation is derived from a life cycle assessment, Trigui et al. (2015). The limits for the utility function are defined as follows: The lower limit (0 % sustainable) assumes energy consumption if there are no EVs in the study area (scenario “without”); the upper limit (100% sustainable) assumes a reduction of 25% of this energy consumption-level. Again, the value of -25% is taken based on the targets set in the European Energy Efficiency Plan (2011).

The acidification potential describes the emissions of SO_2 equivalents per year considering the car mileage in 2025 including the production of the vehicles. The eutrophication potential describes the emissions of phosphate-equivalents per year considering the car mileage in 2025 including the production of the vehicles. The photochemical ozone creation potential (POCP) describes the emissions of ethene-equivalents per year considering the car mileage in 2025 including production of the vehicles. For all three variables, the lower limit (0 % sustainable) is defined as potential for the scenario "without”; the upper limit (100% sustainable) assumes its 25%-reduction. As there are no goals documented for these indicators, the value of -25% is taken based on the targets set in the European Energy Efficiency Plan (2011).

Social Aspects

Two indicators with regard to traffic safety are considered for the SDA: The number of fatalities and the number of injured persons caused by road accidents.

For each scenario in 2025 the number of fatalities is calculated using the car mileage per vehicle type and the number of fatalities per accident with fatalities. As for EREVs and BEVs no accident rates are available we assumed a slightly higher rate for EVs compared to fossil fuel cars according to the assumption of noise reductions (+10%). As we assume the same accident rate for BEVs and EREVs this is a bias towards EREVs in this case. The lower limit can be defined as the highest number of traffic-fatalities in the study area recorded ever. On doing so the number of fatalities is taken from Germany in the year 1970 (Statistisches Bundesamt 2013) and allocated to Baden Württemberg (ibid.) and the greater Stuttgart region according to the distribution of inhabitants. The upper limit is 0 in all cases. For the indicator number of injured caused by road accidents the same approach for the calculation for both the scenarios and limit definition is applied.

Another indicator for considering social aspects in the sustainable development analysis is mobility cost for driving a private car. These costs include fix and running costs considering the composition of the car fleet per scenario in 2025. The costs refer to scenarios for compact class car and average mileage and years of a car life span. They were projected for the total car mileage in the future scenarios.

Table 2. *SDA Indicators and Definition of Upper/Lower Limits of the Utility Function, BW=Baden-Württemberg*

Indicator	Description	unit	Lower limit of utility function (0% sustainable)	Upper limit of utility function (100% sustainable)
ECONOMIC ASPECTS				
Energy consumption during operation	per type of propulsion (BEV; EREV, Diesel, Gasoline)	kWh/year	2010 energy consumption rate for private cars with car mileage 2025	-25% for 2025 (extrapolation of 20-20-20 target from EU until 2020)[1]
Employment effects	Additional work places due to additional investments	unemployed persons	20% unemployment	0% unemployment
ECOLOGICAL ASPECTS				
Noise	number of disturbed persons in study area	disturbed persons	all inhabitants of study area are disturbed	no inhabitant of study area is disturbed
Global warming	CO_2-emissions due to traffic in study area	t/year	2010 emission rate for private cars with car mileage of 2025	-60% for 2050 (White paper "Roadmap to a single European transport area")[2]
Primary energy from non-renewable resources	energy consumption (production & maintenance)	MJ/year	Scenario "without"	-25 % of Scenario "without"
Acidification potential	including production	kg SO_2 eq./year	Scenario "without"	-25 % of Scenario "without"
Eutrophication Potential	including production	kg PO_4^{3-} eq./year	Scenario "without"	-25 % of Scenario "without"
Photochemical Ozone Creation Potential	including production	kg C_2H_4 eq./year	Scenario "without"	-25 % of Scenario "without"
SOCIAL ASPECTS				
Traffic safety	number of fatalities in the study area	fatalities/year	worst situation (Germany 1970) and trend of fatalities in Germany[3], Share of fatalities BW[3]	no fatalities in the study area
Traffic safety	number of injured persons in the study area	injured/year	worst situation (Germany 1970) and trend of injured Germany[3], Share of injured BW[3]	no injuries in the study area
Mobility cost for driving private car	all car users (fix & running cost)	€/year	+50% of 2010 cost for private car, car mileage 2025	-50% of 2010 cost for private car, car mileage 2025

[1]) European Commission, Energy Efficiency Plan 2011, Brussels 2011

[2]) European Commission, Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system, White Paper, 2011

[3]) Statistisches Bundesamt (2013), Unfallentwicklung auf deutschen Straßen 2012, Wiesbaden

Application to the Stuttgart Metropolitan Area

Simulations of these scenarios to define the impacts on mobility and grid are conducted using a microscopic description (MobiTopp model) of cars and users in the Stuttgart metropolitan area as well as a simulated grid with PERSEUSNET-TS model. It is possible to assign a weight to each indicator to represent its relative importance to the overall objective of sustainability. For the greater Stuttgart region, all indicators got the same weight (1); also each aspect (i.e. economic, ecological and social aspects) got an equal weighting (1/3 share of each aspect). Figure 2 and Figure 3 show the contribution of each indicator towards a sustainable development and the overall SDA indicator (sustainable development index - SDI). The SDI of a scenario is the weighted mean value of all indicator values for this scenario and lies between 0 and 1 for each scenario.

It becomes clear that electro mobility contributes to a sustainable development in the greater Stuttgart region. Especially, in the field of economic aspects (energy consumption, employment) there are high differences between the reference scenario "without" and the other future scenarios. The "green" reputation of electric mobility is not clearly reflected in the results of the SDA: High benefits lie in the "energy from new renewable resources" and "POCP"; for the other indicators the differences are small as manufacturing BEVs and EREVs causes greater environmental pollution than producing conventional cars. In terms of social aspects there are hardly any noticeable differences between the scenarios and only small differences for the indicator mobility cost. The overall SDA indicator shows a positive contribution towards sustainability. Whereas the scenarios "most likely" and "low" do not show high differences, a high support of electromobility as assumed in scenario "high" results in higher contributions to a sustainable development in the greater Stuttgart region.

Figure 2. *Part Indices of Sustainability*

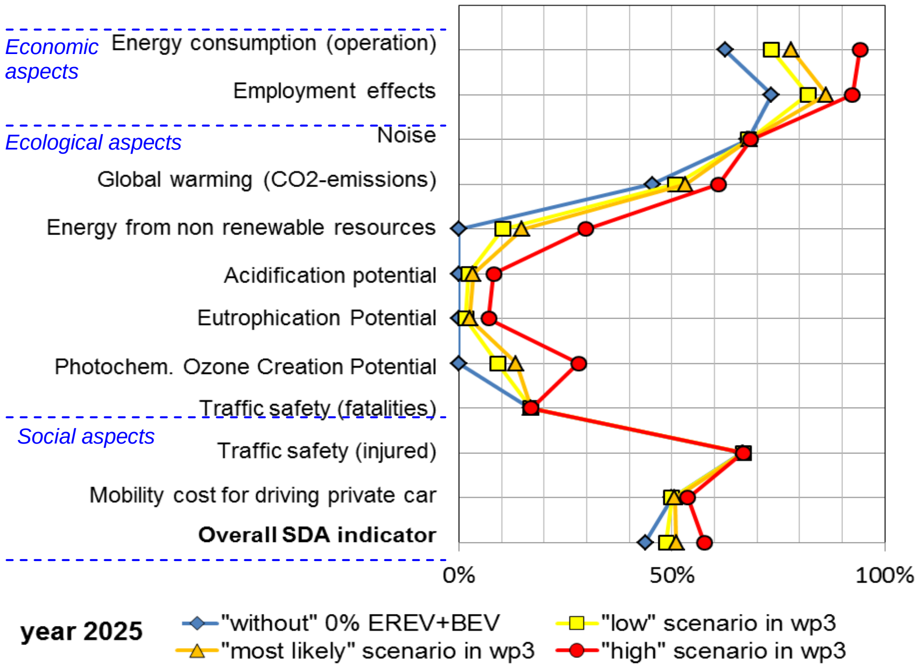
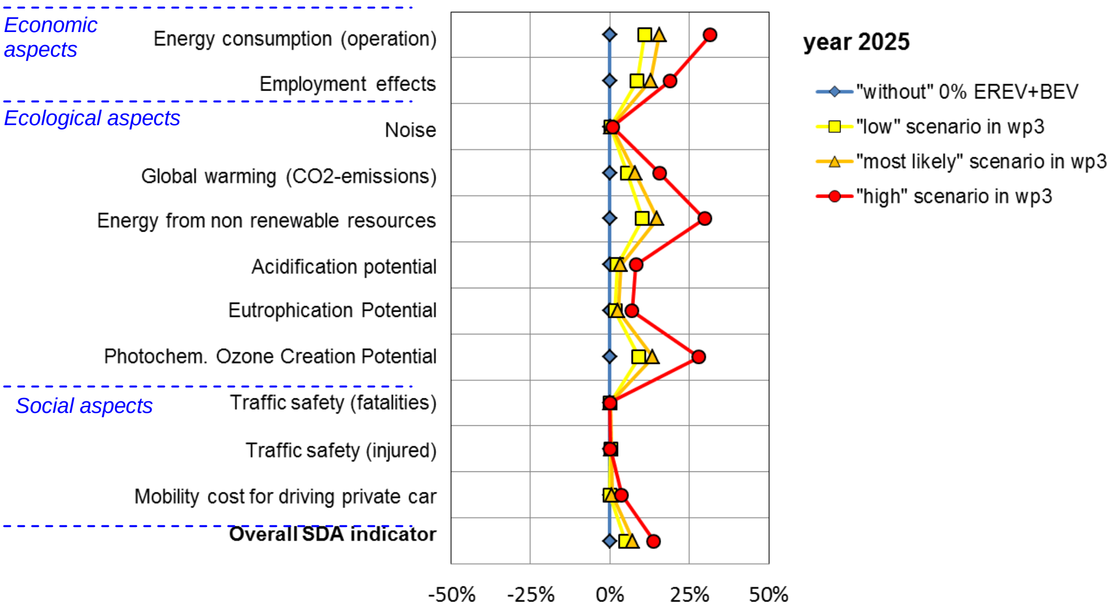


Figure 3. *Part Indices of Sustainability Compared to Reference Scenario "Without"*



Conclusions and Outlook

Against the background of megatrends, such as climate change, but also urbanization, globalization, and demographic change, any opportunity for the development of a more sustainable transport system should be seized. Already today EREVs can show substantial benefits in comparison with BEVs and conventional vehicles. From an environmental point of view, EREVs present advantages even when electricity grid mixes with high shares of fossil-fired power plants (e.g. German grid mix) are used for charging. The environmental benefits of EREVs increase with higher shares of renewable energy in the grid mix of the use phase.

From a technical point of view, the EREV concept opens a wide field of research and development as the RE can be improved in terms of energy consumption and emission. Future RE solutions like fuel cells could be a promising perspective because the hydrogen use does not generate any local pollutant emission (as BEVs). However, as the system efficiency is significantly decreased from above 80% for a BEV to below 30% for a current fuel cell vehicle, the electricity mix that provides the hydrogen production should have an important share of (superfluous) renewables. With EREVs, many drawbacks of BEVs could be erased. Some of them were not sufficiently highlighted in this project. They consist of an intelligent management of energy and heat that allow more flexibility in the vehicle use whatever the weather conditions are. This management should be optimized in order to enhance the all electric range while maximizing the full power range and the comfort.

The project results clearly show that EREVs could become a key player in the future car market of Europe. Nevertheless, the development clearly depends on the future framework conditions as a lot of factors may influence the sales figures. These factors relate amongst others to technological, socio-economical, socio-demographical and political developments and are difficult to predict. However, future scenarios can help to gain a holistic interlinked view on a complex system. They can also clarify which strategies and goals must be pursued to reach the desired developments in the long term. If electric mobility should be pushed further on, there are different political measures that can be used as driving forces.

Society will adapt to the vehicles and vice versa. As a bridging technology on the way to a BEV market, EREVs can also help to overcome scepticism with regard to new technologies from the car users' side. However, it has to be considered that changes in car use will result in changes in the economic sector. The conclusions show that EREVs can contribute to a sustainable development in the transportation sector. Serious efforts have to be targeted in the field of integrating EVs into the existing mobility and energy system (i.e. charging system, intermodal linkages, etc.).

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