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Energy Economic Assessment of Range Extension Technologies for BEVs in 2020

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ABSTRACT: This paper focusses on an energy economic analysis of battery electric vehicles (BEVs), specifically investigating their means to extend the driving range on long distance trips in the year 2020. Three range extension technologies – fast charging, battery switching and driving with an on-board micro internal combustion engine – are hereby compared. The implemented simulation tool ZEVS models the particularities of BEVs in 27 European countries, whereby specifically the methodologies for modelling the daily driving habits of medium and long distance trips and the additional power demand for heating (winter) and cooling (summer) are described. The resulting load curves are then incorporated in a further modelling tool, URBS-EU, which simulates a cost minimal power plant portfolio supplying renewable energy to BEV power demand. An in-depth results analysis shows that BEVs with battery switch technology are responsible for the least amount of CO_2 emissions, have the lowest primary energy generation costs and integrate renewable energy feed-in most efficiently in comparison to the other two range extension alternatives.

Keywords: electric vehicles, range extension, renewable energy, battery switch

1. INTRODUCTION

Future battery electric vehicles (BEVs) will require renewable energy sources to absent from today's mainly nuclear/fossil based electricity generation and thus fulfil higher sustainability criteria than combustion engine vehicles. Previous studies [1] have shown the mostly non-beneficial impact of conventional power production in European countries to supply BEVs with electricity (attributed CO_2 emissions or accumulation of nuclear waste). Furthermore all previous BEV studies relating to the economic and environmental impact of BEVs, have solely focused on short distance trips [1]. This implies that depleted batteries undergo controlled charging via a smart meter, whereby the energy economic effects of this grid friendly charging was evaluated. The impact on the grid due to long distance trips, requiring BEVs to make use of range extension technology (fast charging within 1 hour, battery switching at designated swapping stations or driving with an on-board micro internal combustion engine), have not been analysed to date. Research conducted by partners of the EASYBAT consortium [2] suggests that approx. 10 % of all future trips will make use of range extension (reason being either due to range limitations or simply due to user convenience). Thus a noticeable energy economic impact can be expected.

Figure 1 thus shows a simplified approach of supplying cost-efficient energy from renewable sources (wind onshore and offshore, photovoltaic solar power, biomass power plants) to match the immediate power demand at either battery switch stations (BSS) or fast charge stations (FCS). Thermal power plants such as gas turbines seldom pitch in to compensate meagre renewable feed-in.

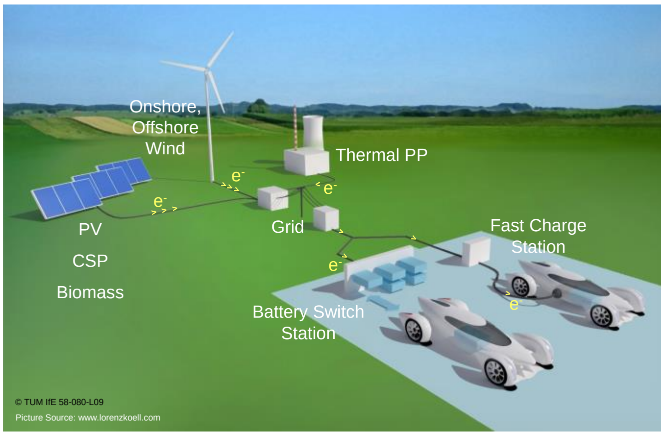

Figure 1: Providing renewable energy for range extension purposes of BEVs at BSS and FCS

The third range extension technology under investigation, BEVs with a micro internal combustion engine (ICE), are not depicted, but will form a reference based on fossil fuel range extension. Thus, the goal of this paper is to compare and assess energy economic criteria reflecting the operational impact of these three range extension technologies on a system level. Influencing technological advances and economic factors are based on predictions and "business as usual" case extrapolations for Europe in 2020.

2. THE SIMULATION AND OPTIMISATION MODELS "ZEVS" AND "URBS-EU"

An overview of the simulation environment used in this analysis for modelling BEVs and their related power generation infrastructure is provided in Figure 2. The green bubble fields – the ZEVS model – show the input parameters of the modelled BEV fleets in different European countries, such as the heating and cooling demand, predicted BEV market penetration rates, extrapolated motorisation rates, daily vehicle usage patterns, etc. Together with future technological advancements in light-weighting and battery technology, the total power demand characteristic of BEVs on an hourly basis can be modelled for each European country.

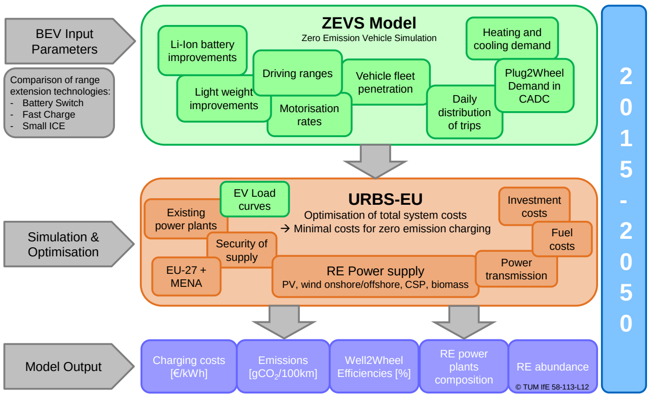

Figure 2: System model for the simulation of BEVs and their related power plant infrastructure in Europe from 2015 to 2050

The resulting load demand curves are transferred to the URBS-EU model – the orange bubble fields – which then optimises the future power plant portfolio and its operation. Hereby, input parameters such as fuel and investment costs, renewable energy influx, power transmission capacities, etc. feed the model, which finds a cost-minimal solution for the system as a whole. As a result, charging costs, emissions, efficiencies, etc. are calculated as model outputs for further analyses – purple bubble fields.

All input parameters, calculations and output results in ZEVS and URBS-EU portrait the optimum under certain conditions and scenarios. These models allow for the prediction of possible future scenarios until 2050. For the analysis provided in this paper, a particular year was selected: 2020. While the results of 2020 show a very realistic picture of the impact of BEVs in the near future, the simulation year 2050 follows the logic of a probable scenario likely to set in, if all of today's assumptions on future developments hold true and no greater political, economic or social changes impact the underlying model assumptions. A discussion of the results containing the simulation year 2050, however, does not form part of this paper.

2.1 The Power Plant Optimisation Model "URBS-EU"

URBS short for "Urban Research Toolbox: Energy Systems" was first developed and applied by Hamacher and Richter [3] in 2004 to model the energy system of the Bavarian city of Augsburg. Over the course of the following years the model expanded to emulate ever larger energy systems of whole economies. At the Chair for Energy Economy and Application Technology at TUM under Huber [4] and Schaber [5] the model has since evolved to simulate the ever more complex power generation and transmission system of the whole of Europe (URBS-EU), while at the same time capitalising on the ever increasing computing and processing power of computers. An up-to-date version of URBS-EU has been adapted by Wimmer [6] to consider and analyse the explicit effects of load curves emulating the impact of BEVs.

The applied simulation methodology in this study is a power system model based on the linear optimisation of overall costs from a social planner perspective. The simulation model, URBS-EU, mirrors the continent's EU-25 states (equivalent to EU-27 without Malta and Cyprus), Switzerland, Norway and the MENA countries (Morocco, Algeria, Tunisia, Libya, Egypt, Saudi Arabia, Jordan, Syria and Turkey). These regions are highlighted dark grey in Figure 3 and are complemented with 33 specific offshore regions. The electricity transmission network is modelled as an aggregated node to node system, based on major existing grid connections and including all future grid extensions projected as most likely and necessary by the European Network of Transmission System Operators for Electricity (ENTSO-E). The temporal resolution is hourly. Owing to this high level of detail, the model is appropriate to analyse the impact of primary energy resources for power generation, ranging from fossil fuels to renewable energy sources.

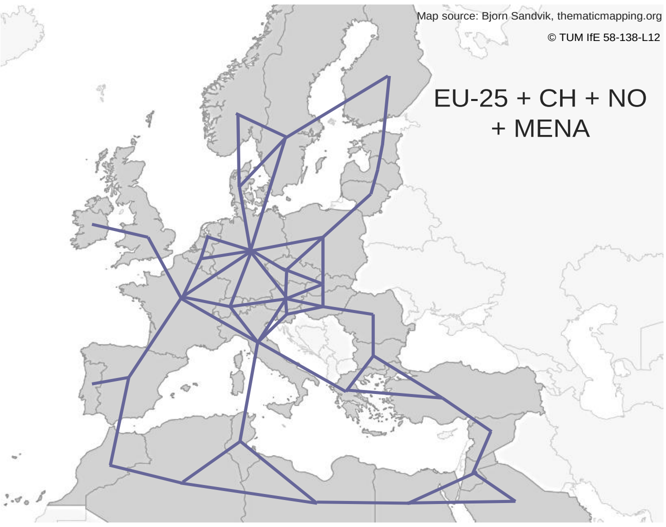

Figure 3: Highlighted countries constituting the 27 differing simulation nodes of the URBS-EU model

The most important aspects of URBS-EU on model methodology and input data are outlined in Schaber et alii's "Transmission grid extensions for the integration of variable renewable energies in Europe: Who benefits where?" [5]. For this analysis of range extension technologies for BEVs greater effort in research and development was put into the Zero Emission Vehicle Simulation Model – ZEVS – which emulates the load demand curves of BEV fleets in the 27 European countries.

2.2 The Zero Emission Vehicle Simulation Model – ZEVS

In the following subchapters the basis of comparison between the three investigated range extension technologies will be described. Furthermore, the two most important parameters accounting for the high fluctuations in the BEV load curves are portrayed in detail; they include the daily distribution of long distance trips necessitating range extension and the power demand for heating and cooling BEVs in winter and summer.

2.2.1 The Three Range Extension Technologies under Analysis

In order to make a fair comparison between the three range extension technologies, several model parameters need to be placed on the same basis, aligned and generalised for all three BEV types equally (compare to Figure 4):

Vehicle platform: The basis of comparison involves similar vehicle setups with single architecture platforms, solely accommodating alterations in the vehicles' range extension technology and its packaging thereof. It can be distinguished either between battery switching, fast charging or deploying a micro ICE to increase the range of the BEV once the battery is depleted. The aerodynamics are identical, while only slight deviations in vehicle masses and the packing of the battery exist: The mass of the BEV with battery switch technology is only slightly higher (not more than 1 % of total vehicle mass [2]) in order to accommodate additional components for an easy and safe switch of the battery in less than 3 minutes at a battery switching station (BSS). On the packaging side the BEV with a micro ICE has a smaller battery considering the additional space and mass of the combustion engine and fuel tank.

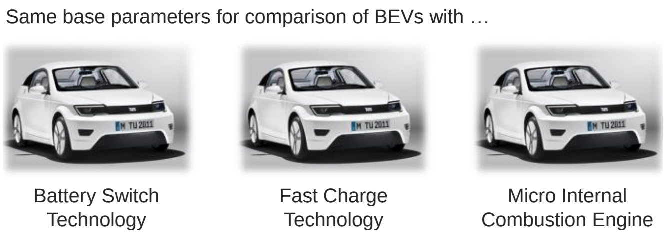

Figure 4: The three range extension technologies with identical BEV platforms under investigation

Effective energy demand (German "Nutzenergiebedarf"): This parameter solely comprises the energy demand for overcoming driving resistances for forward propulsion and is assumed to be the initial point of the comparison, onto which all other parameters are outlined. Its goal is to ensure a general and fair analysis of the three range extending technologies in comparison to each other. All parameters influencing driving resistances such as average BEV weight (1335 kg with a 19 kWh lithium-ion battery and an assumed energy density on cell level of 205 Wh/kg for an average BEV in 2020), drag coefficient, cross sectional area, etc. are considered equal for the three range extending technologies. Therefore the effective energy required to overcome states of motion bound by physical laws is the same for both BEVs with fast charge/battery switch technology and BEVs with ICE range extension. Differences in the final energy demand (plug2wheel, tank2wheel) and primary energy demand will, however, vary due to the two different drive trains used for range extension and according to the higher charging losses incurred during fast charging than during battery switching. The EASYBAT consortium estimates an additional energy demand of 10 % [2] for the whole process of battery switching (charging inefficiencies of inverter and battery, automatic handling of batteries within the switch station, keeping the station at 20°C and occasional inefficiencies due to necessary fast charging). An additional energy demand of 15 % [2] is estimated for fast charge stations (comprising charging inefficiencies of inverter and battery and a high amount of energy necessary to cool the battery and thus prevent rapid cell degradation). All final results, however, will be based on the specific primary energy demand in kWh/100km as a fair mean of comparison between the three range extension technologies.

Electric driving range: For this analysis an average range of 150 km for BEVs in the New European Driving Cycle (NEDC) was selected, which represents a broad average of available BEVs in the A-, B- and C-class vehicle segments. Furthermore the assumption is made, that this average driving range will remain constant for the construction and design of BEVs until 2020. Considering the fact that BEVs will inherently come with additional weight and investment costs in comparison to ICVs, a larger battery and thus a greater electric range proves counterproductive for the following reasons: less economic competitiveness due to higher total costs of ownership, reduced driving dynamics and an increased plug2wheel demand as a result of higher vehicle weight. It is therefore assumed that in future OEMs are hesitant to increase battery size and thus electric range higher than 150 km, in particular when an adequate infrastructure to extend range (either by battery switching, fast charging or filling up at fuel stations) is in place. Due to the availability of range extension technologies it is assumed that further improvements in battery technology (energy density) will lead to a reduction in vehicle weight and plug2wheel demand rather than a further increase in electric range with all its adverse side-effects mentioned before. For this analysis BEVs with an additional micro ICE are assumed to have only 50 km driving range in the NEDC. As mentioned above, a smaller battery provides space for the ICE and fuel tank and thus places the BEV at the same total vehicle weight.

In summary the following parameters were used to simulate the basic energy demand of a reference BEV in the driving cycle CADC (simulation estimations for BEVs on average in 2020):

- Kerb weight $m_{BEV} = 1335$ kg
- Drag co-efficient $c_w = 0{,}25$
- Cross sectional area $A = 2{,}27$ m²
- Rolling resistance $f_r = 0{,}009$
- Energy density li-ion battery $e_{cell} = 205$ Wh/kg
- Power density li-ion battery $p_{cell} = 1000$ W/kg
- Additional battery system weight $w_{bat\text{-}sys} = 27$ %
- Auxiliary on-board power demand $P_{aux} = 100$ W

2.2.2 Modelling the Heating and Cooling Demand of BEVs

One factor, particularly influencing the driving range of BEVs, is the power demand for heating or cooling the interior of the vehicle under certain weather conditions. Next to vehicle speed, air humidity and other minor influencing factors, the power demand mainly depends on ambient air temperatures. These, on the other hand, underlie geographic (northern versus southern Europe), diurnal (day versus night) and particularly seasonal (summer versus winter) variations. For example, ambient winter and summer temperatures in Italy are on average 5-10°C warmer than in Germany. This difference can be seen in Figure 5, depicting the hourly temperatures of the randomly selected year of 2007 (Italy: yellow line, Germany: blue line).

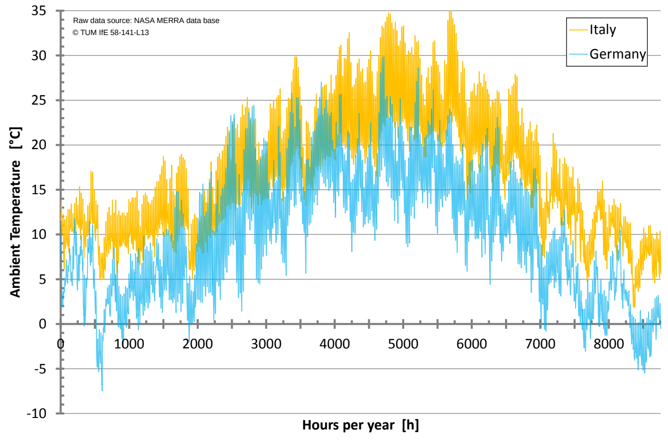

Figure 5: Comparison of hourly temperatures in Italy and Germany (exemplary temperatures from the year 2007)

To obtain the depicted plots, raw data of ambient temperatures in 2 m height on a plain resolution of approx. 50 km² of Europe was obtained from the NASA MERRA data base [7]. Next the temperatures of the five largest cities in each country were weighted according to their population size on an hourly basis. This results in 27 different temperature nodes, each representing hourly temperatures for a BEV fleet in a particular European country.

To determine the heating and cooling demand of BEVs at these temperature nodes, the thermodynamics of a moving vehicle needs to be calculated accordingly. Based on ISO 7730 [8] the ergonomics of the thermal environment are perceived to be most comfortable for humans in an air temperature field centred around 21°C and 50 % humidity. Hence all ambient temperatures diverging from this ideal will result in a necessary power demand to condition the vehicle's interior accordingly. This electric power demand for an exemplary heating and cooling scenario is depicted in dependence of ambient temperatures in Figure 6 (red line). According to Sondermann from Valeo Thermal Systems [9], the figure suffices to represent the power demand for heating and cooling an average B-class vehicle operating in the NEDC. Hereby the minimum of the heating and cooling graph lies at approx. 19°C, considered to be the ideal temperature for a minimum energy amount to sustain the comfort in a vehicle's cabin. A base load of approx. 400 W is required to provide a constant influx of fresh air, regulated to the right humidity and the thermodynamic impact of the occupants.

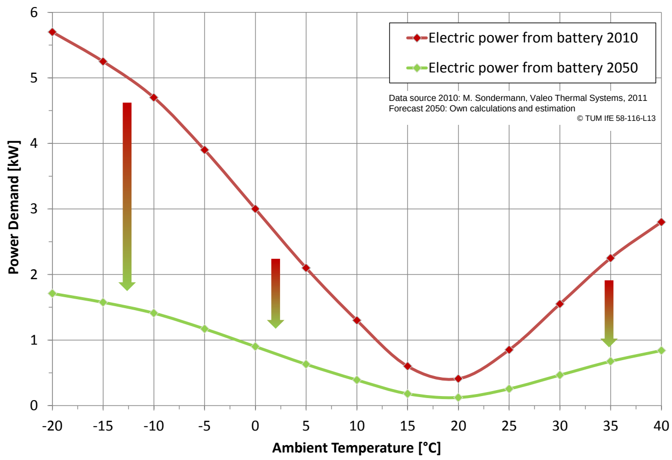

Figure 6: BEV heating and cooling demand with technology of 2010 and estimate of technological improvement until 2050

Over time technological advances will reduce the power demand for heating and cooling a BEV. This development until the year 2050 is estimated by the green line in Figure 6 and demonstrates the technological reduction potential according to engineering experts from EASYBAT's consortium partners [2]. It can result from future technological advancements such as improved vehicle insulation materials, enhanced compression efficiencies of chillers, integrated heat exchangers at relief air outlets, heat pumps and hardware using the magneto-caloric effect for cooling (and in future heating).

When applying the power demand curve of Figure 6 to the temperatures of the 27 different geographic nodes in Europe (Figure 5), the additional electric power demand from the vehicle's battery can be calculated. In Figure 7 this additional power demand was incorporated as part of the vehicle's on-board power demand, while conducting the Common Artemis Driving Cycle (CADC extra-urban and highway). Thus according to the mentioned BEV parameters in Chapter 2.2.1, a BEV requires approx. 14,8 kWh/100km in the CADC. This value is plotted in Figure 7 (red line) indicating those hours of the year, when ambient temperatures are at their most ideal.

All other hours require additional power from the BEV's battery in Italy (yellow line) and respectively in Germany (blue line) to compensate for too cold or warm ambient weather conditions of the exemplary year 2007. Effectively, this leads to an increased power demand from the electric grid when BEVs are charging their greater depleted batteries. Therefore, this matter of fact has a noticeable influence on the power plants' operation pattern in certain climatically cohesive regions, which are required to provide this additional power demand for BEVs.

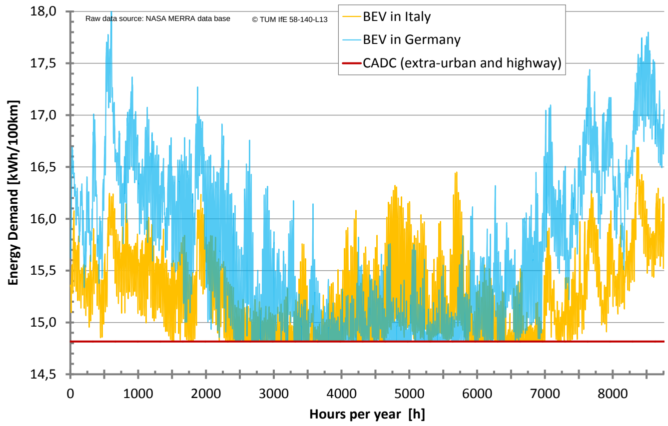

Figure 7: Hourly heating and cooling demand of BEVs in Italy and Germany on the technical basis of 2020

2.2.3 BEV Long Distance Trips Requiring Range Extension

In addition to power plants generating additional electricity to accommodate climatic comfort of approx. 21°C at 50 % humidity within the vehicle, the power demand for heating and cooling adversely lowers the driving range of BEVs noticeably. In Figure 8 a comparison between BEVs under different climatic conditions in Italy and Germany is shown. As exemplary climatic conditions the average ambient temperatures of the 03.02.2007 at 7 pm both in Italy (7,5°C) and Germany (1,6°C) were taken to simulate the driving ranges of BEVs in these respective countries. Hereby a battery capacity of 19 kWh is required for BEVs with a driving consumption of 10,1 kWh/100km to provide an electric range of 150 km in the New European Driving Cycle (NEDC).

However, driving conditions under the NEDC not necessarily reflect true driving conditions. In order to account for more dynamic driving styles of vehicle users (higher acceleration, less anticipatory behaviour) and in general higher road speeds of long distance trips, the Common Artemis Driving Cycle (CADC) for extra-urban and highway usage was loaded into the simulation tool ZEVS. This accounts for an additional energy consumption of the BEV of another 4,8 kWh/100km. This base amount applies to BEVs in both countries equally. However, the energy consumption for heating differs considerably: While in Italy only 1,1 kWh/100km are reserved for heating the vehicles, in Germany 1,9 kWh/100km are required for the same objective of a comfortable vehicle interior. Accumulating all these additional energy demands brings forth a more realistic estimation of the driving range, which can be expected for BEVs in either country. Effectively BEVs in Italy can expect an electric range of approx. 100 km in comparison to BEVs in Germany with only 90 km range.

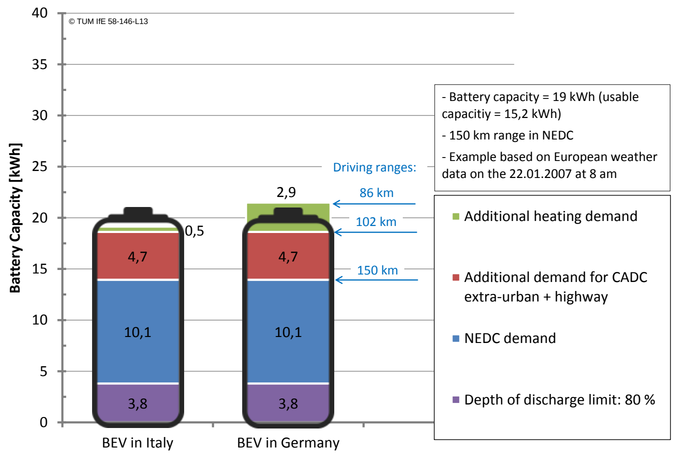

Figure 8: Usage of battery energy content due to different demands and their impact on driving range in Italy and Germany

Further range depreciating effects, such as changing altitudes in geography or precipitation inefficiencies caused by higher rolling resistances, also occur realistically, however, have not formed part as input parameters for the ZEVS simulations in this analysis.

From this it can be deducted that particularly in winter, a higher demand for range extension of BEVs either at the BSS, FCS or driving with the micro ICE is foreseeable. Now, the question is, statistically speaking, how many trips are longer than the 100 km expected range of BEVs in Italy and 90 km in Germany at this particular hour?

For estimations on possible future charging hours of BEVs, data of conventional ICVs concerning their typical driving distances and times were analysed from the German traffic statistics source "Mobilität in Deutschland 2008 (MIB2008)" [10]. Statisticians used a sample group of 60.713 people with 34.601 vehicles (motorisation rate of 570 BEVs/1000 inhabitants). Statistically, the sample group proved to be highly reliable in reflecting the mobility habits of vehicle users in the whole of Germany. A comparison to statistics on mobility habits in France and Italy [11] proves to come to very similar distributions, showing two daily peaks of similar magnitude, one at around 9 am and the second at around 5 pm, while barely any vehicles commute on roads between 0 and 5 am. Due to the high data resolution found on Germany's mobility habits, MIB2008's data base thus forms the basis to analyse possible future charging hours of BEVs for all considered European countries in the simulation tool ZEVS. The analysis hereby especially focuses on long distance trips, where range extension technology becomes a necessity for BEVs, as explained above in Figure 8.

In Figure 9 a breakdown of the distance distribution of all undertaken trips in 10 km increments is shown. Thus, 3 % of all trips undertaken per day are on average longer than 90 km and would require a means of range extension by any of the three mentioned alternatives. These are classified as long distance trips.

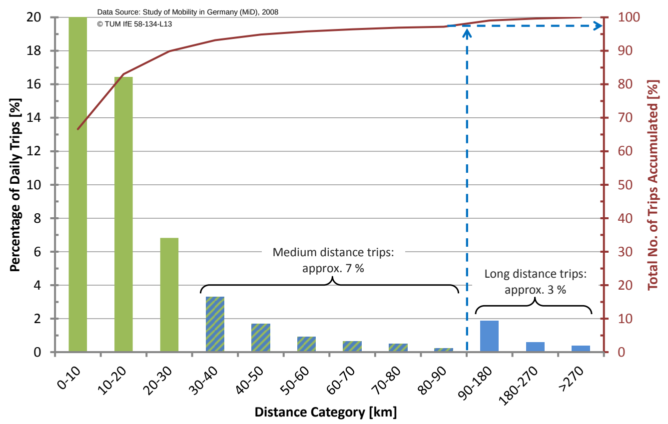

Figure 9: Distribution of daily trips according to trip length in Germany

Trips, which also may take advantage of range extension, are those classified in the diagram as medium distance trips. Due to the fact that statistically each vehicle on average commences three trips per day, BEVs would run into difficulties, if no opportunity arises to slow charge the vehicle's battery in between medium distance trips. Furthermore, research done on drivers with BEVs using battery switch technology in Israel and Denmark showed that battery switching is often conducted just out of convenience in comparison to slow charging the vehicle at home, work or at public charging spots [2]. Medium distance trips eligible for range extension statistically account for approx. 7 % of total daily trips.

Figure 10 depicts the average weekday distribution of range extension demand resulting from medium (green columns) and long distance trips (blue columns). Due to the nature of long distance trips surpassing the realistic driving range of BEVs with a fully charged battery, the distribution shows two peaks correlating with driving habits of leaving and returning to the one same place of spending the night. Contrary to this, the range extension demand of medium distance trips only peaks once later during the day. This can be attributed to BEVs easily completing their first trip, which still lies below the critical driving range discussed in Figure 8. However, trip number two and especially number three will – with increasing likelihood – require range extension the later the hour of day, statistically peaking at 5 pm and decreasing with ever fewer trips commenced in the late evening.

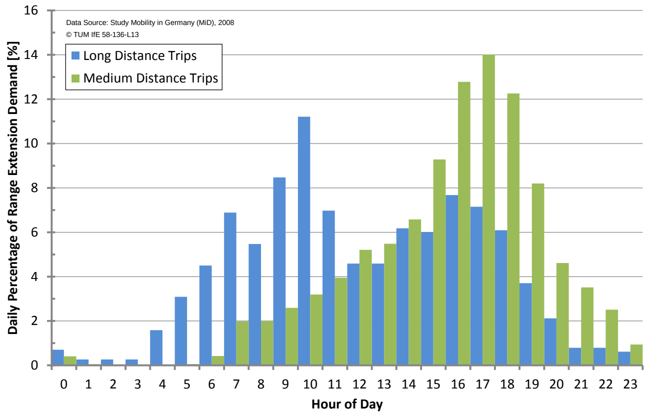

Figure 10: Average distribution of range extension demand resulting from medium and long distance trips on week days

2.2.4 The Resulting Power Demand for Range Extension

In order to assess the hourly power demand of BEVs at BSS or FCS, both distributions of Figure 10 are merged with a factor of 2:1 (medium to long distance trips), totalling to about 9 % of all commenced trips per day. Considering the BEV fleet size of a particular country and accounting for an average state of charge (when arriving at a BSS or FCS) of SOC = 20 % [2], the hourly power demand in each European country can be calculated.

Figure 11 depicts this power demand for the exemplary country of Germany, supplying range extension to a simulated fleet of approx. 350.000 BEVs. Correlating to the energy demand of BEVs in Figure 7, power demand peaks during winter on particularly cold days. The singular peaks recognisable are attributable to Sundays, the day of the week, where statistically most long distance trips are undertaken for leisure reasons. A second line of peaks approx. 30 MW below the Sunday peaks resembles normal weak day peaks as shown at 5 pm in Figure 10, also correlating with a higher demand during the winter months.

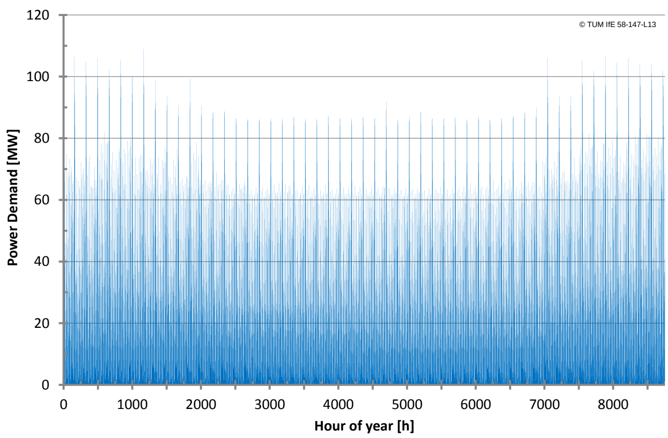

Figure 11: Power demand for range extension of BEVs in Germany 2020

Other northern European countries show similar power demand curves, while in southern European countries the demand curve peaks not only during winter, but also on summer Sundays, resembling in particular the higher cooling demand.

3. SIMULATION RESULTS AND ANALYSES

3.1 Allocation Methodology for Emissions and Costs

A possibility for allocating BEV emissions and costs is by means of the Parallel Market Method, described in detail in [1]. Effectively, this method focuses on the manner of power generation according to certain criteria for which electricity consumers are willing to pay a premium, thus creating another parallel electricity market. Specifically, this for example, can imply a low emission electricity production. Hence parallel to offering the basic service of providing power, electric utilities can also market the manner of power generation according to their ecological footprint. The primary energy source used and its manner of conversion to electricity determine the higher quality and justify a premium. This parallel electricity market is now specifically applied to BEVs such that emissions and costs of renewable energies are solely allocated to their power demands.

The method used here for matching supply and demand focuses on synchronising renewable feed-in simultaneously with the load curve of the fast charge or battery switch stations. This applies to every hour of the year, making it a challenge to accommodate the fluctuating nature of most renewable power generation technologies. It is termed "synchronised supply and demand". TÜV SÜD for example provides a certificate, which may verify zero emissions in the upstream primary energy chain of a BEV's power supply: "Certification Criteria: EE02 – Certification of electricity from renewable energy sources with a simultaneous supply" [12].

The advantages of the Parallel Market Method are a clear cut approach for allocating emissions and costs solely to the power supply of BEVs; hereby primarily BEVs benefit from the new renewable power system and only in a second instance other consumers profit from abundances of such a system, which may be sold on the open market of the European Energy Exchange in Leipzig.

In order to safeguard a zero emission power supply for FCS or BSS, a cost minimised renewable power plant portfolio is a prerequisite for utilities or green energy service providers. These portfolios provide the service of green electricity supply at the lowest possible costs. The optimisation tool URBS-EU was used to find the cost optimal portfolios for 27 European countries, each with their own fleet of BEVs requiring range extension.

3.2 Cost-Minimised Renewable Power Plant Portfolios

At first glance it might seem economically wise to invest in the renewable power plant technology with the lowest electricity generation costs (in €/kWh). To date onshore wind power would meet this prerequisite best, if it were only required to match supply and demand on the balance sheet. However, with the requirement of synchronised supply and demand needed to be fulfilled, renewable power plants with higher generation flexibility and more reliable periodically re-occurring feed-in become interesting. For example power generation from photovoltaics may have higher electricity generation costs (in €/kWh), however, their periodically re-occurring feed-in peaks at midday cover more reliably the demand peak of FCS or BSS and even match them to a certain degree. Thus, under certain constellations the most expensive renewable electricity generation technology, photovoltaics, is able to lower the overall system's portfolio costs.

This claim can be observed in Figure 12, depicting the URBS-EU cost optimisation results of renewable power plant portfolios supplying FCS in several European countries in 2020.

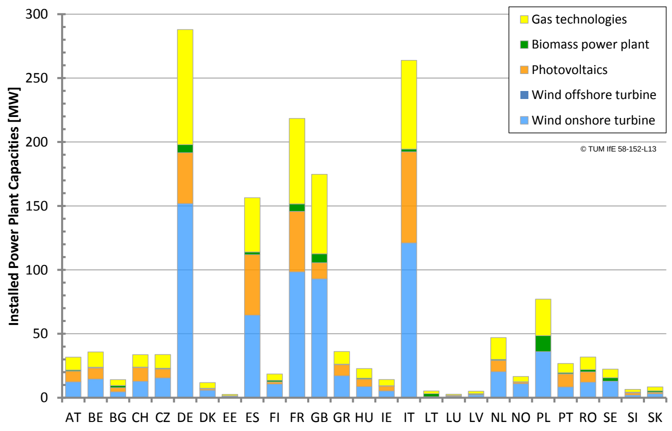

Figure 12: Comparison of the installed power plant capacities to supply FCS in European Countries 2020

When particularly comparing the cost optimised portfolios of the five countries with the largest estimated BEV fleets for 2020, Germany (DE), Spain (ES), France (FR), United Kingdom (GB) and Italy (IT), photovoltaics play an active role in lowering total system costs. This can particularly be observed for countries with high global irradiation sites in southern Europe. Offshore wind power, although technologically available, is not able to lower total system costs in any country and is thus not included in the renewable power plant portfolios.

Furthermore, it can be observed, that the combined capacities of gas turbines and biomass power plants equate roughly to the peak power demand of FCS on Sundays. In Germany (compare to Figure 11) this accounts for roughly 110 MW, in France, United Kingdom and Italy to 70 MW (relatively equal BEV sized fleet) and Spain to 40 MW. This makes clear that these two highly flexible power plant technologies must be held available for times, when neither wind nor solar power generate enough electricity to cover the load demand. Yet due to their higher variable operation costs and their CO_2 emissions, they are limited in use only to critical hours of high load peaks and meagre fluctuating renewable feed-in.

When considering the renewable power plant portfolios required to supply BSS in Figure 13, it becomes evident that fewer total system capacities are required to provide the same service of renewable power supply for range extension purposes of BEVs. This effect can be ascribed to the inherent possibility of delaying the charging of incoming depleted batteries to times with abundant renewable feed-in from wind and solar power. Effectively, when securing peak power supply, the combined installed capacities of gas turbines and biomass power plants can be reduced by approx. 30 % in each country (Germany 75 MW, France and Italy 50 MW, United Kingdom 40 MW and Spain 30 MW).

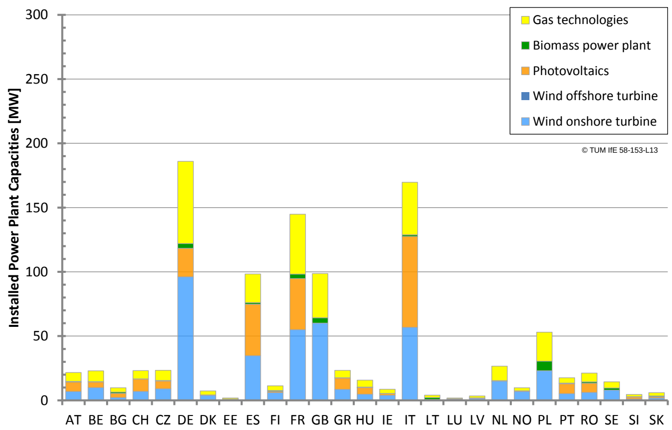

Figure 13: Comparison of the installed power plant capacities to supply BSS in European Countries 2020

The reason for this is made clear in a comparison between Figure 14 with Figure 15, depicting the coverage of the load curve of FCS in Germany with renewable power sources during an exemplary week in spring. The week begins on a Monday ending on the day with traditionally the highest demand peak for range extension: Sunday. While at the beginning of the week a high amount of electricity is provided by onshore wind turbines, this renewable power source fades continuously to remain only a sliver on Saturday and Sunday. Particularly during these critical two days the periodically reliable solar power feed-in from photovoltaics is still able to cover the first of the two demand peaks on weekends (before midday), however, not able to contribute to the second peak after midday. This second peak can be identified as the most problematic to cover throughout the year and thus determines the absolute amount of installed capacity from gas turbines and biomass power plants. As depicted in Figure 14, these two highly flexible power sources are required to step in with their full capacities, when all other renewable power sources fail.

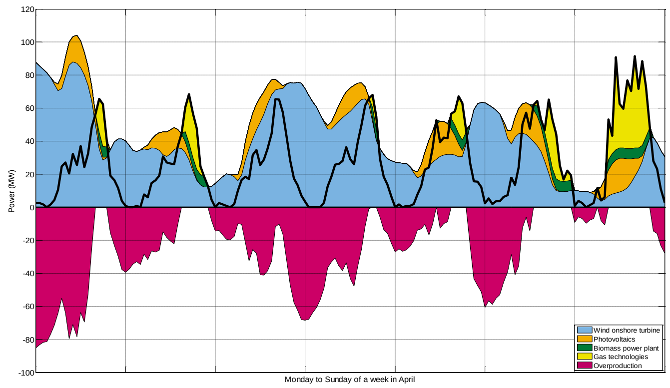

Figure 14: Coverage of the load curve of FCS with renewable energies in Germany 2020 (exemplary spring week)

In Figure 15 the same load curve during the same spring week in Germany is now depicted for a BSS: Evidently, solar and wind feed-in is lower correlating to fewer installed capacities. For the critical second peak at 5 pm the reserve batteries held at BSS step in and effectively lower the demand peak. The consequently depleted reserve batteries are charged again, when abundant renewable power is available (purple areas on the negative y-axis). This occurs mostly during the early morning hours (by wind power) and less often in summer during midday by solar abundance.

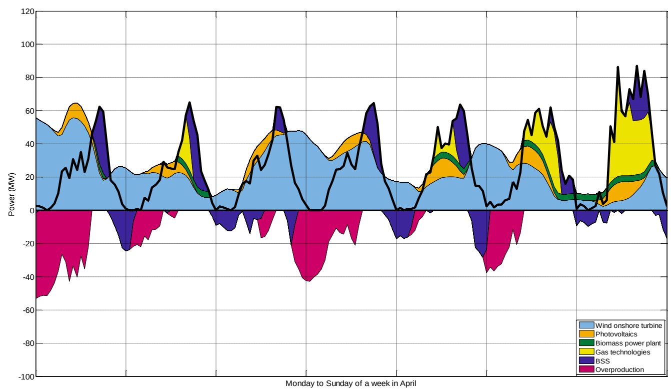

Figure 15: Coverage of the load demand from BSS with renewable energies in Germany 2020 (exemplary spring week)

BSS and their inherent capability of load shifting thus accommodate and integrate fluctuating renewable feed-in to a higher degree than FCS. Effectively the instances of renewable overproduction are lowered by a considerable degree. In comparison to Figure 14 the amount of abundant renewable feed-in (pink area on negative y-axis) is greatly reduced, as shown summed-up in Figure 16. At FCS abundances are higher by approx. a factor of 3, when totalling the overproduction throughout the whole year in Europe. While assuming earnings of only 0,03 €/kWh on the open electricity market, it becomes evident to limit these meagrely reimbursed abundances to an absolute minimum.

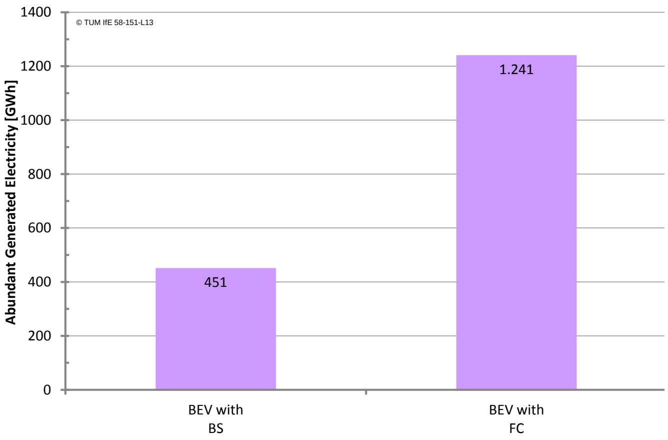

Figure 16: Comparison of the amount of overproduction from renewable power plant portfolios supplying BSS and FCS

3.3 Primary Energy Demand

In Figure 17 a comparison of the total primary energy demand in Europe 2020 is given between the three range extension technologies. The purple columns hereby show the composition of the specific primary energy demands, starting from equal effective energy demands (German "Nutzenergiebedarf") for all three technologies and their losses in the upstream energy chains of the final energy demand (plug2wheel or tank2wheel, German "Endenergiebedarf") and finally the primary energy demand.

BEVs using battery switch or fast charge require a bit more than half the amount of primary energy. This is due to the highly efficient generation (η_{eff} = 1), transmission (η_{eff} = 0,92) and BEV usage (η_{eff} = 0,81) of primary energy from renewable sources generating electricity. While the extraction and refinement of crude oil to E10 benzine (η_{eff} = 0,9), its transportation to filling stations (η_{eff} = 0,98) and its evident use in the micro ICE (η_{eff} = 0,36) including its conversion to kinetic propulsion energy (η_{eff} = 0,73), requires more than double the amount of primary energy. Most of this primary energy demand will necessitate a majority of crude oil imports from countries outside of Europe in 2020.

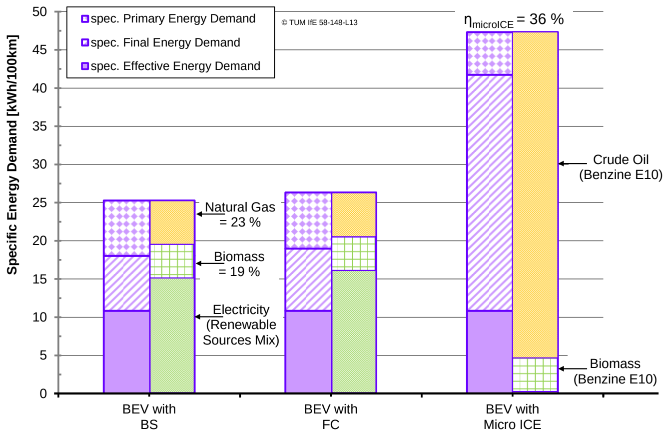

Figure 17: Average primary energy demand for range extension purposes of BEVs in Europe 2020

3.4 CO_2 Emissions on Primary Energy Basis

Correlating to the primary energy sources, the specific CO_2 emissions in gCO_2/km attributable to the three BEV types and their range extension technologies can be observed in Figure 18. The seldom but indispensable usage of natural gas (202 gCO_2/kWh_{therm}) as a primary energy source for electricity production results in BEVs receiving fully charged batteries at either BSS or FCS to be responsible for approx. 12 gCO_2/km. This stands in stark contrast to the 110 gCO_2/km attributable mostly to tail pipe emissions of the micro ICE, as a result of the use of E10 benzine (233 gCO_2/kWh_{therm}). The only option to avoid this would be the use of a biomass or hydrogen (methane) based fuel carrier, which then again would include even higher efficiency losses in the primary energy chain.

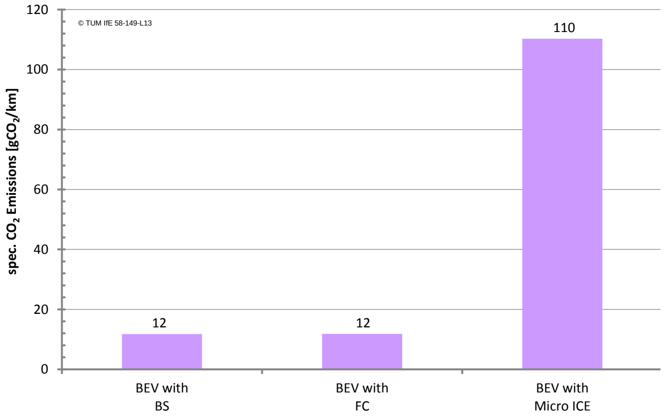

Figure 18: Comparison of the average CO_2 emissions attributable to BEVs for range extension purposes in Europe 2020

3.5 Primary Energy Generation Costs

On the costs side, the comparison between the three range extension technologies is done on the basis of primary energy generation costs. The advantage is hereby, that all taxes placed on fuels and electricity and distinct to each European country do not distort the comparison and are thus excluded. Furthermore primary energy generation costs show the minimum net worth of a commodity required to provide the process of mobility with BEVs.

Figure 19 depicts this cost comparison visualising the high cost advantage of renewable power generation. The generation costs excluding any taxes are based on the equivalent annual cost calculation, considering investment and operation costs of the renewable power plant portfolios and their amortisation over an average period of 20 years with a 6 % interest rate. Abundant renewable energy generated and unused by either BSS or FCS are treated as income and sold for 0,03 €/kWh via the open electricity market. The higher installed capacities necessary to constitute the renewable portfolios of FCS are responsible for higher specific costs per 100 km. Even selling a greater amount of abundant energy on the open market cannot compensate this cost difference, which concludes that this measure is of last resort before discarding abundant energy altogether.

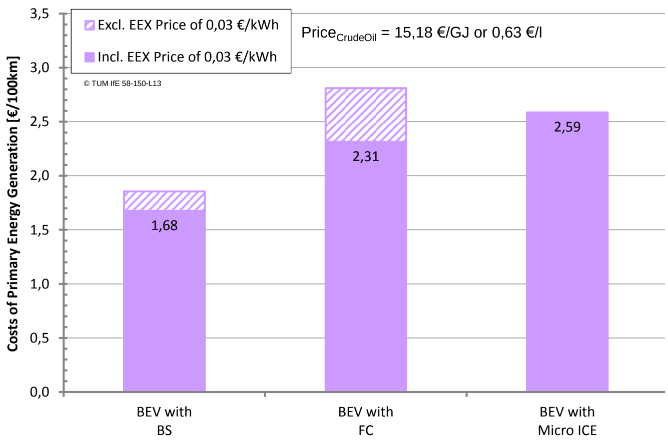

Figure 19: Comparison of the specific primary energy generation costs on average in Europe 2020

Calculating the specific primary energy generation costs of a BEV with micro ICE technology reveals that the high inefficiencies of converting the primary energy carrier, crude oil, into forward propulsion of the vehicle is the driver of the high specific costs. This holds true for an assumed crude oil price in 2020 of 100 $/bbl, which is the benzine equivalent in Germany of approx. 1,70 €/l under today's taxing and currency conversion rates. Thus, from an energy economic perspective the same goal of covering the necessary effective energy demand (forward propulsion) of BEVs for range extension purposes comes at the most efficient and lowest cost when implementing BSS.

4. CONCLUSION

BEVs with battery switch technology:

- require fewer renewable energy capacities to cover their charging demand.
- integrate fluctuating renewable feed-in more efficiently (less overproduction).
- are responsible for the least amount of CO_2 emissions.
- have the lowest primary energy generation costs (excl. taxes).

It therefore can be concluded that BEVs with battery switch technology have a significant energy economic advantage in comparison to BEVs with fast charge or micro ICE technology. Their energy economic advantages are considerable and thus should be considered as a genuine alternative to extend the driving ranges of BEVs with depleted batteries. BEVs in general and in particular for long distance trips with battery switching technology prove to be potential future drivers for renewable energy integration and thus sustainable mobility in Europe.

5. ACKNOWLEDGMENTS

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