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ELECTRIFICATION OF TRANSPORT BY RENEWABLES

Dr.-Ing. Frank Mayer, Christian Strafiel, Dr. Jens Winkler
WRD GmbH, ENERCON GmbH, Aurich, Germany
frank.mayer, christian.strafiel, jens.winkler@enercon.de

Executive Summary

Making the electrification of transport a success story requires that we find a way to deliver the additional energy demand by renewables without overwhelming costs for grid enhancement.

Reducing local emissions and the CO2-Footprint of mobility are main drivers for the current trend towards battery electric vehicles (BEV) worldwide. With reference to the Paris Goal to reduce global warming to 2°C, it is obvious that the electricity used in BEV will have to be generated by renewable sources – only.

This paper investigates several aspects including current end user concerns such as range anxiety, expected use patterns for future BEV and a suitable charging infrastructure to match these use patterns. Furthermore, considerations of BEV charging station operators, distribution grid operators as well as the need for public infrastructure investments and changes in regulatory and market frameworks are discussed.

An approach for a modular technology that allows parallel high power electric vehicle charging and provision of grid stability services such as infeed of reactive power in weak grid areas is introduced. This technology is of particular interest to operators of highway service centers, owners and operators of distribution systems and operators of car fleets such as taxis, car-sharing and public transportation but also to automotive Original Equipment Manufacturers (OEM), who need to rely on the availability of a charging infrastructure that is able to grow for future demands.

Keywords: renewables, renewable sources, electrification of transport, electricity generation, energy demand, charging infrastructure, grid requirements, power quality, distribution network, grid expansion, high power charging, HPC2, fast charging, electric vehicles, BEV, grid support, FACTS, reactive power, power factor control, buffer storage

1 Electrification of Transport

Reducing local emissions and the CO^2-Footprint of mobility are main drivers for the current trend towards battery electric vehicles (BEV) worldwide. With reference to the Paris Goal to reduce global warming to 2°C, it is obvious that the electricity used in BEV will have to be generated by renewable sources.

This results in five main questions with regards to future charging infrastructure:

- How can BEV fulfill typical use patterns in the future
- Is there enough renewable energy available for CO2 free BEV charging
- What are the technical requirements for a charging infrastructure from an electrical grid perspective
- Under what conditions do investments in BEV charging infrastructure make sense
- Do suitable BEV fast charging options exist today

The following paragraphs will address each of the above questions in detail.

1.1 Requirements regarding typical use patterns

Following the goal to transform a high percentage of classic combustion engine cars to BEV means to make them suitable for different use patterns, including the need to drive long distances without having stops of several hours to charge the battery in between.

One of the first questions could be: What does “long distance” mean? Some studies show, that a high percentage of use patterns for cars are in a range of up to 100 or 200 miles (app. 160 or 320 km) [1], Fig. 1.

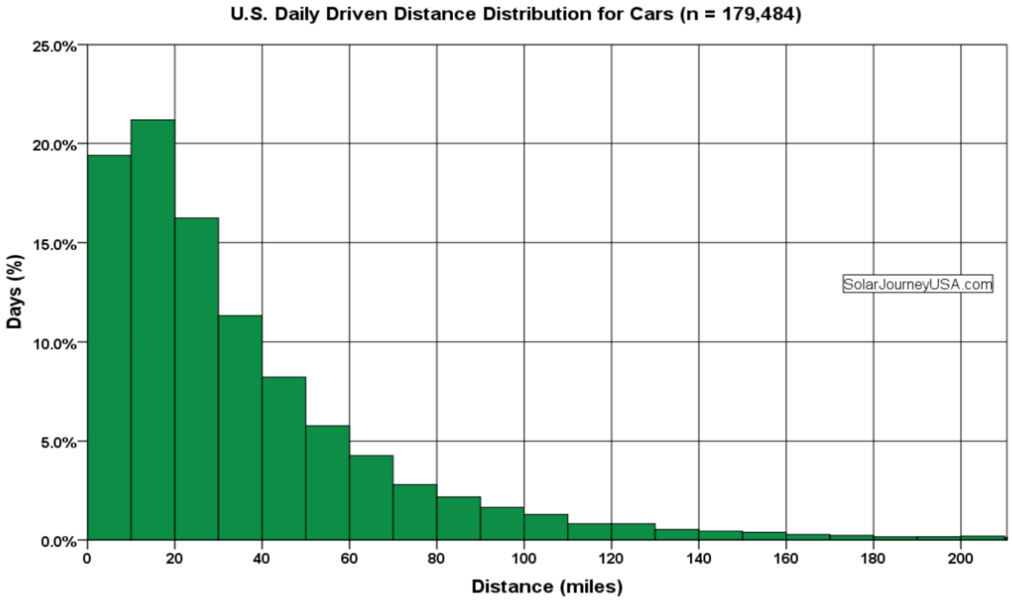


Figure 1: Evaluation of typical distances driven during one day with an individual car. [1]

The evaluation for the US depicted in Fig. 2 (ref. “Additional Figures”, page 11) shows, that 93% of the driven distances per day are below 100 miles (app. 160 km) and there are only 1,5% above 200 miles (app. 320 km). A conclusion out of that could be that 93% of individual cars in the US could be switched to BEV if a realistic range of 100 miles can be achieved with these BEV.

Another study [2], performed in Sweden exclusively with two-car households, shows that the 7% exception of a required range higher than 160 km is a crucial argument to have at least one car with a classic combustion engine meaning with a higher range. This is depicted in Fig. 3, where in the upper left picture an average of the participating households is shown, whereas the other pictures show different specific households. In all the pictures the "Persistant car" is one with a classic combustion engine and the second car is replaced by a BEV for the time of the study.

In [3] the results for Sweden and Germany show that a majority (70%) of second cars fulfils all their driving at a range of 220 km or below, meaning that 70% of second cars could be replaced by BEV without any downside, if the BEV had a realistic range of at least 220 km. Adopting this to first cars in two-car households would require a range of at least 390 km [3] to be able to replace 70% of these by BEV.

In summary, the answer to the question what "long distance" really means is approximately between 200 and 400 km.

Having these figures in mind, range anxiety can be a crucial argument for BEV users or - being correct - for potential users against buying a BEV. To avoid this, the availability of a fast charging network – such as High Power Charging solutions along the main traffic routes - is inevitable. Long distance driving – whatever distance is required – becomes possible, as soon as the charging times decrease to a level that is comparable to how long it takes to fill up a gas tank.

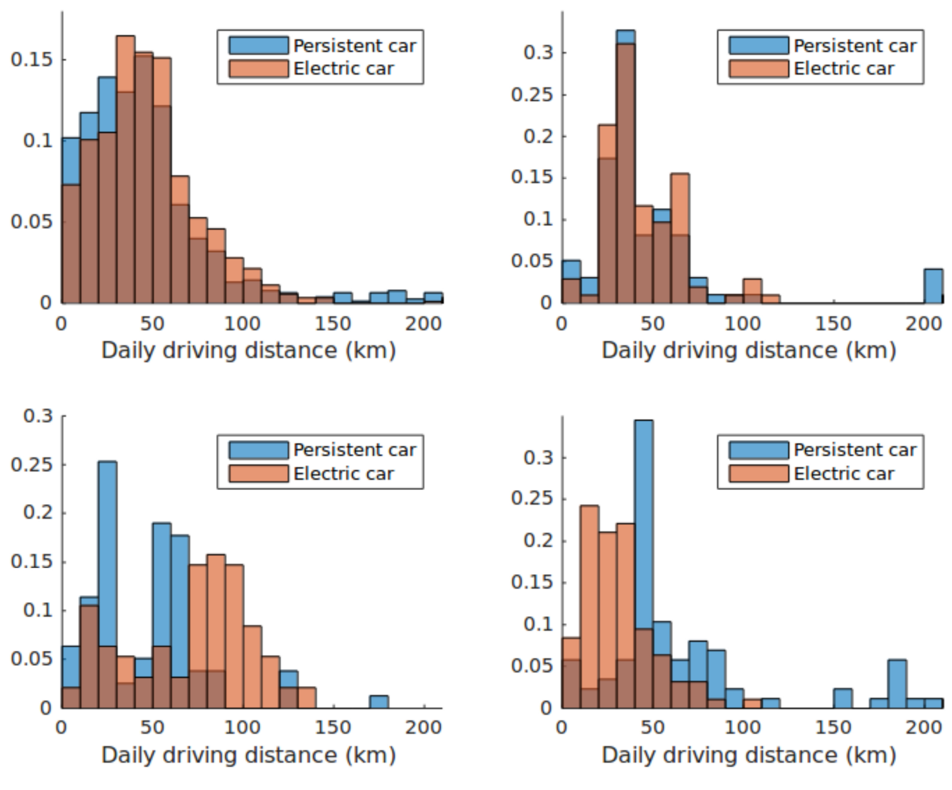
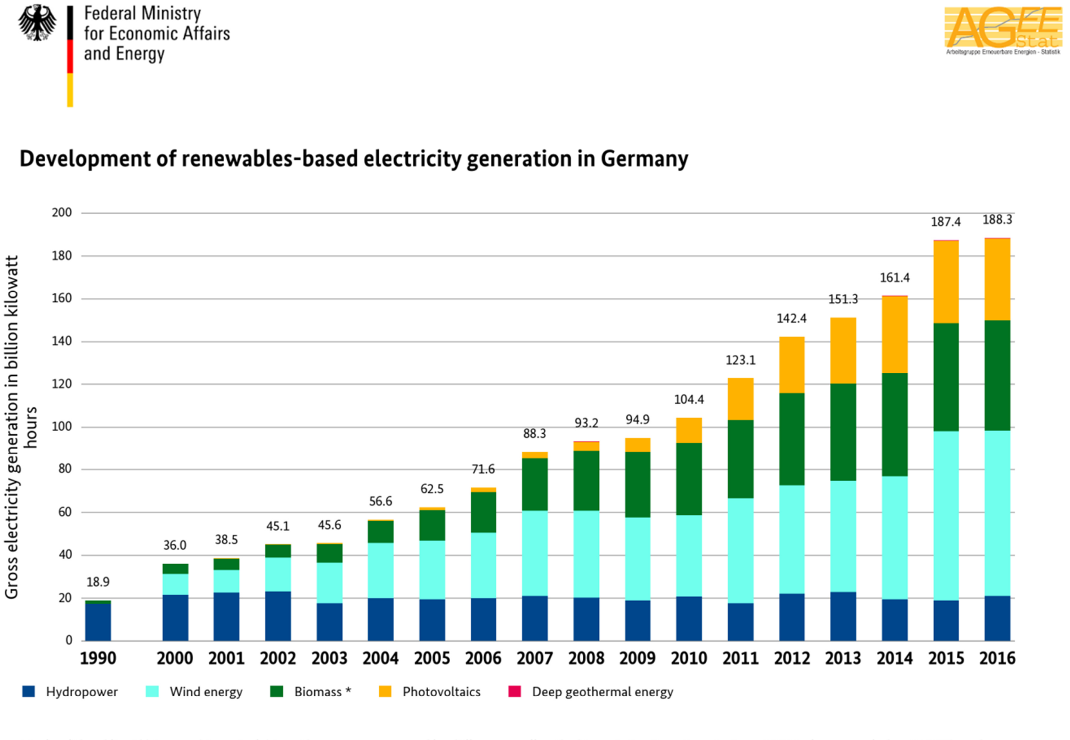


Figure 3: Evaluation [2] of daily driving distances in two-car households. Blue colour shows the conventional car, light brown shows the BEV and dark brown marks overlap between the two cars.

1.2 Availability of renewable sources

Today, in Germany about 535 TWh of electric energy are consumed per year. Also taking efficiency gains into account, this number will roughly double to 1000 TWh p.a. by 2050, as mobility and heating will successively be electrified [4]. But can the increasing electric energy demand be covered by renewable sources? An overview of the increase of renewable electricity generation of the past years is given in Fig. 4.



* incl. solid and liquid biomass, biogas incl. biomethane, sewage gas and landfill gas as well as the biogenic fraction of waste, from 2010 incl. sewage sludge; BMWi based on Working Group on Renewable Energy-Statistics (AGEE-Stat); as at February 2017; all figures provisional

Figure 4: Development of renewables-based electricity generation in Germany
(source: http://www.erneuerbare-energien.de)

The success of Germany's energy transition, the Energiewende, implies a substantial change in energy policy. The Energiewende includes a realignment of strategy from a demand-driven to a supply-driven system as well as a transformation from centralized to distributed electric energy generation. The policy has resulted in a significant expansion of renewables. The installed wind energy capacity makes up for more than 50 GW as of 2016 and contributes 12 % to Germany's electricity production, as shown in Fig. 5 (ref. "Additional Figures", page 11). Even excluding areas inhabited by special species and enlarging the distance from wind turbines to residential buildings it becomes clear that the availability of renewable sources is not a show-stopper for zero carbon e-mobility, as other additional sources like photovoltaics (PV) have a potential of about the same installed capacity as wind.

Based on recent studies about 14 % of the land in Germany is suited for onshore wind energy from a technological and ecological point of view. This equals to a potential electric energy generation of about 2.900 TWh p.a. [5].

Besides the fact that electric energy generated from renewable resources is CO2-neutral by definition, moving towards renewable energy has a second important effect mostly overlooked: It also reduces CO2-emissions by pushing economy to more efficient power usage technologies on the demand side. For example, a heat pump leverages the energy input by a factor of 1:3.5 by extracting energy from up to now untapped resources – the ground or air surrounding a building. And using an electric car improves efficiency from the 30-40 % for a car with combustion engine to 80-90 % of a car with an electric motor.

Thus, we will see an electrification of many processes. Despite tremendous efficiency gains, this will lead to a considerable shift of energy usage in the sectors power, heating and mobility, and the need for electrical power will almost double as compared to today as fossil fuels have to be substituted.

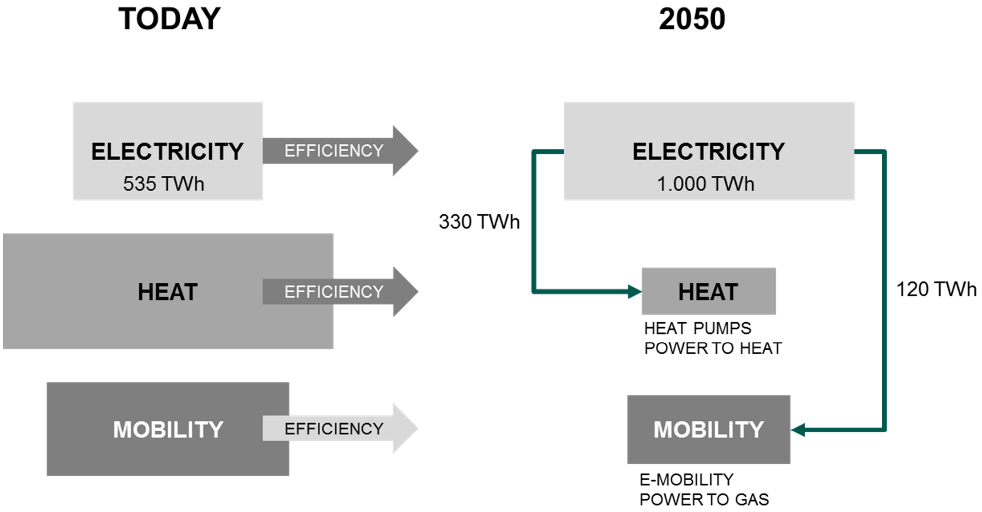


Figure 6: Expected development of energy demand [6]

As current renewable resources contribute a third to todays electricity consumption and consumption will double by 2050 renewables electricity production would have to increase by a factor of six. Is this realistic?

Let’s look at this question from an economical and a technical point of view:

Economically, it can be shown, that the value of the energy transition is positive when considering a period of about 40 years with a rate of return of about 2.3 % p.a.. If taking the difference between savings from fuels not used and investments in new technology as a measure for the capitals saved in the Germany economy, we find a positive contribution starting around 2030 and a considerable surplus in 2050 mostly consisting of the residual value of the investments made in the years before. An optimization has shown, that a mix of 50 GW offshore wind, 180 GW onshore wind and 200 GW PV to be economically ideal (whereas a deviation of +/- 10% does not make a real difference economically) [6], Fig. 7 (ref. “Additional Figures”, page 11).

Technically, it turns out that producing 1000 TWh p.a. from wind and PV comes close to limitations of land use – but it is still possible: Geographic Information Systems (GIS) based studies of Germany have shown, that in principle 14 % of the land is suitable for onshore wind energy [5]. This corresponds to a potential of 1188 GW for onshore wind. But this potential is highly dependent on the assumptions taken, especially the assumptions for the distance to residential areas. As this parameter is under political discussion right now, we’ve taken a more conservative approach and chosen a distance of 1.200 m instead of 600 m. This reduces the potential by 75 % to about 330 GW.

Recent announcements of manufacturers seem to point in a direction with an increase in wind turbine nominal power . Whereas an average wind turbine made up for 2.77 MW in 2013, this number rose to 2.86 MW per wind turbine in 2016 (ref. DEWI GmbH). However, this trend can be neglected from 2013 to 2017, and cannot compensate for increased distances to residential buildings. Similarily, it can be shown, that the 200 GW PV needed – which is five times the installed capacity of 2016 – stands for 1000 km² module area. This corresponds to about 2 % of the area taken up by buildings and roads or 8 % of Germany’s residential area, respectively [6].

This shows, that the technological potential and the economical need for renewable resources are in line even in a densely populated country like Germany. However, decentralized renewable energy supply is also associated with technological und economic challenges. Potential solutions include an optimisation of the interaction between energy producers, consumers and storage batteries for a prospective establishment of Smart Grids [7].

1.3 Grid Requirements for High Power Charging

Anticipating the future additional amount and characteristics of electricity demand from BEV charging, especially distribution grid operators will have to think about new concepts to minimize impacts on their electric networks [8]. Regulatory frameworks may have to be adapted to future needs. As an example, current practice to dimension the entire grid infrastructure for worst case maximum power demands will be too conservative and costly.

Taking into account that there are already successful examples for an optimization of decentralized grid use patterns and the fact that there are options for decentralized grid support activities and electrical storage components available, grid expansion may be deferred or even avoided completely.

The main goal to cope with the power demand in areas where the grid is originally weak, without having to invest large amounts in new infrastructure can be achieved by supporting the grid voltage through an adequate infeed of reactive power. Therefore the ability of a BEV charging infrastructure to provide reactive power to the grid besides drawing active power is necessary. This feature can be fulfilled by using a full converter as an active front-end to the grid.

1.4 Investment aspects for Charging Infrastructure

As the uptake of BEV and charging standards in different markets is widely unknown, it will also be important to avoid stranded investments, but to still offer high power charging (HPC 2) standard [10] nevertheless. Innovative modular charging systems can be installed today and successively be upgraded with inverters as more BEV enter the market. Business models will be easier to create, if the basic investment is very modest and further modular enhancements are only necessary when the business model has already shown positive figures.

Over the recent years, we’ve noticed a number of new entrants in the EV-charging market. These are either specialized companies, or classic utilities searching for a new field of business or local municipalities.

In total, about 20,000 public charging positions have been set up by now (ref. http://www.eafo.eu/ content/ Germany). This corresponds to 34,022 full-electric cars. (ref. https://www.kba.de/DE/Statistik]. Thus, it becomes clear that making a business case from public charging infrastructure is still unrealistic.

Based on the main drivers of a business case, requirements for a positive outcome are identified to be:

- Frequency of charging
- Consumption per charging event
- Investment (Capex)

The first two items are mostly determined by the location (e.g. highway, restaurant parking, , …) and cars in the market (e.g. share of BEV, battery size, driving pattern, …). These requirements have to be taken into consideration in a roll-out plan of an BEV charging infrastructure owner carefully.

Let’s now look more closely at the third point: Ideally, one would start with the lowest possible investment per site. Unfortunately, this does not hold for an important barrier for market success: fighting the range anxiety, the fear of being stuck with an empty battery. Therefore, we have to start with an overarching fast charging infrastructure. In contrast to an already existing infrastructure that is reserved to one particular make of car, a truly public approach has to satisfy all relevant charging standards. According to current car-makers announcements, this will finally be a 350kW CCS charging variant. But this might be overinvesting in a market that could develop slower than expected.

Therefore, we suggest a modular approach that both satisfies the need for low investment and sustainability: A base unit could provide a system power considerably less than the sum of all charging points in a system to lower investment for inverters and grid connection. Once, high power vehicles contribute a considerable share to the market, only the base unit has to be reinforced or multiplied to satisfy the new need for power. Stranded investments can be avoided.

In addition to this, a modular concept also responds to the need for volume for a commodity product like charging infrastructure.

All the mentioned aspects help to ensure, that the total investment of a charging station is in an appropriate proportion to the costs of a single charging point and the distributed amount of energy. Therefore short charging cycles by high charging powers should be aspired, so that the single charging point can be supplied to as many end users as possible.

1.5 Current fast charging options for electric vehicles

As can be surveyed most ‘quick’ charging points – with the exception of Super Charging network of up to 120 kW chargers of a Californian OEM - only offer a charging capacity of 50 - 60 kW (DC, CCS or CHAdeMO), meaning that charging and thus waiting times still exceed one hour, provided the battery capacity exceeds 50 kWh.

The previously mentioned Californian OEM demonstrated impressively, that a key component for a successful sales strategy is the availability of a reasonable charging infrastructure, installing 5000 of the so-called “Super Charger” worldwide till end of 2016 and increasing the number to more than 10.000 end of 2017. A very good overview of the European charging infrastructure can be found on the website of the European Alternative Fuels Observatory (EAFO): http://www.eafo.eu/electric-vehicle-charging-infrastructure.

From the writers’ point of view only the upcoming standard known as ‘High Power Charging 2’ (HPC 2) with a charging capacity of up to 350 kW (DC) can be regarded as quick; it allows vehicle batteries to reach an SOC of eighty percent in just a few minutes.

2 Electric Vehicle High Power Charging in the Future

The fast charging solution presented in this paper already meets the advanced new HPC 2 standard. In addition, the new technology has many characteristics which can support the electric network they are connected to be labelled as “grid-friendly” and follow the well-known rules for existing Wind Energy Converters (WEC).

A pilot recently introduced at the 2017 Hannover Trade Fair represents one approach of future quick charging solutions. It is based on already existing technology that is used for connecting DC battery outputs of energy storage systems to AC grids. The key components of this Power Conversion System are inverters, which have been used in wind turbines for more than 30 years.

It is apparent that by exploiting the opportunities of power electronics drawing power from the grid can be done very smooth and also completely balanced. The current flow from the supply grid used to charge vehicles is then nearly sinusoidal so it minimises harmonic effects during fast charging. Reactive power is fed into the grid in parallel, to help maintaining a normal grid voltage at the connection point. The project task was that the newly developed system must be compatible with global grid guidelines and requirements relating to grid feed-in quality. The result is that connection is possible at a low- or medium-voltage connection point designed for rapid and grid-friendly charging.

2.1 Grid voltage support from charging infrastructure

One of the main tasks for the grid operator having high power charging stations installed in his medium or low voltage network is to maintain a suitable voltage level for all connected customers. Especially the randomly used charging power will cause fast and high gradients in the voltage present in his network. To counteract the problems of the voltage fluctuations the charging station offers the ability to feed reactive power to the grid. In order to have a convenient solution for mitigation of voltage fluctuation problems the station offers various strategies to control the reactive power support. Starting from the infeed of constant reactive power over power factor control up to Q(U)-control, just to give some examples. All these different strategies can be parametrized in the control system of the charging station directly or, if the grid operator wishes so, controlled via all different kinds of standard remote control systems from the grid operators control center.

As an example for the voltage support the voltage distribution in a medium voltage grid has been simulated. To compare the different situations the simulation was done without any charging infrastructure installed, then with a standard charging station installed and last with a charging station feeding reactive power and having a voltage controller installed.

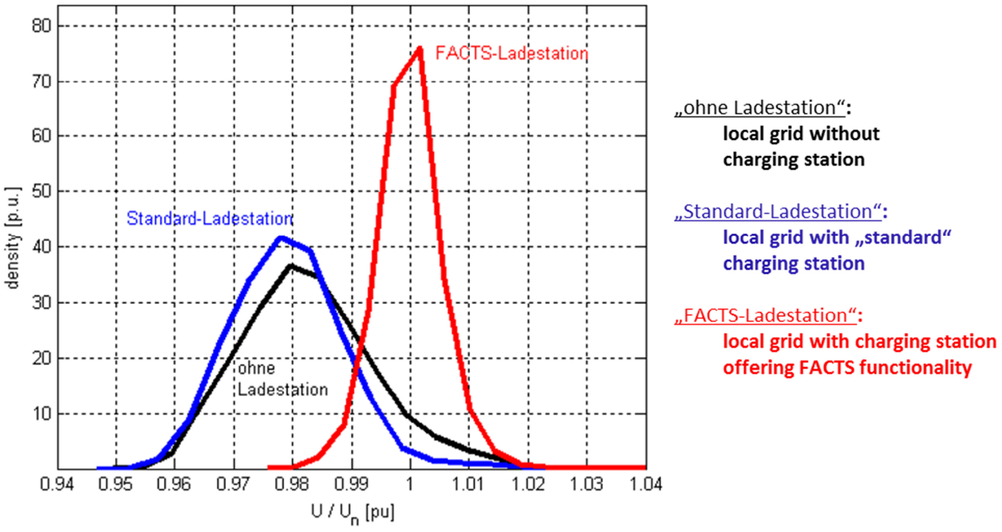


Figure 8: Simulated [4] spread of voltage in a local grid with different charging station options

2.2 Charging Power reduction on grid demand

The maximum power that can be drawn from an electric network at a specific connection point is set by the relevant operator based on calculations reflecting a worst case scenario for the existing loads on a round the clock base. In reality there often is the possibility to draw power above this limit without exceeding any physical limitations. To make best use of this situation at existing grid connection points the charging station offers the ability to react to given power limitations that are sent by the grid operators control center. So it becomes possible to draw the maximum power not violating any physical limits, whenever other loads operate below their maximum, which is the case most of the time. If the grid operator does not support the charging station with an online maximum power setpoint a second option comes into place. It is possible to install own measurement devices in the substation the charging station is connected to, to measure the overall substation power. Thereby the charging station can on its own determine the remaining power for charging purposes summing up to a maximum value set by the grid operator for the overall substation power.

Using one of the possible options, a charging station can be installed even in existing grids making use of the stochastical behaviour of charging and all other loads. As a result more existing grid connection points can be used for charging purposes without grid reinforcement measures. The charging station will be able to draw maximum power most of the time reducing its power demand only when necessary in peak hours.

2.3 How is the Power Managed in the Charging Station

The heart of the High Power Charging BEV Station presented in this paper is a set of two inverters with a total nominal active power of 600 kW. Focusing on reactive power only there is a maximum capacity of 500 kVar if only grid support is required.

Based on an intermediate DC link the available power is distributed to power converter units of 60 kW nominal power each. These units are galvanically isolated and perfectly correspond to the power demand of DC fast charging of today's BEV. Required voltage and current for the charging processes are given by the battery management systems of the BEV. By choosing between parallel or serial operation of the internal converter units the nominal voltage can be adjusted up to 1000 V and the current can be regulated up to 350 A on a 1000 V basis, or up to 500 A on a 500 V basis. By an intelligent power distribution system, a power of up to 350 kW can be routed to each of the charging posts.

In Fig. 9 some examples of actual power distribution to four charging posts with one power station are shown. Each time a BEV is connected to one charging post of the charging station, the battery management system (BMS) of the car will build up communication to the charging station and based on the requirements of the BMS and the driver of the car the charging process will be started.

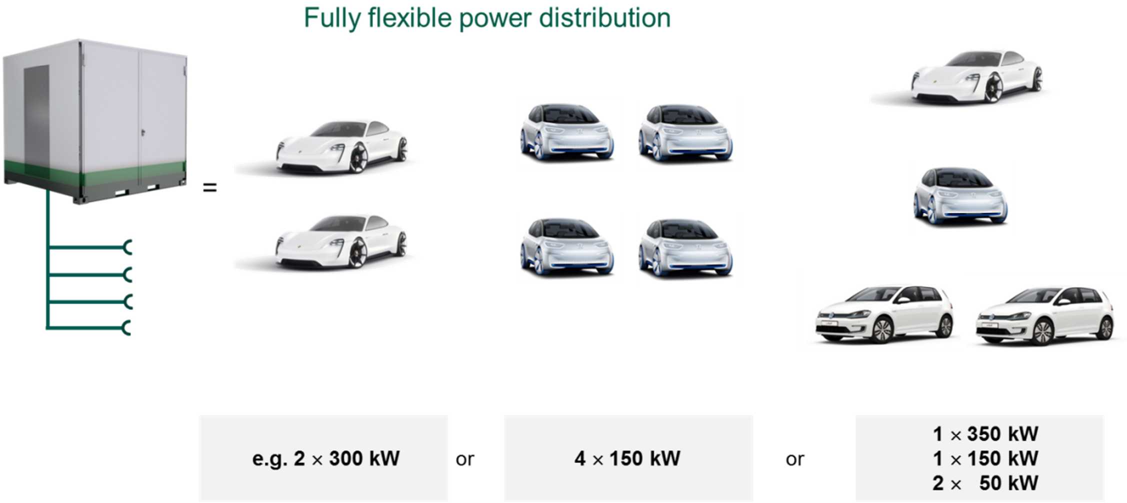


Figure 9: Examples for the fully flexible power distribution of ENERCON's High Power Charging Station

To have a power of 600 kW available at the grid point of contact (POC) the typical connection point will be to the medium voltage (MV) grid. In Fig. 10 a possible configuration of the standard charging solution is depicted. The POC on the MV-Grid could be e.g a shared POC with a wind farm, to have the physical availability of renewable energy at the same location. In other cases the renewable energy could be available in the grid just by balance sheet.

The MV-Container – as depicted in the figure – can also be a standard MV-station, comparable to the stations that are already available in the grid of a specific operator. In a standard configuration – based on BMS of currently available BEV – one Low Voltage (LV)-Container with four charging posts are proposed. This can be modified to the needs of the specific operator. More important than just adaptability is the characteristic expandability. For future needs the system can be expanded modularly by additional LV-Containers, transformers with a higher power or e.g. a battery buffer storage.

2.4 Additional Use of Buffer Storage

In case the grid connection is very weak and all the measures discussed in chapters 2.1 and 2.2 are not enough to fulfill the needs of the charging cars there is an option to install a buffer storage system at the spot of the charging station. Having the battery system on site the grid connection can be used 24/7 drawing just as much power as the grid can deliver to keep the buffer storage full. When a high power vehicle then arrives for charging the instantaneous high power demand can be served drawing part of the power from the grid directly and all the further power needed from the buffer storage.

If combined with other sources of income, such energy storage units may also support the so far difficult business case for BEV charging infrastructure.

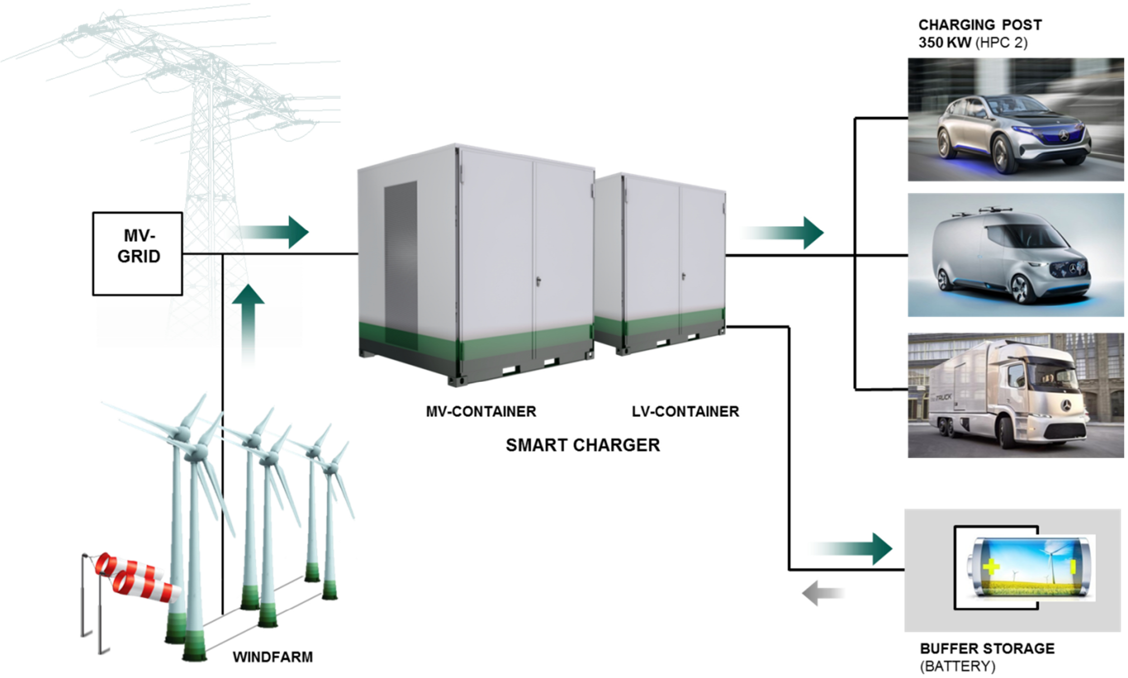


Figure 10: Possible configuration of future HPC 2 charging station

3 Conclusions and Outlook

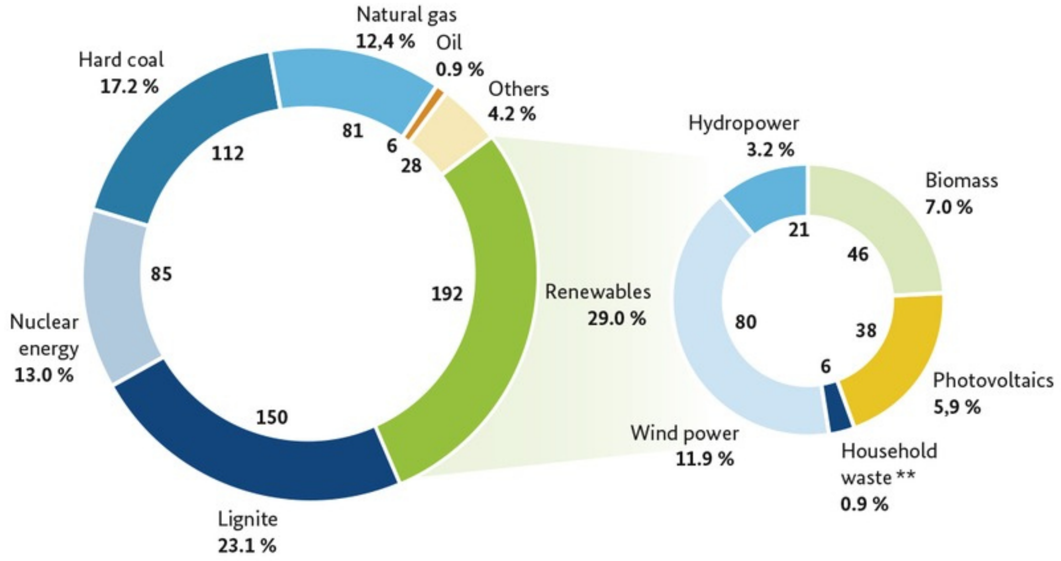
To make the electrification of transport a success story the following aspects, discussed in the present paper require to be taken into account or technical solutions will have to be presented:

- minimum realistic driving range of BEV of about 200 – 400 km
- increase of electricity generation by renewable sources
- adaptation of grid requirements and legal aspects to future needs
- increase willingness of public sector and industry to invest in charging infrastructure
- availability of high power electric vehicle charging infrastructure along main traffic routes
- increase of BEV types that are ready to be DC (ultra fast) charged

Current economic and regulatory framework conditions on the German market are slowly changing. Other European countries support the electrification of transport sector more already today. Good examples are tax exemptions for private use of company BEV in the Netherlands, or the supported installation of charging infrastructure in some neighbouring countries. There is a lot of work to be done to convince decision-makers before all the singular steps – that are strongly interconnected and can be influenced by different groups – fit together and lead to a successful change in the transportation sector.

Additional Figures

Figure 2: Cumulative percentage [1] of daily driven distances with individual cars.



* Preliminary figures ** Regenerative part

Figure 5: Electricity production in billion kWh and percentage in 2016 (source: Electricity production in billion kWh in 2016 https://www.bmwi.de/Redaktion/DE/Dossier/erneuerbare-energien.html, downloaded May 8th, 2017)

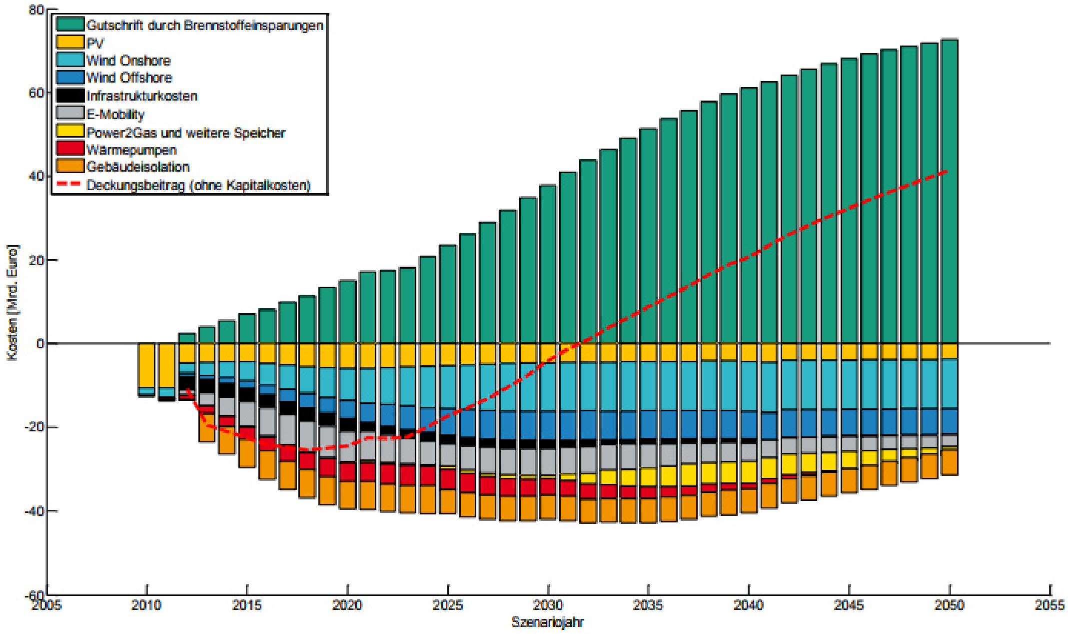


Figure 7: Simulation of marginal return development for different szenarios

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Authors

	Dr.-Ing. Frank Mayer studied Electrical Engineering and elaborated his PhD-Thesis in Computational Electromagnetics at University of Technology Darmstadt. After more than ten years of experience in consultancy, project management and cost center responsibility in engineering services, he changed to Wobben Research and Development (WRD) GmbH, to put all his effort in the development of new technologies to provide solutions for an intensive use of renewable energy in other sectors, e.g. transport.
	Christian Strafiel studied Electrical Engineering at the University of Applied Sciences Würzburg-Schweinfurt where he received his Dipl.-Ing. (FH) degree in 2010. Since 2009 he is with Wobben Research and Development (WRD) GmbH. Here he is working in the field of control systems for the grid side converter of wind energy converters. He also is working in the field of high power Charging solutions for electric mobility and especially the development and grid behaviour of those.
	Dr. Jens Winkler is a graduate physicist (University of Göttingen and University of California at Berkeley) and holds a doctorate degree of economics (University of Oldenburg). Since 2011, Jens Winkler has been responsible for the development of future-oriented energy systems in the ENERCON Group. In this position, he is responsible for the direct marketing segment and various pilot projects using battery storage and power-to-gas plants. Prior to this, he was responsible for the strategy, organizational and optimization projects at the regional provider N-ERGIE Aktiengesellschaft in Nuremberg as Head of Corporate Development since 2004. His first occupational post was from 1999-2004 the management consultancy Booz Allen Hamilton, where he carried out projects along the entire energy industry value chain for utilities.