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Analysis of Renewable Energy Power Demand for Specifically Charging EVs

Research Report: Better Place

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1 Broad Context and Research Objective

The planned introduction of electric vehicles (EVs) into the mass market over the next coming decade holds many opportunities for dealing with environmental and economical mobility challenges of the present. In Germany alone the transportation sector accounts for roughly a fifth of primary energy demand and carbon dioxide emissions. In addition there is no other sector, which is so outright dependent on a single primary energy source – crude oil – than the transportation sector. Its susceptibility to price hikes and security of supply is hence excessively high. EVs thus hold the opportunity of shifting the energy carrier for individual mobility away from oil to any arbitrary energy carrier in the power generation sector – these being renewable, fossil or nuclear based energy sources. Furthermore the transportation sector's degree of energy utilisation averaging below 20 % in common well to wheel analyses makes it one of the most inefficient sectors of developed economies.

Research conducted at the Institute for Energy Economy and Application Technology (IfE) at TU München identifies and analyses changing implications for the German power plant mix of the future, its operation pattern, costs and emissions. A series of published papers describes the interactions between EVs, Germany's power plant mix and the role of renewable energies [3 and 5]. The focus of this proposed research study lies in a detailed analysis of determining the necessary power generation capacity to supply the Better Place electric mobility concept for Germany with a high amount of renewable energy. Better Place thus intends to provide a charging concept in Germany, which should only seldom make use of thermal power generation

Figure 1 portrays the main leverage factors of this research objective, involving a comparison between Better Place's concept of battery exchange stations (BES) and commonplace fast charge stations (FCS).

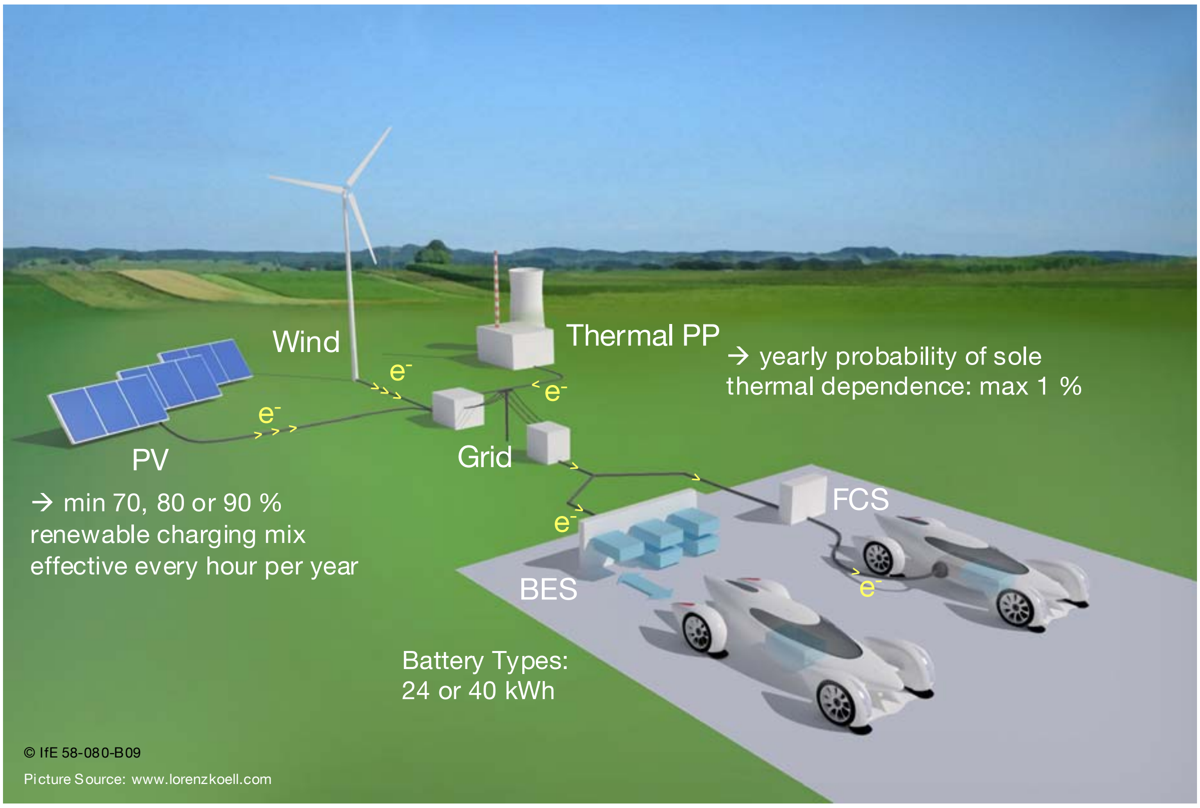


Figure 1: Conceptual Blueprint: Providing Renewable Energy for EV Power Demand at BES and FCS

In order to meet the energy demand of BES and in comparison of FCS, photovoltaic systems (PV) and wind turbines are allocated at a given ratio of 20 to 80 %. At times of meagre renewable feed-in, thermal power plants take over charging the batteries of EVs. However, it is a goal to limit the amount of thermal power to a minimum. An IfE simulation tool analyses the capacity demand from renewable sources necessary to receive an EV charging mix, which guarantees a majority of “green power” on an hour-sharp basis. The research objective intends to quantify the advantage of the storage ability of BES in comparison to FCS.

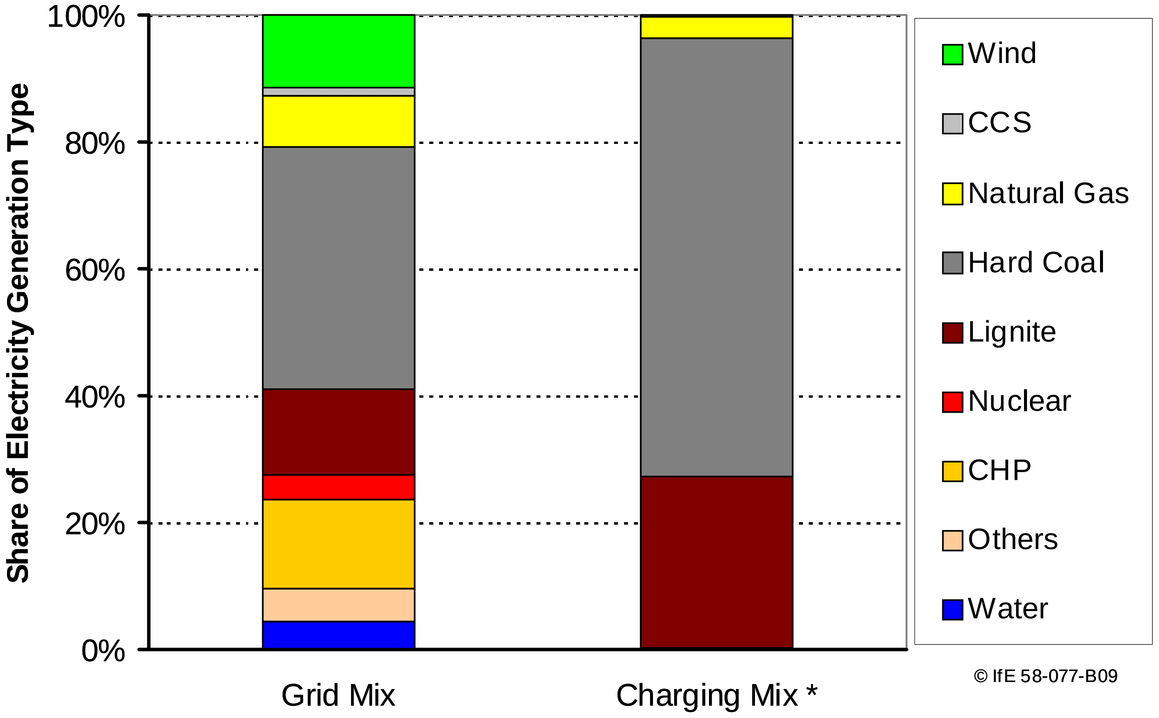
2 Status Quo in Allocating the Charging Mix of EVs

Recent EV studies conducted at the Institute for Energy Economy and Application Technology (IfE) at TU München have demonstrated that a controlled EV charging mix differs strongly from the overall grid mix in Germany – with reference to [3] and [5]. This was achieved by means of the Institute's simulation tool *ifeon*, which models the degree of power plant utilisation and future plant construction [2].

This software tool allows a calculation of the electricity mix, which is used to charge the growing number of connected EVs from the year 2009 to 2040. As a prerequisite the assumption is made, that the German power plant mix operates under conditions representative of a free and fair market economy. Thus the commanding parameter is determined as the power generating technology with minimum operating and investment costs at all times. The growing contingent of renewable energies is also accounted for by means of their binding priority access to the grid. Hence they are the first source of power generation to be drawn upon to cover the load demand of the grid. Whatever load demand thereafter cannot be covered by renewable feed-in, which at most times is the largest part of the load, is generated by thermal power plants.

Input parameters consist of Germany's power plant specifications taken from the Institute's database (efficiencies, date of construction, lifetime, power output, fuel costs, etc.) as well as consumer load profiles and estimates of the development of renewable energy input. Next to the growing number of EVs, further factors of influence have a noticeable effect on the development of the power plant mix and are incorporated in the *ifeon* simulation model: Germany's nuclear phase out, the incentive driven growth of renewable energies and CHP (combined heat and power utilisation), the long term estimated development of fuel prices and CO_2 certificate prices including CO_2 credit caps [4]. Furthermore new coal fired power generation technology is considered in the simulation tool. From 2020 onwards industry experts estimate that the first commercial carbon capture and storage (CCS) power plants will enter into service in Germany. By then they are considered to be technically and economically competitive in comparison to conventional coal fired power plants [4].

Figure 2 depicts the difference between the EV charging mix and the grid mix for the year 2020, as simulated by *ifeon*. In 2020 an estimated fleet of approx. 1 million EVs were simulated under the prerequisite of controlled charging during off-peak hours.



* General charging mix of all common EVs, not applicable to EVs from Better Place

Figure 2: Composition of the Charging Mix of EVs in Comparison to the Overall Grid Mix in 2020

At times of low consumer load in the grid, the charging mix originates mainly from middle load power plants. This is due to the unused generating capacity in the early morning hours, generally between 1 and 6 am, where most of the hard coal power plants operate only at part load. Nuclear and most lignite base load power plants, however, generate electricity at full capacity 24 hours a day. Thus capacity utilisation of nuclear power plants cannot be further increased to supply electricity for EVs. A few lignite fired plants, however, are operated during the year at part load, resulting in an increase of their capacity utilisation for charging EVs.

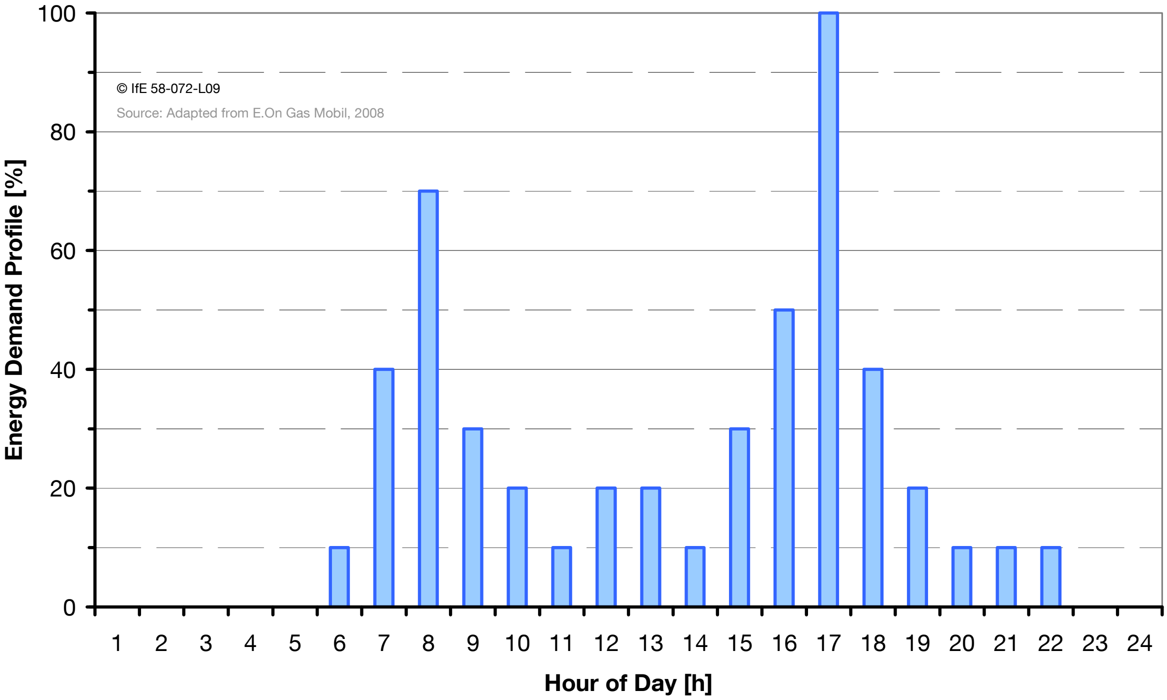
According to the German Renewable Energies Act – Erneuerbare Energien Gesetz (EEG) – power generated from renewables enjoys binding priority access to the grid. Therefore renewable power is the first to cover the consumer load demand of the grid, followed as per merit order by base load, middle and peak load power plants until the full load demand can be met. Due to the extra electricity demand of EVs, only power plants operating in part load can thus be drawn upon to satisfy this additional demand. In compliance with the EEG renewable power sources may therefore not be classified as EV charging power.

Hence this research study takes up the challenge of analysing a methodology, which allows EVs to be charged solely with fluctuating renewable power sources. The focus hereby lies on solar and wind installation options, which are coupled to the grid, yet exclude the financial incentive given by the EEG. This methodical approach ultimately caters for an EV charging mix from predominantly carbon-free power generating sources, exact to the hour and amount of energy required at a particular time of day.

3 Research Methodology and Framework Parameters

3.1 Energy Demand Profile of BES and FCS

Starting off a general energy demand profile (P1) for battery exchange stations (BES) and fast charge stations (FCS) as depicted in **Figure 3** is required. P1 displays the daily frequency of energy demand on an hourly basis with the daily maximum attained at 5 pm and the energy demand of all other hours scaled accordingly. With reference to a single exemplary swapping lane a maximum of 12 batteries per hour can be exchanged requiring approx. 5 minutes per vehicle. Furthermore each swapping lane has 10 available chargers at its disposal resulting in a maximum charging/storage capacity of 20 batteries per hour (30 minutes charging time per battery). The modified distribution depicted in Figure 3 was acquired from the hourly and daily frequency for filling up at an exemplary gas station in Germany. Based on the 5 pm maximum of 12 battery swaps, BES and FCS would thus have to provide energy for 60 empty batteries per day (24 kWh system) or for 36 empty batteries per day (40 kWh system). The total overall energy demand per day (60 batteries * 24 kWh * 0,8 SOC = 1152 kWh) hence remains the same for both battery systems. This allows a comparison between the simulated results.



Source: Adapted from E.On Gas Mobil, 2008

Figure 3: Daily Energy Demand Profile (P1) at Battery Exchange Stations and Fast Charge Stations

3.2 Fluctuating Renewable Energies

The fluctuating feed-in characteristic of renewable energies, as shown in **Figure 4**, provides a challenge when trying to cover the hourly energy demand of P1. An abundance of renewable power sources as well as certain storage facilities come to mind in trying to find an answer to this problem. An ideal would be to align electricity supply and demand on an hour-sharp basis, converging on the technical (and economic) requirements of both these systems.

For this research study energy production from photovoltaic systems and wind energy farms was fixed at a ratio of 20 to 80 %. Next to onshore wind generation the energy production from offshore wind turbines is also considered, comprising a 50/50 share of total wind feed-in. The data depicting all wind feed-in characteristics is based on a wind modelling simulation for German on- and offshore wind turbines extrapolated for an installation level in the year 2020 [1]. Hereby the characteristic of a total of 14 wind years is generated in order to account for higher and lower wind-yielding years.

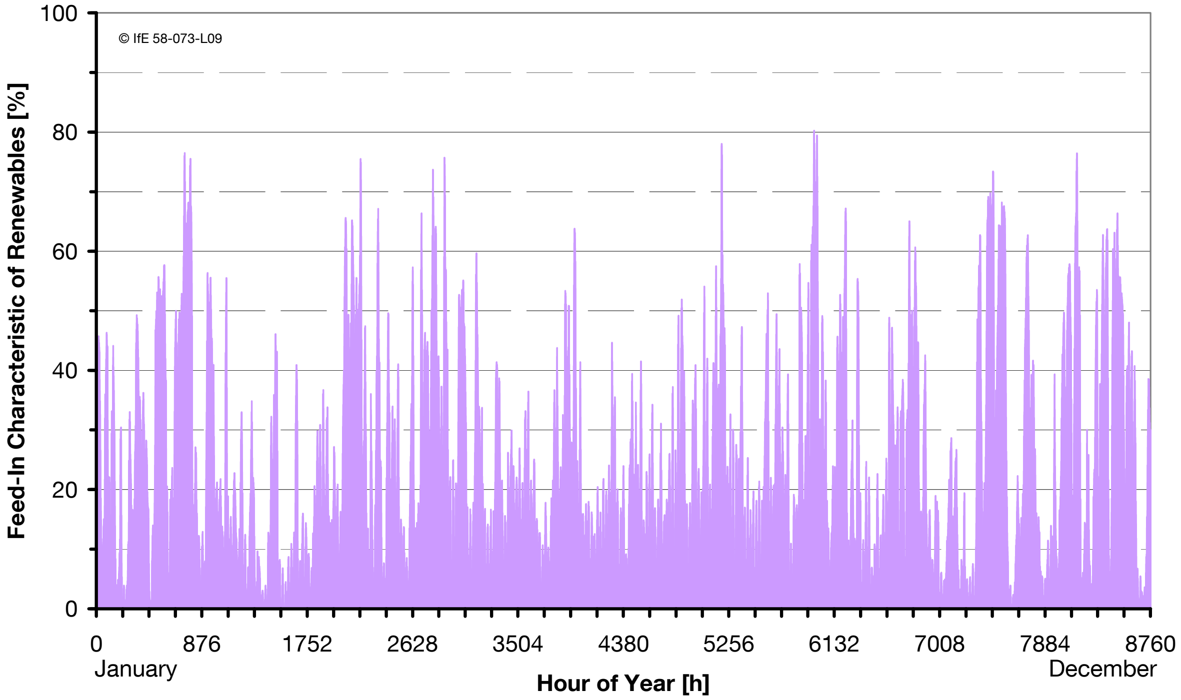


Figure 4: Hourly Fluctuations of Renewable Energy Feed-In (Wind Onshore/Offshore, PV) in 2020

A closer analysis of Figure 4 allows certain typical features of photovoltaic and wind power feed-in to be distinguished: From approx. March to September an almost continued influx of power close to 10 % of installed renewable capacity is noticeable. This can largely be attributed to the higher and steadier power generation from photovoltaic systems during the summer months. Furthermore, feed-in characteristics of between 80 and 100 % can generally be deemed most unlikely in this constellation of PV systems and on- and offshore wind farms. In that case a number of weather specific events would need to coincide: This would encompass a clear summer day at noon, where the sun stands at its highest, to insure that

PV systems may harvest at their full potential; a strong gust also needs to be blowing geographically across the whole of Germany to guarantee the maximum power generation from on- and offshore wind farms. Considering the characteristics of a typical European high pressure weather system, such constellations are extremely rare.

Even tough such renewable feed-in peaks offer a great quantity of usable energy, their impact on the project concept to function reliably is negligible. Of far greater importance are the instances, where renewable power influx almost completely abates for several days. This typically occurs more often during winter months as demonstrated in Figure 4. These power influx troughs mark the main focus of the analysis. They can only be overcome by energy storage options (as provided by BES to a certain extent) or by allowing thermal power plants from the grid to pitch-in and provide energy for the required charging demand.

3.3 Simulation Algorithm

In order to visualise the methodology of the simulation algorithm an exemplary day is illustrated in **Figure 5**. The hourly energy demand profile corresponds to P1 depicted in Figure 3, yet in this example absolute numbers are taken representing a single swapping lane. The overall renewable energy availability of an arbitrary day is displayed (green line) together with the demand covered by this renewable feed-in (green area). Due to the fact that at a given time, e.g. 8 am, the renewable energy supply falls short of its demand, two batteries in storage (blue area) have to be drawn upon to conduct the required battery exchanges of the swapping lane at that specific hour. The batteries taken from storage were charged at an earlier point in time, where renewable power influx occurred in abundance and thus exceeded the energy demand of the BES. Then after 8 am an oversupply of renewable energy accommodates the recharging of the two empty batteries waiting in storage (not depicted here).

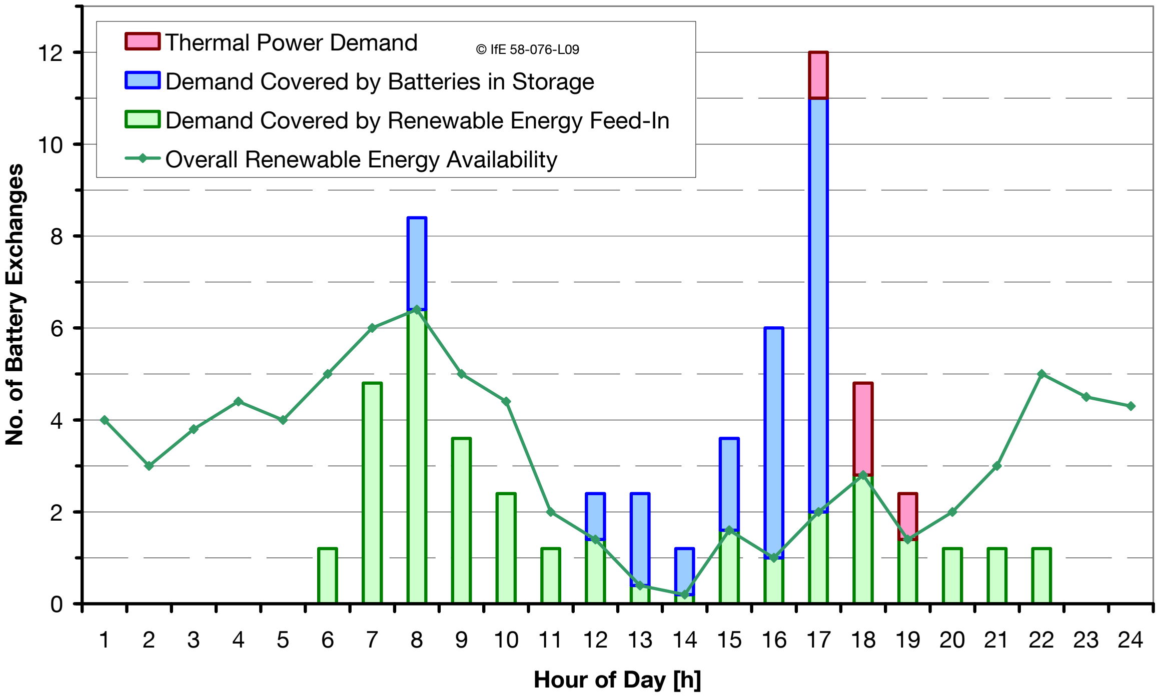


Figure 5: Power Supply Composition of a Single Swapping Lane over an Exemplary Day (P1)

From 12 to 19 o'clock, however, renewable energy feed-in turns out to be quite meagre. Over the next few hours the advantage is apparent, to fall back on fully charged batteries in storage, yet only as long as the storage itself is not depleted or in other words filled with empty batteries. Due to the fact that a single swapping lane accommodates a storage capacity of 20 batteries, additional charging power from thermal power plants is required from 5 pm onwards (red area). This method permits the most efficient way of covering the hourly battery demands, especially considering the daily peak of 12 batteries at 5 pm. At 6 and 7 pm thermal power is still needed, whereas the battery storage remains empty until the next abundance of renewable influx allows the charging of the 20 empty batteries. In this example this can be expected from 8 pm onwards. For the next day the cycle of the swapping lane then begins anew with the simulation algorithm functioning according to the following priorities:

- fulfilling the hourly battery exchange demand has top priority
- this is executed by tapping the energy supply first and foremost of renewable feed-in, then batteries charged with renewables in storage and lastly thermal power
- renewable energy in abundance is drawn upon to charge all empty batteries in storage
- only when all of the above are fulfilled, excess renewable energy may optionally be fed into the grid or dealt with otherwise.

In order to prevent such instances, where thermal power has to be drawn too often from the grid, more renewable capacity needs to be installed. Only then the hourly amount of renewable energy feed-in can be increased. The simulation algorithm thus optimises the amount of installed renewable capacity necessary to attain a minimum hourly charging mix of say 70, 80 or 90 % solely from renewable sources. The few times, where thermal power of more than accordingly 30, 20 or 10 % gets drawn from the grid, are limited to only 1 % of all hours per year (max 87 hours).

Furthermore the simulation algorithm differentiates between two battery capacity variants, namely 24 and 40 kWh. Hence the energy demand per swapping lane – depicted in Figure 5 for 24 kWh batteries – is scaled down accordingly to 60 % thereof for the 40 kWh battery types. It is thus assumed that overall driving distance and thus the overall energy demand of EVs remains the same for the simulation of either battery type. It is further assumed that each battery in need of charging has a remaining state of charge (SOC) of 20 %.

4 Simulation Results

4.1 Battery Exchange Stations (BES)

In **Figure 6** the courses of the specific renewable power demand for charging the two different battery types are illustrated in blue (24 kWh) and purple (40 kWh). The y-axis hereby describes the capacity of wind turbines and PV, which have to be installed to cover the daily energy demand of P1. In each case the course of the graph steadily increases for a minimum charging mix of 55 to 99 %. Thus it can be generally said that the higher the renewable charging mix of EVs should be, the more renewable power is necessary to cover demand. It is important to note that the x-axis in Figure 6 shows the minimum hourly share of renewables in the charging mix at any given hour of the year. The average share of renewables per hour calculated over the whole year is therefore higher.

Furthermore the advantages of the storage capability of batteries in reserve are apparent. The storage capacities given in Figure 6 relate to the 20 batteries per single swapping lane in reserve (e.g. 20 batteries * 24 kWh * 0,8 = 384 kWh). Thus BES operating with 40 kWh batteries have a 67 % higher storage capacity in comparison to their 24 kWh counterparts. In effect less renewable power needs to be installed to achieve the same renewable charging mix.

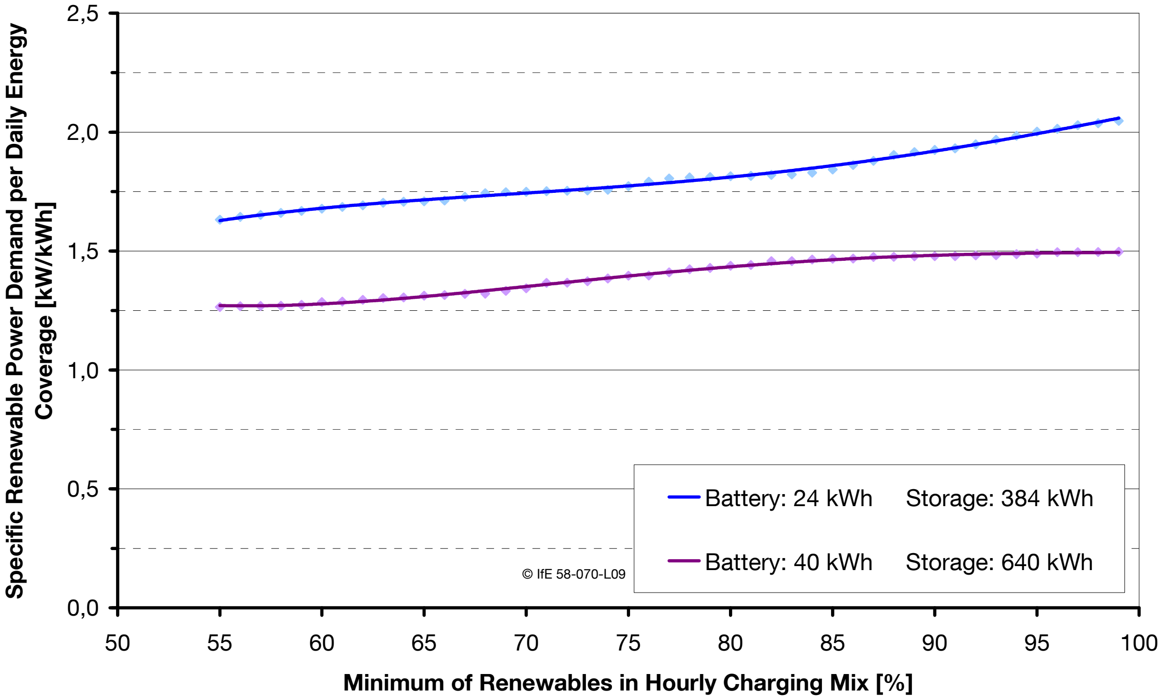


Figure 6: Development of the Specific Renewable Power Demand for Battery Exchange Stations (P1)

Figure 6 can now be used to scale up the energy and power demand according to the number of batteries required. An example will demonstrate this as follows: It is required to accommodate a daily energy demand of 1000 empty batteries of the 24 kWh type (SOC of 20 %). This amounts to an energy demand of 19.200 kWh. A strategic target furthermore states that all 1000 batteries swapped at various exchange stations throughout Germany be charged with power originating from at least 80 % renewable sources. Thus a total of approx. 34,56 MW (19.200 kWh * 1,8 kW/kWh$_{daily}$, Figure 6) of renewable capacity is necessary (80 % wind turbines, 20 % PV). This can be guaranteed for a daily energy demand profile as depicted in Figure 3 and for at least 99 % of all hours per year of critically low wind yielding years. From a total of 8760 hours per year only 87 hours may therefore not reach this target. In these very seldom cases more than 20 % of the charging mix may come from thermal power plants.

4.2 Renewable and Thermal Power Demand of BES

Figure 7 shows the occurrence of (non-renewable) thermal power demand at times when the influx of renewable energy is not sufficient to cover the power demand of EVs. For illustrative purposes 24 kWh batteries and a minimum 80 % renewable charging mix were taken as an example below.

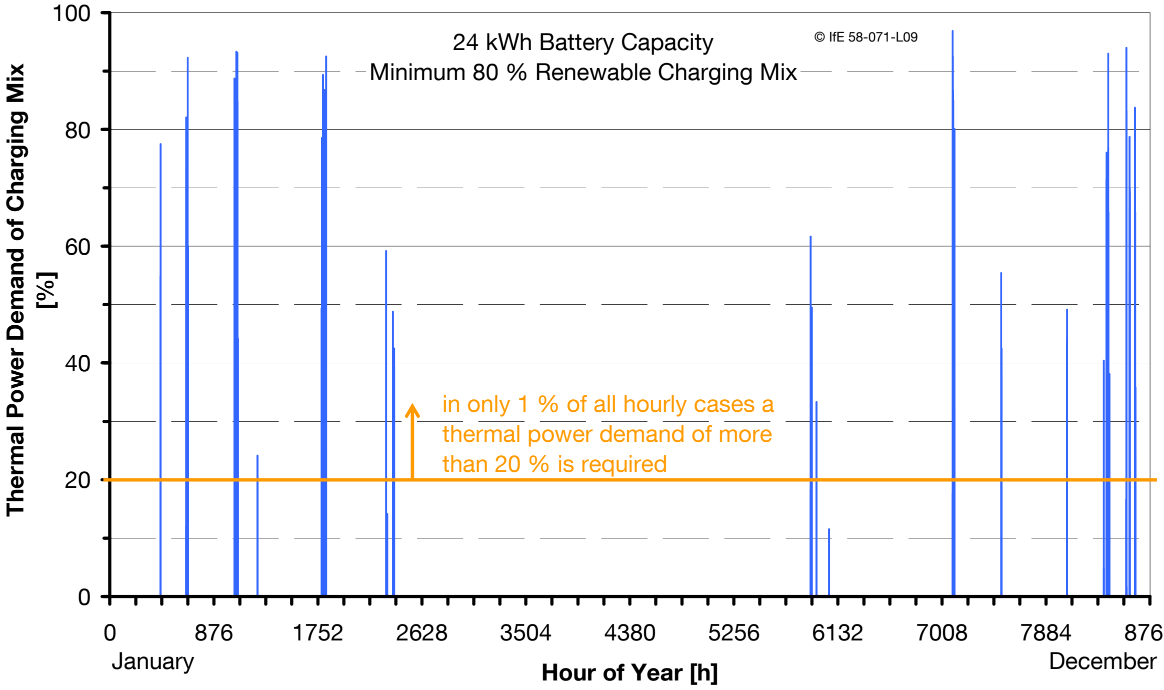


Figure 7: Occurrence of Thermal Power Demand Due to Lack of Sufficient Renewable Energy Feed-In (P1)

In 99 % of all hours of the year (8673 hours) the tough requirement of an 80 % renewable charging mix per every hour of EV demand needs to be adhered to. Thus only during 87 hours and therefore in only 1 % of all hourly cases thermal power may assist in charging the batteries, then making up more than 20 % of the charging mix. If this requirement cannot be met, only a further increase in the necessary renewable power would reduce the number of critical hours. Hence the then greater renewable feed-in reduces thermal power demand to the number of critical hours of 87 or below.

In Figure 7 a dip in thermal power demand during the summer months can be observed. This can mainly be attributed to the increased energy feed-in from PV due to higher and longer sun irradiation per day and corresponds with Figure 4. During the winter months, however, it is weather-wise more likely that renewable feed-in both from PV as well as wind abates completely at the same time. Thus several hours in succession of scarce renewable influx occur more often, requiring the BES to rely on the rest of the grid to cover the needed power demand for charging EVs.

4.3 Fast Charge Stations (FCS)

In order to make a direct comparison between BES and FCS, certain technical requirements for charging EVs from FCS can only be done theoretically. With reference to 3.1, an exemplary BES station is able to deal with a total of 12 batteries per hour (5 minutes per swap). Due to its storage potential, a maximum of 20 batteries per hour at 10 chargers can be accommodated. Thus a single battery is plugged in for 30 minutes, thereby requiring 38,4 or 64 kW in order to fill an 80 % depleted 24 or 40 kWh battery respectively.

The ongoing comparison, however, requires a single FCS to achieve the same efficiency in supplying fully charged batteries. Hence a fast charge of 5 minutes is demanded for 12 EVs per single FCS per hour. It becomes clear that this rate of fast charging can only be deemed as purely theoretical. In Germany for general purposes in residential areas the low voltage level of public power supply is upheld by a 400 V three-phase current system. Considering other electrical consumers connected to a standard residential power outlet, maximum charging power and hence “fast charging” with approx. 20 kW is realistic. Infrastructure with a higher power output and thereby satisfying shorter charging intervals would require additional investments.

In addition the following two points need to be considered: Up until today it is technically not possible to charge batteries in such short periods of time without severely damaging thermal and chemical processes within the cells. A high battery life cycle as it is standard today cannot be warranted. In addition the upstream grid impact will cause further technical challenges, due to simultaneous charging demands by EV users. Without an intelligently controlled charging algorithm further grid infrastructure investments will become necessary.

This basic train of thought clearly highlights the advantages of BES in comparison to FCS, considering far less implications on power transmission infrastructure, battery parameters and EV electronic lay-out.

Figure 8 shows the necessary specific capacity demand for renewable power sources, when considering the charging requirements of FCS. Starting at a renewable charging mix of 55 % and going up to 99 %, specific renewable power doubles from approximately 6,6 to 12 $\mathrm{kW/kWh_{daily}}$.

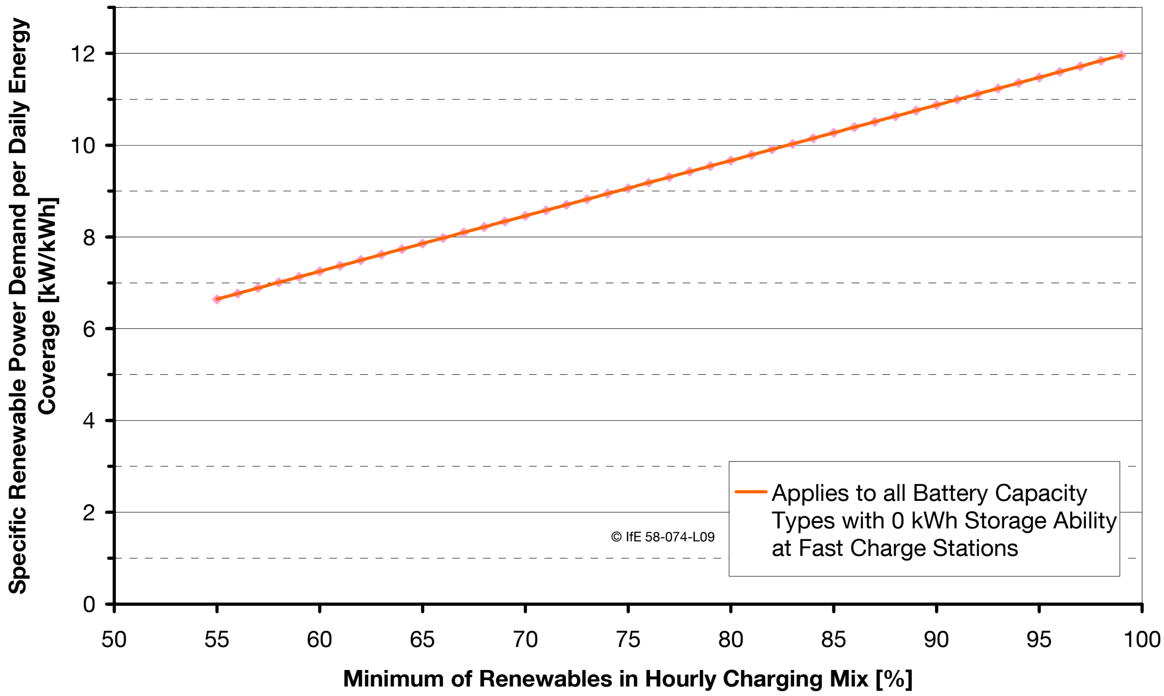


Figure 8: Development of the Specific Renewable Power Demand for Fast Charge Stations (P1)

In comparison to BES in Figure 6, FCS require a much higher installed capacity of renewable power sources, in order to achieve the same renewable charging mix. As per example: For an 80 % renewable charging mix a specific capacity of 9,7 kW/kWh$_{daily}$ has to be installed. This is more than fivefold the amount required when working with BES, using several 24 kWh batteries in reserve. The difference between BES and FCS increases even further when considering the following aspects:

- increasing the available battery storage capacity of BES to 40 kWh
- increasing the number of batteries in reserve (now 20 batteries)
- increasing the mandatory amount of renewables in the charging mix to above 80 % (steeper gradient of orange graph)

4.4 Renewable Energy Utilisation

Another important aspect for assessing the effectiveness of BES in comparison to FCS is depicted in **Figure 9**. The coupling of fluctuating renewable energy feed-in with the energy demand of EVs is especially challenging on an hourly basis. As demonstrated before a multiple of installed renewable power is necessary in order to cover the energy demand of EVs at FCS during 99 % of all hours in a year. Thus it is inevitable that a large amount of renewable energy will be generated in abundance and quantitatively overshoots the mark for charging EVs. This additional electricity would then be fed into the grid and marketed otherwise.

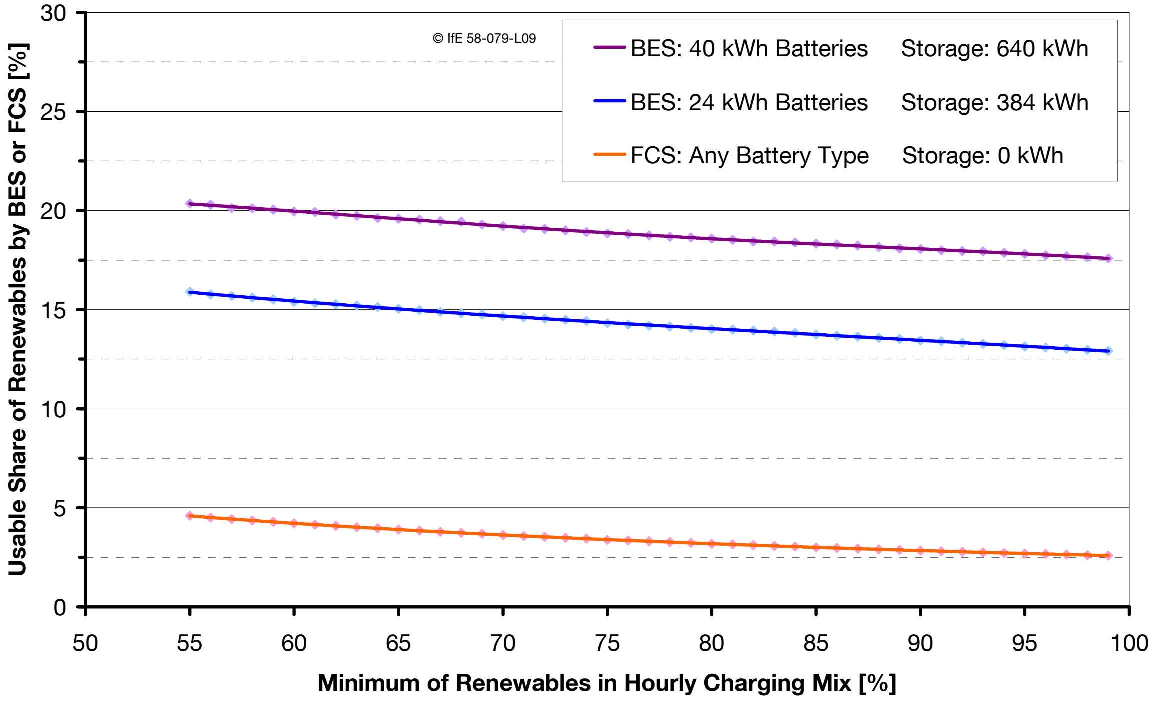


Figure 9: Renewable Energy Utilisation by BES and FCS (P1)

Considering a minimum hourly charging mix of 80 % renewables, FCS are only able to utilise 3,2 % of renewable energy generated (orange line). BES with differing storage abilities, however, make use of a multiple thereof. In comparison to FCS a system with 24 kWh battery types has the ability to incorporate 14 % of "green power" generated (blue line). The usable share of renewable energy by BES furthermore increases to 18,6 % with the higher storage capability of its 40 kWh battery types (purple line). It can thus be concluded that BES contribute a reasonable deal in reducing the volatility of the residual load curve, necessary for the operation of thermal power plants. This effect can be attributed to the controlled hourly charging of batteries at times with an offset to the direct load demand of EVs and in correlation to a high renewable energy influx. The integration of renewable energy can therefore be improved and harmonised according to the requirements of the grid.

5 Summary and Conclusion

The aim of this analysis was to quantify in which way renewable energies can be used directly for charging electric vehicles by using fast charge stations (FCS) or battery exchange stations (BES). Because of the fluctuating character and hence insufficient predictability of renewable energies, a precise correlation of renewables and the charging of EVs is only possible by keeping a high installed capacity of renewables in reserve for charging purposes. This capacity is dependent on the desired share of the renewable charging mix as well as the storage possibilities. By implementing BES the accommodation of renewables in the charging mix is considerably easier than by using FCS.

The results also show that in many cases the electricity production of renewables exceeds the charging demand considerably. This again is less so, the higher the storage capacity.

In conclusion it is thus evident that a renewable and at the same time economic EV charging mix requires storage capacities. Only then a precise correlation between renewable energy feed-in and EV power demand can be made. The present analysis only considered batteries that are used for traction purposes. Thus additional stationary storage systems can be taken into account both for a better integration of renewables and for technically efficient grid use. However, an estimate of the most cost-effective ratio between installed renewable power and storage capacity goes beyond this research assignment and would require further simulations and detailed analysis of the results generated.

A further research assignment should examine the effects and correlations of different storage systems from an economic point of view. Hereby a multitude of storage systems may be considered ranging from a higher number of EV batteries to solely stationary storage options such as flywheels or discarded vehicle batteries, of which diminished energy and power densities are negligible. Another option for reducing abundantly generated renewable energy would involve the use of smart charging meters for EVs connected directly to the grid at home or in the office. Hence at times of high renewable influx at night or in the early morning hours the charging of EVs may be controlled in accordance with the demands of BES. This bundle of options will undoubtedly increase renewable utilisation while at the same time reduce and optimise investment and operation costs.

6 Addendum

In a further simulation the impact of a more evenly distributed energy demand profile (P2) at BES and FCS was considered, corresponding to **Figure 10**. Except for the absolute amount of electricity drawn from the grid, all other parameters in the simulation were left unchanged. In comparison to the energy demand profile in Figure 3, double the amount of electricity (120 charges * 24 kWh * 0,8 SOC = 2.304 kWh) is required to cover the daily energy demand per BES or FCS.

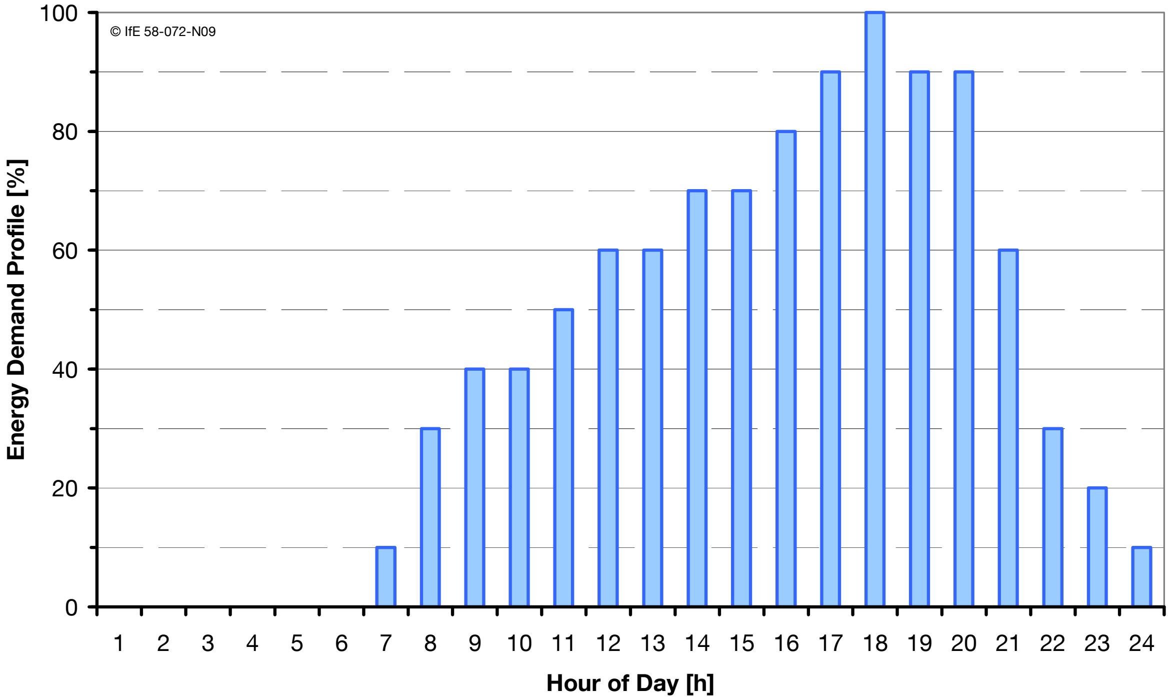


Figure 10: Daily Energy Demand Profile (P2) at Battery Exchange Stations and Fast Charge Stations

BES and FCS now have a higher daily utilisation, because double the amount of battery swaps and charges are completed. Thus not all the results following below may be compared one to one with the simulated results corresponding to Figure 3 of the main report. This is due to the fact that the storage capacity of BES remains at 384 kWh (20 batteries in storage * 24 kWh * 0,8 SOC). In case of the 40 kWh BES the storage capacity remains at 640 kWh. In effect a higher energy turnover now has to be met with the same storage capacity in the respective stations. In other words the specific storage ability of the BES has been reduced.

With this in mind the results in Figure 11 to Figure 14 accordingly show higher specific values overall. None the less the conclusion of the main report also applies here in every aspect: BES are superior to FCS in dealing with renewable energy feed-in and EV charging.

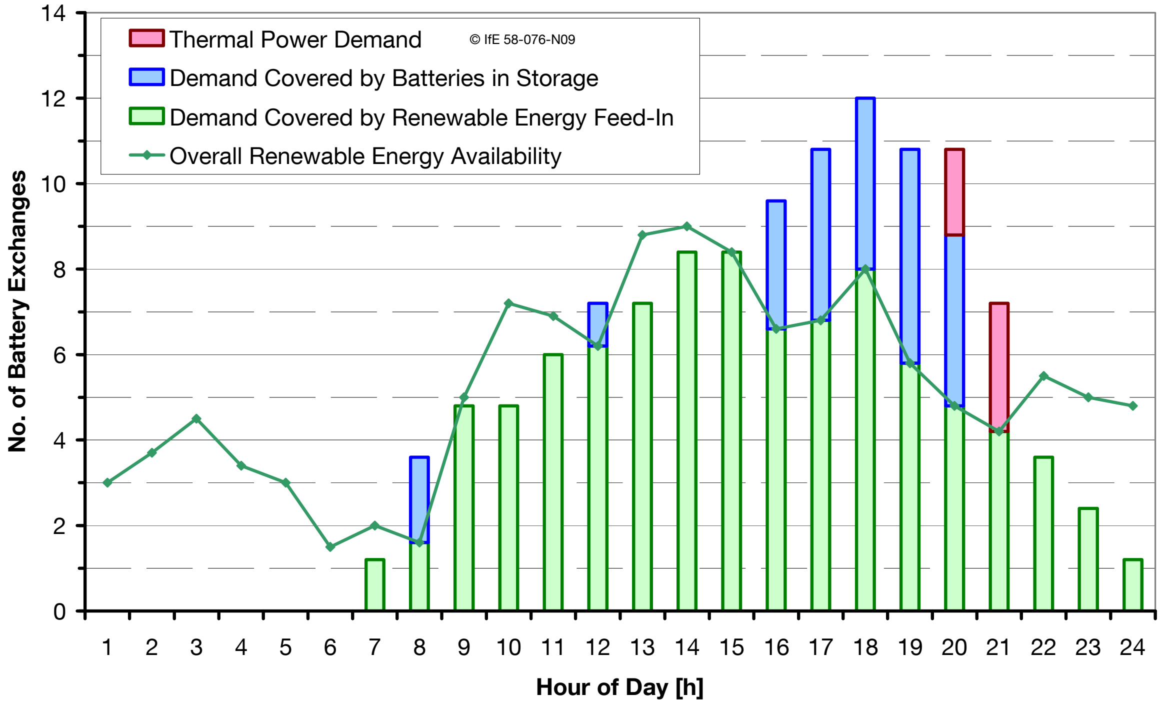


Figure 11: Power Supply Composition of a Single Swapping Lane over an Exemplary Day (P2)

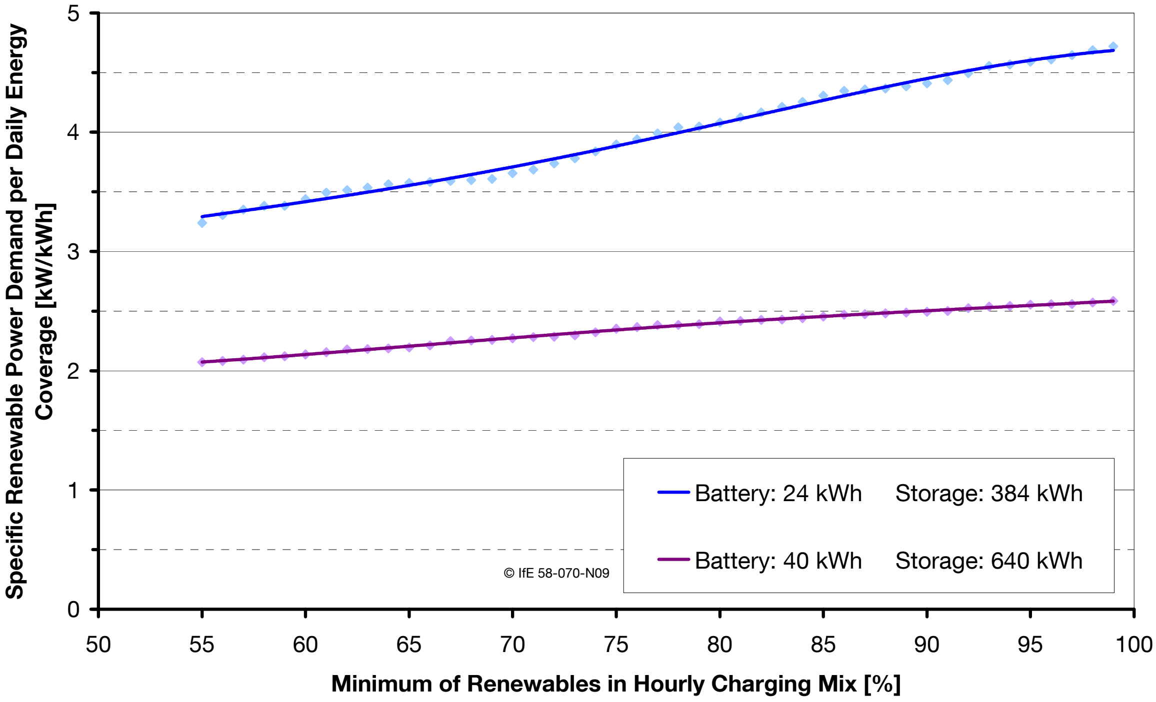


Figure 12: Development of the Specific Renewable Power Demand for Battery Exchange Stations (P2)

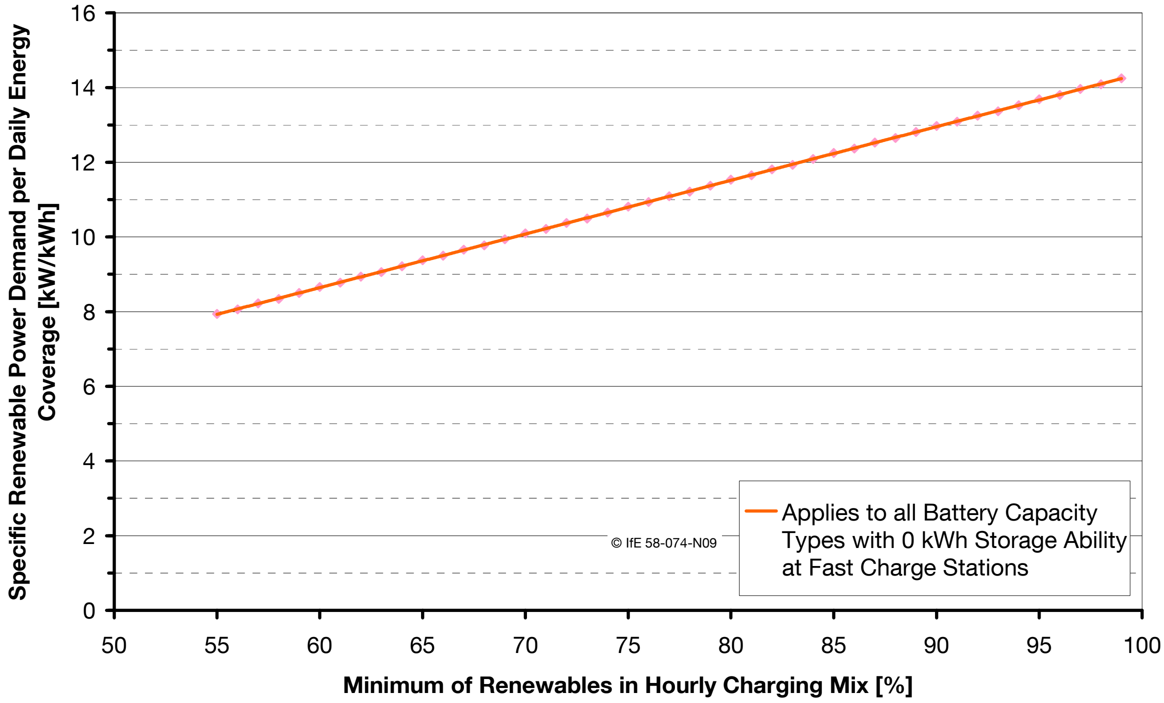


Figure 13: Development of the Specific Renewable Power Demand for Fast Charge Stations (P2)

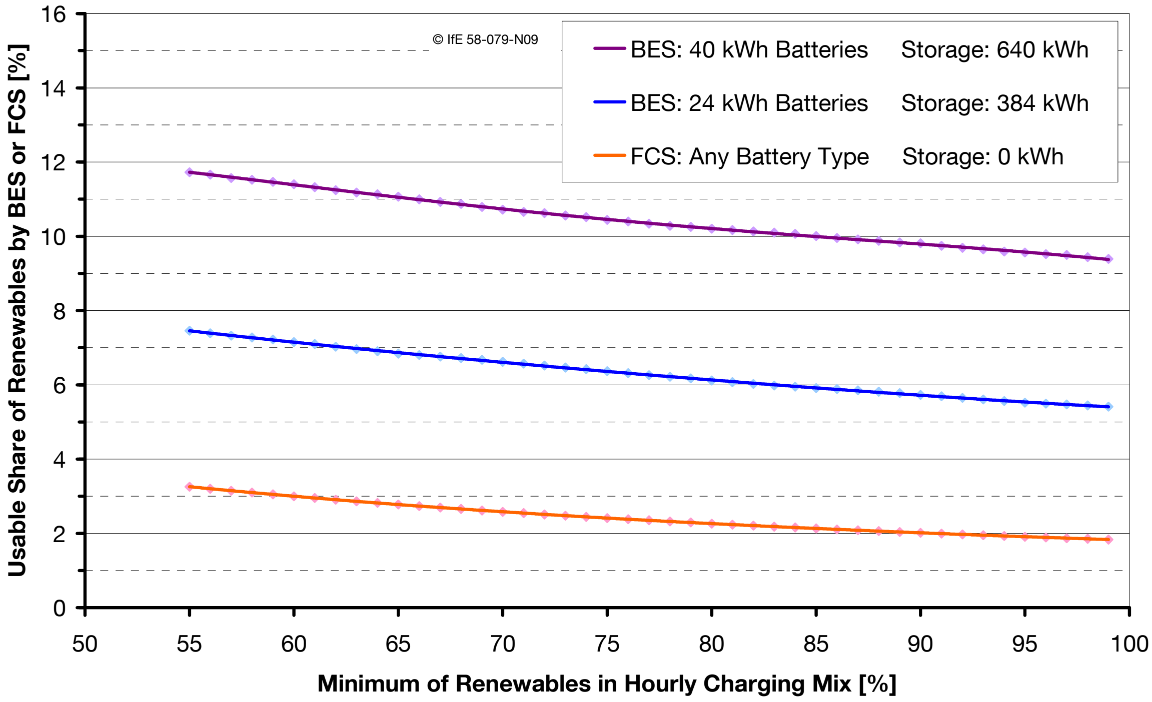


Figure 14: Renewable Energy Utilisation by BES and FCS (P2)

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