Translation from German original

THE CONCEPT OF EFFICIENCY IN THE GERMAN CLIMATE POLICY DEBATE ON ROAD TRANSPORT

A comprehensive approach to assessing the efficiency of technologies (translation from the German original version)

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CONTENT

THE STUDY AT A GLANCE

The efficiency of the production and use of climate-neutral fuels (PtL) used in internal combustion engine vehicles (ICEVs) and green electricity used in battery-powered vehicles (BEVs) is similar in magnitude when viewed from a comprehensive, system-wide perspective. This is the key finding of this study.

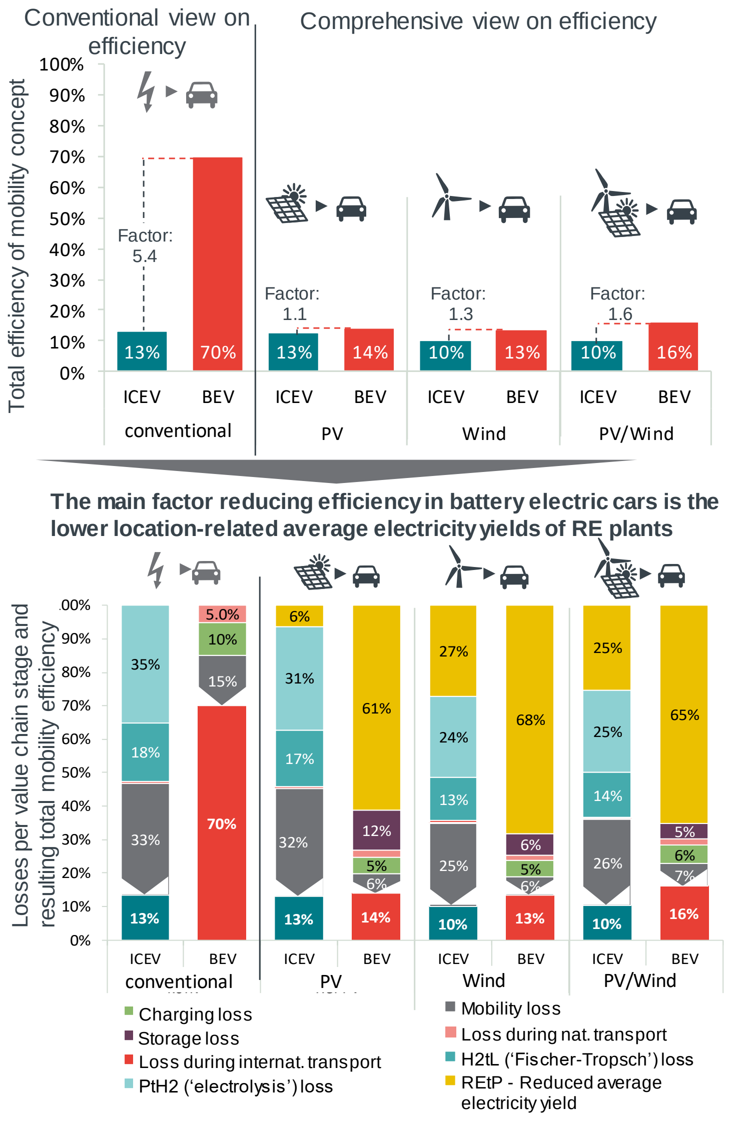
The efficiency of the use of green electricity in BEVs of around 70%, as shown in previous conventional analyses, shrinks in our extended comprehensive analysis to between 13 and 16%. It is thus of comparable magnitude to that of cars powered by combustion engines and PtL with efficiency of 10 and 13% depending on the scenario.

Conventional efficiency comparisons of battery electric vehicles and renewable fuels leave aside key parameters an appropriate comparison to inform political decision makers would require.

- Above all, it is always assumed that both BEVs and the production of PtL are supplied with electricity on a purely domestic basis, thus **neglecting** a major advantage of the **importable PtL products**: the **possibility to use international locations with high average electricity yields from renewable energies**. We extend the conventional perspective and include the average yield of renewable plants (capacity factor) in order to factor in the quality of the location in terms of renewable energy supply.
- Moreover, conventional studies often disregard energy losses in battery electric mobility while transporting, storing and charging power, as well as the considerable additional energy required for in-vehicle air conditioning (heating/cooling) (**cf. Figure 1**). We consider all energy losses.

In further scenarios, the individual parameters are varied, and the results show that cars operated with PtL may show a higher comprehensive efficiency in some cases.

Figure 1. Comprehensive efficiency of BEV and ICEV at similar level

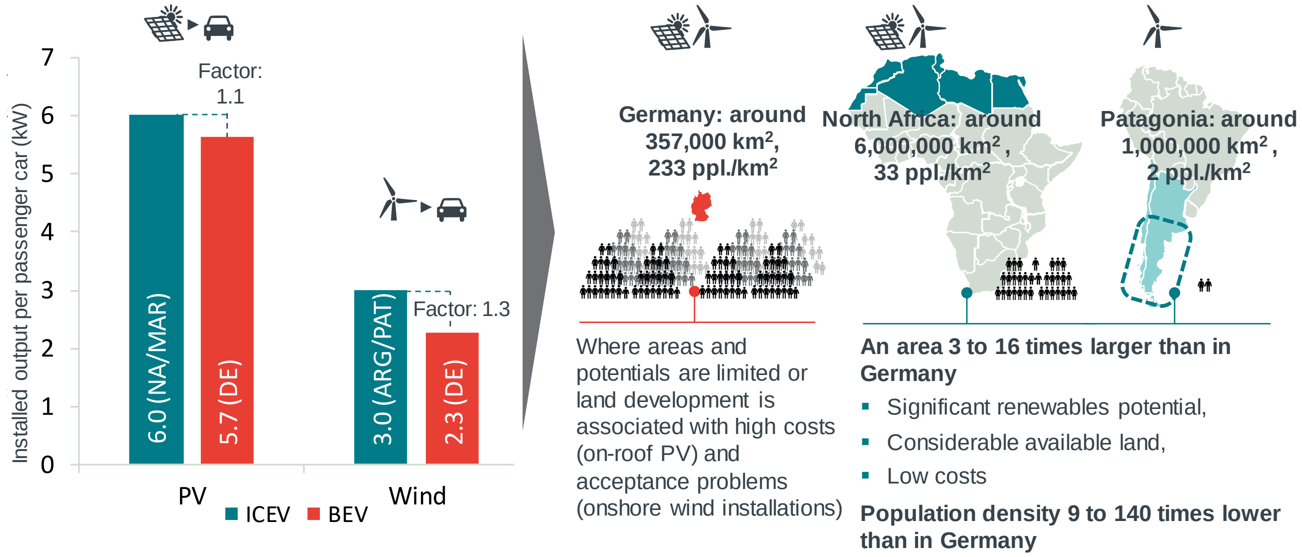


Source: Frontier Economics

*Note: Electricity yield efficiency, i.e. capacity factor (here "reduced electricity generation yield"): Global best location for wind or PV = 100% (for details see section 3). **PV** - BEV: plants in Germany (DE); ICEV = plants in North Africa (NA); **wind** - BEV: plants in DE (onshore and offshore); ICEV: plants in Patagonia; PV/wind, 50% each - BEV: PV and wind plants in DE; ICEV: PV and wind plants in NA*

The result becomes particularly clear when comparing **how many wind turbines and solar plants need to be installed to meet the annual energy requirements of an average car in Germany**. While running a car with green PtL requires a PV capacity of 6 kW in North Africa, a BEV requires 5.7 kW PV capacity in Germany; the capacity requirements are similar in magnitude (**cf. Figure 2**). In the case of electricity generation from wind, 3 kW must be installed in Argentina/Patagonia for a car with green PtL compared to 2.3 kW in Germany for a BEV. However, land with high RES potential and low population density is far more readily available in regions such as North Africa or Patagonia than Germany and the costs and acceptance hurdles are correspondingly lower.

Figure 2. PV or wind capacity requirements in Germany for a BEV are almost as high as in North Africa or Patagonia for a PtL-powered ICEV



Source: Frontier Economics

Note: For details see chapter 4.

Political decisions should **also be based on the costs and climate impact** of the respective drive system. In this context, e.g. energy losses and CO2 emissions are assessed. The importance of technical energy efficiency, which has been used repeatedly in the past, is declining against the background of the large quantities of green electricity available worldwide, while the importance of providing climate-friendly energy **at the right time, at the right place and with the required capacity** is growing massively.

Politically pre-selecting drive technologies solely based on technical efficiency concepts neglects other aspects such as the availability of existing infrastructure, including the existing vehicle fleet and user needs. An international perspective is equally important: imports of green electricity in the form of liquid green fuel are becoming essential to provide needs-based and affordable climate-neutral energy in Germany, both for the economy and for consumers.

This study shows that a future-oriented climate policy in the transport sector should aim to use and keep open all technologies that meet the climate target. There is a need for revision of the legislative framework at both European and national level. This should be done as soon as possible, as the transformation of the energy system towards renewable energies is becoming increasingly urgent in view of the ongoing climate change.

SUMMARY

The German government's ambitious climate protection goals[1] require substantial reductions in greenhouse gas emissions in all energy-consuming sectors, including the transport sector.

In the current energy policy debate, the energy efficiency of technologies is an important parameter for setting the political course. This applies in particular to the climate policy assessment of various drive technologies in road transport (such as battery electric vehicles and vehicles with combustion engines). Within the framework of the present study, we would like to examine previous methodological approaches to determining the efficiency of drive technologies for road transport and identify new approaches to efficiency assessment. Especially in this important phase of the transformation of the energy system, a system-wide solid information and factual basis is of utmost importance for the upcoming political directional decisions.

Our goal: A comprehensive efficiency analysis of BEVs and PtL-powered ICEVs, taking into account all stages of generation and energy conversion

The aim of the study is to show essential aspects of a comprehensive technical[2] efficiency analysis of energy paths that start with renewable energies (RES) and end with their use in different drive technologies. In particular, we focus on renewable energies and the electricity generated from them, which

- on the one hand is used in battery electric vehicles (BEV path); and
- on the other hand is further converted into synthetic liquid fuels (e-fuels or power-to-liquids (PtL)) which are used to power combustion engine vehicles (ICEV path).

In doing so we point out,

- that many present-day efficiency analyses (hereinafter referred to as “conventional”) are limited and can lead to false conclusions, namely, that battery electric vehicles represent the only possible solution for defossilisation;

> Objective: A comprehensive efficiency analysis taking into account all stages of generation and energy conversion.

[1] 55% $_{CO2\ reduction}$ compared to 1990 in 2030, preferably climate neutrality in 2050.

[2] For the sake of simplicity, we use the terms "technical efficiency" and "efficiency" and "energy efficiency" as synonyms in the following.

- that for a fair comparison of technologies, a comprehensive efficiency analysis must be applied and which stages of the value chain must be taken into account; and
- that, as a result of a comprehensive view, PtL-powered ICEVs have similar efficiency to BEVs, especially since the importability of PtL products allows RE sites with high average electricity yields to be used.

Current efficiency analyses have a limited, national perspective and leave out important aspects

> Due to their high energy density, PtL products can be transported over long distances without great technical and energy expenditure.

The current debate on energy efficiency is based to a large extent on the idea of largely national energy self-sufficiency, using only domestically produced renewable energy for all consumption sectors.

This Germany-centric view ignores the fact that PtL products can be transported over longer distances with minimal technical and energy expenditure due to their high energy density under atmospheric environmental conditions such as normal pressure and usual ambient temperatures. Globally, there are abundant renewable energy potentials, often much higher than in Germany. PtL products thus make it possible to utilise renewable energy potential almost independently of their geographical location.

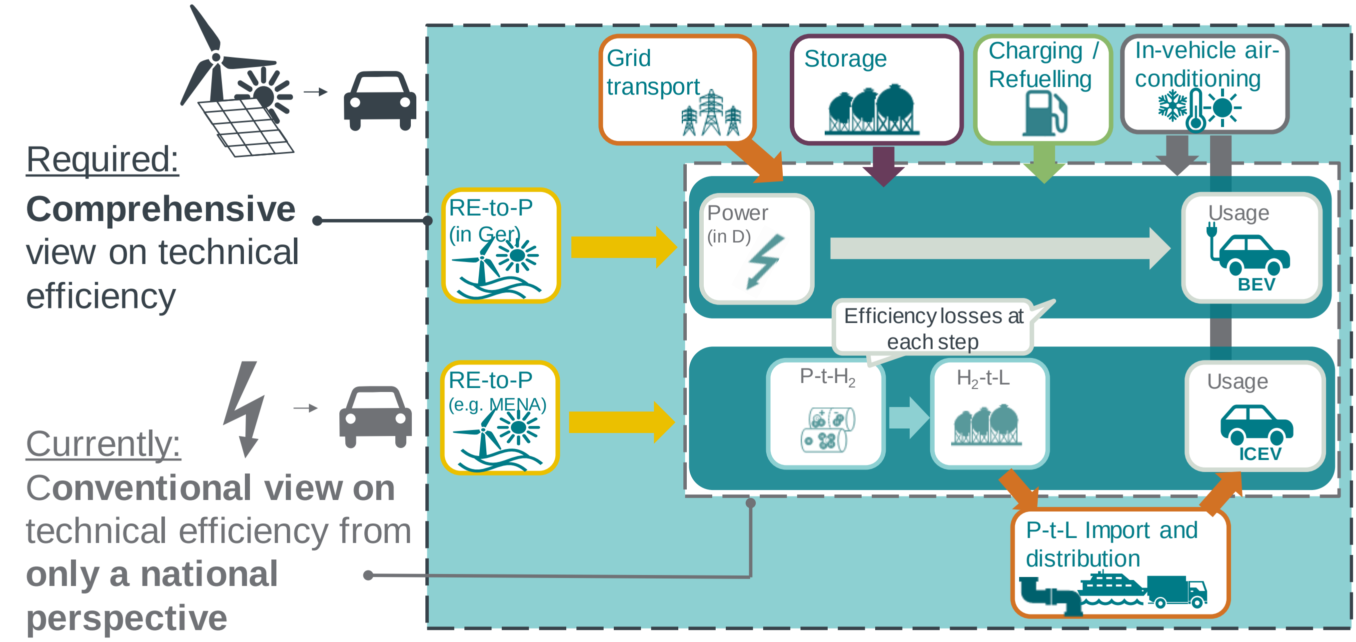
It is doubtful whether a comparative statement based on a conventional efficiency analysis is viable in the political context: it does **not consider location-specific factors of RE generation** and the associated **yield efficiency**[3] **of renewable electricity generation**. For a fair comparison of technologies, on the other hand, **a comprehensive efficiency analysis across national borders is** necessary.

In addition, conventional efficiency analyses often fail to take this into account:

- **Energy losses from transmission**;
- **Losses from energy storage**;
- **Charging losses** in battery-electric vehicles; as well as;
- **Energy consumed** for in-vehicle air-conditioning, particularly to heat the interior during colder weather.

[3] In this study, we examine the electricity yield efficiency in relation to location, not technology: For wind turbines, for example, we do not distinguish between different wind power technologies, but only between site-dependent wind conditions and thus different electricity yields, i.e. yield efficiencies. A site with the highest wind frequency worldwide that can currently be converted from wind turbines to electricity (measured by full load hours to express the average electricity yield or capacity factor) has a yield efficiency of 100% (cf. Chapter 3, p. 42 ff.).

Figure 3. Comprehensive efficiency considers all conversion stages and international renewable energy potentials

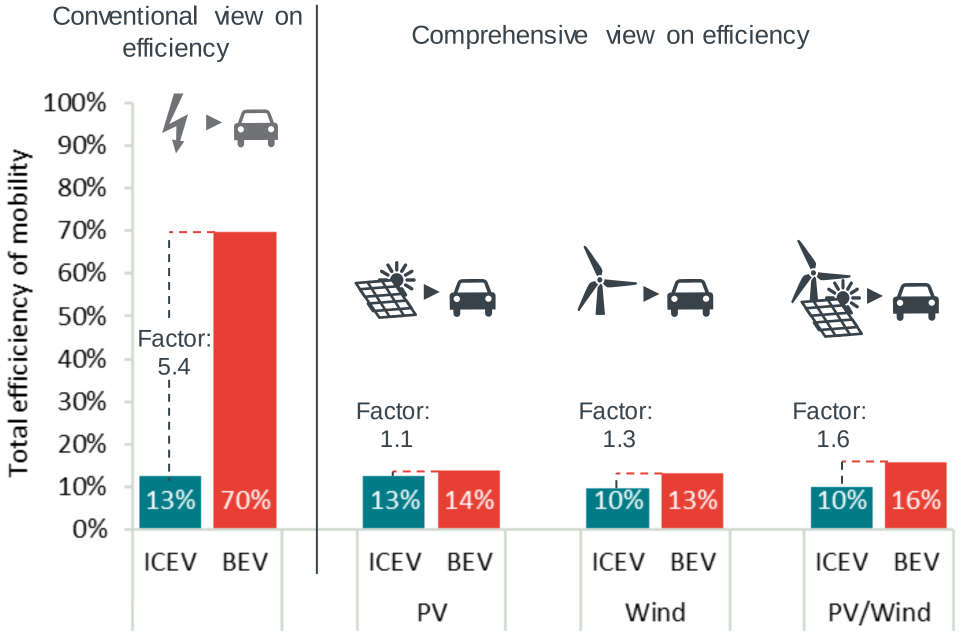


Source: Frontier Economics

In a comprehensive assessment, PtL-powered ICEVs show similar efficiency to BEVs, especially since the importability of PtL products makes renewable energy sites with high electricity yield efficiencies usable

In this study, we take into account the aspects of a comprehensive efficiency analysis as illustrated in the **Figure 3** The technical efficiency of electric vehicles powered by renewable electricity and green PtL-powered burners is at a similar level: in contrast to the technical efficiency of approx. 70% shown in conventional analyses to date, the comprehensive efficiency of battery electric vehicles is approx. 13-16%. This is of a similar order of magnitude to the comprehensive efficiency of PtL-powered ICEVs of 10-13% (cf. **Figure 4**).

Figure 4. Differences in efficiency between BEVs and ICEVs almost even out – reference scenarios per electricity generation technology



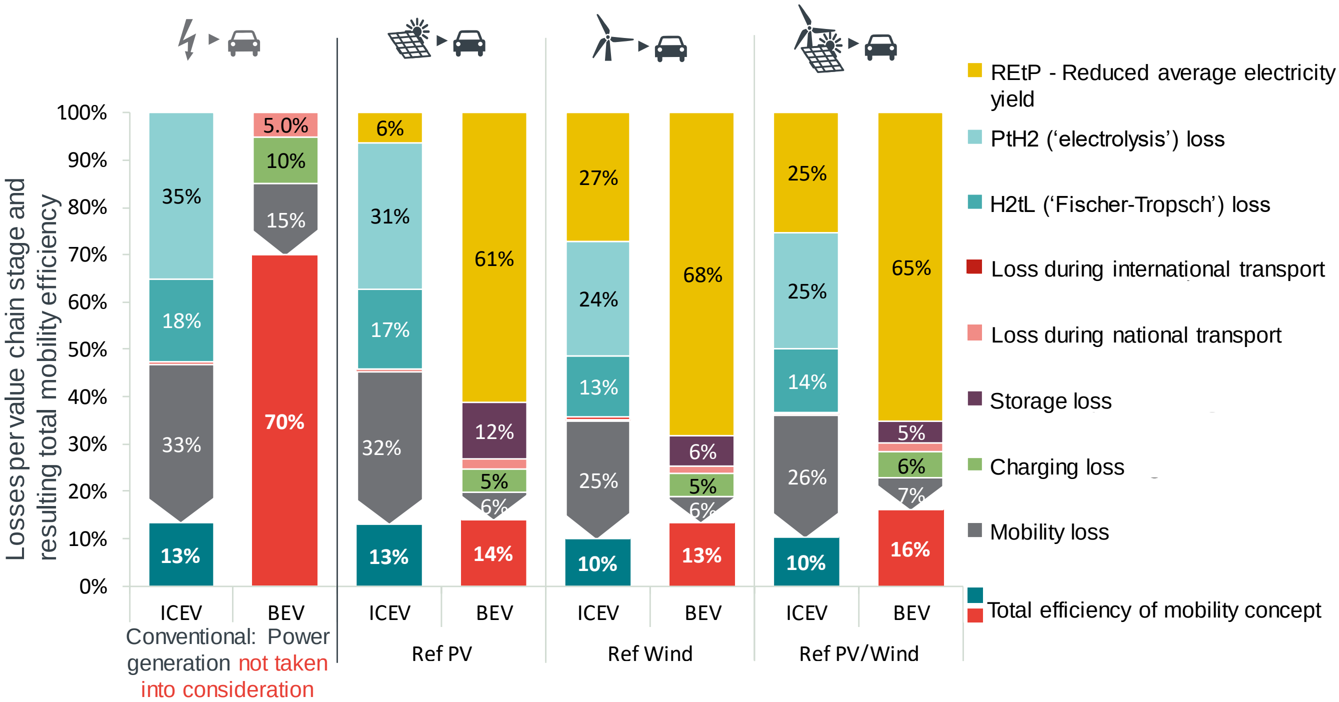
Source: Frontier Economics

Note: ***Conventional scenario****: 100% yield efficiency, cf. Chapter 2.*
PV *- BEV: PV systems in Germany; ICEV: PV systems in North Africa/Morocco.*
Wind *- BEV: wind farms in Germany, 90% onshore and 10% offshore (weighted by installed capacity in 2019). ICEV: wind farms in Argentina/Patagonia*
Mix *- BEV: PV and wind plants for electricity generation in Germany, 50% each; ICEV: PV and wind plants in North Africa/Morocco, 50% each.*

The **efficiency losses are distributed** over different stages of the value chain (cf. **Figure 5**).

- In the case of BEVs, additional efficiency losses compared to conventional efficiency arise mainly due to the low electricity yield of RE plants in Germany (reduced electricity generation yield), but also due to seasonal storage requirements and additional consumption due to air conditioning of the vehicle interior (included in the "mobility" value-added stage).
- For PtL-powered ICEVs, the main drivers are conversion losses (PtH2, ‘electrolysis’, and H2tL incl. CO2 sourcing via direct air capturing, ‘Fischer-Tropsch synthesis’) in addition to engine efficiency, which are already covered by conventional efficiency analyses.

Figure 5. Efficiency losses occur at all stages of the value chain - above all, location-related lower electricity generation yields reduce BEV efficiency



Source: *Frontier Economics*

Note: ***Ref PV*** *- BEV: PV systems in Germany; ICEV: PV systems in North Africa/Morocco.*
Ref Wind *- BEV: wind plants in Germany, 90% onshore and 10% offshore (weighted by installed capacity in 2019). ICEV: wind farms in Argentina/Patagonia*
Ref PV/Wind *- BEV: PV and wind plants for electricity generation in Germany, 50% each; ICEV: PV and wind plants in North Africa/Morocco, 50% each.*
Further note: *the respective specific efficiency of a value chain stage, e.g. the conversion of electricity into hydrogen, is identical across the scenarios (namely 67% for electrolysis), only the share in the overall result differs (cf. figure "electrolysis loss": ICEV PV: 31% vs. ICEV Wind: 24%).*

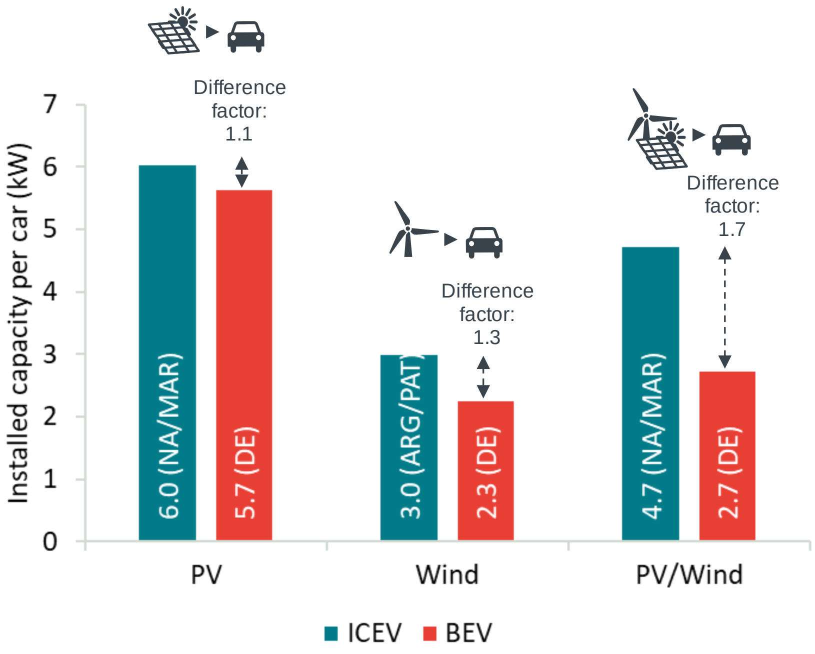
The capacities of PV and wind plants to be installed also differ depending on the site conditions - for BEVs in Germany and for ICEVs/PtLs in e.g. Argentina/Patagonia or North Africa/Morocco

The implications of a comprehensive concept of efficiency can also be seen in the number of wind turbines and solar plants that need to be installed to power a certain number of cars. In order to meet the annual demand of an average car in Germany, for example, electricity generation from solar energy requires a capacity of

- 6 kW per PtL-powered ICEV (renewable energy (PV) site in North Africa/Morocco) and
- 5.7 kW per BEV (renewable energy (PV) site in Germany).

> Operating a car with green PtL requires a calculated PV capacity of 6 kW in North Africa, a battery electric car requires with 5.7 kW PV capacity in Germany almost as much.

Figure 6. Implicit capacity requirement per car for the annual mileage of a BEV and an ICEV in the respective reference scenarios

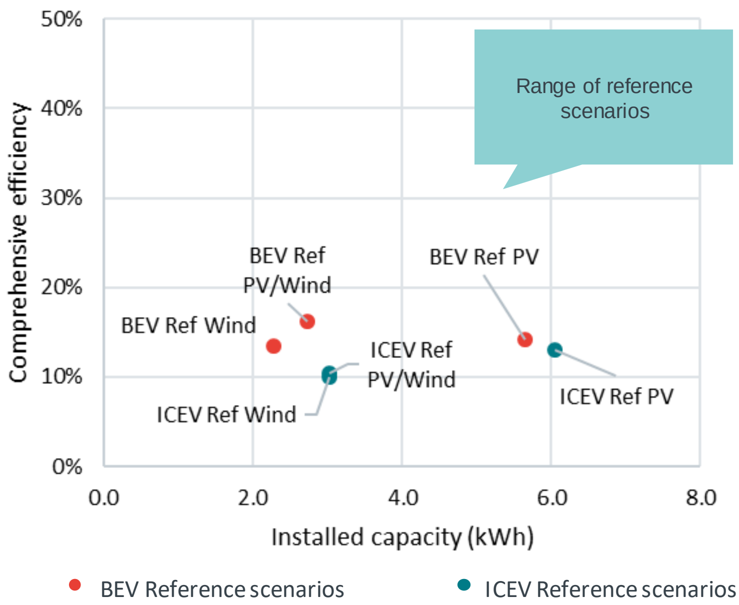


Source: Frontier Economics

Note: Assumed annual mileage of a car in Germany: 13,975 km (average value 2014-2018 based on KBA (2020)). [4]

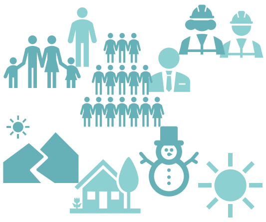
The result shows that in the reference scenario one BEV and one ICEV are very much on par both in terms of comprehensive efficiency and installed capacity. Another key factor is the far greater availability of land in sparsely populated regions like North Africa than densely populated countries like Germany.

Figure 7. Comprehensive efficiency and capacity of PV and wind plants to be installed (to meet the required energy demand per vehicle)



Source: Frontier Economics

[4] The difference factor for the generation technology combination of PV and wind differs slightly from the absolute kW consideration shown above (1.7) due to rounding differences between the % consideration (1.6 in Figure 4).



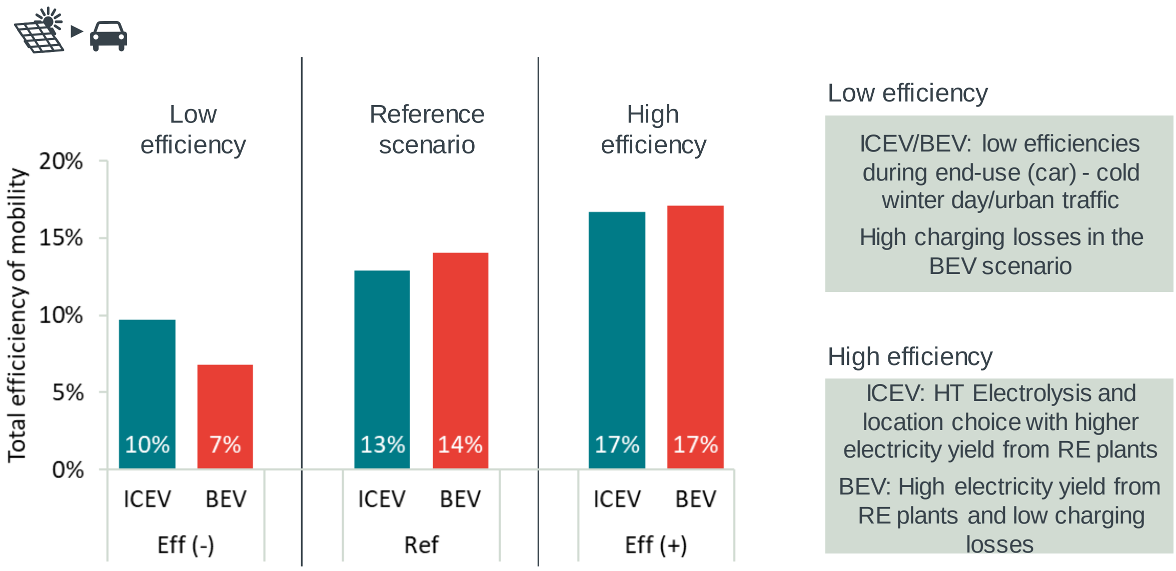
In reality, technical efficiencies depend on a variety of factors.

Sensitivity analyses confirm the small differences in efficiency of the reference scenarios between the drive technologies

The variation of individual or several influencing factors leads to a further spread of results for the comprehensive efficiency of the drive technologies of passenger cars. Here, distinctions are made between:

- (in addition to the locations of renewable energy production) the use setting of cars (urban/rural),
- the usage behaviour of consumers (e.g. fast charging vs. charging at standard speed for BEVs),
- climatic conditions during use (variations in outside temperatures) and
- possible future technology options (e.g. efficiencies of different electrolysis processes) (cf. **Figure 8**).

Figure 8. Sensitivities show that each technology may have an efficiency advantage depending on the use case, using PV as an example



Source: *Frontier Economics*

Note: ***Eff (-)*** *- BEV: PV plants in Germany, ICEV: PV plants in North Africa/Morocco; low efficiencies in each case, cf. Figure 47 and Figure 48.*
Ref *- BEV: PV systems in Germany; ICEV: PV systems in North Africa/Morocco.*
Eff (+) *- BEV: PV systems in Germany; ICEV: PV systems in North Africa/Morocco; high efficiencies in each case, cf. Figure 47 and Figure 48.*

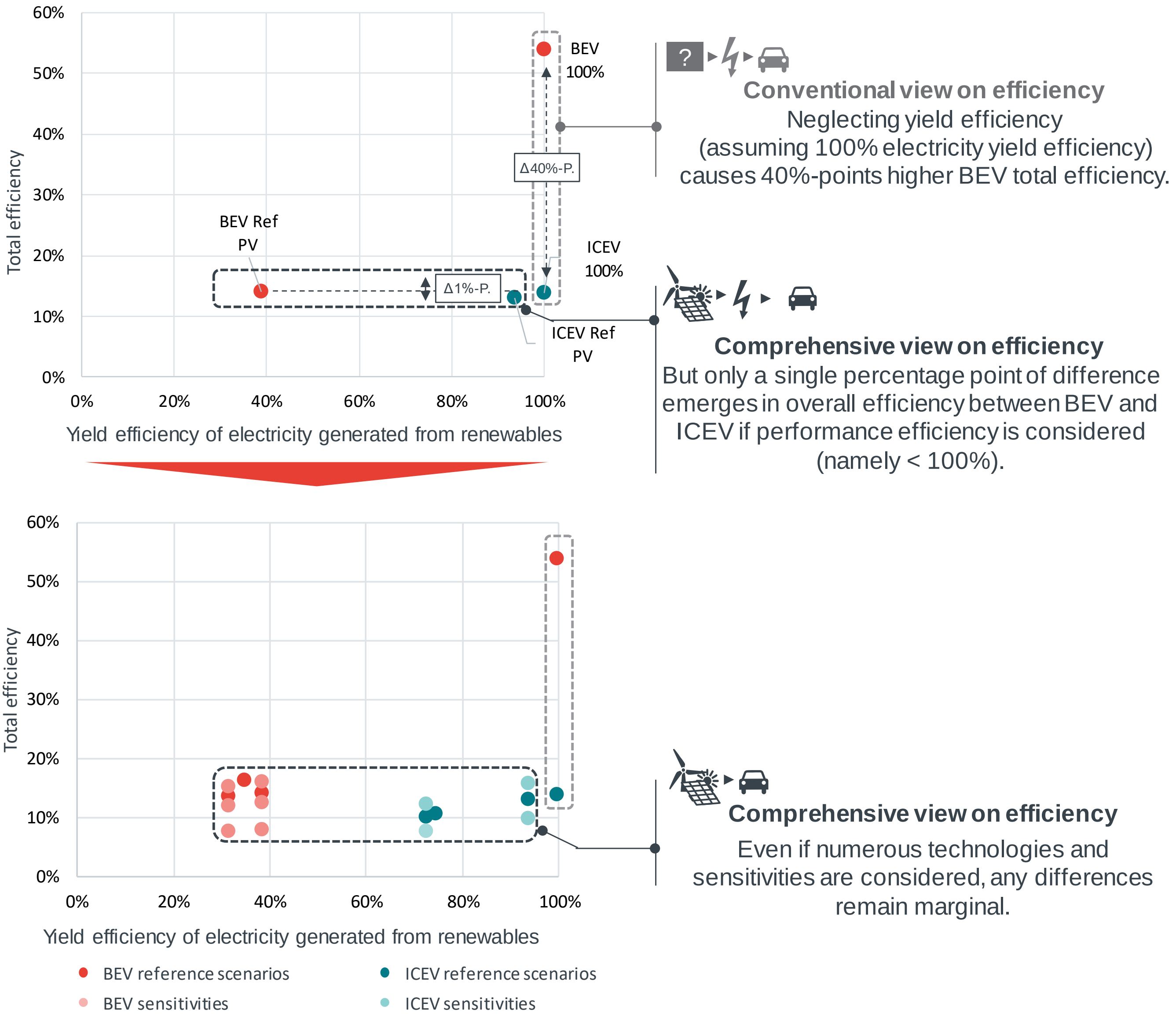
In certain sensitivity constellations, PtL-powered ICEVs have a higher efficiency than BEVs powered by renewable electricity. Factors are not only the different average yields of the renewable energy plants (Germany for BEVs, North Africa/South America for ICEVs) but also the energy storage requirements, battery charging losses and the energy expenditure for in-vehicle air conditioning.

Viewed across all scenarios (**Figure 9**), it becomes clear that

> In certain constellations, BEVs can be more inefficient than PtL-powered ICEVs when viewed comprehensively.

- the **yield efficiency of renewable electricity generation** strongly influences the results - it is consistently higher for ICEVs (about 75% to 95%) than for BEVs loaded with RES-E from Germany (30% to max. 40%) due to the advantage of sourcing renewables from international locations with abundant RE; and
- accordingly, the **comprehensive efficiency** for BEVs and ICEVs reaches a similar order of magnitude (within a range of about 10% to 20%).

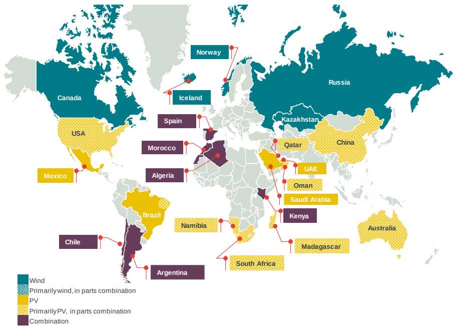
Figure 9. Looking at the complete picture, the difference in comprehensive efficiency between ICEVs and BEVs shrinks



Source: Frontier Economics

Note: For details on the scenarios and sensitivities see Chapter 4, Chapter 5 and Appendix.

A comprehensive efficiency analysis in the political context must consider the international perspective



> The comprehensive efficiency analysis does not provide any justification for the preference for a single technology.

A political pre-selection motivated by the efficiency analysis is not expedient, neither in favour of the BEV nor of the PtL-powered ICEV – political framework conditions must be open for defossilisation with both propulsion systems

To date, the term technical efficiency has been used in a very limited way in the climate policy debate. Taking renewable electricity generation within Germany as the sole starting point for the usual efficiency analyses leads to technologically misleading results. This comparison fails to reflect the energy systems reality. It neither considers the challenges associated with a system-wide direct electrification in Germany nor the technically feasible possibilities of electricity-based fuels to import energy from regions of the world with far higher RE yield potentials and more favourable electricity generation costs than in Germany.

Against this background, the following conclusions provide a basis for policy guidance:

- **Efficiency comparisons of different technologies** should start from the renewable energy source and consider the site-dependent electricity yield of the renewable plants. Thus, the comprehensive technical efficiency analysis should replace conventional efficiency considerations.

- **The comprehensive efficiency analysis does not justify a political pre-selection of one single technology**. The comprehensive analysis of energy supply chains and their efficiency losses shows that under real conditions, the technical efficiency assessment does not justify a political pre-selection of one individual drive technology in road transport over another: neither in favour of battery electric vehicles, nor in favour of internal combustion engines powered by green PtL fuels.

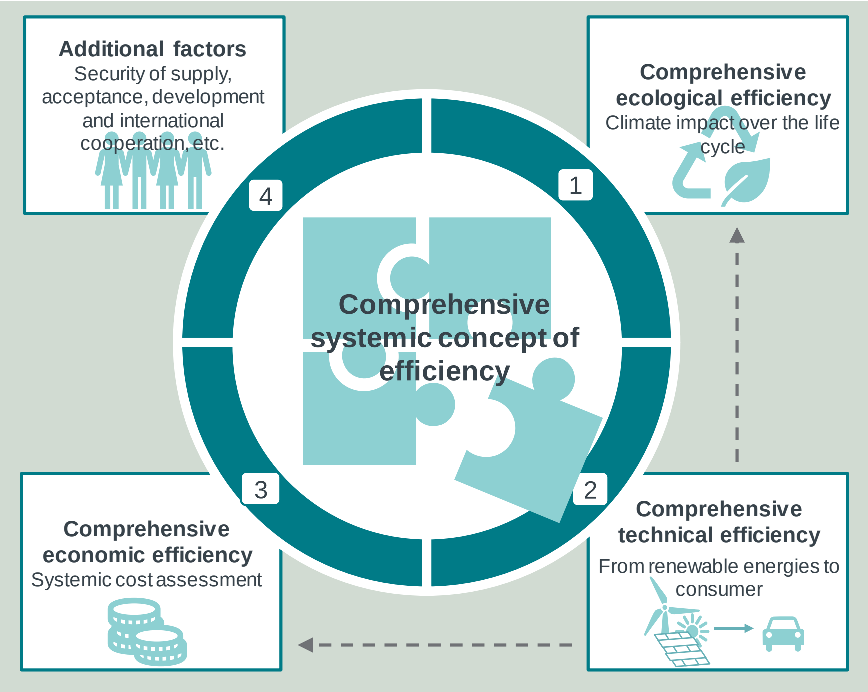
The comprehensive technological efficiency provides *a partial* knowledge base for technology assessments motivated by climate policy, but not the *whole picture*: For technology-related political decisions, in **addition to the comprehensive technological efficiency,** a **more comprehensive, systemic efficiency assessment** should be made. This systemic efficiency also includes, for example

- economic efficiencies (measure of achievable climate protection effects per monetary unit used) and
- ecological efficiencies (measure of the scale and stability of technological measures against climate change).

Comprehensive technical efficiency is one building block of a wider systemic efficiency - including technical, economic and ecological efficiencies.

The systemic efficiency also weights and assesses energy losses and CO_2 emissions, for example, and is not just based on kilowatt hours (kWh). Thus, the relevance of technical energy efficiency is diminishing against the background of large quantities of renewable energy available worldwide, while the importance of providing climate-friendly energy at the right place at the right time with the required output is growing massively.

Figure 10. Technical efficiency is one component of a more comprehensive systemic efficiency



Source: Frontier Economics

Moreover, technology selection is not carried out on a greenfield site and to the exclusion of users: In this context, aspects such as the availability of existing infrastructures (storage, transport and distribution infrastructure, vehicle fleet) and user preferences and needs should be considered. Also in this context, a political focus on one or a few specific technologies based on a narrowly understood technical efficiency concept does not appear to be appropriate.

So instead of relying on one or a few specific technologies, **all technology paths for defossilising road transport should be pursued with an open mind** – using all future procurement options for renewables: A future-oriented climate policy in the transport sector should aim to use and keep open all possible defossilisation technologies. The international perspective must also be taken into account: Imports of renewables, e.g. as liquid green fuel, are becoming essential to provide all sectors of the economy and private households with affordable and demand-oriented climate-neutral energy in Germany.

1. THE CONCEPT OF TECHNICAL EFFICIENCY ON THE TEST BENCH

The current energy policy debate - including climate policy assessment of various drive technologies in road transport (battery electric vehicles, combustion engines) shows that energy efficiency of technologies has become a dominant orientation parameter with a major influence on political decisions. In the light of this, it seems necessary to take a closer look at existing and new methodological approaches to determining technology-specific efficiencies and to assign them to a comprehensive systemic efficiency.

UNITI and MWV have therefore commissioned Frontier Economics to take a closer look at how efficiency is perceived in the current political debate, both in terms of quantity and quality, and to objectively classify it.

Our goal: A comprehensive examination of efficiency

The aim of the study is to show essential aspects of a comprehensive technical[5] efficiency analysis of energy paths, from the electricity yields of renewable energy production plants to the way in which the energy is used in different vehicles. In particular, we focus on renewable energies and the electricity generated from them, which is

- used “directly” in battery-electric vehicles (BEV path); and
- further processed into synthetic liquid fuels (E-Fuels or Power-to-Liquids, PtL) powering internal combustion engine vehicles (ICEV path).

In doing so, we point out

- which **stages of value-adding** need to be in a comprehensive efficiency analysis; and
- what **results** a comprehensive efficiency analysis leads to, compared to the narrow method often used today (hereinafter referred to as conventional technical efficiency).

The study is structured as follows:

[5] For simplicity reasons, the terms “technical efficiency” and “efficiency” and “energy efficiency” are used as synonyms in the following.

- In chapter 2 we explain the currently narrow interpretation of the concept of technical efficiency and what efficiency analyses are missing;
- in chapter 3 we summarise our approach and our efficiency analysis assumptions;
- in chapter 4 we give an overview on the results of our BEV/ICEV efficiency analysis and compare them to conventional calculations;
- in chapter 5 we explain the different drivers and sensitivities of the results in detail;
- in Chapter 6 we classify technical efficiency as part of a broader concept of system-wide efficiency, including economic and ecological efficiencies and other aspects that are relevant to decision-making; and
- finally, in chapter 7 we draw conclusions from our efficiency analysis for the political debate.

2. CONVENTIONAL ENERGY EFFICIENCY ANALYSES ARE INCOMPLETE AND CAN LEAD TO WRONG CONCLUSIONS

The climate policy debate often refers to the technical efficiency of different drive systems for vehicles

The ambitious climate policy goals of the German government (55% CO2 reduction compared to 1990 in 2030, preferably climate neutrality in 2050) require substantial reductions in greenhouse gas emissions in all energy-consuming sectors, including the transport sector. In addition to sector coupling and the further expansion of renewable energies, increasing energy efficiency (the triad of energy system transformation) is an important element in the German government's strategy for achieving its climate protection targets:

> *"The German government is pursuing the goal of making the German economy the most energy-efficient economy in the world and halving primary energy consumption by 2050 compared to 2008.* (Efficiency Strategy 2050) [6]

There is a consensus in both the scientific and energy policy debate that energy efficiency will be an important element for the energy transformation in Germany. This is reflected by the considerable efficiency improvements of vehicle engines already achieved over the past decades[7]. Without such efficiency improvements, CO_2 emissions from road transport would have risen significantly in recent years due to an increased demand for mobility and larger and heavier vehicles and it would not have stabilised at an annual level of around 160 million tonnes (CO_2)[8]. But despite this efficiency gains, achieving Germany’s climate targets will require a massive reduction in CO_2 over the next decades.

[6] See Energy Efficiency Strategy 2050 of the Federal Ministry of Economics and Energy (BMWi), https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/energieeffiezienzstrategie-2050.pdf?__blob=publicationFile&v=12.

[7] Cf. e.g. Details of average consumption, BMVi (2020), p. 309.

[8] Cf. BMVi (2020), p. 311.

In this respect, emissions from road transport have lately become part of an intense debate about reducing greenhouse gas emissions.

The focus of political action to date has been on federal government's efforts to massively promote the sale and use of battery-electric vehicles in coming years and thus expand them, to gradually replace vehicles with internal combustion engines.

> The use of PtL produced on the basis of renewable electricity enables the **defossilisation of the vehicle fleet** and the **use of already available** energy distribution and -storage infrastructure.

However, there are alternatives to this transport policy strategy: vehicles with internal combustion engines can be refuelled with green fuels such as biodiesel or "green" synthetic petrol/diesel produced on the basis of renewable energies (power-to-liquids, PtL). As long as fuels are produced in a green way, there would not be any (net) CO2 emissions. There are various advantages to such a strategy: for example, existing infrastructure (such as filling stations or fuel depots) can still to be used and the same applies to vehicles with internal combustion engines already in use. Accordingly, there is no need to develop a new energy distribution and storage infrastructure. Furthermore, restrictions from the consumer's perspective, such as long charging times, can be avoided and the vehicle fleet can be defossilised.

The primacy of energy efficiency derives, among other things, from the desire for energy self-sufficiency

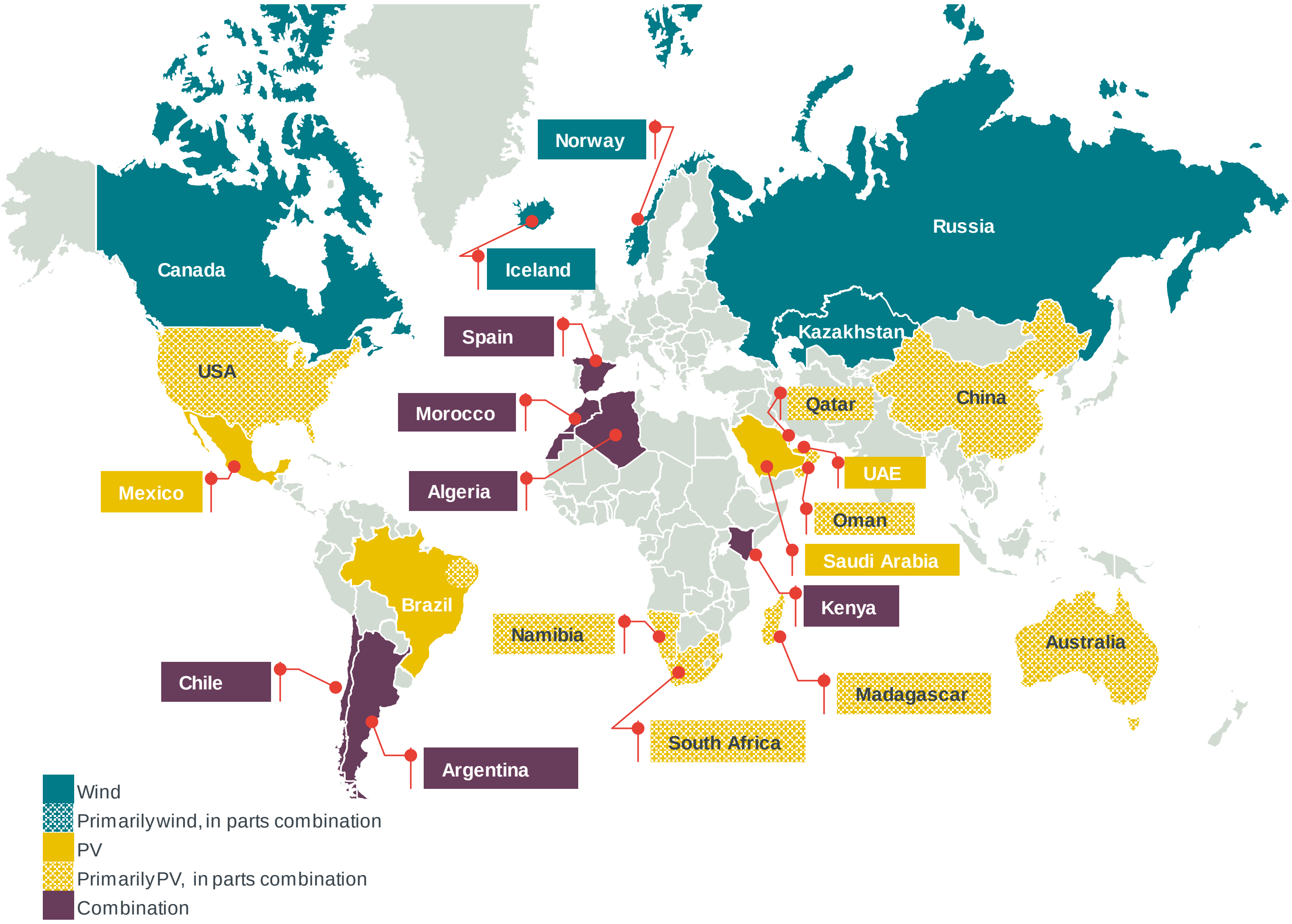
To a large extent, a greener road traffic in Germany will be achieved by the use of renewable energies. This applies both to the direct use of green electricity in battery electric vehicles and to the indirect use of green electricity, e.g. in synthetic fuels (petrol/diesel) or by hydrogen in fuel cell vehicles, respectively. [9]

However, there are restrictions to the provision of green electricity depending on the type of drive technology considered. Renewable electricity from synthetic fuels could be produced in high-yielding and low-cost locations outside Europe. Chemical energy sources, and liquid fuels such as petrol or diesel in particular, can easily be stored in an atmosphere with a high energy density and can be transported efficiently. Accordingly, Germany can use established transport and trade routes to import these energy sources almost irrespective of the geographical position of their production site. There are numerous locations with a high renewable energy yield potential and other favourable conditions (e.g. large land availability)

[9] In this study we focus on the analysis of battery electric vehicles and vehicles with internal combustion engines that are powered by synthetic fuels (petrol/diesel) from renewable energies. Fuel cell vehicles are not subject of this study.

worldwide that can be used., for example regions in Africa, the Middle East, Australia and South America.

Figure 11. Potential non-European export regions for PtL products



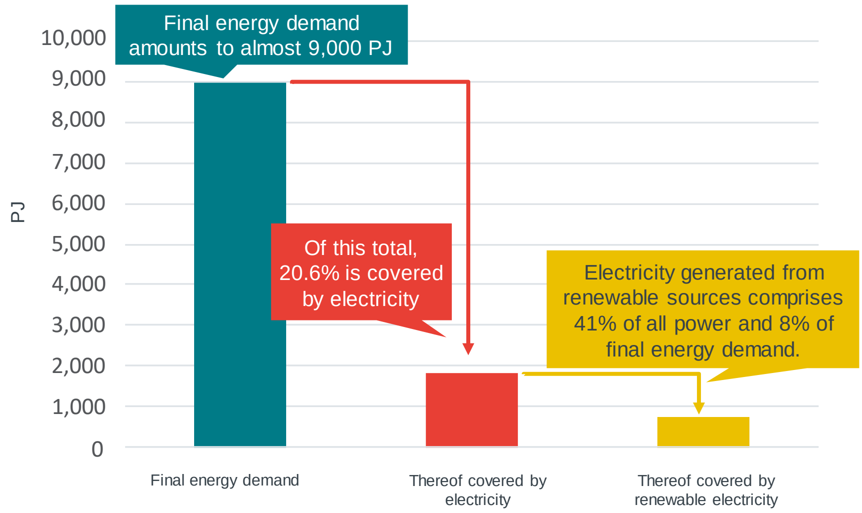
Source: Frontier Economics (2018)

In contrast, the direct use of electricity in battery electric vehicles faces a number of substantial challenges:

- **Electricity from renewable energies must replace conventional electricity generation - even without additional sector coupling**: Great efforts are already being made to further increase the share of renewables in Germany's electricity production from around 41%[10] with the goal of replacing electricity generation from coal, natural gas and nuclear energy completely. With the increasing electrification of additional sectors, the demand for renewable electricity is also going to increase further in future.

[10] See https://www.bdew.de/media/documents/2449_Nettostromerzeugung.jpg

Figure 12. The share of renewable electricity is only 8% of total energy demand



Source: AG Energiebilanzen e.V., values for 2018

Domestic RES quantities are limited

Limited land availability and a limited renewable energy potential make it impossible for Germany to cover its energy need from domestic RE electricity generation only

- **The availability of domestic RES-E volumes seems to be increasingly limited**: Although the use of renewable energies also comes with opportunities for a country like Germany that traditionally imports fossil energy to generate its own energy and provide it for domestic demand, in the real-world domestic RE electricity generation is insufficient. The main reason for this is that land availability and RE potentials are limited in Germany due to relatively few hours of sunshine and low wind resistance (indicators include, for example, discussions on the installation and clearance regulations for wind turbines, grid expansion and power line routing). Lessons learned from the past show that, despite considerable efficiency efforts, energy demand in Germany will remain very high if it continues to be an industrialised country with increasing economic growth.
- **Moreover, importing additional quantities of electricity proves to be difficult due to the limited transport capacities of electricity:** Today**,** energy supply for the energy industry, for transport and other sectors is mainly effected by using imported chemical energy carriers, e.g. oil (products) for road transport and oil and gas for the heating sector and the industry. If in future this energy demand is supposed to be increasingly covered by electricity and in view of the limited domestic generation potential, large parts of the energy demand would have to come from electricity imports instead of imports of chemical energy carriers. However, since the capacities are currently not even close to being available, this would result in an enormous need to expand the international electricity networks, which would be

prohibitively expensive. For the time being, projects aiming to import electricity from distant regions such as North Africa to Germany, such as Desertec, have failed due to high costs and a lack of economic efficiency.

Electricity imports problematic due to limited transportability

Projects that were intended to transport electricity from more remote regions such as North Africa to Germany initially failed due to the cost of transporting the electricity.

In view of the **limited renewable energy potentials within Germany, reducing the demand for energy appears to be the only solution in order to ensure an adequate energy supply.** This could be done by trying to do without energy, by relocating production processes abroad so that their energy consumption would no longer appear in the German energy balances, and/or by focusing exclusively on technologies that, from a limited conventional perspective, have the highest possible efficiency.

Consequently, the limited availability of renewable energies in Germany is a major **reason for the current debate that strongly focuses on efficiency and technical efficiencies**.

This leads to a preference of technologies with as little conversion stages as possible. The logical consequence: 1. direct electricity applications are considered the means of choice, and 2. other climate-neutral options only play a downstream role. At present, this also applies to PtL products which are regarded as supposedly "inefficient" options due to their production requiring further process engineering steps.

From a conventional perspective, battery electric drives always have considerable efficiency advantages

In the context of the debate around the "right" drive systems for road transport, reference is regularly made to these efficiency or effectiveness considerations for the various technologies (battery electric vehicles, vehicles with combustion engines, fuel cell vehicles, etc.). [11,12, 13]

In the extreme case of these considerations, they concentrate solely on the efficiency of the engines, with the efficiency of an electric

[11] Cf. German Bundestag (2020), answer of the Federal Government to the small question [...] of the parliamentary group DIE LINKE: "Currently the overall efficiency of a battery vehicle is 70 to 80 percent [...] (assuming 100 % renewable energy sources).

[12] Cf. German Bundestag (2019a), answer of the Federal Government to the parliamentary question [...] of the Bündnis 90/DIE GRÜNEN parliamentary group: "[...] Above all, a considerable amount of energy is lost during the conversion of electricity into fuels. This electricity, on the other hand, could be used directly and therefore much **more efficiently** in battery electric vehicles.

[13] Cf. German Bundestag (2019b), Federal Government's answer to the FDP parliamentary group's question [...]: "For this reason [conversion losses], direct and **efficient** use of primary energy sources should always be examined first with regard to ecology and economy before using conversion products.

motor[14]amounting to about 85-90%[15], while internal combustion engines will only achieve an energy efficiency of around 25%-45% (petrol engines 25%-35% and diesel engines 35%-45%). [16]

If the consideration is expanded to the production of traction energy (charging current or synthetic diesel/synthetic petrol) in addition to engine efficiency, it proves that battery electric vehicles also have an advantage over internal combustion engines in terms of energy efficiency: If the conversion losses along the production process from renewable electricity to the PtL product (synthetic diesel, synthetic petrol) are added when synthetic fuels are used (from 2 kWh of electricity, approx. 1 kWh synthetic fuel), the energy balance for internal combustion engines deteriorates further to efficiency values in the order of 13% to 20%.

If energy losses in the charging current are taken into account, e.g. for electricity storage in the battery installed in the vehicle, relevant sources show an efficiency of battery electric vehicles of just under 70% (cf. **Figure 11**). [17][18] This is based on the following factors:

- Use of the vehicle: 85% efficiency [19]
- Loading efficiency: 90% [20]
- Mechanics 95% [21]
- Transmission and feeding into the electricity grid: approx. 95%. [22]

[14] See https://www.adac.de/verkehr/tanken-kraftstoff-antrieb/alternative-antriebe/elektroantrieb/

[15] Cf. UBA (2015), p.22.

[16] Cf. UBA (2015), p.22.

[17] See https://www.adac.de/verkehr/tanken-kraftstoff-antrieb/alternative-antriebe/synthetische-kraftstoffe/

[18] See Acatech et al (2017).

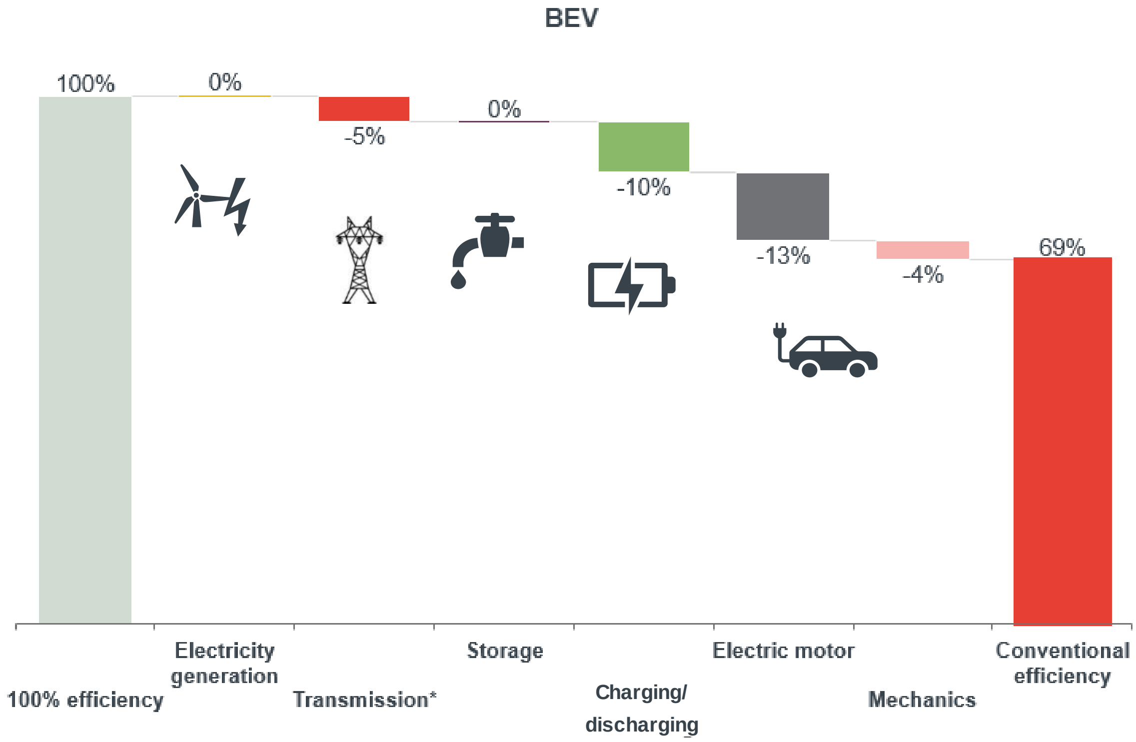
[19] See UBA (2015), p. 22.

[20] See UBA (2016).

[21] Cf. Acatech et al. (2017), Figure 5.

[22] Frontier Economics based on BDEW 2017.

Figure 13. Conventional efficiency of a BEV path is just under 70%.



Source: Frontier Economics based on Acatech et al. (2017)
*Note: *Local transport of electricity"*

In the political debate, this finding often leads to the perception that PtL products should only be used for efficiency reasons if there are no technically feasible alternatives, as it would be the case in the aviation sector. It is further perceived that in application fields such as road traffic or heat provision, PtL products should not be used due to their lower energy efficiency compared to direct flow applications.

It is questionable whether the efficiency concept on which this political argumentation is based is justified from an objective and technical perspective. Defining efficiency like that falls far short as it completely neglects, for example, the different yields of PV or wind power plants that depend on their respective location. This also implies that the political conclusions we have shown as examples have been drawn on a misleading basis. We will explain this further below.

In comparison to Germany, the same PV or wind power plant can "harvest" many times the amount of renewable electricity at non-European renewable energy sites.

Conventional efficiency considerations fail to consider the different annual yields of wind and PV

So far, the term efficiency used in comparative efficiency analyses for drive systems in road traffic has been defined under limited premises and perspectives. This is proven by the basic assumption that the renewable electricity required for climate-neutral drive technologies used in Germany must be produced and made available exclusively in Germany. However, as already described above, this assumption is not reasonable:

- **Direct applications of green electricity**, e.g. battery electric vehicles: Due to transport and storage restrictions, electricity must indeed be generated very close to its consumption, i.e. usually in Germany.
- **Indirect applications of green electricity,** e.g. synthetic fuels in combustion engines: Electricity from renewable energies can be generated in windy and/or sunny regions such as North Africa, South America or Australia and processed into synthetic fuels. The products can then be transported to Germany or Europe relatively easily.

This difference has a massive impact on the yield efficiency of energy supply. In comparison to a plant in Germany, a multiple amount of renewable electricity can be "harvested" from the same PV or wind power plant at more favourable non-European RE locations. This difference in the yield of energy production should be included in the analyses of the technical efficiency of drive systems in road transport (see calculations in sections 4 and 5).

(Seasonal) energy storage demand is an essential but often neglected factor.

In addition, other factors that are relevant in practice are often neglected

Conventional efficiency analyses often fail to include or sufficiently include a number of factors that are relevant in practice. These include, for example:

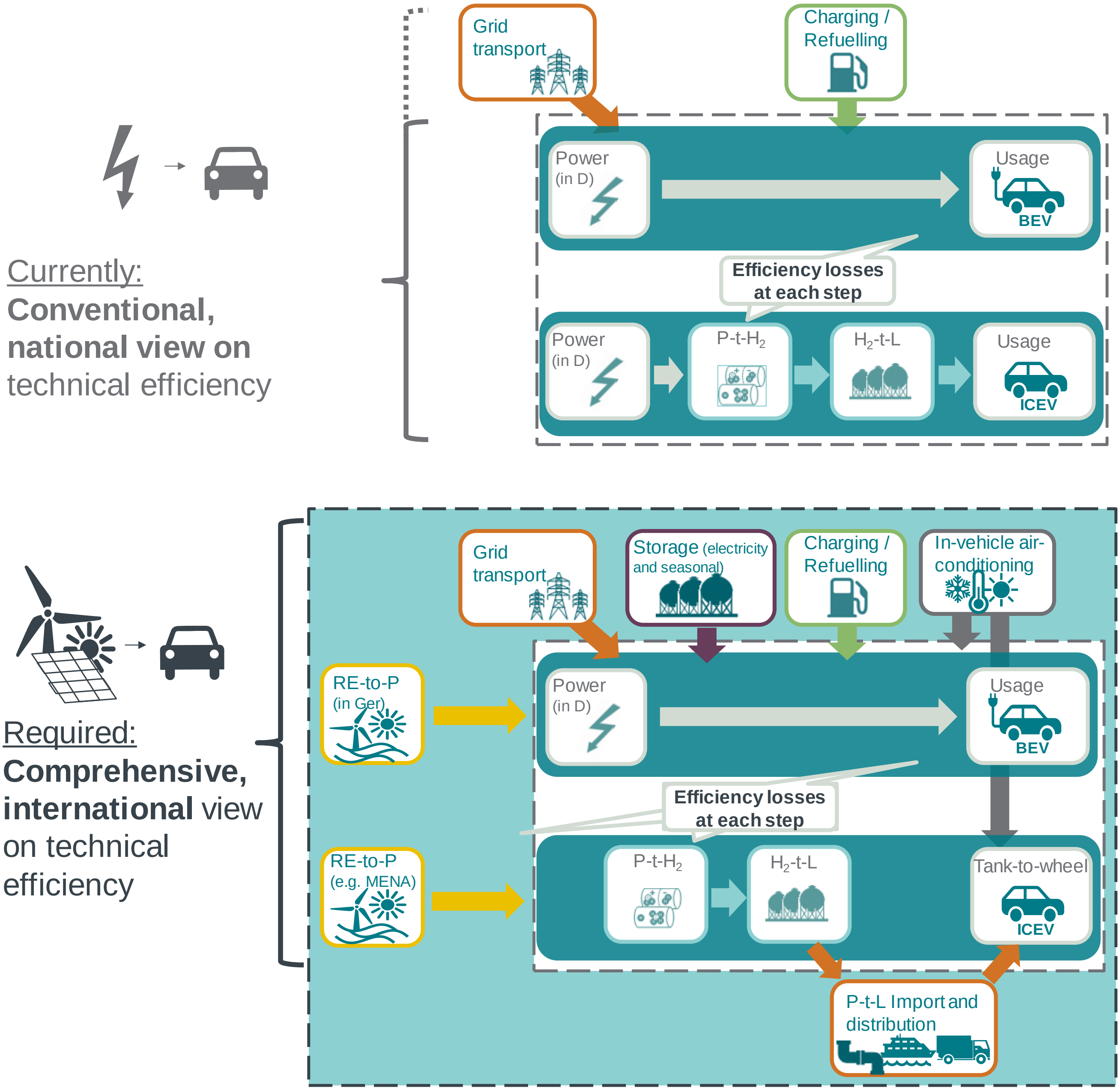
- **Energy losses during transport**: Both electricity (on a large scale) and synthetic fuels (petrol/diesel) are subject to energy losses or energy requirements during transport and distribution.
- **Losses in energy storage**: The availability of electricity from renewable generation varies enormously over the course of the year. In Germany, for example, electricity production from PV systems is significantly lower in the winter half of the year than in the summer half. Accordingly, it is necessary to seasonal storage of

electricity is necessary, which in turn is associated with efficiency losses. This does not apply to chemical energy sources such as diesel or petrol, which can be stored

- **Charging losses in battery electric vehicles**: When batteries are charged, considerable charging losses are sometimes incurred. This applies in particular to the rapid charging of batteries, which is intended to achieve a certain (but by no means complete) harmonisation of the comfort of use of vehicles.
- **Energy requirements for air conditioning the interior of vehicles**: The energy required for air conditioning vehicles is often underestimated. While in summer, both battery electric vehicles and vehicles with combustion engines require additional energy to cool the interior of the vehicles, in winter with combustion engines the waste heat from the engine can be used to heat the interior. A vehicle with an internal combustion engine has efficiency advantages in this respect, as some of the waste heat from the engine is not emitted directly into the ambient air, but can be used for air conditioning.

This requires a **comprehensive analysis of the technical efficiency** of various drive systems, considering all necessary processes and ensuring user comfort (cf. **Figure 14**). The efficiency of electricity generation must be part of the assessment just as much as conversion, transport, storage and application losses do. We pursue this approach in the following sections 3 and 4.

Figure 14. Comprehensive efficiency takes into account all conversion stages and international renewable energy potentials



Source: Frontier Economics

3. WE MODEL THE COMPREHENSIVE EFFICIENCY OF DRIVE SYSTEMS ALONG THE ENTIRE VALUE CHAIN

In the following sections (chapters 4 and 5) we calculate the efficiencies of BEVs and ICEVs running on "green" synthetic fuels. In the case of BEVs, we consider the energy path from the production of renewable energies (RE) to the use of the charging current in the BEV, while in the case of ICEVs we consider the energy path from the production of RE to the production of PtL, likewise to its use in internal combustion engines). The conversion steps covered are thus

- **Production of the electricity** (renewable electricity) - here the actual electricity harvesting factor or yield, which depends, among other things, on the location of the renewable energies, is taken as a basis;
- **conversion** and corresponding losses in the production of synthetic fuels;
- **Transport of the energy** - energy losses are relevant here, especially in the field of electricity;
- **Seasonal storage of** electricity: conversion losses in the production of hydrogen and conversion losses in the conversion of electricity back into electricity;
- **Use of the vehicle**: this includes
  - Propulsion of the vehicles, i.e. efficiency of the respective type of drive;
  - Storage of energy (e.g. battery storage losses);
  - Air conditioning of the vehicle interior throughout the year and associated energy requirements (e.g. through the use of air conditioning systems in summer) or gains (e.g. through the (partial) use of waste heat from combustion engines;
  - Energy losses during vehicle charging (especially relevant in the field of electricity); consideration of additional losses during rapid charging due to necessary intermediate storage.

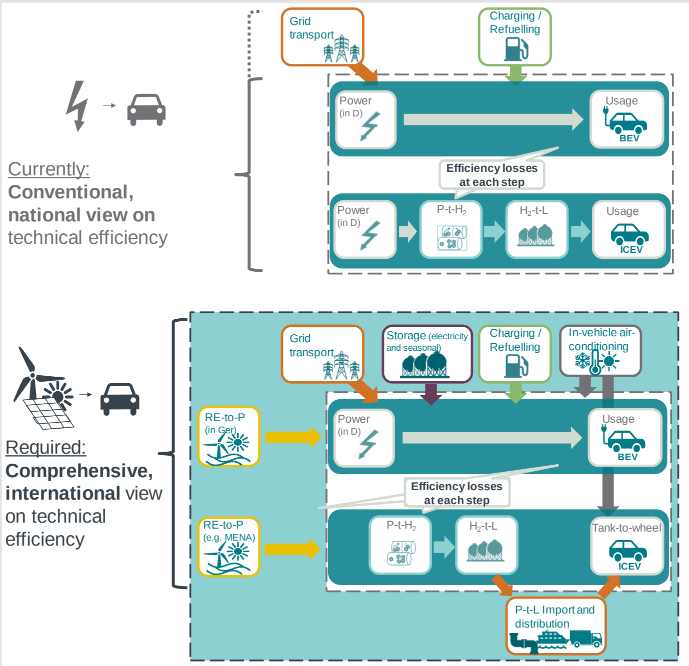
This means that we are going beyond previous analyses, especially with the step of generating energy from renewable sources.

DEMARCATION CONVENTIONAL VS. COMPREHENSIVE EFFICIENCY CALCULATION

In this study we consistently show the differences between the conventional and the comprehensive approach to technical efficiency analysis. As described in chapter 2, there is currently no fixed definition of the conventional approach. Particularly with regard to the BEV path, some analyses focus entirely on the efficiency of the engine, while others take into account a number of other factors of vehicle use and thus, for example, battery charge losses.

We define the **conventional approach** as an analysis that includes the following stages in the value chain:

- RES-E produced in Germany;
- Power grid transmission;
- PtL production and transport in Germany;
- Loss of charge;
- Vehicle consumption at approx. 20° C.



In our **comprehensive analysis** we also take into account

- Location-dependent **electricity yield efficiency** of the production of electricity, e.g. from solar radiation energy and/or wind energy, international PtL generation and transport;
- the non-seasonal use of vehicles and thus **seasonal storage of** electricity; and
- the **air conditioning of** the vehicle.

Our assumptions and variants are listed in the overview table (**Figure 15**) and are based on relevant sources and our own estimates.

Figure 15. Assumptions and variants

Variants with different efficiency losses		
Value chain stage	**Energy path up to BEV**	**Energy path up to ICEV / (mild) hybrid**
Location of electricity generation	• Germany	• Patagonia • North Africa/Morocco
Renewable energy sources	Wind, PV, Wind/PV combination	
Conversion	-	• P-t-H2 (Low temp. electrolysis) • *Sensitivity: High temp. electrolysis* • H2-t-L-t-Fuel
Transport	Electricity grid	Diesel/petrol by tankship and trucks
Storage	• Storage P-t-H2-t-P	• As liquid fuel to prevent efficiency losses
Charging	• AC and DC average • *Sensitivities: less/more losses*	Excl. stationary battery storages that are necessary to provide sufficient capacity for fast loading
Car types	• Compact class, e.g. Ford Focus	
Air temperature & topography	• Annual average: WLTP consumption (test conditions at 23°C), plus heating and cooling requirements • *Sensitivity: Higher consumption through heating in winter (ca. 0°C) and in cities*	

Source: Frontier Economics

*Note: *For DC charges with high power, quantities of electricity must be stored at a filling station via local stationary storage. Depending on many factors such as the duration of storage, storage losses can also occur. As these charging processes are currently still exceptions, we do not consider this storage loss in this study.*

We record site-specific factors of renewable electricity generation in the "electricity yield efficiency".

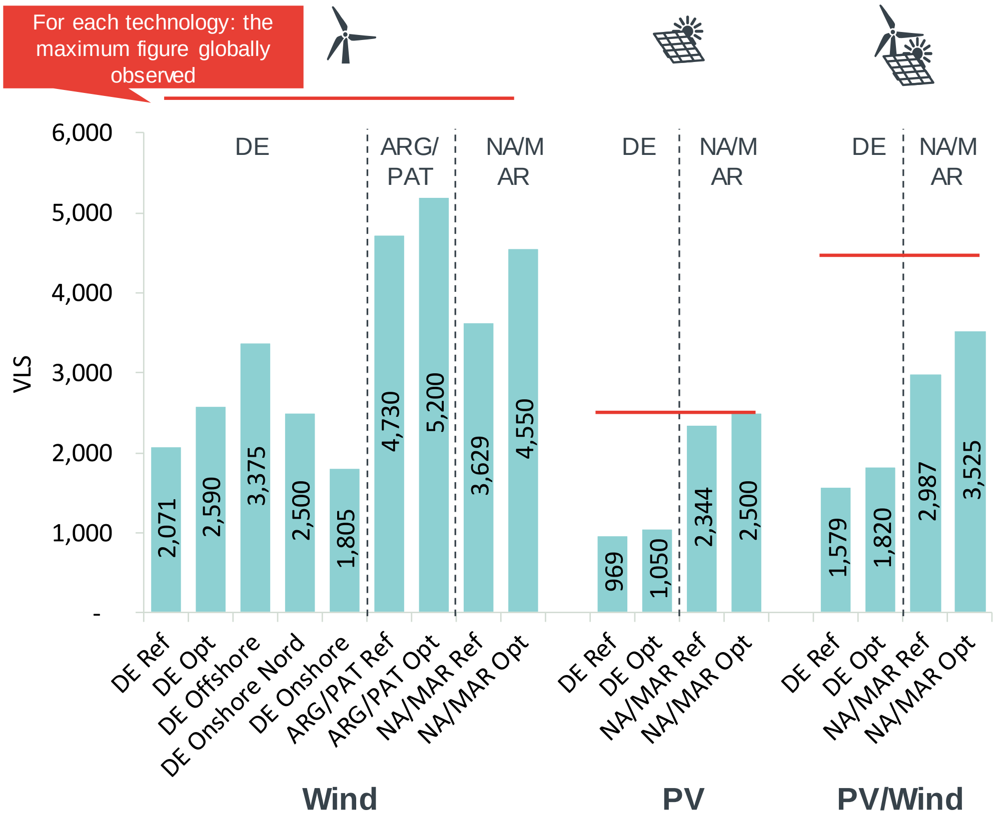
In current studies on energy efficiency, it is generally assumed that the renewable electricity used in battery electric vehicles and for the manufacture of PtL products is generated in Germany.

This assumption ignores the fact that PtL products can be transported efficiently over very long distances due to their high energy densities under atmospheric environmental conditions, unlike electricity. PtL products thus make it possible to exploit the significantly higher renewable energy yield potential available worldwide for applications in all regions, including Germany, almost independently of their geographical location.

Electricity yield potentials and therefore also full load hours of RE plants vary considerably depending on the location and are determined by the number of hours of sunshine and wind speed. This means that the same wind power or PV plant can generate different amounts of electricity depending on the location.

Conversely, a different number of wind and PV installations must be installed for a given distance travelled by a specific vehicle.

Figure 16. Full load hours according to EE technology with sensitivities



Source: Frontier Economics based on BMWi (2020), BDEW (2020), Fraunhofer ISE (2018), EVWind (2019), FZ Jülich (2017), Roland Berger/Prognos (2019).

Note: Opt = Optimistic scenario, Ref = Reference scenario

Conventional efficiency comparisons, however, start the efficiency calculation only with the kWh of electricity produced and therefore do not take into account the differing full-load hours (FLH) and electricity yields. With this limited analysis perspective, a meaningful comparison of the RE mobility solutions BEVs and ICEVs operated with PtL is therefore not possible.

For a complete efficiency assessment, we capture this factor in the following analysis. Since full-load hours are based on different RE yield potentials, an efficiency analysis should also assign an efficiency score - an "(electricity) yield efficiency" - to the electricity generation stage.

In order to translate the full-load hours into an efficiency score (yield efficiency), a benchmark is necessary which puts the respective full-load hours achieved in relation to each other. We use the maximum full-load hours that can currently be achieved worldwide with the respective technology as a benchmark for 100% efficiency of PV and wind systems. For PV systems this is 2,500

> High full-load hours in electricity generation lead to high RES yield efficiencies, which play a central role in the comprehensive efficiency analyses.

hours (e.g. in the South American Atacama Desert) and for wind systems 6,500 hours (e.g. Patagonia, Tibet). [23]

- For example, if a **PV system** reaches 2,344 full-load hours (kWh/kW) as in North Africa/Morocco, the calculated yield efficiency according to our definition is 94% (= 2,344h/2,500h*100%), or
- For example, if a **wind turbine** reaches 3,629 kWh/kW as in North Africa/Morocco, the calculated yield efficiency is 56% (= 3,629/6,500*100%).
- When considering the efficiency of a wind/PV combination, the full-load hours are calculated by the **weighted average of installed turbines** and thus lie between the full-load hours of the respective individual technologies. Instead of calculating how many kWh(el) are generated by 1 kW installed capacity of wind or PV, the wind-PV combination examines how many kWh(el) are generated by the installation of 1 kW capacity in total of wind and PV, i.e. about a 0.5 kW wind plant and 0.5 kW PV plant. For a wind-PV combination in North Africa/Morocco this means a yield efficiency of 75% (= 0.5 * 56% + 0.5 * 94%).

For comparison: Conventional efficiency analyses wrongly implicitly assume a 100% efficiency of yield across all locations by neglecting the different yields.

A number of studies - including one by Frontier Economics[24] - show that there are a number of possible and attractive generation centres for PtL products worldwide. The renewable energy potential of these countries or regions is enormous and can in part be harnessed for Germany and Europe through PtX exports.

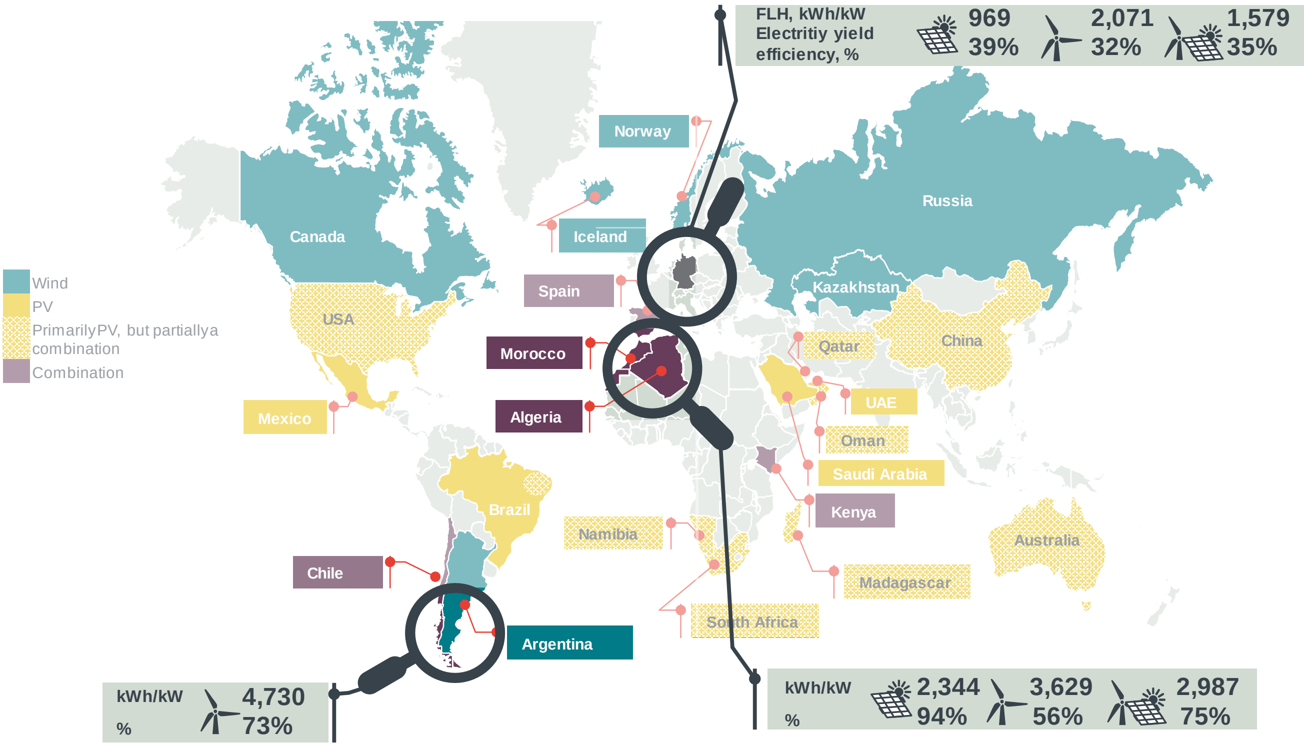
In order to keep the analysis clear, we focus in this study on the following exemplary locations for electricity generation (cf. **Figure 17**):

- **RE electricity for BEVs**: Germany (PV, wind and PV-wind combination)
- **RE electricity for PtL**: On the one hand, North Africa/Morocco as a low-cost RE location with great proximity to Europe and high RE potentials (PV, wind and PV-wind combination); on the other hand, Argentina/Patagonia as an example of a more distant production region with very good conditions for electricity generation from renewable energies, also equipped with large RE potentials (here the focus is on wind-onshore).

[23] See Fasihi and Breyer (2020), page 7.

[24] See Frontier Economics (2018).

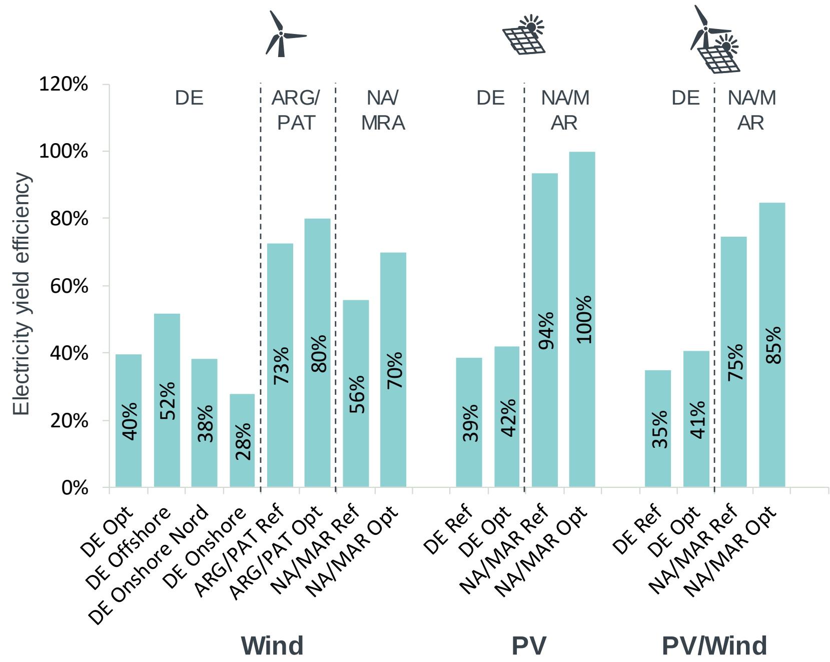
Figure 17. Reference scenarios - Full-load hours (in kWh/kW) and efficiency score (in %) by region



Source: Renewable energy potentials at country level: Frontier Economics (2018); FLH: D - PV/wind/mix: Calculated by Frontier on the basis of BMWi (2020) - Time series on the development of renewable energy in Germany; Calculated on the basis of the actual yield efficiency of the technologies; Wind: Onshore share 90% and offshore share 10%, mix: 50:50 ratio between wind and PV. North Africa/Morocco PV/wind/mix: Frontier Economics based on Agora and Frontier Economics (2018) and expert interviews. Argentina/Patagonia wind: Frontier Economics based on EVwind (2020) - Wind energy in Argentina: YPF wind farm

In addition, the **Figure 18** also shows the earnings efficiency of other scenarios.

Figure 18. Electricity yield efficiency after renewable energy technology with sensitivities



Source: Frontier Economics based on BMWi (2020), BDEW (2020), Fraunhofer ISE (2018), EVWind (2019), FZ Jülich (2017), Roland Berger/Prognos (2019).

Note: Opt = Optimistic scenario, Ref = Reference scenario

Multi-stage energy conversion of PtL production:

Losses in the conversion of electricity to liquid fuels are already the subject of the current debate on the technical efficiency of drive technologies. What is needed is the energy conversion of electricity to hydrogen (P-t-H2) and of hydrogen to liquid fuel (H2-t-L):

- **P-t-H2**: In our ICEV reference scenario, we assume low-temperature electrolysis (NT) with an efficiency of 67% for the conversion of renewable electricity to hydrogen.[25] This corresponds to the current state of the art. This can be PEM or alkaline electrolysis.
- **H2-t-L**: For the further processing of hydrogen into liquid fuel (e.g. via Fischer-Tropsch synthesis) and the "upgrading" to diesel or petrol in refineries, we assume an efficiency of 73%.[26]

[25] Frontier Economics based on Agora and Frontier Economics (2018) and expert interviews.

[26] Frontier Economics based on Agora and Frontier Economics (2018), expert interviews, Brynolf et al (2018) for the efficiency of Fischer-Tropsch synthesis. The CO_2 required for this can be obtained either from industrial waste gases or from the air (direct air capture, DAC). The efficiency already covers the energy demand for DAC. The waste heat from the Fischer-Tropsch synthesis supplies the heat demand of DAC, cf. Prognos (2020).

Losses of efficiency in energy transport and distribution of minor importance

We assume that in the ICEV scenarios the e-fuels in the ICEV scenarios will be transported to Germany by tankers from both North Africa/Morocco and Argentina/Patagonia. The energy requirement here is between 0.2% and 1% of the amount of energy transported. [27]For distribution within Germany, we estimate a flat-rate requirement of an additional 1%.

For the direct use of electricity in battery electric vehicles (BEV scenarios) we estimate grid losses for transport and distribution of 5%. [28]

Seasonal storage requirements for the continuous supply of drive energy should not be underestimated

> Energy storage requirements will continue to increase in the future as the share of renewables in electricity generation rises.

Storage requirements arise when energy production and demand are delayed. The supply dependency of electricity from wind and sun, combined with the seasonality of energy demand, poses great challenges for the future energy system. Even under the simplified assumption of a constant demand for charging current in electrified passenger road transport, fluctuations in the energy supply result in storage requirements.

Intermediate storage of electricity is always associated with efficiency losses and should therefore be part of an efficiency analysis.

In our comprehensive approach, we abstract as far as possible from short and medium-term storage requirements of hours or days for the charging current supply of **BEVs** and focus the analysis on seasonal storage requirements. We assume P-to-H2-to-P as seasonal storage, since there is currently and in the foreseeable future no alternative to storage using chemical gaseous or liquid energy sources for seasonal storage. According to our assumptions, these conversion steps are accompanied by efficiency losses of 73% (only in relation to the amount of energy to be stored, not the total consumption). This value is based on the following assumptions on efficiencies of the different steps of interim storage:

- 67% P-t-H2 conversion efficiency of the electrolyser;
- 90% efficiency through hydrogen storage[29]; and
- 45% H2-t-P efficiency based on assumptions for H2 gas-fired power plants.

[27] Berechnet auf Basis von http://hb.hr/wp-content/uploads/2014/12/tankers.pdf und https://www.searates.com/services/distances-time/.

[28] BDEW (2017a).

[29] See Fraunhofer UMSICHT (2013), pp. 50-51.

The amount of charging current that has to be temporarily stored depends on the seasonal profile of renewable energy supply and demand:

- For simplicity's sake, we assume a **constant demand for energy** from passenger cars throughout the year.
- In contrast, **energy production** from renewable energy plants in Germany **fluctuates over the course of the year** and therefore causes storage requirements for sufficient supply to meet mobility demand:
  - **PV systems** produce considerably more electricity in summer than in winter. Therefore, if PV systems are predominantly used to supply electricity, part of the electricity generated in summer must be stored for the winter. We assume that with a purely PV solution, 15%[30] of the year-end energy demand must be temporarily stored. This leads to an efficiency of 68% at this stage of the value chain.
  - Electricity generation from **wind turbines** is somewhat more evenly distributed over the year, with slightly more electricity being generated in winter than in summer. In the case of a wind power supply, therefore, energy generated in winter must be made usable for the summer months. We assume 10% of the year-end energy demand. This leads to an efficiency of 79% at this stage of the value chain.
  - If the majority of the electricity is generated by a combination of **PV and wind**, the wind surplus in winter partially balances the PV electricity surplus in summer. Nevertheless, a surplus of electricity remains in summer. With a mix of both technologies (50:50), we assume that only 5% of the year-end energy demand is temporarily stored. This leads to an efficiency of 86% at this stage of the value chain.

The **ICEVs** may also have storage requirements. However, liquid fuels can be temporarily stored without significant losses. For ICEV scenarios, efficiency losses due to seasonal storage are therefore negligible.

30 The estimates for storage requirements are based on our model-based analyses of storage requirements in the "Electricity and Gas Storage" scenario, cf. Frontier Economics et al. (2017).

10% to 30% loss of charge

must be taken into account for battery electric vehicles.

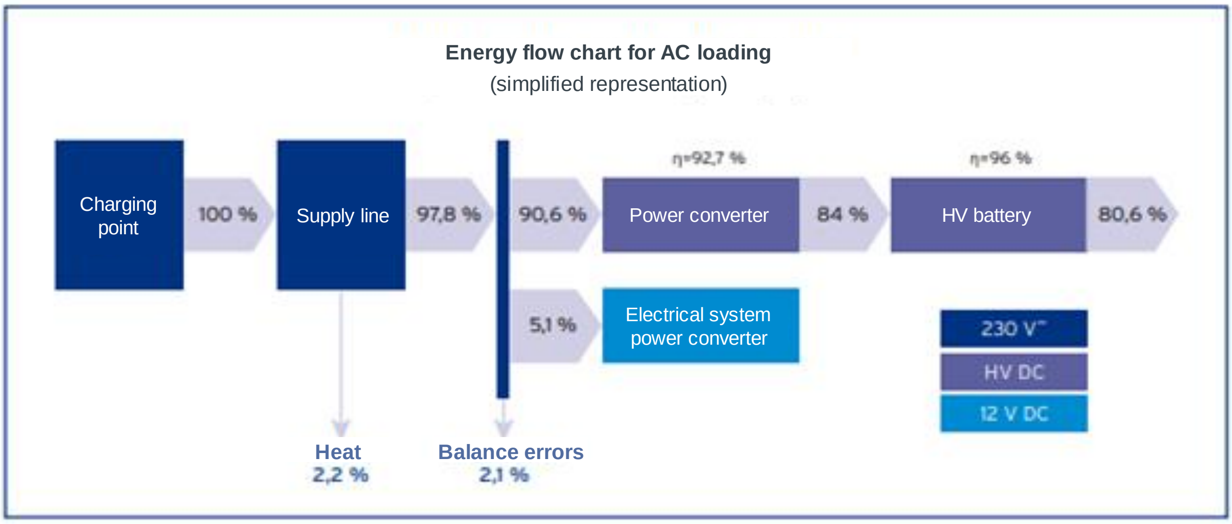
Charge losses must be taken into account in the BEV path regardless of whether the charge is AC or DC

When the battery is charged, there is a loss of charge, unlike when an ICEV is refueled. These are usually between 10% and 30%[31] (other ranges of 5% to 40% are also mentioned).[32] Generally speaking, the losses increase with the speed of the charging process. So if a BEV is charged via a powerful DC fast charging station, more energy is lost than with an AC charge, e.g. when charging at home, which usually has a charging capacity of 11 kW.

With an AC charging station, the losses are generated by the charger (Onboard Charger) installed in the BEV, and with a DC charging station, the losses are generated inside the vehicle. This is why some analyses only take into account the charging losses for AC charges, i.e. the charging losses behind the interface with the charging point.

Because we analyse not only the efficiency of a battery electric vehicle, but the entire BEV path from renewable energies to charging current and vehicle use, we take into account all charging losses in both AC and DC charging processes. We assume average charging losses of **20%** for the reference scenario.

Figure 19. Example of charge losses during AC charging



Source: Translation of BMVI and NOW GmbH (2016)

[31] See ifeu and Wuppertal Institute (2007), p. 6.

[32] See BMVI and NOW GmbH (2016), p. 68.

Efficiency during vehicle use includes not only energy consumption to cover a distance, but also for air conditioning the vehicle's interior throughout the year

In the **conventional efficiency approach,** often only engine efficiency is taken into account. If this is given as 85%, for example (cf. page 22ff.), factors such as non-optimal driving behaviour, weather conditions and use of electrical consumers as media/radio, heating and air conditioning are usually not taken into account.

In our **comprehensive approach,** we also include the aspect of the outside temperature and the corresponding air conditioning requirements. While driving behaviour is highly individual, an average heating and cooling requirement can be derived from temperature profiles. This leads to a range loss of 15% for a battery electric reference vehicle[33]. This also affects ICEVs, although to a lesser extent of 4%[34], as the waste heat can be used to heat the interior of the vehicles. The comprehensive efficiency of vehicle use is thus

- **71% for BEVs**[35] and
- **29% for ICEVs**[36] **.**

> “
>
> Heating in electric cars reduces the range due to their electricity consumption. Short distances and reheating each time lead to increased energy consumption.
>
> *https://www.adac.de/verkehr/tanken-kraftstoff-antrieb/alternative-antriebe/elektroantrieb/*

[33] The calculations are based on: temperature profiles for Germany for the years 2015 to 2019, an assumed heating requirement at outside temperatures below 15°C and cooling requirements above 19°C (cf. https://de.statista.com/statistik/daten/studie/1031883/umfrage/entwicklung-der-temperatur-im-auto-nach-standzeit-und-aussentemperatur/ , based on Dr. Andrew Grundstein, American Meteorological Society 2010), and a range loss of **BEVs** through heating of 18% on average and through cooling of 14% on average (cf. Doyle and Muneer (2019)). Our results also fall within the range of range losses for BEVs, which, according to experts, range from an average of 11.2% annually for heat pumps to 25.6% for PTC heaters.

[34] The calculations are based on: temperature profiles for Germany from 2015 to 2019, an assumed heating requirement at outside temperatures below 15°C and cooling requirements above 19°C (cf. https://de.statista.com/statistik/daten/studie/1031883/umfrage/entwicklung-der-temperatur-im-auto-nach-standzeit-und-aussentemperatur/, based on Dr. Andrew Grundstein, American Meteorological Society 2010) and an additional consumption of **ICEVs of** 2% for heating requirements and 15% for air conditioning requirements (cf. https://www.adac.de/rund-ums-fahrzeug/ausstattung-technik-zubehoer/ausstattung/auto-klimaanlagen/).

[35] 71% results from a drive efficiency of 83% for a BEV (locomotion efficiency including losses due to battery thermal management and use of auxiliary equipment such as lighting, radio, cf. e.g. Acatech et al. (2017)) reduced by a range loss of 15%, i.e. 71% = 83% * (1-15%). To determine the renewable energy generation capacity to be installed (cf. Chapter 4), we use a total electricity consumption including range loss due to air conditioning of 20.1 kWh_{el}/100km = ADAC test consumption at > 20°C – test charging losses at 22 kW + heating/cooling consumption. Example for compact to middle class car Opel Ampera-E: 19.7 kWh_{el}/100 km test consumption – test charging losses = 17.5 kWh_{el}/100 km. 17.5 * 15% heating/cooling losses = 20,1 kWh_{el}/100 km. Source:https://www.adac.de/_ext/itr/tests/autotest/at5606_opel_ampera-e_first_edition/opel_ampera-e_first_edition.pdf

[36] As in the case of the BEVs, this value results from the drive efficiency reduced by the 4% additional consumption. As the corresponding total consumption, we use 4.8 l diesel/100 km to determine the RE generation capacity to be installed (cf. Chapter 4).

4. WHEN VIEWED COMPREHENSIVELY, THE TECHNICAL EFFICIENCY OF BEVS AND ICEVS CONVERGE

The comprehensive efficiency analysis shows significant differences to an approach with a narrower (conventional) view. In the following we show the results of our efficiency calculations

- both in terms of efficiency (figures in %);
- as well as with regard to the associated need for PV plants and wind turbines to be installed (figures in kW).

From a comprehensive perspective, the BEV path shows a significantly reduced efficiency and the difference to the ICEV path shrinks

Differences in efficiency...

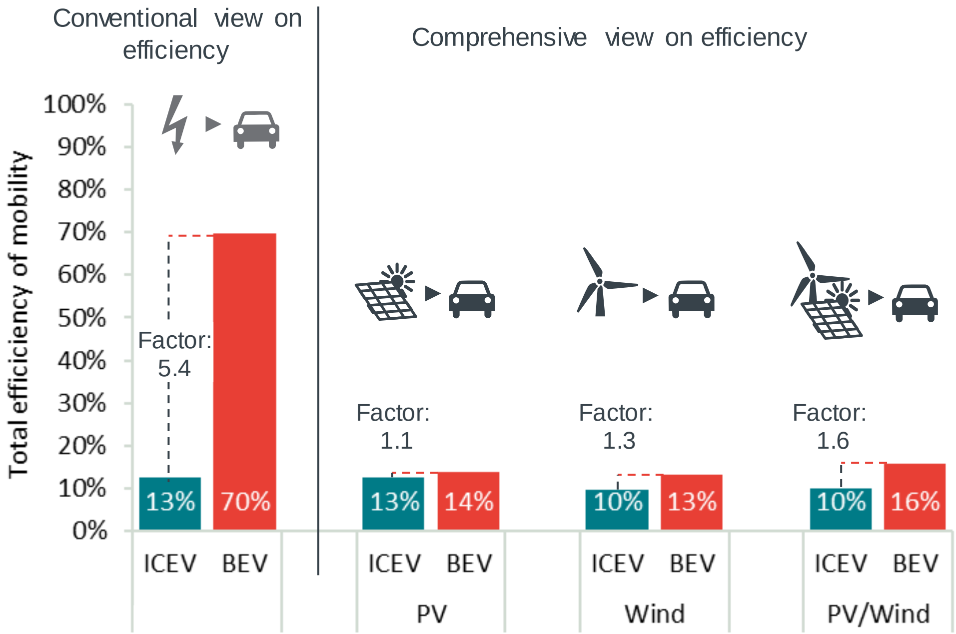
between BEVs and ICEVs operated with PtL are melting together when viewed as a whole.

The comprehensive efficiency of BEVs powered by green German-made charging current and ICEVs powered by imported green synthetic fuels are very close to each other, in contrast to the conventional view (cf. **Figure 20**):

- In the **conventional view, BEVs** are initially **5.4** times **more efficient** than ICEVs.
- On the basis of the **comprehensive efficiency approach,** it appears that BEVs have fewer efficiency advantages relative to ICEVs than is often assumed. Instead of BEVs being 5.4 times more efficient than ICEVs, the factor is with power generation technology
  - **Wind** (electricity generation in the BEV scenario in Germany and in the ICEV scenario in Argentina/Patagonia) **at 1.4**;
  - **PV** (BEV scenario in Germany and in the ICEV scenario in North Africa/Morocco) at **1.1**; and
  - **PV-wind combination** (BEV scenario in Germany and ICEV scenario in North Africa/Morocco) at **1.6** (see **Figure 20**).

This means that the comprehensive efficiencies of the propulsion technologies (BEV and ICEV) are of a comparable order of magnitude.

Figure 20. Efficiency differences between BEV and ICEV according to the approach under consideration and RE technology - reference scenarios for each electricity generation technology



Source: Frontier Economics

Note: ***Conventional scenario**: 100% yield efficiency, cf. Chapter 2.*
***PV** - BEV: PV systems in Germany; ICEV: PV systems in North Africa/Morocco.*
***Wind** - BEV: wind power plants in Germany, 90% onshore to 10% offshore (weighted by installed capacity in 2019). ICEV: wind power plants in Argentina/Patagonia*
***Mix** - BEV: PV and wind power plants for electricity generation in Germany, 50% each; ICEV: PV and wind power plants in North Africa/Morocco, 50% each*

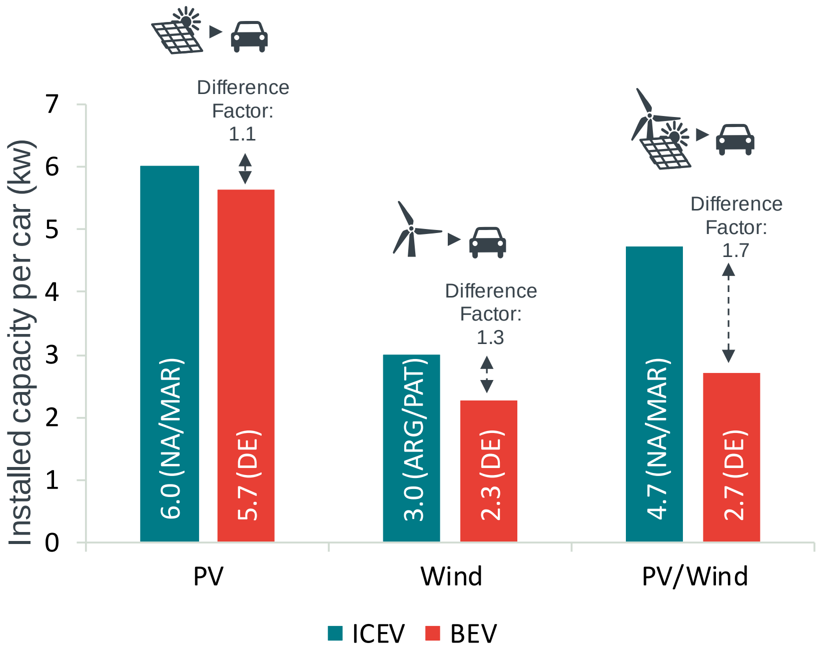
The different electricity yield efficiency of RE plants is also reflected in the capacity requirements of RE plants to operate the vehicles

Including the yield efficiency in renewable electricity generation not only provides a realistic picture of the comprehensive efficiency of the BEV and ICEV drive technologies, but also allows the calculation of the respective RE capacities to be installed.

Figure 21 shows the capacities to be installed per BEV and ICEV according to renewable energy technology. The starting point for determining the capacity is the average annual mileage of a passenger car in Germany. [37]Here, too, it can be clearly seen that the actual capacity expansion requirement per ICEV hardly differs from the expansion requirement of a BEV.

[37] The starting point for the power requirement is the average annual mileage of a passenger car in Germany (13,975 km/year - average value for 2014-2018, based on KBA (2020)) and the associated total amount of energy required per BEV or ICEV.

Figure 21. Implicit PV capacity requirement per car for annual mileage with BEV and ICEV in the respective reference scenarios



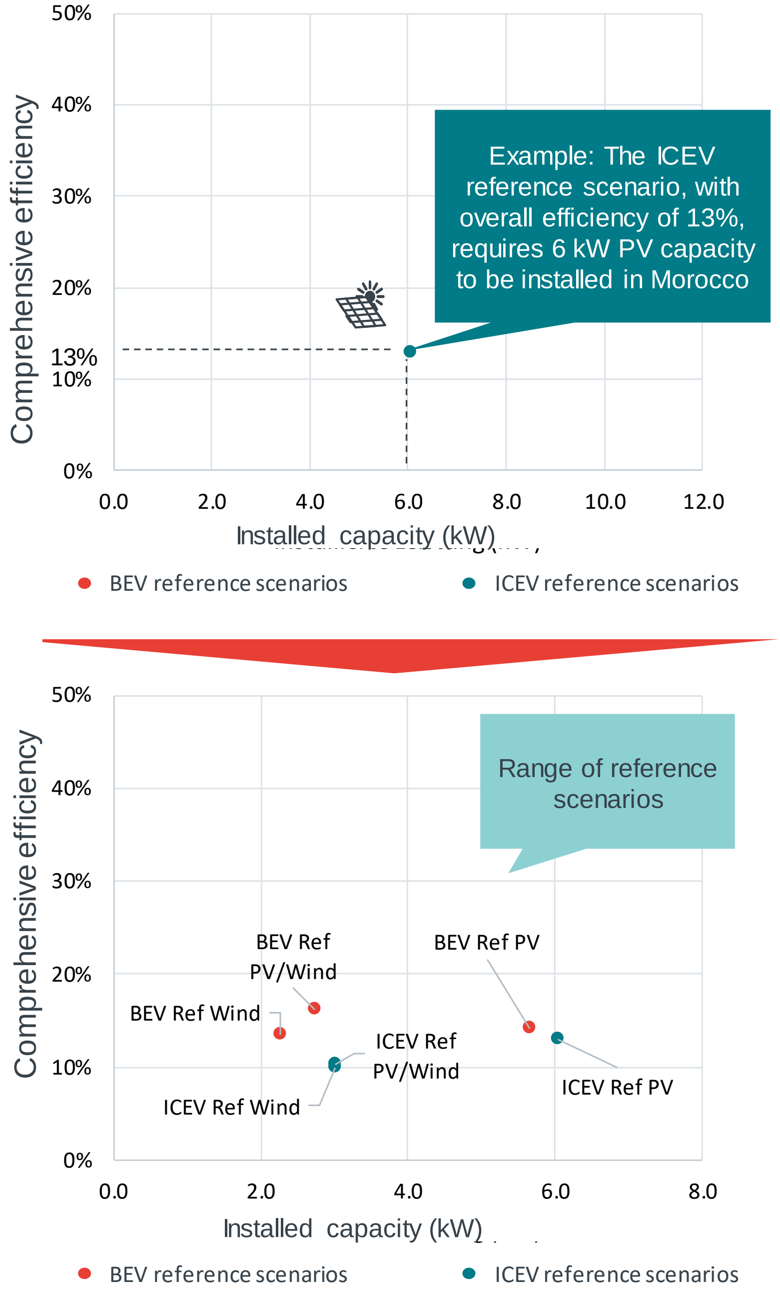
Source: Frontier Economics

Note: Assumed annual mileage of a car in Germany: 13,975 km (average value 2014-2018 based on KBA (2020)). [38]

Figure 22 compares the capacity to be installed per car in the reference scenarios with the comprehensive efficiency of the respective reference scenarios. The result shows that in the reference scenario BEVs and ICEVs are very close to each other in terms of both comprehensive efficiency and installed capacity. It should also be noted that the availability of land is significantly better in sparsely populated regions such as North Africa than in densely populated countries such as Germany.

[38] The difference factor for the generation technology combination of PV and wind differs slightly from the absolute kW consideration shown above (1.7) due to rounding differences between the % consideration (1.6 in Figure 20).

Figure 22. Comprehensive efficiency and capacity to be installed (to meet the energy demand per vehicle)



Source: Frontier Economics

In the following chapter, we take a closer look at the individual stages of the value chain and explain the drivers for the differences between conventional and comprehensive efficiency.

5. EFFICIENCY LOSSES ARE DISTRIBUTED OVER DIFFERENT STAGES OF THE VALUE CHAIN

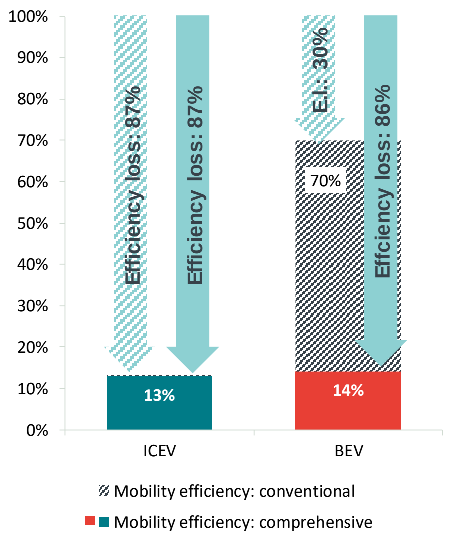
In the previous chapter we have shown the differences between conventional and comprehensive efficiency for the electricity generation technologies PV, wind and PV-wind combination (cf. **Figure 20**). In this chapter we go into detail about the main drivers for these results.

The overview graph on the left shows that the difference between conventional and comprehensive efficiency is much greater for the BEV (56% points) than for the ICEV (1% point).

This is mainly due to the fact that the conventional view does not take into account the main drivers of efficiency losses in BEVs, whereas it does for ICEVs. In addition, the efficiency losses of BEVs and ICEVs are distributed over different sections of the energy path (cf. **Figure 23** and **Figure** 24):

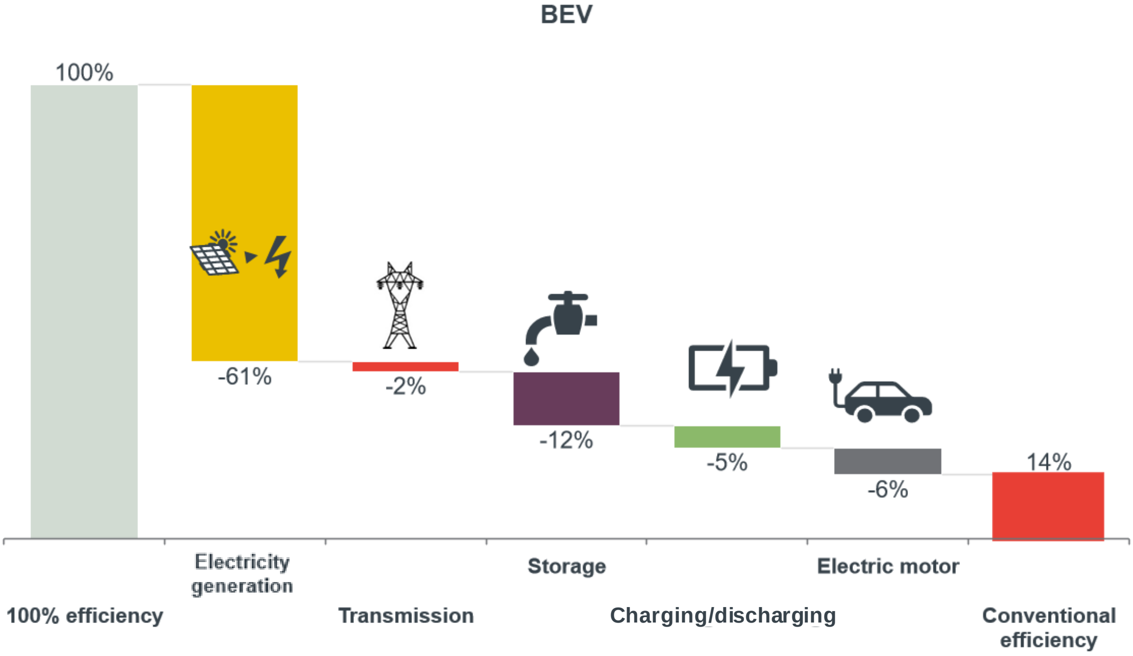
- The conventional view does not take into account **reduced electricity yields due to the different yield efficiencies of electricity generation.** These affect both technologies, but BEVs much more so, since the yield efficiency of PV or wind is lower in Germany than in North Africa/Morocco (94%) or Argentina/Patagonia (73%).
- **Losses due to seasonal storage** are not conventionally recorded, but play an important role in BEVs with a supposedly "direct" electricity supply in an energy supply system that has been completely converted to renewable intermittent energies.
- **Losses during battery charging** are also often not included in efficiency comparisons.
- **Losses in efficiency in vehicle use ("mobility")** are regularly taken into account and drive above all the result for the ICEV.
- In **ICEVs,** additional efficiency losses are caused by the **conversion of** electricity to hydrogen and synthetic fuel ("losses electrolysis" and "loss Fischer-Tropsch" synthesis). These are also often included in previous efficiency comparisons.

Efficiency loss according to the - approach for scenario PV



These efficiency losses can, for example, be represented graphically for the reference scenario with PV generation in Germany and electricity use in a BEV as shown in the **Figure 23**

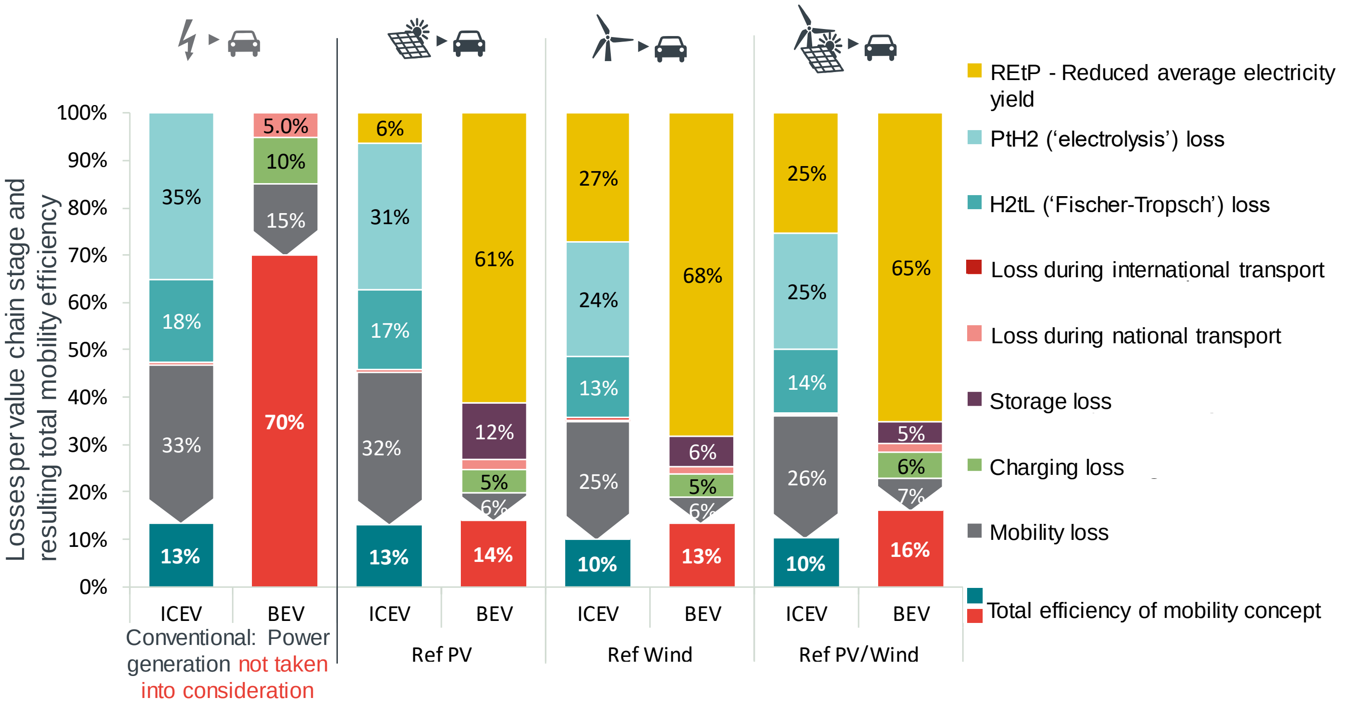
Figure 23. Efficiency losses illustrated by the BEV reference scenario



Source: Frontier Economics

In this way, the losses for all scenarios and the resulting comprehensive efficiency can be presented. The **Figure 24** below provides a summary illustration of the reference scenarios for BEVs and ICEVs in comparison for different RES-E generation variants. The scenario shown in the **Figure 23** corresponds to the second pillar from the left in the **Figure** 24.

Figure 24. Efficiency losses in the reference scenarios by value chain compared with the conventional view



Source: *Frontier Economics*

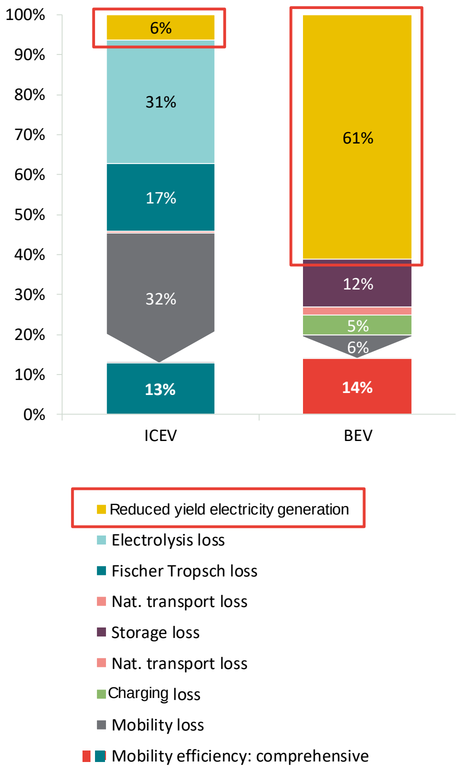
Note: ***Ref PV*** - *BEV: PV generation in DE (969 FLH/ 39% yield efficiency), grid/transport losses: 5%, charging losses: 20%, storage losses (seasonal): 15%, BEV efficiency: 71%; ICEV: PV generation in North Africa/Morocco (2344 FLH/ 94% yield efficiency), electrolysis (NT) efficiency: 67%, Fischer Tropsch efficiency: 73%, transport losses (int.): < 1%, transport losses. (nat.): 1%, efficiency ICEV: 29%.* ***Ref Wind*** - *BEV: wind power plants in Germany (2071 FLH/ 32% yield efficiency), grid/transport losses: 5%, charging losses: 20%, storage losses (seasonal): 10%, BEV efficiency: 71%; ICEV: wind generation Argentina/Patagonia (4730 FLH/ 73% yield efficiency), electrolysis efficiency: 67%, Fischer Tropsch: 73%, transport losses (int.): < 1%, transport losses. (nat): 1%, efficiency ICEV: 29%.* ***Ref PV/Wind*** - *BEV: PV and wind power plants for electricity generation in Germany, 50% each (1,579 FLH/ 35% yield efficiency), grid/transport losses: 5%, charging losses: 20%, storage losses (seasonal): 5%, efficiency BEV: 71%; ICEV: PV and wind power plants in North Africa/Morocco, 50% each (2nd half of the year).987 FLH/ 75% yield efficiency), efficiency (by weight) electrolysis (NT): 67%, by weight Fischer Tropsch: 73%, transport losses (int.): < 1%, transport losses. (nat.): 1%, efficiency ICEV: 29%.*

In the following, we go into more detail about the main influencing parameters and sensitivities, in particular

- on the electricity yield efficiency of electricity generation technologies;
- on the cross-seasonal vehicle use and the resulting seasonal storage requirements and additional consumption for air conditioning of the vehicle compartment; and
- Sensitivities in relation to electrolysis technologies and charging losses.

Finally, we give a summary overview of the different sensitivities.

Main driver electricity yield efficiency



> Conventional efficiency implicitly assumes 100% yield efficiency for PV systems in Germany, i.e. the highest solar energy potential worldwide.

The capacity utilisation of renewable electricity generation plants, which varies greatly depending on the location, has a significant impact on comprehensive efficiency

In Chapter 3 we explain why the consideration of different locations for electricity generation is an essential part of a comprehensive efficiency analysis and how we derive the efficiency of this stage of the value chain, i.e. the electricity yield efficiency. Here we show,

- how electricity yield efficiency affects comprehensive efficiency; and
- how much capacity of RE plants have to be installed to supply the ICEV and BEV paths each.

The electricity yield efficiency significantly affects comprehensive efficiency

The electricity yield from the RE plants is a major driver of the efficiency losses of the BEV path as used in this study. We assume here that the charging current is produced in Germany. However, Germany has relatively low wind speeds and hours of sunshine compared to the global maximum benchmark. For example, according to our definition, the efficiency of PV systems in Germany is only 39% (969 h (full load hours in DE) / 2,500 h (maximum full load hours worldwide) * 100)[39].

In the **Figure 25** we graphically illustrate the effect of the RES yield (x-axis) on the efficiency (y-axis).

- The **conventional efficiency approach** ignores the yield efficiency of renewable electricity generation. For this reason a PV and wind electricity yield efficiency of 100% is implicitly assumed (cf. Chapter 3, p. 30ff.). In this case, with otherwise identical assumptions, the total technical efficiency is over 50% for BEVs and 14% for ICEVs. The electricity yield efficiency of a PV system in Germany is thus assumed to be as high as the yield of a PV system in a location with significantly better generation conditions.
- In the **comprehensive efficiency analysis, on the** other hand, the electricity yield efficiency in reality is taken into account, which results from the ratio of the full-load hours of a RE plant at a certain location compared to the maximum full-load hours observable worldwide:

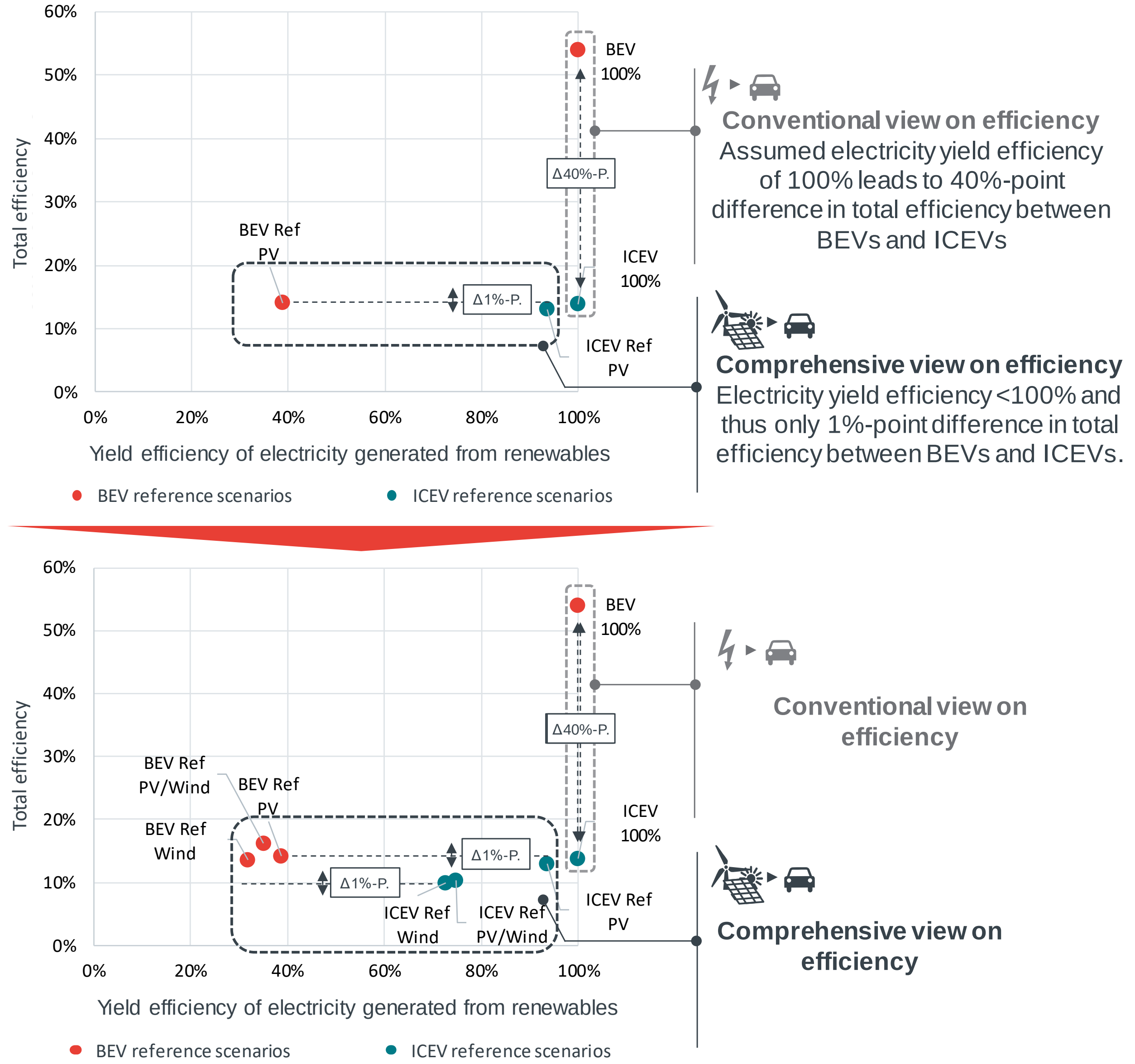
[39] Calculated on the basis of the average yield efficiency of solar installations in Germany in 2019, cf. BMWi (2020). For maximum full-load hours worldwide, see Fasihi and Breyer (2020).

- The electricity yield efficiencies of the RE plants for the **ICEV scenarios** are between 65% and 94%, as the RE electricity is produced in regions with high FLH (wind in Argentina/Patagonia, solar in North Africa/Morocco).
- For **BEV scenarios,** we assume that renewable electricity is generated in Germany. Under this assumption, the electricity yield efficiencies of the RE plants reach values of only 32% to 39% due to the less favourable site conditions.

This means that all results for comprehensive technical efficiency are generally below the results of conventional calculations, e.g. for the PV path 14% for BEVs and 13% for ICEVs.

In particular, the higher electricity yield efficiencies of renewable energy plants abroad mean that the ICEVs, when viewed as a whole, are at a similar level of efficiency to the BEVs in the end result, despite taking into account the conversion steps from electricity to liquid fuel.

Figure 25. Comprehensive efficiency and electricity yield efficiency for the reference scenarios: Differentiation from the previous conventional view



Source: *Frontier Economics*

Note: ***Conventional scenario****: 100% yield efficiency, cf. Chapter 2.*
PV Ref *- BEV: PV systems in Germany; ICEV: PV systems in North Africa/Morocco.*
Wind Ref *- BEV: wind power plants in Germany, 90% onshore and 10% offshore (weighted by installed capacity in 2019). ICEV: wind power plants in Argentina/Patagonia*
Mix Ref *- BEV: PV and wind power plants for electricity generation in Germany, 50% each; ICEV: PV and wind power plants in North Africa/Morocco, 50% each*

The renewable energy capacities to be installed also differ depending on the site conditions

The relevance of considering the electricity yield efficiency of RE plants is also evident when considering the necessary plant capacity to be installed for the mobility solutions under consideration (see **Figure 26**). In the final analysis, a key question is how many wind and solar power plants need to be built to operate a certain number of vehicles. For this purpose, we consider the capacity that must be installed to meet the annual energy demand of an average car in Germany. [40] We derive this from four steps (**Figure 26**):

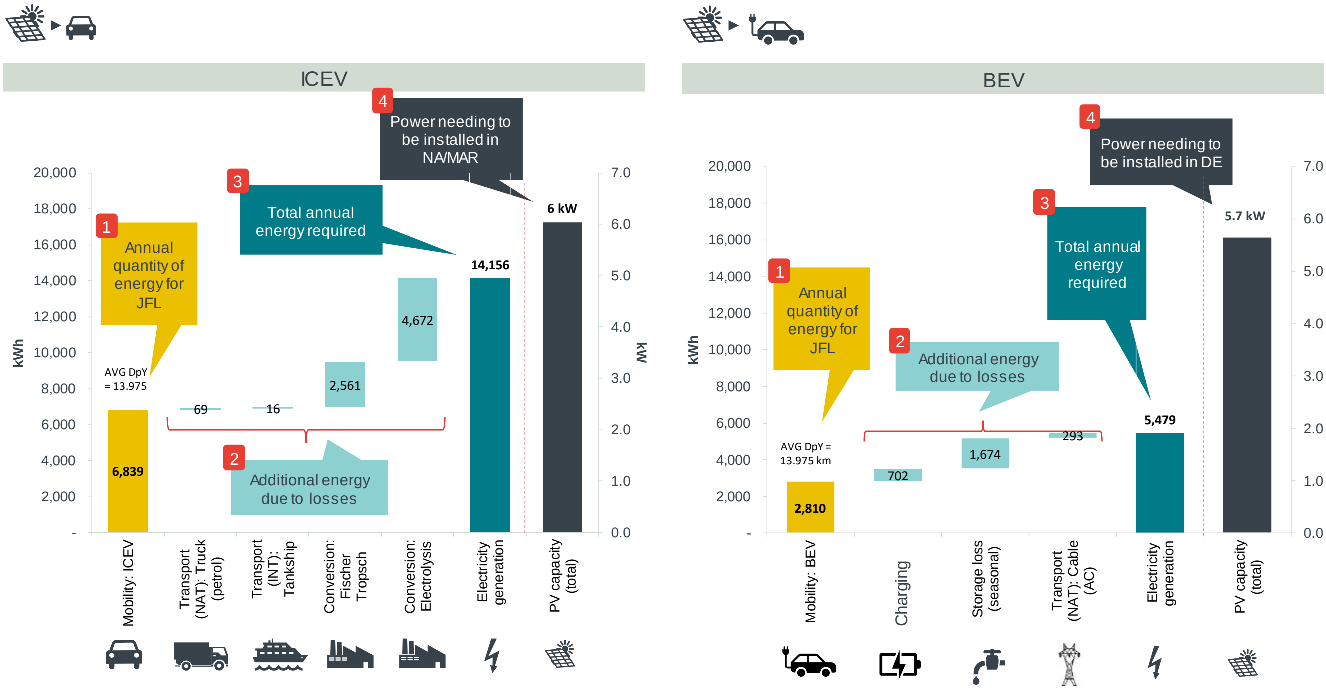
- **Step 1**: Due to the lower efficiency at the **end-use stage (mobility),** an ICEV needs approx. 6,840 kWh p.a. for a distance of 13,975 km. while a BEV consumes only 2,810 kWh p.a.
- **Step 2**: In addition, the total amount of energy required increases due to the necessary conversion steps.
- **Step 3**: This results in a total amount of energy required
  - in the ICEV scenario of a total of approx. 14,156 kWh per car p.a.,
  - while the annual energy demand of a passenger car in a BEV scenario only rises to about 5,479 kWh per passenger car p.a. due to other efficiency losses (step 2).
- **Step 4**: The capacity of RE plants to be installed resulting from the energy demand depends on the full load hours that can be realised in the scenarios. This can be illustrated using the example of the required output of PV systems:
  - The PV capacity required to provide the annual consumption of a **BEV is 5.7 kW per car** in **Germany** at less than 1000 full load hours.
  - For the one-year use of an **ICEV,** the capacity to be installed is **6 kW** in **North Africa/Morocco**.

The difference between ICEV and BEV is therefore much smaller than the conventional approach would suggest.

For the one-year use of a **BEV, 5.7 kW of PV capacity** is required **in Germany**, and **6 kW** for an **ICEV in North Africa/Morocco**.

[40] Average annual mileage of a car in Germany: 13,975 km (2014-2018), based on: KBA (2020) - traffic in kilometres - domestic mileage.

Figure 26. To supply a car with green PtL requires a calculated PV capacity of 6 kW in North Africa, a battery electric car requires 5.7 kW PV capacity in Germany



Source: *Frontier Economics*

Note: ***BEV**: Reference scenario BEV/ PV: - PV generation in DE (969 FLH/ 39% yield efficiency), grid/transport losses: 5%, charging losses: 20%, storage losses (seasonal): 15%, efficiency BEV: 71%.*
***ICEV**: PV generation in North Africa/Morocco (2344 FLH/ 94% yield efficiency), reference scenario ICEV/PV: efficiency (by weight) electrolysis: 67%, by weight Fischer Tropsch: 73%, transport losses (international): < 1%, transport losses (natural): 1%, efficiency ICEV: 29%.*

A battery electric supply of about 1/4 of the car fleet with solar electricity would require the doubling of the currently installed PV capacities in DE

Supplying Germany with green electricity is already proving challenging. This is due to the need to install renewable energy plants, most of which have to be built in Germany or Central Europe due to the limited transportability of electricity. However, the availability of sites for RE plants in Germany or Central/Western Europe is limited. This is due not only to the limited availability of suitable sites themselves, but also to regulatory obstacles (environmental protection, civil protection, etc.) and acceptance problems.

Currently, on average only 40%[41] of electricity is produced from renewable sources. Germany currently has 49 GW of PV capacity and 61 GW of wind capacity installed[42].

The challenge of expanding RE facilities will increase with the electrification of other sectors such as heating, transport and industry.

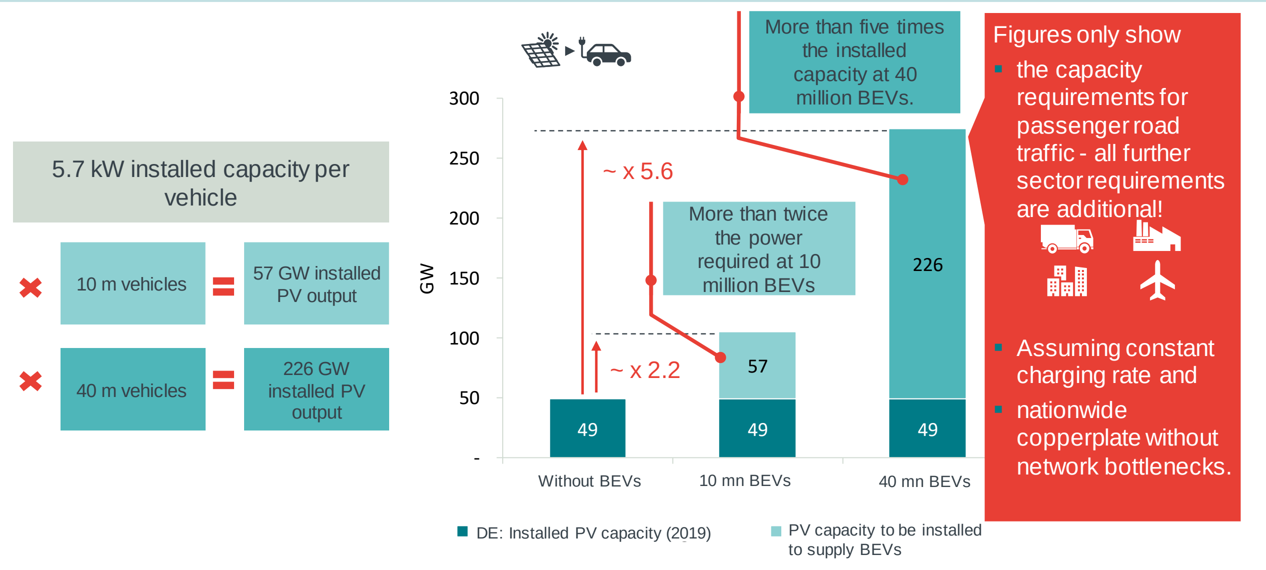
It is therefore of great importance how much capacity of RES production facilities is needed in the different sectors and how the locally produced RES can ultimately be distributed among the different sectors, or how an economy wide decarbonisation can be realised.

[41] See AG Energiebilanzen (2020).

[42] Cf. BMWi (2020).

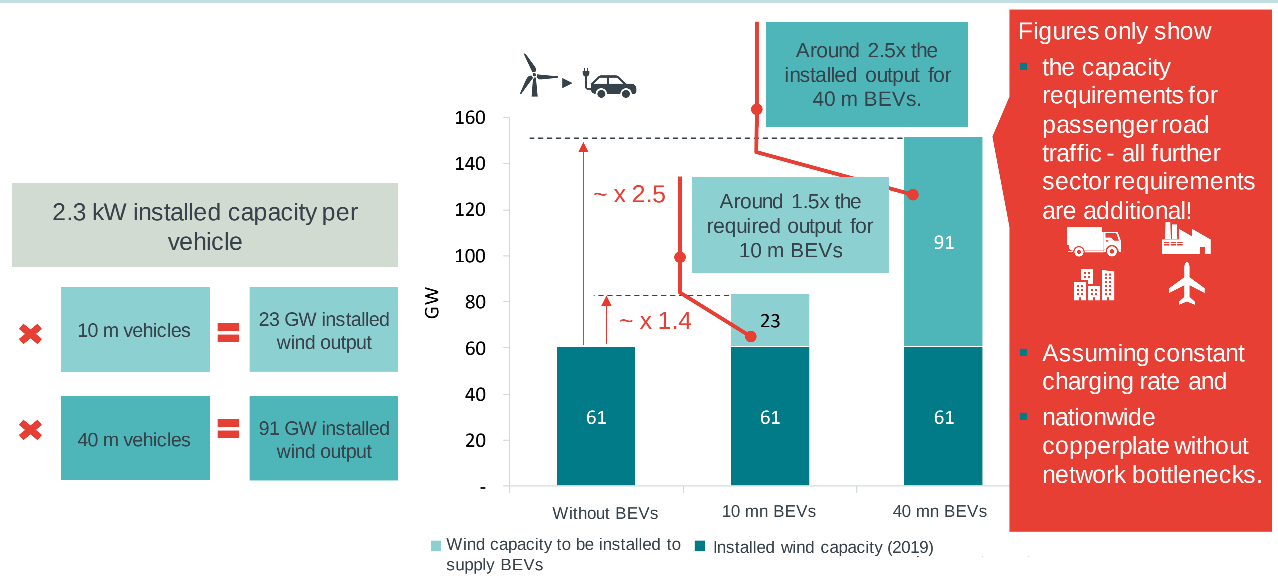
In the following we illustrate the RE capacity requirements for supplying BEVs with green charging current. For example, a purely PV-based battery electric supply of the car fleet (BEV solution) would require the installation of 226 GW_{PV}, while a purely wind-based BEV solution would require the installation of 91 GW_{Wind}. These figures are significantly higher than the PV and wind capacities installed in Germany to date (see above). If a quarter of the car fleet is powered by batteries, the corresponding expansion requirements are still 57 GW for PV and 23 GW for wind, i.e. in the case of PV this still means a doubling of the currently installed capacities. And these **results are based on the assumption of a Germany-wide copper plate, constant charging behaviour** and **without any additional requirements for new or old electricity applications!**

BEV path based on PV



Source: Installed PV capacity Germany: Cf. BMWi (2020) - Time series on the development of renewable energies in Germany.

BEV path based on wind



Source: Comparisons for installed wind capacity Germany: BMWi (2020) - Time series on the development of renewable energies in Germany.

Sensitivity analysis shows the influence of the electricity yield efficiency on comprehensive efficiency and performance requirements

The results of the comprehensive approach depend strongly on the assumption of feasible full load hours. In addition to our reference cases (see above), we therefore also consider sensitivities to full-load hours that may occur in reality.

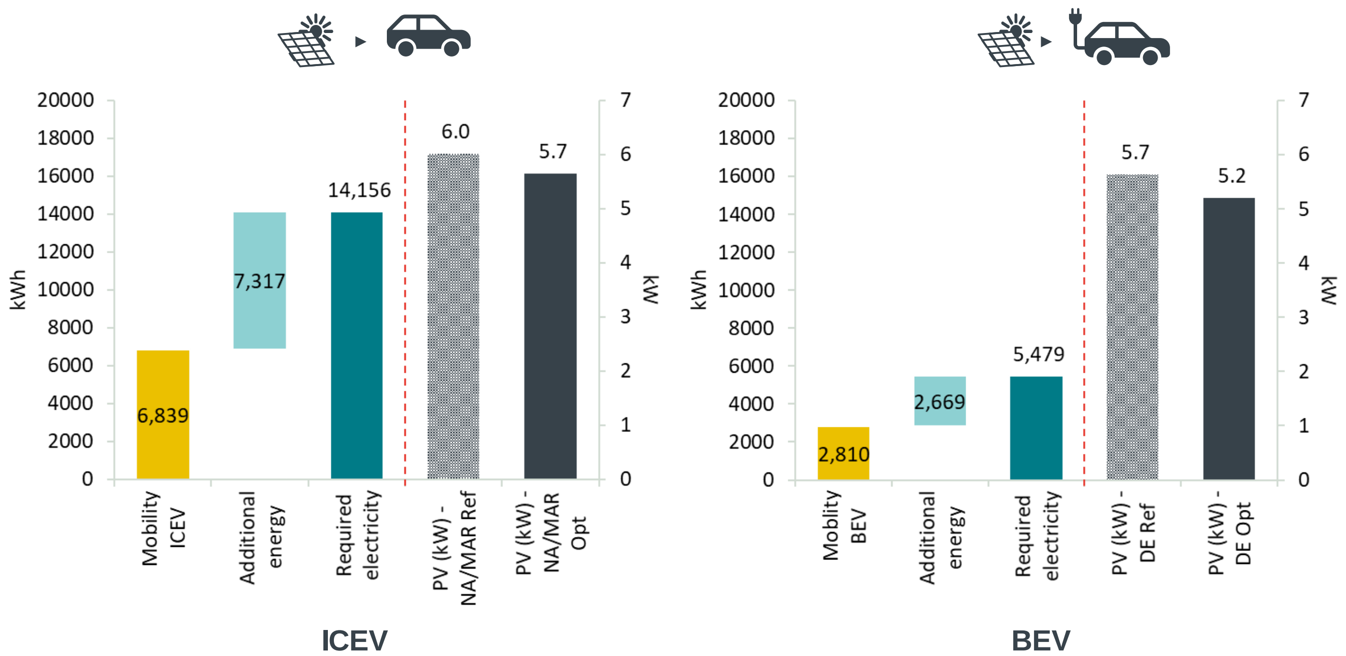
In the case of **PV power generation**, the realisable FLH

- although there are **large differences between the regions** - for example, the FLH in North Africa/Morocco are 2 to 2.5 times higher than in Germany
- but **only relatively small differences per region**: in both North Africa/Morocco and Germany, FLH are only marginally higher than in the Reference Scenario under more optimistic assumptions; in North Africa/Morocco we assume 2,500 FLH in the scenario with higher efficiencies[43] instead of 2,344 FLH in the Reference Scenario, in Germany 1,050[44] instead of 969 FLH. Accordingly, there are only minor differences in generation capacity requirements between the scenarios (see **Figure 27**).

[43] Cf. Frontier Economics based on Agora and Frontier Economics (2018), expert interviews and discussions in a parallel project for GIZ Morocco (Frontier Economics (2020)). Full load hours for onshore wind are based on Tizgui et al. (2018) and Agora Energiewende (2017). The full load hours (FLH) of the PV-wind combination are equal to the sum of the FLH of the PV and the wind system, multiplied by a factor of 90% to account for overlaps in the FLH of PV and wind plants. According to Breyer (2012), the overlap in the FLH of PV and wind is 1-8% worldwide and 2% in many regions of the world. According to Fasihi and Breyer (2020), the overlap is less than 500 hours in most regions of the world. With a discount of 10% or approx. 600-650 hours, the discount assumed by us can therefore be classified as rather conservative.

[44] Cf. Roland Berger and Prognos (2019), average FLH for new installations.

Figure 27. Influence of full-load hours at PV sites on the capacity to be installed to cover the required energy demand of the reference car



Source: *Frontier Economics*

Note: ***BEV - PV DE Ref****: PV generation in DE (969 FLH/ 39% yield efficiency), grid/transport losses: 5%, charging losses: 20%, storage losses (seasonal): 15%, efficiency BEV: 71%.*
BEV - DE Opt*: PV generation in DE (1050 FLH/ 42% yield efficiency), c.p.*
ICEV - PV NA/MAR Ref*: PV generation in North Africa/Morocco (2344 FLH/ 94% yield efficiency), efficiency (wg.) electrolysis: 67%, wg. Fischer Tropsch: 73%, transport losses (int.): < 1%, transport losses. (nat.): 1%, efficiency ICEV: 29%.*
ICEV - PV NA/MAR Opt*: PV generation in North Africa/Morocco (2500 FLH/ 100% yield efficiency), c.p.*

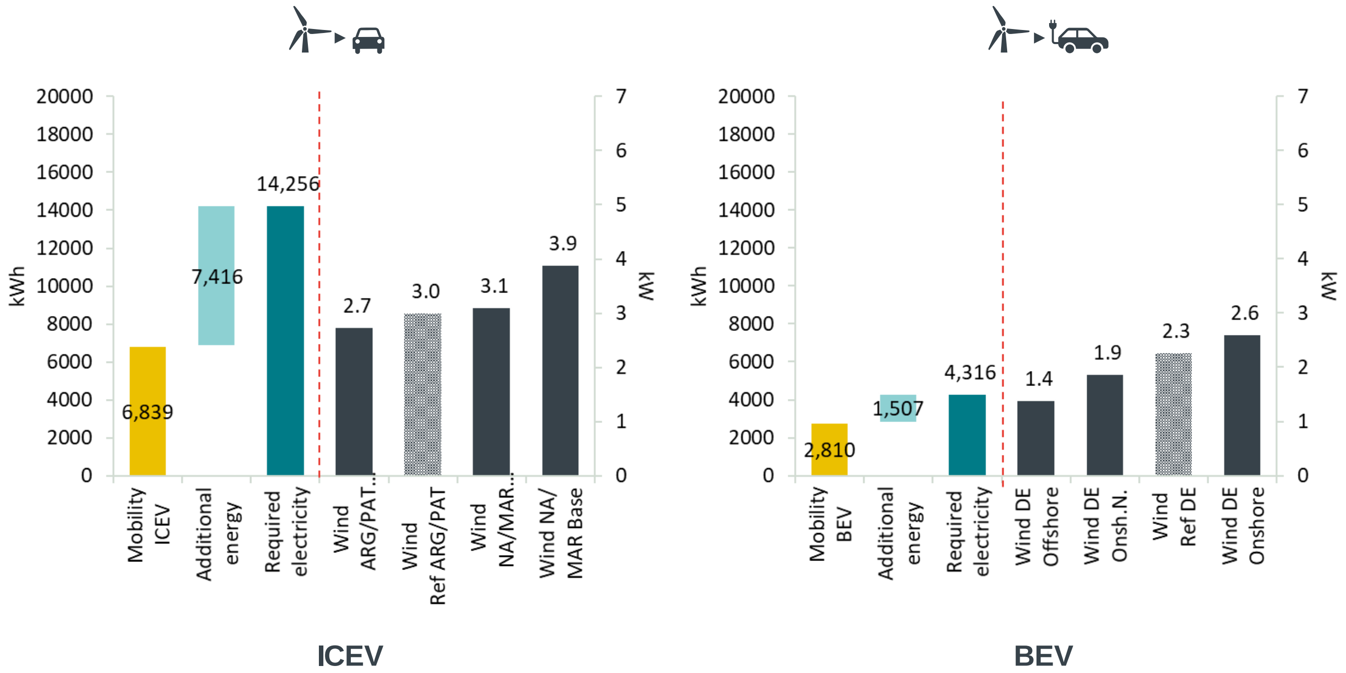
In principle, there is a greater variance in the number of possible full-load hours that can be achieved with **wind-generated electricity** (**Figure 28**).

- The best locations worldwide are in Argentina/Patagonia, among others. High full-load hours are also achieved in North Africa/Morocco in various parts of the country.
- In Germany, much lower capacity utilisation rates are achieved, but there is a wide range, especially between onshore and offshore plants and also between northern and southern Germany.

In the case of wind turbines, however, it is not always clear which sites can actually be used. For example, the regional topography (e.g. mountainous or impassable terrain) can make installation difficult or even impossible. For our reference scenario Wind ICEV we therefore use the wind frequency and full load hours of a realistic site (4,730 kWh/kW) and not those of the best (6,500 kWh/kW) in Patagonia.

But in Germany, too, there is a sharp divide between feasible FLH in the offshore and onshore sectors, particularly in the interior. The expansion at good to very good locations within Germany is limited by geographical restrictions (offshore and onshore) as well as existing wind turbines at good locations, regulatory obstacles (environmental protection, etc.) and acceptance problems (onshore). In our assumptions for the reference scenario, we have therefore weighted the feasible full-load hours in Germany between onshore and offshore according to currently installed capacity.

Figure 28. Influence of full-load hours at wind power sites on the capacity to be installed to cover the required energy demand of the reference car



Source: Frontier Economics

Note: ***ICEV - Wind Ref ARG/PAT****: Wind generation Argentina/Patagonia (4730 FLH/ 73% yield efficiency), efficiency (wg.) electrolysis: 67%, wg. Fischer Tropsch: 73%, transport losses (int.): < 1%, transport losses. (nat): 1%, efficiency ICEV: 29%.*
ICEV - Wind ARG/PAT Opt*: Wind generation Argentina/Patagonia (5200 FLH/ 80% yield efficiency), c.p.*
ICEV - Wind NA/MAR Opt*: Wind generation North Africa/Morocco (4550 FLH/ 70% energy yield efficiency), c.p.*
ICEV - Wind NA/MAR Base*: Wind power generation North Africa/Morocco (3629 FLH/ 56% efficiency), c.p.*
BEV - Wind Ref DE*: wind generation DE (2071 FLH/ 32% yield efficiency), grid/transport losses: 5%, charging losses: 20%, storage losses (seasonal): 10%, efficiency BEV: 71%.*
BEV - Wind DE Offshore*: wind generation DE Offshore (3375 FLH/ 52% yield efficiency), c.p.*
BEV - Wind DE Onsh.N.*: Wind Generation Onshore Northern Germany (2500 FLH/ 39% yield efficiency), c.p.*
BEV - Wind DE Onshore*: Wind Generation DE Onshore (1805 FLH/ 28% efficiency), c.p.*

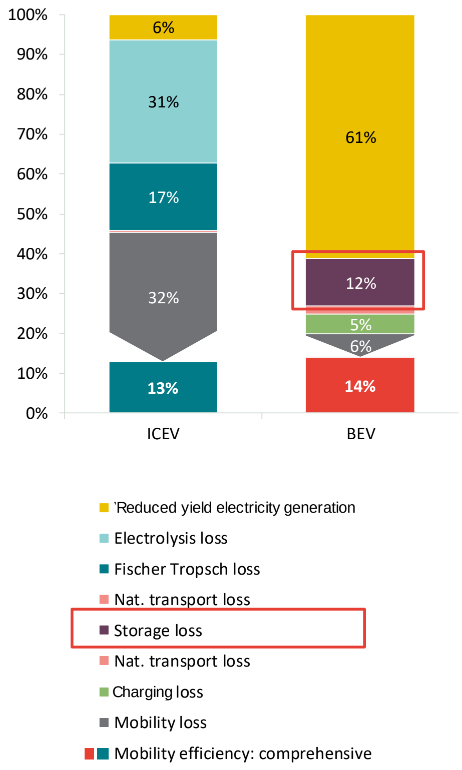
The timing of vehicle use also affects comprehensive efficiency

The efficiency analysis should also take into account that vehicles are driven throughout the year, i.e. not only when the sun is shining, for example, and PV systems generate electricity. In addition, due to the fluctuating outside temperatures, the vehicles must be heated or cooled. This leads to

- losses in the supply of drive energy due to seasonal storage of energy; and

- Losses due to additional consumption caused by air conditioning (heating or cooling) of the driving compartment.

Seasonal storage losses



Seasonal storage requirements reduce the comprehensive efficiency of BEVs, especially for PV electricity

As described in chapter 3 from page 35 onwards, our comprehensive approach to **BEV** supply focuses on seasonal storage requirements in the form of P-to-H2-to-P. Based on the simplified assumption of constant mobility demand over the year and the seasonal characteristics of the generation profiles of the respective RE technologies, the following influence on efficiency results:

- Since **PV systems** produce considerably more electricity in summer than in winter, efficiency is reduced by 12%.
- As electricity generation from **wind turbines** is distributed more evenly throughout the year, seasonal storage requirements are correspondingly lower and efficiency is reduced by 6%.
- If the bulk of the electricity is generated by a combination of **PV and wind,** efficiency is reduced by 5%.

Under real conditions, indoor climate control consumes substantial amounts of energy

As explained in chapter 3, the efficiency of the direct end-use application for both ICEVs and BEVs changes with the outside temperature, i.e. if not operated at moderate temperatures (WLTP e.g. at 23°C) without any special heating or cooling requirements, as is the case in current test cycles.

In our reference cases, we take into account the temperature throughout the year and thus determine the average annual consumption of a compact class vehicle. The resulting efficiency of the direct end use, i.e. the vehicle, is 71% for BEVs and 29% for ICEVs. The corresponding energy losses of the vehicles measured in terms of total energy consumption are 32% (PV) and 25% (wind) in the ICEV scenarios and 6% (PV) and 6% (wind) in the BEV scenarios.

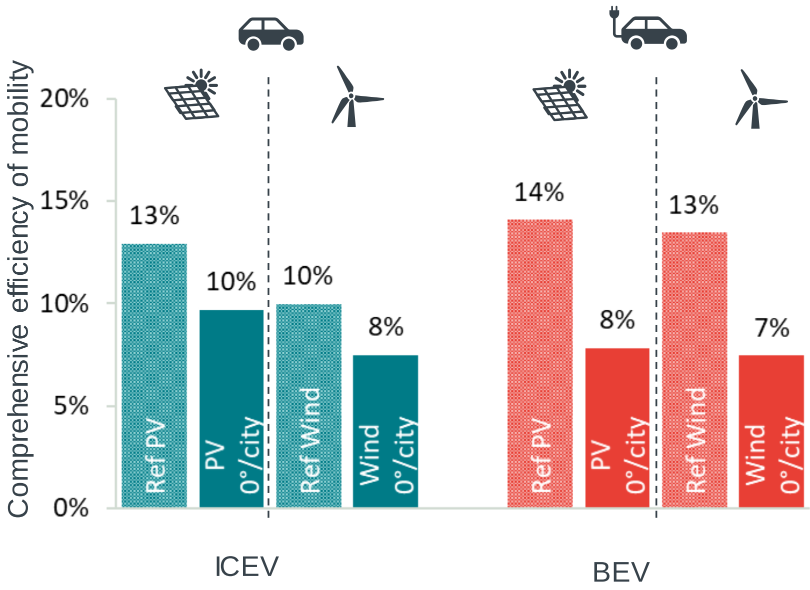
We supplement our reference scenario with the sensitivity of **vehicle operation in the city** on a **winter day with temperatures not exceeding 0°C**. Both factors of this scenario (winter temperatures and urban traffic) lead to increased consumption for both ICEVs and BEVs.

In winter...

ICEVs powered by green PtL can be more efficient than BEVs due to the heating needs of the vehicles.

- With **BEVs,** the heating requirement affects the efficiency of vehicle use, as hardly any waste heat can be used and the battery must be heated in addition to the driver's cab. Moreover, the additional consumption of the heating system in BEVs is higher per kilometre if the vehicle is moved at a lower speed.[45] We assume additional consumption of 50%, which reduces the comprehensive efficiency
  - to 8% (PV) and
  - to 7% (wind).
- **ICEVs** also consume more in this scenario. The assumed 28% increase in consumption is due to less efficient driving, frequent starting and braking, and heating requirements that cannot be met by the waste heat from the engine.[46]This reduces the comprehensive efficiency
  - to 10% (PV) and
  - to 8% (wind).

Figure 29. Efficiency effects of vehicle use in winter at about 0 °C in the city.



Source: Frontier Economics

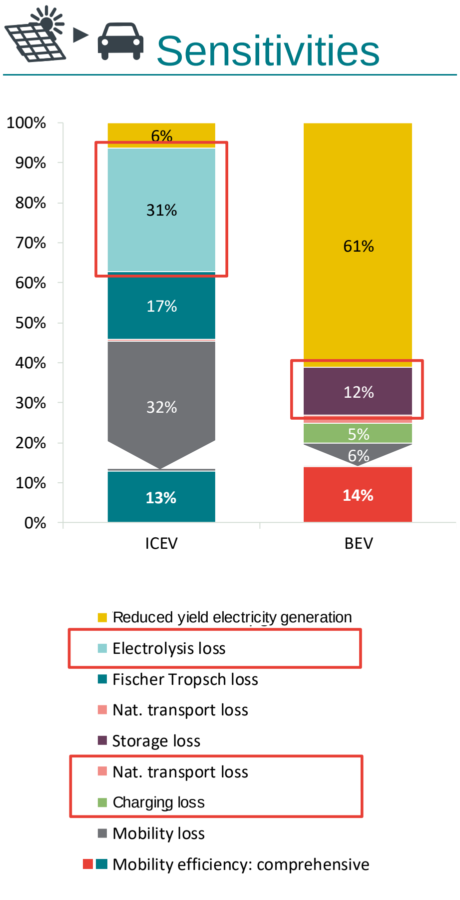
*Note: **ICEV - Ref PV**: PV production in North Africa/Morocco (2344 FLH/ 94% yield efficiency), efficiency (wg.) electrolysis: 67%, wg. Fischer Tropsch: 73%, transport losses (int.): < 1%, transport losses. (nat.) = 1%, efficiency ICEV: 29%. **ICEV - PV 0°/city** (cold winter day, urban traffic): Efficiency ICEV: 22%, c.p.. **ICEV - Ref Wind**: Wind generation Argentina/Patagonia (4730 FLH/ 73% yield efficiency), electrolysis efficiency (ww.): 67%, ww. Fischer Tropsch: 73%, transport losses (int.): < 1%, transport losses, ICEV efficiency: 29%. **ICEV - Wind 0°/city** (cold winter day, city traffic): Efficiency ICEV: 22%, c.p.. **BEV - Ref PV**: PV generation in DE (969 FLH/ 39% yield efficiency),*

[45] See https://www.adac.de/rund-ums-fahrzeug/elektromobilitaet/info/elektroauto-reichweite-winter/.

[46] See ADAC autotest (2019), p. 9.

grid/transport losses: 5%, charging losses: 20%, storage losses (seasonal): 15%, efficiency BEV: 71%.
***BEV - PV 0°/city** (cold winter day, urban traffic): BEV efficiency: 36%, c.p..*
***BEV - Ref Wind**: wind generation DE (2071 FLH/ 32% yield efficiency), grid/transport losses: 5%, charging losses: 20%, storage loss (seasonal): 10%, efficiency BEV: 71%.*
***BEV - Wind 0°/city** (cold winter day, urban traffic): Efficiency BEV: 36%, c.p..*

Further sensitivities with regard to electrolysis and charging losses



Possible other key drivers for the efficiencies of drive technologies could be variations in the efficiency of electrolysers or, for example, charging losses of BEVs. For both drivers, there are considerable ranges with regard to efficiency losses in practice or possible future technological developments.

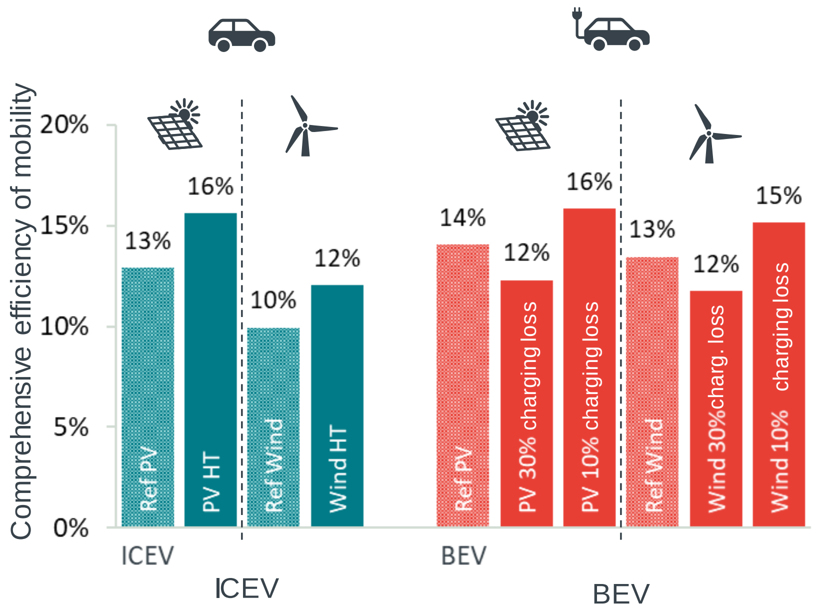
Accordingly, the following section shows sensitivities for these two influencing factors (**Figure 30**):

- For ICEVs, we assume the more efficient high-temperature electrolysis (HT electrolysis) instead of the low-temperature electrolysis (NT electrolysis) assumed in the Reference Scenario for the efficiency losses in the conversion of electricity to hydrogen.
- With BEVs, we vary the charging losses depending on the charging capacity.

It has been shown that even in these sensitivities, the efficiency of the ICEV can be higher than that of the BEV in certain cases, e.g. if electrolysis is carried out in future on the basis of the more efficient HT process and at the same time the BEV is predominantly charged by rapid charging.

In the following, we explain the derivation of the result in more detail.

Figure 30. Comprehensive efficiency by relevant sensitivities



Source: Frontier Economics

Note: ***ICEV - Ref PV***: *PV generation in North Africa/Morocco (2344 FLH/ 94% yield efficiency), efficiency (ww.) ww. electrolysis (NT): 67%, ww. Fischer Tropsch: 73%, transport losses (int.): < 1%, transport losses. (nat.): 1%.*
ICEV - PV HT: *by weight electrolysis (HT): 81%, c.p.*
ICEV - Ref Wind: *Wind generation Argentina/Patagonia (4730 FLH/ 73% yield efficiency), electrolysis efficiency: 67%, Fischer Tropsch: 73%, transport losses (int.): < 1%, transport losses (nat.): 1%.*
ICEV - Wind HT: *electrolysis (HT): 81%, c.p.*
BEV - Ref PV: *PV generation in DE (969 FLH/ 39% yield efficiency), grid/transport losses: 5%, charging losses: 20%, storage losses (seasonal): 15%, efficiency BEV: 71%.*
BEV - PV 30% load loss: *load loss: 30%, c.p.*
BEV - PV 10% loss of charge: *loss of charge: 10%, c.p.*
BEV - Ref Wind: *wind generation DE (2071 FLH/ 32% yield efficiency), grid/transport losses: 5%, charging losses: 20%, storage losses (seasonal): 10%, efficiency BEV: 71%.*
BEV - Wind 30% load loss *Charge loss: 30%, c.p.*
BEV - Wind 10% loss of charge *: Loss of charge: 10%, c.p.*

High temperature electrolysis (HT) increases the comprehensive efficiency of ICEVs by up to 3%-points

Future technological progress...

along the value chain can further shift the relationship of efficiencies between technologies.

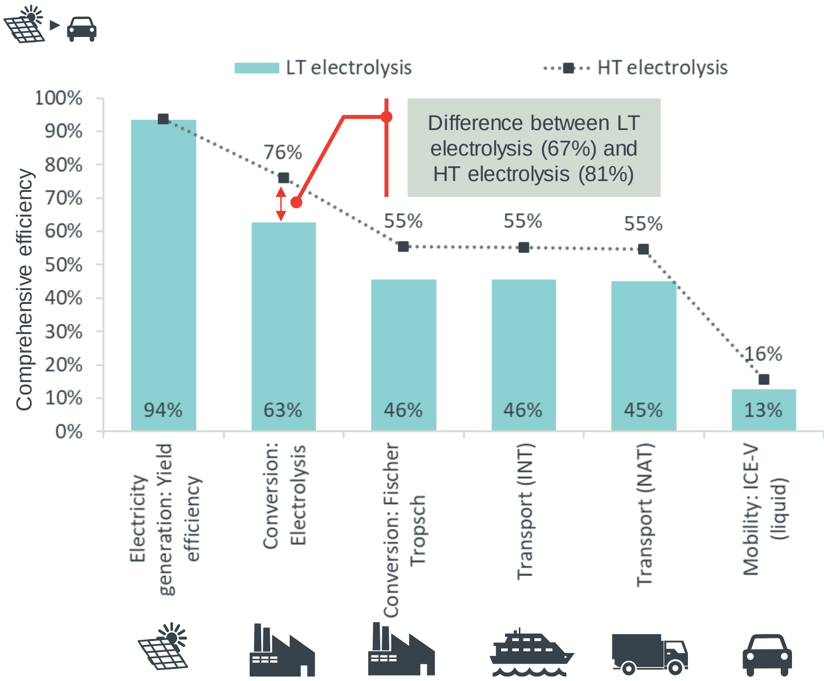
In the ICEV reference scenario we assume low-temperature electrolysis (NT) with an efficiency of 67%[47] for the production of hydrogen from green electricity (cf. Chapter 3 page 33). In the

[47] Frontier Economics based on Agora and Frontier Economics (2018) and expert interviews.

sensitivity scenario we assume a high-temperature electrolyser (HT) with an efficiency of 81%.[48]

Compared to the PV reference scenario, this increases the comprehensive efficiency of ICEVs from 13% to 16% and compared to the wind reference scenario from 10% to 12%.

Figure 31. Comprehensive efficiency in the "Reference scenario PV" with HT and NT electrolysis (by value chain stages)



Source: Frontier Economics

*Note: **NT Electrolysis** (low temperature electrolysis): Reference scenario PV (NT electrolysis: 67% efficiency).*
***HT Electrolysis (**high temperature electrolysis): Reference scenario PV with HT electrolysis (81% efficiency).*

Different electricity charging losses reduce or increase the comprehensive efficiency of BEVs by about 2%.

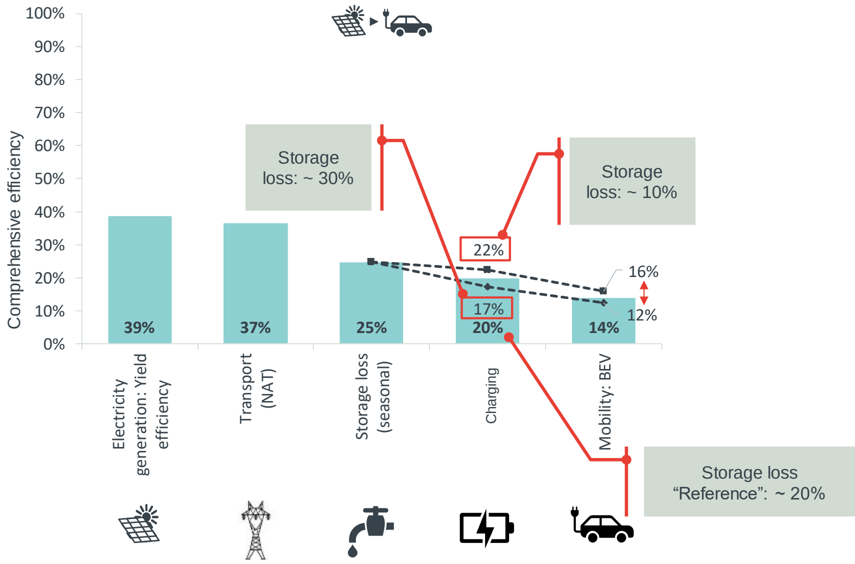
As explained in Chapter 3, we assume charging losses of 20% in the BEV reference scenario. These reduce the total efficiency in the comprehensive approach by 6% (PV) and 6% (wind) and 7% (wind & PV combination).

Additionally, we calculate two sensitivities with charge losses of 10% and 30%. The resulting range of values for the comprehensive efficiency (cf. **Figure 30**) is

- between 12% and 16% (PV);
- between 12% and 15% (wind).

[48] Frontier Economics based on Agora and Frontier Economics (2018) and expert interviews.

Figure 32. Comprehensive efficiency in the "Reference scenario PV" with low and high charging losses (by value chain stages)



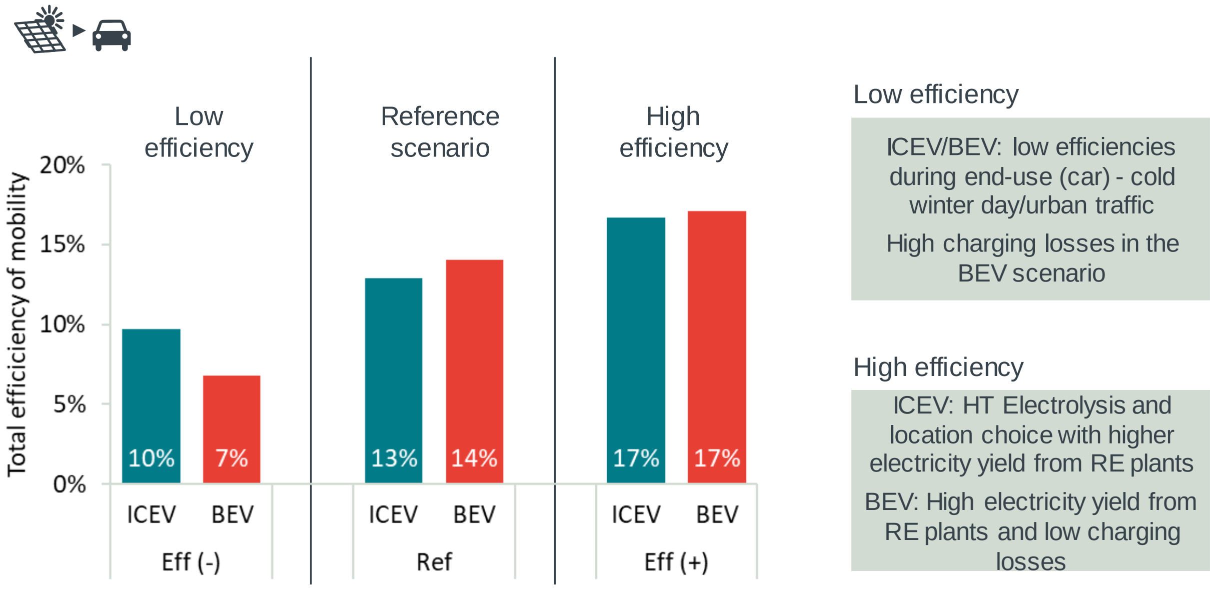
Source: Frontier Economics

Note: PV reference scenario (DE) with sensitivities.

Sensitivities show a mixed picture

If, for example, the above-mentioned factors are not only isolated but varied in combination, this results in a wider range of efficiency values. For example, if all the drivers included in this study are varied for a scenario with production of renewable electricity in PV systems, the efficiency of the drive systems fluctuates between 10% and 17% for the ICEV and between 7% and 17% for the BEV (**Figure 33**). It should be noted that in reality a large number of other case variations are conceivable, which could lead to even greater fluctuation in comprehensive efficiency.

Figure 33. Variation in comprehensive efficiency per technology path and scenario using the example of PV (based on selected parameter variations)



Source: Frontier Economics

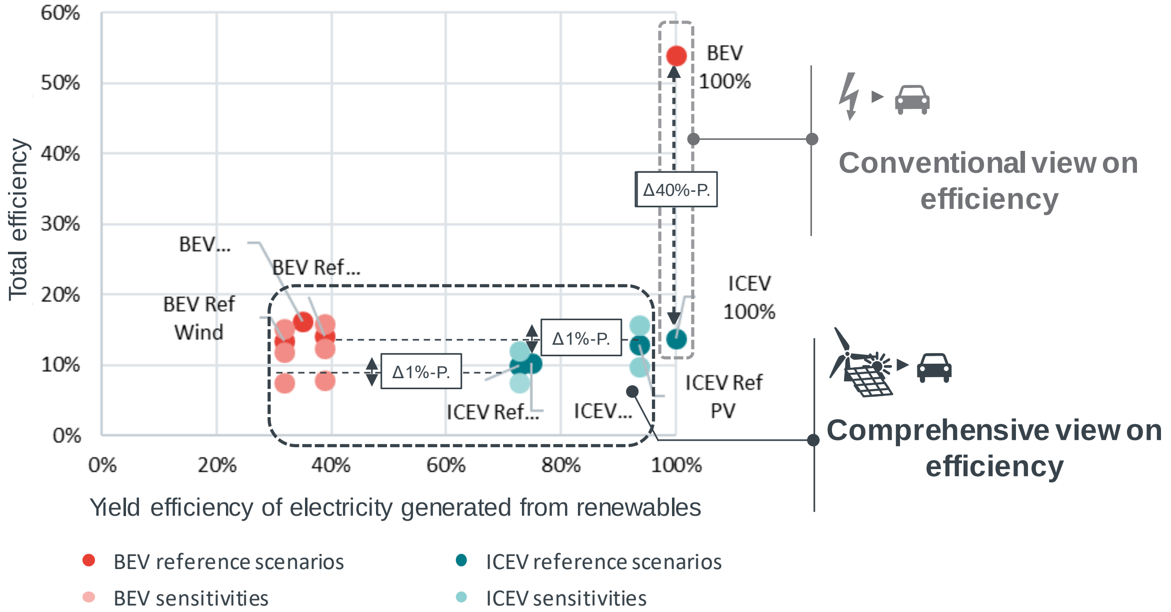
Note: ***Eff (-)** - BEV: yield efficiency: 35% (Germany), grid losses: 5%, storage losses (seasonal): 15%, charging losses: 30%, efficiency BEV: 39%. ICEV: Yield efficiency: 94% (North Africa/Morocco), electrolysis (NT) efficiency: 67%, Fischer Tropsch efficiency: 73%, international transport loss: <1%, national transport loss: 1%, ICEV efficiency: 22%.*
***Eff (+)** - BEV: yield efficiency: 42% (Germany), grid losses: 5%, storage losses (seasonal): 15%, charging losses: 10%, efficiency BEV: 71%. ICEV: Yield efficiency: 100% (North Africa/Morocco), electrolysis (HT) efficiency: 81%, Fischer Tropsch efficiency: 73%, international transport losses: <1%, national transport losses: 1%, ICEV efficiency: 29%.*

As a result, in the comprehensive efficiency analysis, there are constellations in which ICEV technology using PtL fuels produced at favourable locations has efficiency advantages over BEVs powered by renewable electricity generated in Germany. A role is played here, for example, by the yields of renewable energy systems, energy storage requirements, rapid charging losses or the energy expenditure for vehicle interior air conditioning. Optimisation potential in the manufacturing process of PtL products and the reduction of conversion losses, e.g. through the progressive integration of process steps, also have an influence.

This is illustrated by means of **Figure 34** for some conceivable scenarios and sensitivities for the conventional and comprehensive efficiency approach. It is shown that

- due to the advantages of international RE potential sites, the **yield efficiency of RE electricity generation** is consistently higher for ICEVs (roughly in a range between 75% and 95%) than for BEVs based on RE electricity from Germany (30% to max. 40%) and
- therefore the **comprehensive efficiency** for BEVs and ICEVs is of approximately the same order of magnitude (roughly in a range between 7% and 20%).

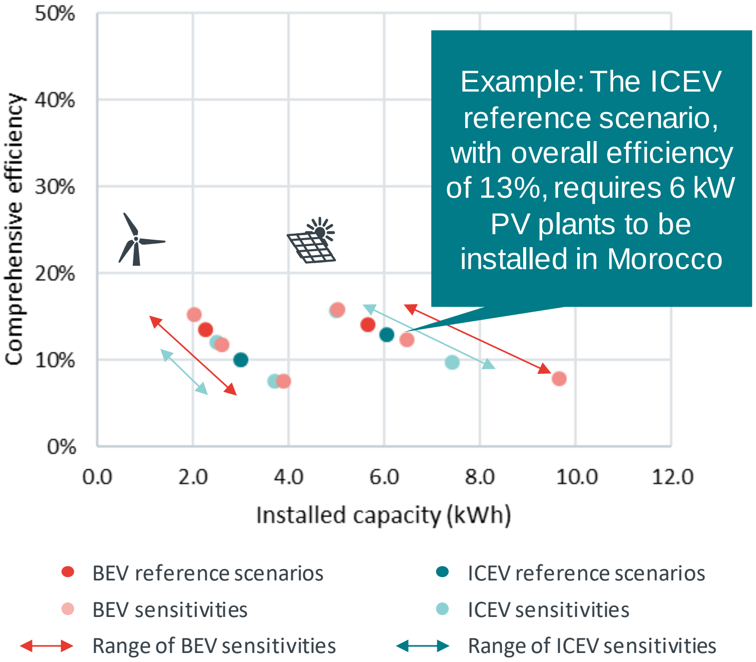
Figure 34. Total efficiency of ICEV and BEV according to conventional and comprehensive approach



Source: Frontier Economics, see annex for details.

In the **Figure 35,** we compare the capacity to be installed in the reference scenarios with the sensitivities of the respective comprehensive efficiency. Both approaches show that the results for BEVs and ICEVs operated with green PtL show clear overlaps, depending on the case constellation and assumptions. The efficiencies are consistently within similar ranges.

Figure 35. Comprehensive efficiency and capacity to be installed (to meet the energy demand per vehicle)



Source: Frontier Economics, see annex for details.

6. TECHNICAL EFFICIENCY IS PART OF A BROADER CONCEPT OF EFFICIENCY

Even though the comprehensive technical efficiency of drive systems can be an important orientation parameter for energy policy decisions, the energy policy debate on efficiency to date has not gone far enough. The concept of technical efficiency in itself leaves out essential factors for the evaluation of technologies:

> Technical efficiency is to be interpreted in the system-wide context of the energy industry.

- Energy losses must be assessed against the background of **energy availability:** In a future global energy system in which renewable energies will in future be relatively cheap and available in very large quantities, efficiency losses are less decisive than in the case of energy shortages. This already applies today, for example, if in extreme cases no other use is possible for renewable electricity on site (keyword: surplus electricity): in this case renewable energy must be stored if it is to be made at least partially usable, efficiency losses fade into the background.
- Against this background, the future challenge of the global energy system is less the absolute availability of energy, but rather the availability of the right amount of energy at a certain time at a certain place, i.e. the provision of **power**. This challenge can be met by storage technologies or energy carriers with storage capacity, such as synthetic fuels. The increasing relevance of the provision of power and thus of supply security usually does not adequately reflect the previous debate on technical efficiency.
- Previous discussions on technical efficiency have often failed to take sufficient account of other essential aspects for technology assessment: these include the **usability of existing infrastructure and the need for new infrastructure**.
- Moreover, technological developments do not usually take place "on a greenfield site" and to the exclusion of users. Here, too, the sole focus on technical efficiency quickly reaches its limits, since, for example, aspects **of ensuring a variety of usage requirements and expectations** are not included.

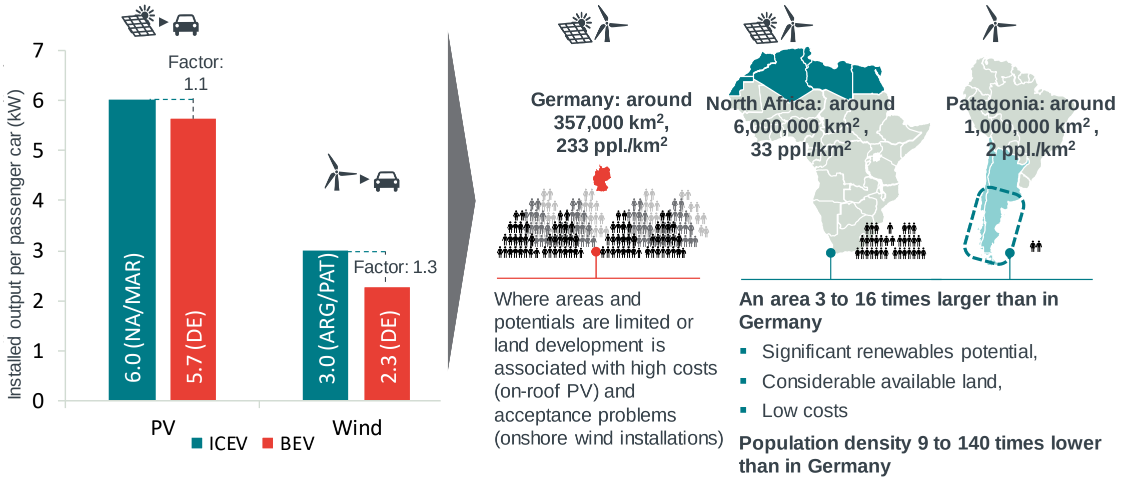
Energy policy decisions should not be based solely on the technical efficiency of technologies, but on a **comprehensive concept of efficiency**.

For groundbreaking climate policy debates and directional decisions, comprehensive technical efficiency should therefore be seen and interpreted in the context of a **more comprehensive, systemic mechanism of action, taking into account other efficiency categories.** In addition to comprehensive technical efficiency, this systemic concept of efficiency includes in particular

- the **comprehensive economic efficiency** (= measure of achievable climate protection effects per monetary unit used), taking into account, for example
  - the costs for the development and utilisation of renewable energies;
  - the usability of existing infrastructures,
  - the generation of scaling potentials;
- the **comprehensive ecological efficiency** (= measure of the effectiveness of technological measures against climate change) taking into account e.g.
  - the level of greenhouse gas reductions achievable over the life cycle of a technology;
  - the speed of implementation of a climate-neutral technology;
- **Other factors** related to the use of technology, such as
  - Acceptance of technologies with regard to adverse impacts on the environment and the general public, and thus also, for example, the availability of land for the expansion of renewable energies (cf. **Figure 36**);
  - the reliability and usability of a technology on a global scale in the breadth of its usage requirements;
  - Potentials of international cooperation and further development of sustainable trade relations.

The concepts of technical, ecological and economic efficiency and other factors go **hand in hand**.

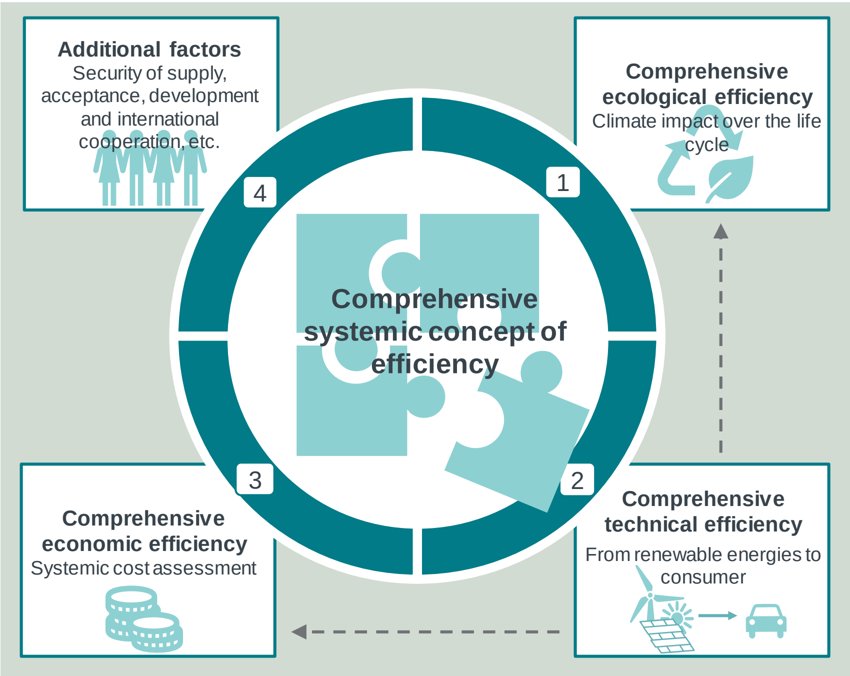
Figure 36. PV or wind capacity requirements in Germany for a BEV and in North Africa or Patagonia for a PtL-powered ICEV



Source: Frontier Economics

Note: For details see chapter 4.

Figure 37. Comprehensive technical efficiency as a component of systemic efficiency



Source: Frontier Economics

The various efficiency concepts go hand in hand: technical efficiency influences both economic and ecological efficiency, i.e. the costs and ecological footprint of the use of technologies. Higher efficiencies tend to reduce costs and protect the environment, but energy losses and CO2 emissions are assessed economically and ecologically, and not just in terms of kWh.

The integrated approach of the central efficiency categories is thus an essential basis for a target-oriented and reliable course towards climate neutrality.

7. POLITICAL ACTION SHOULD BE OPEN TO THE DEVELOPMENT OF ALL CLIMATE-FRIENDLY TECHNOLOGIES

Against the background of the results of the study, the **following principles** can be derived for the definition, selection and interpretation of efficiency analyses in the context of the climate policy debate:

- The **political focus on a single technology on the** basis of a conventional efficiency view, here in the passenger car mobility sector, is **misleading** because it disregards key influencing parameters. In the present study, this could be quantitatively demonstrated for the car drive technologies BEV (using renewable electricity produced in Germany) and ICEV (using PtL produced in international renewable potential regions).
- **The method of the comprehensive technical efficiency analysis** takes into account all essential value-added stages and influencing parameters and thus provides a more suitable basis for the efficiency assessment of technologies. Within the framework of these investigations, the comprehensive efficiency analysis leads to the conclusion that a sole preference neither in favour of the BEV nor in favour of the ICEV makes sense.
- A **national definition of system boundaries as a starting point for technology focus is not appropriate**. Imports and exports of renewable energies will in future be part of the international energy landscape. The potential of international cooperation should therefore be tapped and turned into reality.
- The technical efficiency analysis should be interpreted in the context of a **systemic concept of efficiency**, which also includes economic efficiency and ecological efficiency. This gives technical efficiencies an economic and ecological value, not only in terms of kWh saved.

The studies show that a future-oriented climate policy in the transport sector should aim to use and keep open all technologies that meet the climate target. In this respect, there is a need for revision of the legislative framework - at both European and national level. This should be done as soon as possible, as the transformation of the energy system towards renewable energies is becoming increasingly urgent in view of the ongoing climate change.

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	alternating current
BEV	Battery Electric Vehicle
c.p.	ceteris paribus, under otherwise identical conditions
DC	Direct current
EE	Renewable energies
E-Fuels	synthetic liquid fuels
h	hour
H2	Hydrogen
HT	High temperature (electrolysis)
ICEV	Internal Combustion Engine Vehicle
int.	international
konv	conventional
kWh	Kilowatt hour
NT	Low temperature (electrolysis)
nat.	national
MENA	Middle East & North Africa
Opt	Optimistic
PEM	Proton Exchange Membrane (electrolysis)
PtL	Power-to-liquid; synthetic liquid fuels produced from renewable electricity
PtX	Power-to-X; gaseous, liquid or solid, chemical energy sources produced from renewable electricity
PV	Photovoltaics
Ref	Reference scenario
t	tonne
FLH	Full load hours
WKA	Wind turbine
WLTP	Worldwide harmonized Light vehicles Test Procedure

REFERENCES

- **Acatech et al. (2017)**, »Sektorkopplung« – Optionen für die nächste Phase der Energiewende, acatech – Deutsche Akademie der Technikwissenschaften e.V. und Deutsche Akademie der Naturforscher Leopoldina e.V. und Union der deutschen Akademien der Wissenschaften e.V., Stellungnahme, November 2017, https://www.acatech.de/wp-content/uploads/2018/06/ESYS_Stellungnahme_Sektorkopplung.pdf
- **ADAC autotest (2019)**, Ford Focus 1.5 EcoBlue ST-Line - Fünftürige Schräghecklimousine der Kompaktklasse (88 kW / 120 PS), April 2019, https://www.adac.de/_ext/itr/tests/Autotest/AT5825_Ford_Focus_1_5_EcoBlue_ST_Line/Ford_Focus_1_5_EcoBlue_ST_Line.pdf.
- **ADAC ecotest (2018), Honda Civic** https://www.adac.de/infotestrat/tests/eco-test/detail.aspx?IDMess=4138&info=Honda+Civic+1.6+i-DTEC+Executive
- **AG Energiebilanzen (2020)**, Stromerzeugung nach Energieträgern 1990 - 2019 (Stand Februar 2020), https://ag-energiebilanzen.de/index.php?article_id=29&fileName=ausdruck_strerz_abgabe_20200217.pdf.
- **Agentur für Erneuerbare Energien e.V. (2016)**, Metaanalyse – Flexibilität durch Kopplung von Strom, Wärme & Verkehr, Forschungsradar Energiewende, Agentur für Erneuerbare Energien und Prognos AG, April 2016.
- **Agora Energiewende (2017)**, Future Cost of Onshore Wind - Recent auction results, long-term outlook and implications for upcoming German auctions, April 2017, https://www.agora-energiewende.de/fileadmin2/Projekte/2017/Future_Cost_of_Wind/Agora_Future-Cost-of-Wind_WEB.pdf.
- **Agora und Frontier Economics (2018)**, Die zukünftigen Kosten strombasierter synthetischer Brennstoffe, Frontier Economics, Studie im Auftrag von Agora Energiewende und Agora Verkehrswende, März 2018, https://www.agora-energiewende.de/fileadmin2/Projekte/2017/SynKost_2050/Agora_SynCost-Studie_WEB.pdf
- **BDEW (2017),** Stromzahlen 2017 – Vorläufige Zahlen für 2016, https://www.bdew.de/media/documents/BDEW-Stromzahlen-2017.pdf.
- **BDEW (2020),** Jahresvolllaststunden 2018/2019, https://www.bdew.de/service/daten-und-grafiken/jahresvolllaststunden/.
- **BMVI (2020),** Verkehr in Zahlen 2019/20, https://www.bmvi.de/SharedDocs/DE/Artikel/G/verkehr-in-zahlen.html
- **BMVI und NOW GmbH (2016)**, Abschlussbericht Bewertung der Praxistauglichkeit und Umweltwirkung von Elektrofahrzeugen, Bundesministerium für Verkehr und digitale Infrastruktur (BMVI) und Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie, Berlin, 2016.
- **BMWi (2020)**, Zeitreihen zur Entwicklung der Erneuerbaren Energien in Deutschland, unter Verwendung von Daten der Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat) (Stand: Februar 2020), https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/zeitreihen-zur-

entwicklung-der-erneuerbaren-energien-in-deutschland-1990-2019.pdf?__blob=publicationFile&v=26.

- **Breyer (2012)**, Economics of Hybrid Photovoltaic Power Plants, Dissertation, Universität Kassel, August 2012, https://kobra.uni-kassel.de/bitstream/123456789/2012102242017/3/DissertationChristianBreyer.pdf.
- **Brynolf et al. (2018),** Electrofuels for the transport sector: A review of production costs, Renewable and Sustainable Energy Reviews, Volume 81, Nr. 2, Januar 2018, S. 1887-1905.
- **Deutscher Bundestag (2019a)**, Antwort der Bundesregierung auf die Kleine Anfrage der Abgeordneten Stephan Kühn, Oliver Krischer, Dr. Julia Verlinden, weiterer Abgeordneter und der Fraktion BÜNDNIS 90/DIE GRÜNEN, Drucksache 19/8204, Mengen, Kosten und Einsatzbereiche strombasierter Kraftstoffe im Verkehr, 25.03.2019.
- **Deutscher Bundestag (2019b)**, Antwort der Bundesregierung auf die Kleine Anfrage der Abgeordneten Bernd Reuther, Frank Sitta, Grigorios Aggelidis, weiterer Abgeordneter und der Fraktion der FDP, Drucksache 19/15198, Synthetische Kraftstoffe im Luftverkehr, 06.12.2019.
- **Deutscher Bundestag (2020)**, Antwort der Bundesregierung auf die Kleine Anfrage der Abgeordneten Lorenz Gösta Beutin, Sabine Leidig, Hubertus Zdebel, weiterer Abgeordneter und der Fraktion DIE LINKE, Drucksache 19/18122, Ökologische Folgen und Kosten der Wasserstoffwirtschaft, 24.04.2020.
- **Doyle und Muneer (2019)**, Energy consumption and modelling of the climate control system in the electric vehicle, Energy Exploration & Exploitation 2019, Volume 37, Nr. 1.
- **Fasihi und Breyer (2020)**, Baseload electricity and hydrogen supply based on hybrid PV-Wind power plants, Journal of Cleaner Production, Nr. 243, 2020.
- **FZ Jülich (2017),** Techno-Economic Analysis of a Potential Energy Trading Link between Patagonia and Japan Based on CO2 free Hydrogen, http://juser.fz-juelich.de/record/837682.
- **EVWind (2019),** Wind energy in Argentina: YPF wind farm, 20.08.2019.
- **Fraunhofer UMSICHT (2013)**, Speicher für die Energiewende, Fraunhofer-Institut für Umwelt-, Sicherheits- und Energietechnik UMSICHT, September 2013, https://speicherinitiative.at/assets/Uploads/18-Speicher-fuer-die-Energiewende-Fraunhofer-UMSICHT.pdf.
- **Fraunhofer ISE (2018),** Stromgestehungskosten Erneuerbare Energien, https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/DE2018_ISE_Studie_Stromgestehungskosten_Erneuerbare_Energien.pdf.
- **Frontier Economics et al. (2017)**, Der Wert der Gasinfrastruktur für die Energiewende in Deutschland - Eine modellbasierte Analyse, Studie im Auftrag von FNB Gas, https://www.fnb-gas.de/files/fnb_gas_wert_von_gasinfrastrukturendbericht.pdf
- **Frontier Economics (2018)**, International Aspects of a Power-to-X Roadmap, Studie im Auftrag des Weltenergierats Deutschland (WER Deutschland), https://www.frontier-economics.com/media/2642/frontier-int-ptx-roadmap-stc-12-10-18-final-report.pdf.
- **hzwei (2016)** - TU Berlin erforscht nasse Verbrennung, https://www.hzwei.info/blog/2016/06/14/tu-berlin-erforscht-nasse-verbrennung/.

- **ifeu und Wuppertal Institut (2007)**, Elektromobilität und Erneuerbare Energien, Institut für Energie- und Umweltforschung Heidelberg (ifeu) und Wuppertal Institut für Klima, Umwelt, Energie GmbH, https://wupperinst.org/uploads/tx_wupperinst/Energiebalance_AP5.pdf.
- **KBA (2020)**, Verkehr in Kilometern - Inländerfahrleistung (VK), Entwicklung der Fahrleistungen nach Fahrzeugarten seit 2014, https://www.kba.de/DE/Statistik/Kraftverkehr/VerkehrKilometer/vk_inlaenderfahrleistung/vk_archiv/2014/verkehr_in_kilometern_kurzbericht_pdf.pdf;jsessionid=BD0C2427E9AEDA8D1DEB3B81FB383B8C.live11291?__blob=publicationFile&v=1.
- **Prognos (2020),** Kosten und Transformationspfade für strombasierte Energieträger, Studie im Auftrag des BMWI, Mai 2020.
- **Roland Berger und Prognos (2019)**, Wegweiser Solarwirtschaft: PV Roadmap 2020.
- **SMARD Strommarktdaten (2020)**, https://www.smard.de/home.
- **UBA (2015)**, Postfossile Energieversorgungsoptionen für einen treibhausgasneutralen Verkehr im Jahr 2050: Eine verkehrsträgerübergreifende Bewertung, INFRAS AG, Studie im Auftrag des Umweltbundesamtes, April 2015, https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_30_2015_postfossile_energieversorgungsoptionen.pdf.
- **UBA (2016)**, Weiterentwicklung und vertiefte Analyse der Umweltbilanz von Elektrofahrzeugen, ifeu – Institut für Energie- und Umweltforschung Heidelberg GmbH, Studie im Auftrag des Umweltbundesamtes, April 2016, https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_27_2016_umweltbilanz_von_elektrofahrzeugen.pdf.
- **Tizgui et al. (2018)**, Estimation and Analysis of Wind Electricity Production Cost in Morocco, International Journal of Energy Economics and Policy 2018, Volume 8, Nr. 3, S. 58-66.

ANNEX: OVERVIEW OF REFERENCE SCENARIOS

Figure 38: Methods of calculating the efficiency values of the individual stages of the value chain

Value creation stage	Description
Electricity generation/ yield efficiency	Calculation based on expected FLH by technology and location in relation to the maximum FLH number that can currently be achieved worldwide with the respective technology. For PV systems, the best possible value is currently 2,500 h (e.g. in the South American Atacama Desert) and for wind systems 6,500 h (e.g. Patagonia, Tibet). The best possible value for PV/wind (combination) systems corresponds to the respective benchmark to weight the actual used PV and wind values against.
Grid losses, *BEVs only*	Calculation based on the total German grid losses in relation to the total German electricity consumption.
Storage losses (seasonal), *BEVs only*	Efficiency losses due to intermediate storage of electricity due to the unequal (seasonal) distribution of RES production in Germany in the BEV scenarios. Consideration of seasonal (summer to winter) and day-night storage of PV electricity and seasonal (winter to summer) storage of wind electricity. The simplified basic assumption is that the demand for mobility is evenly distributed over the year. Estimates of the energy volumes to be temporarily stored are based on historical generation volumes of PV and wind in Germany. As storage technology we assume a PtH2tP solution. The assumptions on electrolysis used here correspond to those of the ICEV reference scenarios. In addition, we assume a gas storage loss of 10% and an efficiency of 45% for the conversion of electricity using a H2 gas power plant. Due to the loss-free storage or storage possibility of synthetic fuels, we do not consider (seasonal) storage losses in the ICEV scenarios.
Loss of charge, *BEVs only*	Loss of charge during loading and unloading of the battery.
Electrolysis efficiency, *ICEVs only*	efficiency of the conversion of renewable electricity to hydrogen.
Efficiency Fischer-Tropsch, *ICEVs only*	Efficiency of the conversion of hydrogen into synthetic liquid fuels using the Fischer-Tropsch process, including CO3 capturing via DAC and refinement/refinement to the final synthetic fuel product.
Losses internat. transport, *only ICEVs*	Loss of efficiency due to the international transport of synthetic fuel by shipping. Estimated on the basis of the daily fuel requirement of a typical tanker and the distance to be transported to Germany.
Losses nat. transport	efficiency losses due to the national transport of synthetic fuel. Fixed at a flat rate of 1%.
Efficiency Mobility	In other words, the efficiency of vehicle use takes into account the efficiency of the engine (internal combustion engine or electric motor), the efficiency losses due to the mechanics or the rest of the drive train and the efficiency losses due to other applications in the vehicle such as interior air conditioning. Other efficiency losses, such as during charging or transport, are taken into account in the upstream stages of the value chain.
Comprehensive efficiency	For BEVs and ICEVs, all relevant stages of the value chain are taken into account, from the yield efficiency of the RE plants to the efficiency of vehicle use.
Capacity per car	Calculation of the capacity of PV and wind plants to be installed, which is required to generate the average annual energy demand of a vehicle. The basis of the calculation is the average annual mileage of a passenger car in Germany (in km/year) and the vehicle consumption of BEVs and ICEVs (in kWh/km) in order to calculate the annual energy demand as well as the feasible FLH of the respective RE technologies depending on the location in order to translate the annual energy demand into capacity to be installed (kW).

Source: Frontier Economics

Note: **Power generation/efficiency of yield***: based on BMWi (2020), BDEW (2020), Fraunhofer ISE (2018), EVWind (2019), FZ Jülich (2017), Roland Berger/Prognos (2019).*
Grid losses*: based on BDEW (2017)*
Storage losses (seasonal)*: Fraunhofer UMSICHT (2013), Frontier Economics et al. (2017), hzwei (2016), SMARD electricity market*

data (2020).
Charging losses: *based on ifeu and Wuppertal Institute (2007), BMVI and NOW GmbH (2016).*
Electrolysis efficiency: *based* on Agora and Frontier Economics (2018) and expert interviews.
Efficiency Fischer Tropsch: *Agora and Frontier Economics (2018), expert interviews, Brynolf et al.*
Losses int. transport: *based on* *http://hb.hr/wp-content/uploads/2014/12/tankers.pdf* *and* *https://www.sear.ates.com/services/distances-time/*.
Efficiency mobility: *based on Doyle and Muneer (2019), https://de.statista.com/statistik/daten/studie/1031883/umfrage/entwicklung-der-temperatur-im-auto-nach-standzeit-und-aussentemperatur/, https://www.adac.de/rund-ums-fahrzeug/ausstattung-technik-zubehoer/ausstattung/auto-klimaanlagen/, http://www.mx-electronic.com/pdf-texte/link-e-mobility/Der-Elektrofachmann-Wirkungsgrad-Vergleich-zwischen-Fahrz.pdf*
Output per car: *annual mileage based on KBA (2020)*

Figure 39. Reference scenarios BEV - Efficiency factors and efficiency losses by value chain

Value creation stage	PV Reference Scenario	Wind reference scenario	PV/wind reference scenario
Electricity generation/ yield efficiency	Germany: 969 FLH/ 39%	Germany: 2,071 FLH/ 32%	Germany: 1,579 FLH/ 35%
Network losses	5%	5%	5%
Storage losses (seasonal)	15%	10%	5%
Lost charging	20%	20%	20%
Efficiency Mobility	71%	71%	71%
Comprehensive efficiency	14%	13%	16%
Power per car	5.7 kW	2.3 kW	2.7 kW

Source: Frontier Economics

Figure 40. ICEV reference scenarios - efficiency factors and efficiency losses by value-added stages

Value creation stage	PV Reference Scenario	Wind reference scenario	PV/wind reference scenario
Electricity generation/ yield efficiency	North Africa/Morocco: 2,344 FLH/ 94%	Argentina/Patagonia: 4,730 FLH/ 73%.	North Africa/Morocco: 2,987 FLH/ 75%
Electrolysis efficiency	67%	67%	67%
Efficiency Fischer-Tropsch	73%	73%	73%
Losses int. transport	0,2%	0,9%	0,2%
Losses nat. transport	1%	1%	1%
Efficiency Mobility	29%	29%	29%
Comprehensive efficiency	13%	10%	10%
Power per car	6.0 kW	3.0 kW	4.7 kW

Source: Frontier Economics

Figure 41. FLH sensitivities BEV

Value added stage	PV DE Opt	Wind DE Offshore	Wind North-DE Onshore	Wind DE Onshore
Electricity generation/ yield efficiency	Germany: 1,050 FLH/ 42%	Germany: 3,375 FLH/ 52%	Germany: 2.500 FLH/ 38%	Germany: 1.805 FLH/ 28%
Network losses	5%	5%	5%	5%
Storage losses (seasonal)	15%	10%	10%	10%
Lost charging	20%	20%	20%	20%
Efficiency Mobility	71%	71%	71%	71%
Comprehensive efficiency	15%	22%	16%	12%
Power per car	5.2 kW	1.4 kW	1.9 kW	2.6 kW

Source: Frontier Economics

Figure 42. FLH sensitivities ICEV

Value added stage	PV NA/MAR Opt	Wind ARG/PAT Opt	Wind NA/MAR Opt	Wind NA/MAR Base
Electricity generation/ yield efficiency	North Africa/Morocco: 2,500 FLH/ 100%	Argentina/ Patagonia: 5,200 FLH/ 80%	North Africa/ Morocco: 4,550 FLH/ 70%	North Africa/Morocco: 3,629 FLH/ 56
Electrolysis efficiency	67%	67%	67%	67%
Efficiency Fischer-Tropsch	73%	73%	73%	73%
Losses int. transport	0,2%	0,9%	0,2%	0,2%
Losses nat. transport	1%	1%	1%	1%
Efficiency Mobility	29%	29%	29%	29%
Comprehensive efficiency	14%	11%	10%	8%
Power per car	5.7 kW	2.7 kW	3.1 kW	3.9 kW

Source: Frontier Economics

Figure 43. Winter/city sensitivity BEV

Value creation stage	PV 0°/city	Wind 0°/city	PV/wind* 0°/city
Electricity generation/ yield efficiency	Germany: 969 FLH/ 39%	Germany: 2,071 FLH/ 32%	Germany: 1,579 FLH/ 35%
Network losses	5%	5%	5%
Storage losses (seasonal)	15%	10%	5%
Lost charging	20%	20%	20%
Efficiency Mobility	39%	39%	39%
Comprehensive efficiency	8%	7%	9%
Power per car	9.7 kW	3.9 kW	4.7 kW

Source: Frontier Economics

*Note: * Additional information, i.e. not included in the main body of the report.*

Figure 44 Winter/city sensitivity ICEV

Value creation stage	PV 0°/city	Wind 0°/city	PV/wind* 0°/city
Electricity generation/ yield efficiency	North Africa/Morocco: 2,344 FLH/ 94%	Argentina/Patagonia: 4,730 FLH/ 73%.	North Africa/Morocco: 2,987 FLH/ 75%
Electrolysis efficiency	67%	67%	67%
Efficiency Fischer-Tropsch	73%	73%	73%
Losses int. transport	0,2%	0,9%	0,2%
Losses nat. transport	1%	1%	1%
Efficiency Mobility	22%	22%	22%
Comprehensive efficiency	10%	8%	8%
Power per car	7.4 kW	3.7 kW	5.8 kW

Source: Frontier Economics

*Note: * Additional information, i.e. not included in the main body of the report.*

Figure 45. Technical sensitivities BEV, variation of charge losses

Value added stage	PV 30% Charging reliability	PV 10% Charging reliability	Wind 30% Loading capacity	Wind 10% Loading capacity	PV/wind 30% charge reliability *	PV/Wind 10% Charging reliability *
Electricity generation/ yield efficiency	Germany: 969 FLH/ 39%	Germany: 969 FLH/ 39%	Germany: 2,071 FLH/ 32%	Germany: 2,071 FLH/ 32%	Germany: 1,579 FLH/ 35%	Germany: 1,579 FLH/ 35%
Network losses	5%	5%	5%	5%	5%	5%
Storage losses (seasonal)	15%	15%	10%	10%	5%	5%
Lost charging	30%	10%	30%	10%	30%	10%
Efficiency Mobility	71%	71%	71%	71%	71%	71%
Comprehensive efficiency	12%	16%	12%	15%	14%	18%
Power per car	6.5 kW	5.0 kW	2.6 kW	2.0 kW	3.1 kW	2.4 kW

Source: Frontier Economics

*Note: * Additional information, i.e. not included in the main body of the report.*

Figure 46. Technical sensitivities ICEV, variation of electrolysis technology (HT instead of NT)

Value creation stage	PV HT	Wind HT	PV/Wind HT*
Electricity generation/ yield efficiency	North Africa/Morocco: 2,344 FLH/ 94%	Argentina/Patagonia: 4,730 FLH/ 73%.	North Africa/Morocco: 2,987 FLH/ 75%
Electrolysis efficiency	81%	81%	81%
Efficiency Fischer-Tropsch	73%	73%	73%
Losses int. transport	0,2%	0,9%	0,2%
Losses nat. transport	1%	1%	1%
Efficiency Mobility	29%	29%	29%
Comprehensive efficiency	16%	12%	13%
Power per car	5.0 kW	2.5 kW	3.9 kW

Source: Frontier Economics

*Note: * Additional information, i.e. not included in the main body of the report.*

Figure 47. Efficiency sensitivities BEV

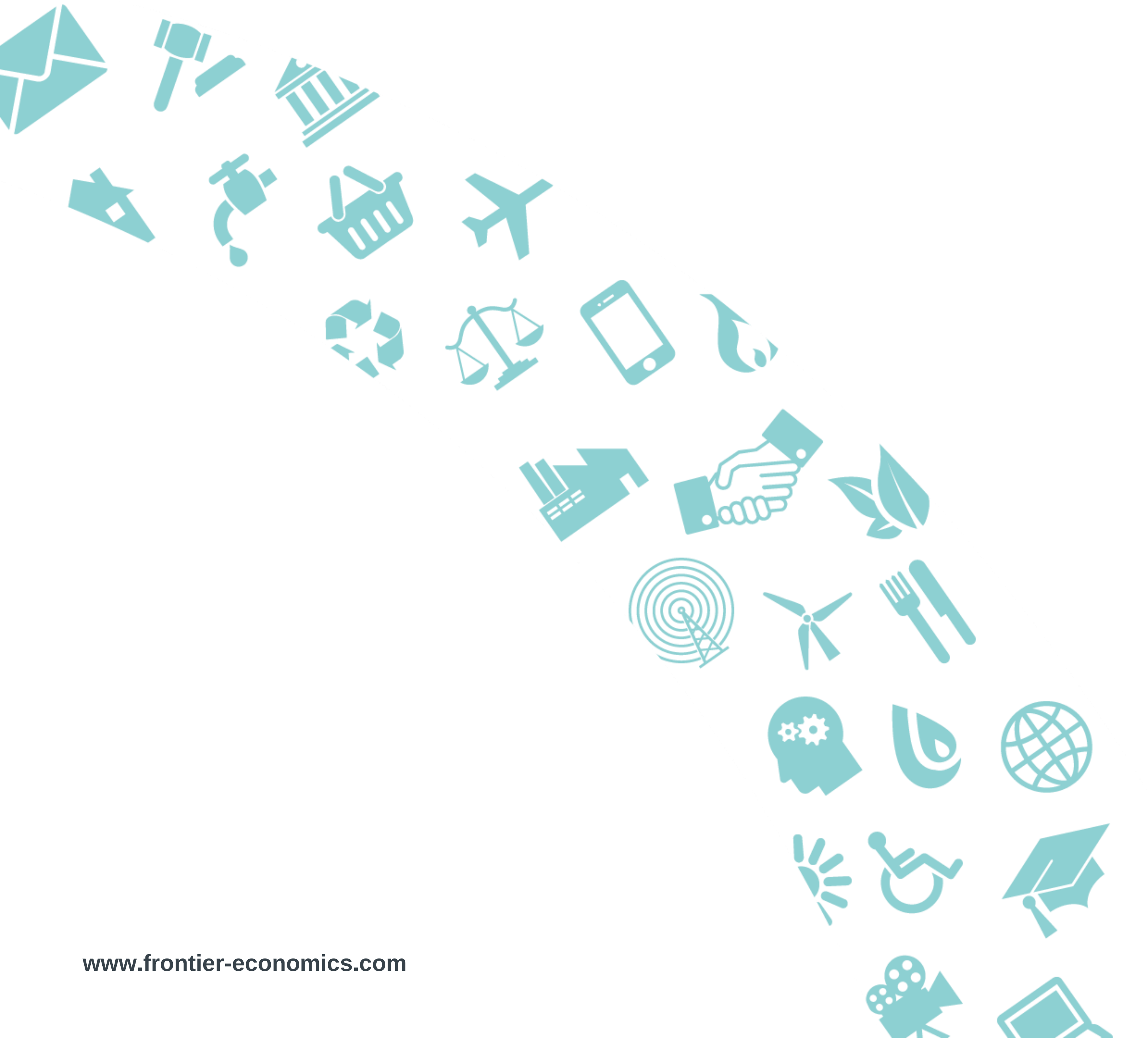
Value creation stage	low efficiency	high efficiency
Electricity generation/ yield efficiency	PV Germany: 969 FLH/ 39%	PV Germany: 1,050 FLH/ 42%
Network losses	5%	5%
Storage losses (seasonal)	15%	15%
Lost charging	30%	10%
Efficiency Mobility	39%	71%
Comprehensive efficiency	7%	17%
Power per car	11.0 kW	4.6 kW

Source: Frontier Economics

Figure 48. Efficiency sensitivities ICEV

Value creation stage	low efficiency	high efficiency
Electricity generation/ yield efficiency	PV North Africa/Morocco: 2,344 FLH/ 94	PV North Africa/Morocco: 2,500 FLH/ 100%
Electrolysis efficiency	67%	81%
Efficiency Fischer-Tropsch	73%	73%
Losses int. transport	0,2%	0,2%
Losses nat. transport	1%	1%
Efficiency Mobility	22%	29%
Comprehensive efficiency	10%	17%
Power per car	7.4 kW	4.7 kW

Source: Frontier Economics



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