Energy efficiency quo vadis? – the role of energy efficiency in a 100 % renewable future

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Abstract
Following the decisions of the Paris climate conference at the end of 2015 as well as similar announcements e.g. from the G7 in Elmau (Germany) in the summer of 2015, long-term strategies aiming at (almost) full decarbonisation of the energy systems increasingly move into the focus of climate and energy policy. Deep decarbonisation obviously requires a complete switch of energy supply towards zero GHG emission sources, such as renewable energy. A large number of both global as well as national climate change mitigation scenarios emphasize that energy efficiency will likewise play a key role in achieving deep decarbonization. However, the interdependencies between a transformation of energy supply on the one hand and the role of and prospects for energy efficiency on the other hand are rarely explored in detail.

This article explores these interdependencies based on a scenario for Germany that describes a future energy system relying entirely on renewable energy sources. Our analysis emphasizes that generally, considerable energy efficiency improvements on the demand side are required in order to have a realistic chance of transforming the German energy system towards 100 % renewables. Efficiency improvements are especially important if energy demand sectors will continue to require large amounts of liquid and gaseous fuels, as the production of these fuels are associated with considerable energy losses in a 100 % renewables future. Energy efficiency on the supply side will therefore differ considerably depending on how strongly the use of liquid and gaseous fuels in the various demand sectors can be substituted through the direct use of electricity Apart from a general discussion of the role of energy efficiency in a 100 % renewable future, we also look at the role of and prospects for energy efficiency in each individual demand sector.

Introduction
The Paris Agreement adopted in December 2015 by more than 190 countries (UNFCCC 2015) as well as the Elmau declaration of the G7 leaders from June 2015 (G7 Heads of State 2015) make it very clear that the world needs to take significant steps towards decarbonising the global economy and energy systems until the middle of the century. Limiting the increase in the global average temperature to well below 2 °C over pre-industrial levels means that global greenhouse gas (GHG) emissions need to peak and decline very soon. Emissions in industrialised countries need to be reduced by as much as 80 to 95 % by the middle of the century compared to 1990 levels (IPCC 2014). Globally and even more so in most industrialised countries, the energy system is by far the biggest source of anthropogenic GHG emissions.

In recent years, a number of global, regional and country-level scenario studies have been released to show how an energy system transformation towards very low or zero CO_2 emissions could be realised (e.g. European Commission, 2011; IEA, 2016a, 2016b; Jeffries et al., 2011; Nagl et al., 2011; Teske et al., 2015). In all these scenarios, considerable and accelerated energy efficiency improvements are assumed to be a key prerequisite to achieve ambitious emission reductions.

Previous studies have emphasized the relevance of energy efficiency (Kriegler et al. 2014; Chaturvedi/Shukla 2014) and direct electrification (Williams et al. 2013; McCollum et al. 2014; Deng et al. 2012) to enable deep decarbonisation in the energy system. Despite various advantages associated with the direct electrification of end use applications, Andrews and Shabani (2012) maintain that in some areas hydrogen will likely still play a role in a future sustainable energy system. Grubler (2012) generally emphasises the relevance of transformations at the energy end-use level in driving energy transitions. While we build on the insights gained from these publications, there appears to be a lack of studies that analyse the potentially different role or relevance of energy efficiency improvements depending on the specific mitigation strategies chosen for the decarbonisation of energy supply. Furthermore, scenario studies or related research rarely discuss the advantages and disadvantages of increasing (relative to a specific mitigation scenario) the low-carbon energy supply in order to reduce the need for energy efficiency improvements – or vice versa.

This paper therefore attempts to contribute to a better understanding of the role of energy efficiency improvements in a future low or zero carbon energy system. Specifically, the paper analyses the role of energy efficiency in a 100 % renewable energy future and how this role varies in such a system depending on the extent of direct electrification in the end use sectors.

In the following, we first illustrate the relevance of demand side energy efficiency improvements in a low carbon energy future by looking at the role that such improvements play in three recent global climate change mitigation scenarios. Based on a very far-reaching scenario for Germany, we then analyse the role and relevance of demand side energy efficiency improvements in a 100 % renewable energy future and how this role varies depending on the extent of direct electrification in the end use sectors. In the conclusion, we attempt to provide some insight in how the future role of (demand-side) energy efficiency can be framed.

The role of energy efficiency in global decarbonisation scenarios

For a first insight into the role that energy efficiency may play in the context of very ambitious climate mitigation scenarios, we briefly analyse global energy scenarios with moderate to high ambition regarding GHG mitigation. We use three global energy scenarios from two recent studies, the 2DS scenario by IEA (2016a) and two scenarios on behalf of Greenpeace et al. (Teske et al. 2015). Compared to 1990, these scenarios by 2050 achieve a decline in global energy system CO_2 emissions of 32 % (2DS scenario from IEA 2016a), 79 % (Energy Revolution from Teske et al. 2015) and 100 % (Advanced Energy Revolution, also from Teske et al. 2015), respectively[1].

The change in primary energy demand in the scenarios is deconstructed using a modified Kaya-equation (Kaya 1990; Kaya and Yokobori 1997), which on a macroeconomic level splits up the development of global primary energy demand (PE) as a function of changes in population, affluence (GDP per capita), final energy intensity (final energy per unit of GDP (FE/GDP) – a measure which includes also structural effects in the composition of GDP and changes in consumption; see Knoop & Lechtenböhmer 2016, Schlomann, Rohde, Plötz 2015) and energy supply system efficiency (units of primary energy needed per unit of final energy, PE/FE). When looking at CO_2 or GHG emissions, the emission intensity (CO_2 emissions per unit of primary energy) can be included as an additional factor, as it is also an important lever to mitigate emissions. However, as this paper concerns the role of energy efficiency, we focus here on primary energy, not CO_2 emissions.

As can be seen in Figure 1, over the 23 years from 1990 to 2013, global primary energy use grew by 1.9 % on average or a total of 55 %. About half of this can be explained by population growth, while GDP per capita growth alone resulted in a 56 % demand growth. The combined effect of these two factors was, however, mitigated by final energy efficiency improvements, which reduced energy demand by 36 % in the same period. The energy supply system, however, on average did not improve in terms of the amount of primary energy required per unit of final energy in this period but even had a small upward effect on primary energy demand. This overall effect is the result of several diverging effects: the increase in the share of electricity in final energy demand, increased primary energy demand per unit of final energy demand, while improvements in the efficiency of thermal power plants as well as higher shares of renewable electricity generation (most of which is statistically assumed to be converted with an efficiency of 100 %) both reduced primary energy demand. Historically, the diagram shows that final energy efficiency – on global average – was the main factor that limited the growth in primary energy demand. Without improved final energy efficiency, primary energy demand would have grown considerably stronger than it did.

This overall pattern is expected to gradually change over the coming decades in ambitious climate change scenarios. Increasing factors such as population growth and GDP per capita are expected to slow down (please note the 60 % longer time period as compared to the historical values) but will, until 2050, still lead to around 13 % to 14 % (population growth) and 48 % to 59 % (GDP per capita growth) of energy demand growth in the scenarios by Teske et al. (2015) and in the IEA's 2DS scenario.

Counteracting these growth effects, final energy efficiency will significantly increase compared to historical values and reduce energy demand by about 60 % in the 2DS and by more than 70 % in the scenarios by Teske et al. (2015) by 2050. This is expected to compensate for GDP per capita growth in the 2DS scenario, with primary energy growing roughly at the same percentage as population. In the Teske et al. (2015) scenarios, final energy efficiency will slightly outweigh the sum of the effects of GDP per capita growth and population growth.

Energy supply system efficiency in total (PE per unit of FE) is characterized by diverging trends historically as well as in the scenarios. In the 2DS scenario it remains stable, because increasing effects such as energy consuming carbon capture and storage (CCS) and higher shares of electricity are compensated by more efficient power plants plus the (statistical) effects of increased renewable electricity generation (RES). The Energy [R]evolution scenario assumes no CCS but more RES, which

1. It should be noted that the scenario from the IEA (2016a) includes process-related emissions from the industrial sector, while the Teske et al. (2015) scenarios do not.

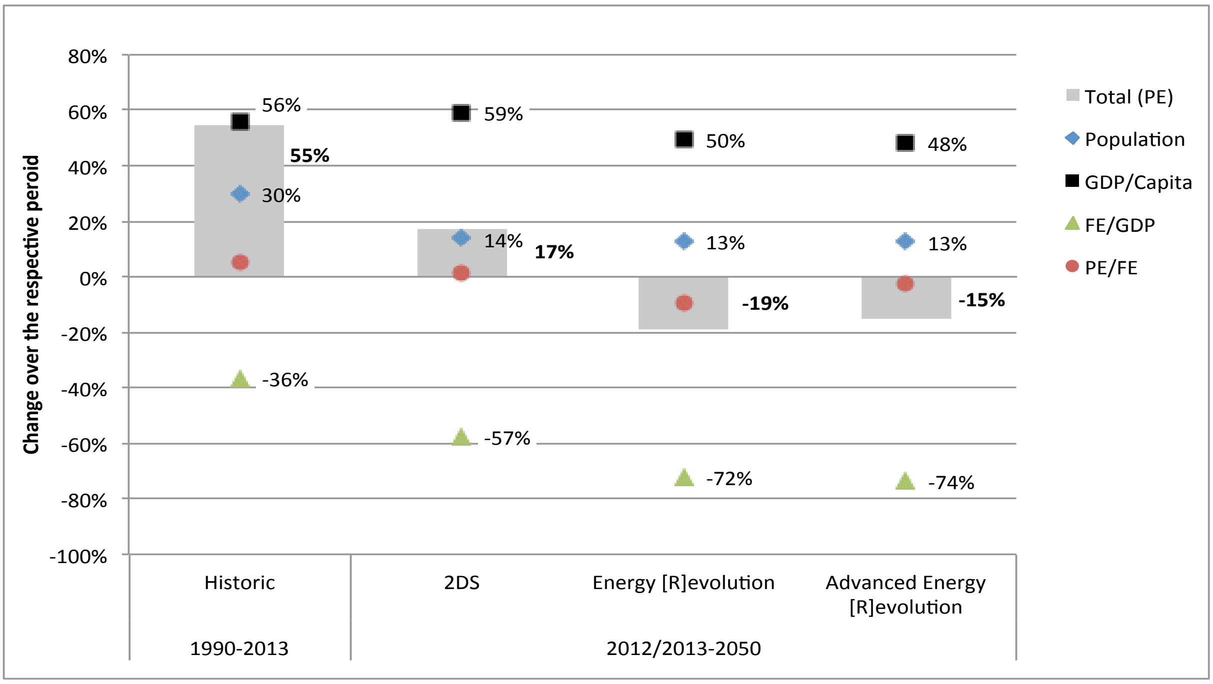

Figure 1. Influencing factors on primary energy demand in ambitious global energy scenarios.

leads to significant improvements in terms of the ratio between primary energy and final energy demand. The Advanced Energy [R]evolution scenario, in turn, assumes a larger role of hydrogen and derived energy carriers based on RES electricity, which decrease the supply system efficiency and almost fully compensate for the effects of high RES share and more efficient gas fired electricity generation.

Concluding the brief analysis of current ambitious bottom-up energy scenarios, it becomes clear that all three analysed scenarios expect further strong primary energy demand growth effects from an increasing global population and sustained per capita economic growth. However, these growth effects are expected to become largely decoupled from energy demand growth, with only a modest overall increase in primary energy demand in the 2DS or even a decline of primary energy demand in the more ambitious scenarios by Teske et al. (2015). Primary energy efficiency, in contrast, consists of diverging trends which in sum are expected to deliver only small reductions in the Energy [R]evolution scenario and almost none in the (even) more ambitious Advanced Energy [R]evolution scenario because of higher shares of electricity based fuels incurring high primary energy losses. Therefore, the by far most important factor for the decoupling in all scenarios is final energy efficiency. Although the final energy efficiency effect identified here does include structural effects in the composition of GDP, targeting improvements in final energy efficiency can be regarded as the key strategy for achieving deep decarbonisation – in combination with the switch to a low-emission fuel supply, a result that is also supported by the analysis of 12 different global decarbonisation scenarios by Loftus et al. (2015).

The question however, remains: What are the real driving forces for final energy efficiency in scenarios that achieve very low GHG emissions? After all, it can be (and is, occasionally) argued that efficiency does not reduce CO_2 emissions in a hypothetical future energy system, which is supplied entirely by carbon-free sources. By analysing a very ambitious scenario that achieves almost zero GHG emissions from the German energy system we try to explore in the following which role energy efficiency needs to play in very ambitious decarbonisation scenarios and how sectoral strategies for achieving very strong energy efficiency improvements might interact with other demand and supply side decarbonisation strategies.

Strategies for near zero GHG emission energy systems – an example

In order to assess the role of final energy efficiency in near zero GHG emissions scenarios we construct four archetypical scenarios based on the scenario developed by the German Environment Agency (UBA 2014). In their study, UBA provided a bottom up analysis of GHG emission reductions for all emitting sectors for Germany, based on own research as well as other studies. In their scenario they describe a "climate neutral Germany" for the year 2050, including a complete decarbonisation of the energy system by the means of a full supply of all energy by renewable electricity and renewable electricity-derived energy carriers. This includes also the non energetic use or feedstock supply to chemical industries, which is also assumed to be supplied by synthetic feedstocks derived from electricity and captured CO_2.

Following the UBA (2014) aim, all of our four archetypical scenarios assume a 100 % GHG free energy supply, more specifically an energy supply that is based entirely on renewable energy sources. Almost all of the final energy demand is supplied by electricity (direct supply by geothermal and solar is expected to be of only very small relevance and is therefore disregarded).

The scenarios follow two basic strategies for achieving a fossil-free energy supply:

A. A moderate electrification of the energy system with increasing shares of electricity in final energy demand in all sectors plus a conversion of conventional fossil gas and fuel based infrastructures and technologies towards gaseous/liquid energy carriers that have been produced based on RES electricity (via electrolysis of water to hydrogen and methanization or other processes using CO_2). This strategy is termed *indirect electrification*.

B. A strong electrification of almost all final energy demand with direct electricity applications wherever possible plus some power-based energy carriers for those end-use segments (such as airplanes) in which electricity cannot be used directly. This strategy is termed *direct electrification*.

These strategies are typically combined with a strong strategy of improving final energy efficiency (as the examples above from the global scenarios show) the following.

For two of the scenarios, we use the final energy demand by UBA 2014 which assumes roughly 50 % savings on final energy (FE)-levels vs. 2010, which – at an assumed level of GDP growth of 0.7 % per year or 32 % until 2050 – would roughly mean an efficiency improvement of 62 %, or something between the global studies quoted above. These savings are achieved through very ambitious energy efficiency improvements in the end-use sectors, e.g. through high market shares of energy efficient electrical appliances, house insulation and highly efficient cars. Furthermore, the savings include the effects of efficiency improvements typically achieved by switching from gaseous or liquid fuels to electricity. Changes in modal split of transport modes and some moderate lifestyle changes ("sufficiency") are also assumed, as well as structural changes in the economy, which are also expected to contribute to final energy savings. This strategy is termed *high efficiency*.

For analytical purposes we contrast two scenarios assuming such strong final energy reductions and a moderate electrification on the one hand as well as a strong electrification on the other hand with two mirror-image scenarios that remain on 2010 levels of efficiency. Doing so, we aim to demonstrate what kind of effects no or weak efficiency improvements would have on PE/FE-intensity as well as the amount of green electricity needed. This strategy is termed *frozen efficiency*.

By combination of both strategy elements, four scenarios are created (see Figure 2), with the high efficiency & indirect electrification scenario being the original scenario by UBA (2014), whereas the other three scenarios are constructed here for analytical purposes. The four scenarios all deliver more or less the same energy services to the German economy and population, however, with different efficiencies on all levels, from useful energy via final energy to primary energy.

We first compare the scenarios regarding indirect vs. direct electrification: Clear advantages of the direct electrification route are the lower energy demand on final energy stage due to often higher efficiency of electric devices vs. conventional fuel combusting technologies (i.e. heat pumps and motors) as well as significantly lower primary electricity demand, as the losses for transmission and storage in the electricity system are moderate compared to the high level of losses of the two step conversion of electricity into hydrogen and then fuels or gases.

For costs and material use, however, the advantages are not that clear. The two-step conversion of the indirect electrification route most probably leads to lower energy supply costs in the direct route as much less electricity has to be produced and transported and the costly conversion system for converting electricity into fuels is much smaller. The higher costs in an indirect electrification scenario may very well overcompensate for the higher costs of storage and balancing as well as the conversion of final energy supply technology and infrastructures (e.g. electricity supply for electric vehicles) towards electricity in a system based strongly on direct electricity supply. The same may hold true with regards to the resource-intensity of the systems, although there might be exceptions for certain (critical) materials needed for electric engines and storage devices.

Despite the direct route looking perhaps more preferable at first sight, there may also be disadvantages compared to an indirect electrification strategy. In the case of the direct electrification strategy, there is a stronger need to transform energy

Table 1. Useful, final and primary energy demand of four decarbonisation scenarios for Germany 2050. Source: own calculations, data for scenarios are based on UBA 2014.

Efficiency:	**High**		**Frozen (2010 level)**	
RES electrification strategy:	indirect	direct	indirect	direct
useful energy demand	1,004	1,004	1,875	1,903
final energy demand	1,406	1,177	2,678	2,284
synthetic fuels (liquid/gaseous)	*839*	*75*	*1,472*	*168*
direct electricity	*466*	*1,000*	*1,206*	*2,116*
ambient and solar heat	*101*	*101*	*–*	*–*
non energetic/material use (feedstock)	282	282	282	282
indirect electricity demand				
for synthetic fuels & methane	*1,632*	*153*	*2,834*	*344*
for material use	*499*	*499*	*499*	*499*
total net electricity demand	2,597	1,653	4,539	2,959
gross electricity production	2,845	1,914	5,029	3,476

demand applications (more technological advances required, higher upfront investments needed in demand sectors) as well as a need for an extensive additional electricity infrastructure including storage to buffer fluctuating supply and demand. This will be emphasised by the potentially also increased thermosensitivity of the electricity system which might need additional buffer/reserve capacities. A direct electricity system will therefore be more ambitious with regards to the needed structural changes in supply infrastructures as well as technically regarding the need to balance fluctuating supply and demand at all time for the entire energy system. Further, energy imports have to be almost completely electric while in the indirect system huge amounts of electricity based fuels might be imported (in gaseous or liquid form) from abroad, using more or less the traditional energy trading infrastructures such as ships and pipelines – particularly if RES based fuels were produced e.g. at low costs in the sunny regions of the Middle East and were to replace current conventional exports of hydrocarbons to Europe.

In a next step, the importance of efficiency in different scenarios shall be discussed: The first observation from Figure 2 is the sheer volume of renewables based energy needed in the frozen efficiency scenarios which is about 5,000 TWh of electricity in the indirect and almost 3,500 TWh in the direct electrification scenario. This compares to current German electricity production of 650 TWh and about 3,700 TWh of primary energy supply in 2015 (AG Energiebilanzen 2016). These numbers pose the question if there is sufficient (realisable) potential to generate so much electricity based on renewable energy sources, taking economic and social barriers as well as ecological issues into account. At least so far no study has been published that assumes such high amounts to be available within Germany. The UBA (2014) study estimates that even 3,000 TWh would be significantly beyond the potential for domestic electricity production and assumes high imports, particularly regarding gaseous and liquid energy carriers. The only one of the scenarios that could be assumed feasible with a domestic/regional supply approach is the high efficiency, direct electrification scenario. In this scenario about 2,000 TWh of electricity are needed, with about 640 TWh of it dedicated for conversion to hydrogen and derived fuels. A study by SRU (2011) found a domestic potential of renewable electricity of about 800 to 900 TWh.

The second observation is on the economic side. Both, the reduced need for primary energy supply as well as the savings due to the reduction in costs of converting electricity to electrofuels make efficiency economically very attractive in a 100 % renewables system, even more so if it is characterised by relatively strong *indirect* electrification.

Finally efficiency contributes to reduce the infrastructure as well as system challenges of the energy supply systems particularly in the direct electricity scenario. Although it is not clear how much more infrastructure, and storage capacities would be needed for ramping up electricity supply from 2,000 to 3,500 TWh in a scenario with direct electrification and frozen efficiency, it is plausible that the additional effort needed would be significant. Further, e.g. in the building sector a strong efficiency strategy would reduce the thermosensitivity of demand and would thus benefit the supply system (see below). For the indirect electrification, primary electricity demand in the frozen efficiency case would be more than 2,000 TWh higher than in the high efficiency case, although 1,200 TWh of this additional electricity would be required for electrolysis (which would perhaps not need to be done domestically, at least not fully).

As discussed, the overall picture indicates that the scenarios combined with high efficiency clearly seem to be more feasible than those without it, even when taking into account the challenges associated with realising such efficiency improvements. In the following sections we discuss the systemic, costs and strategy differences between the scenarios with and without high efficiency in more detail for the three key demand sectors space heating in residential and tertiary sector buildings, transport and industry.

How do near zero GHG emission strategies influence/interact with energy efficiency strategies in different sectors?

In the following we discuss the interaction between zero emission energy supply and energy efficiency for three core sectors, which together account for more than 90 % of final energy demand.

LOW TEMPERATURE/SPACE HEATING

The 2050 (scenario) vision of space heating (for households) described in UBA's (2014) THGND study can be characterized by a nearly stable demand for energy service compared to today, due to a shrinking population and moderate per capita increases in living space.

The level of energy service in the scenarios presented below is identical, i.e. the floor space and temperature level are the same. For the frozen efficiency scenarios no additional insulation of the building envelopes is assumed compared to today. CO_2 neutral space heat is supplied by electric off-peak storage heating systems with an assumed efficiency of 90 %. A system like this is often regarded attractive in a mid-term perspective because of the very low invest needed in the building system. Proponents of such a vision also hope that significant amounts of off-peak electricity will be available in the future at relatively low cost.

However, Table 2 shows that the amount of electricity exclusively needed for space heating is huge in the frozen efficiency + direct electrification case: More than 560 TWh would be needed for space heating only, which is almost equivalent to Germany's current total electricity demand. In the scenario with more indirect electrification, primary electricity demand of 674 TWh would even exceed current production.

In the high efficiency scenarios almost all buildings will have been converted to very high insulation standards by 2050. The direct electricity demand for low temperature space heating is at 80 TWh and 36 TWh in the direct and indirect electrification scenarios, respectively, and the level of thermosensitivity is therefore much lower than in the frozen efficiency scenarios. Buildings with ambitious insulation can be supplied by low temperature heating systems completely relying on heat pumps with a high share of ambient and solar heat (ca. 70 % of useful energy supply assumed[2]) and low electricity demand. If

2. The 70 % figure is derived from final energy presented in UBA (2014) and an assumption about electric efficiency of heat pumps of 333 %.

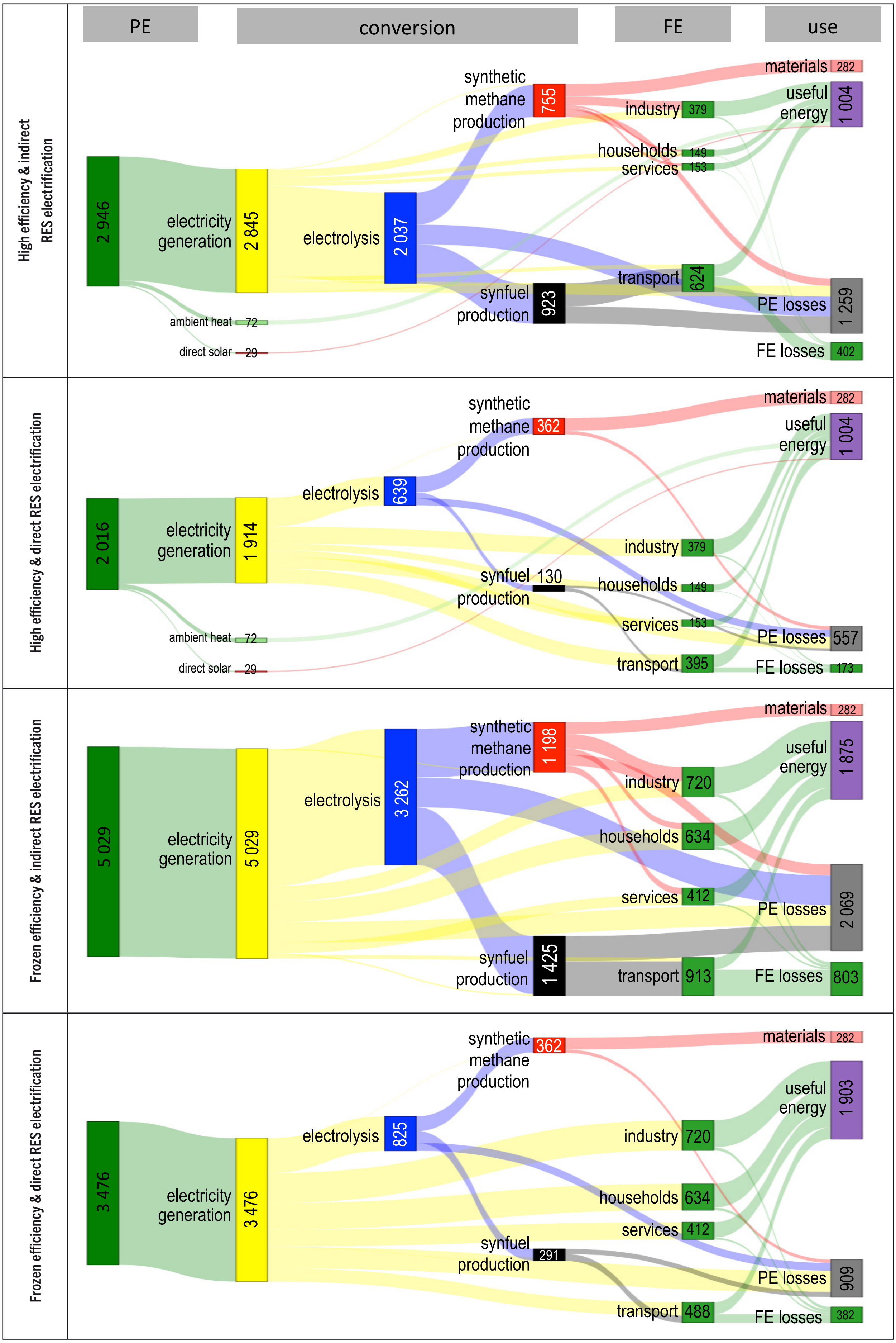

Figure 2. Zero-GHG emission energy scenarios for Germany, 2050 (own figures, data for scenarios are based on UBA 2014).

equipped with thermal storage, heat pumps can be an effective means to balance out electricity supply fluctuations. Highly insulated buildings, on the other side, reduce peak heat demand at low temperatures in winter and thus significantly reduce thermosensitivity. The remaining non-refurbished buildings are supplied by synthetic methane with high losses in primary energy. For this relatively small number of buildings, direct electrification by off-peak heaters could be an alternative option. This is the strategy assumed in the "high efficiency and direct electrification" case; additional electricity demand for electric heaters makes up 45 TWh compared to 79 TWh of indirect electricity use when supplied by methane.

The results from Table 2 and the discussion above show that ambitious demand side efficiency through building insulation pays off not only in the size of the supply system needed but also contributes to electricity system stabilisation. However, in terms of realizing emission reduction potentials, often electrification and heat pumps are seen as attractive alternatives to ambitious insulation, as they could be operated emission-free if supplied by RES electricity and as investments in the building stock could be be much lower and easier than in the case of extensive thermal refurbishments of existing buildings.

In a modelling exercise by Bürger et al. (2016), the authors identify benefits of such a lower-insulation strategy: They analyse a case within a less ambitious 83 % GHG reduction "environment" for Germany in which low insulation ambition (low refurbishment rates and low shares of ambitious refurbishment standards) goes in line with a high share of gas-fired heat pumps as well as electrical air heat pumps. The respective simulations have been carried out with the aim of minimizing total system costs. As renewable electricity shares are high in this case, a high amount of excess energy is available and due to the relative low level of GHG reduction ambition (-83 % by 2050), the study identifies little need to decarbonize transport and industry via synfuels. Therefore, a high amount of excess electricity can be used in the building sector. In another study, however, Henning and Palzer (2015) used the same optimization model to analyse a case with a 90 % GHG reduction target for the German energy system combined with an externally set *rate* of refurbishment for buildings. In this optimization, ambitious refurbishment strategies are chosen by the model, indicating that refurbishment strategies become more attractive compared to mere "green heating options" as the overall mitigation target becomes more stringent.

TRANSPORT

Despite the expected decrease in the German population until 2050, energy service demand in the transport sector is widely assumed to continue to increase in the coming decades. This is true for passenger traffic, and particularly for freight traffic. Here, increasing distances of international transport (which are accounted for in the scenario) and increasing goods transit through Germany are assumed as drivers.

Although energy prices for consumers are higher in the transport sector than in other sectors (due to higher taxes), energy efficiency considerations have in the past only played a relatively minor role in consumers' passenger car purchasing decisions. However, Table 3 suggests that much stronger efficiency improvements are needed in the future in the transport sector than in the past. Otherwise it is difficult to imagine how energy demand in the transport sector could be met in a decarbonised future. Efficiency improvements are especially important for those kinds of transport modes which will likely continue to depend to a great extent on liquid fuels, as these fuels – in the future envisioned here – can only be produced at the expense of high energy losses. These modes of transport are mainly road-based heavy freight transport (although catenary technology for trucks may allow a relevant share of this transport to be electrified), aviation and shipping.

The difficulty of supplying large amounts of fuels based on electricity from renewable energy sources is also the reason why many scenario studies emphasise the special importance of energy demand reductions in the transport sector, usually through a combination of higher technical efficiency, a modal shift towards less energy-intensive modes of transport and – sometimes – also through a reduction in passenger and/or freight kilometres as well as passenger car sizes (Samadi et al. n.y.).

Supplying the same amount of transport (useful energy), final energy losses are significantly different between the four cases that we differentiate. While in the case with frozen efficiency and very moderate electrification final energy demand reaches 913 TWh, it could – theoretically – be almost cut in half (-47 %)

Table 2. Useful, final and primary energy demand for low temperature space heating, four scenarios for Germany in 2050.

	High efficiency		Frozen efficiency	
in TWh/a	indirect RES electrification	direct RES electrification	indirect RES electrification	direct RES electrification
useful energy demand	159	159	508	508
final energy demand	164	164	565	565
"power based" methane	*45*	*0*	*142*	*0*
electricity	*36*	*80*	*423*	*565*
ambient and solar heat	*83*	*83*	*0*	*0*
electricity demand of methane production	79	0	251	0
total net electricity demand	115	80	674	565
total losses	39	4	166	56

Table 3. Useful, final and primary energy demand for transport, four scenarios for Germany in 2050.

	High efficiency		Frozen efficiency	
in TWh/a	indirect RES electrification	direct RES electrification	indirect RES electrification	direct RES electrification
useful energy demand	286	286	286	286
final energy demand	624	395	913	488
liquid synfuels	*533*	*75*	*822*	*168*
electricity	*91*	*320*	*91*	*320*
electricity demand of synfuel production	1,091	153	1,682	344
total net electricity demand	1,182	473	1,773	664
total losses	896	187	1,487	378

by a strong direct electrification of passenger transport alone. Further efficiency improvements could reduce demand by another 20% in the direct electrification and more than 30 % in the case using mainly liquid fuels. In the high efficiency cases, internal combustion engines in trucks and cars are assumed to be significantly more efficient than today, and a 60 % cut in specific energy demand is reached in air transport compared to the base year 2010. Electrifying the total land based transport system – which is technically a very ambitious strategy – theoretically could reduce energy demand even further. Another strategy – not analysed by UBA – would be the use of fuel cell vehicles. Blanck et al. (2013), who delivered the underlying transport case for the UBA study, argue that (endothermic) high-temperature electrolysis combined with (exothermic) Fischer-Tropsch synthesis may reach a slightly higher overall efficiency in delivering chemical energy than stand-alone (steam) electrolysis. However, fuel cells combined with electrical propulsion have an efficiency advantage compared to internal combustion engines (ICEs) in converting chemical energy to mechanical energy (efficiency of about 45 % or even higher when using an additional electrical storage system (Özbek 2010) compared to an efficiency of about 40 %[3] for tank-to-wheel). So fuel cells supplied by hydrogen could be an alternative strategy that would probably be more efficient from a total system view compared to synfuels, although less efficient than battery vehicles.

In the transport sector the differences between the direct and indirect electrification strategies are particularly strong. Supplying energy via liquid fuels based on electricity has the advantage that infrastructures as well as current practises do not have to be changed. However, electricity demand is almost three times as high as compared to the scenarios that assume a significant fuel switch towards direct electrification.

INDUSTRY

Germany still has a diversely structured industry that contributes around 25 % to GDP. Heavy industries such as iron and steel making, aluminium, cement, glass, and paper as well as basic chemicals supply large volumes of the demand of the huge and diverse manufacturing industries of cars, machines etc. Heavy industries, however, are responsible for more than 50 % of Germany's industrial GHG emissions. For the main energy intensive products, as a simplification, UBA (2014) assumes stable physical production volumes. So the demand of energy services in industry in 2050 is assumed to be about the same as today.

In industry, final energy consumption can be disaggregated into the physical minimum required to produce a good, process related energy losses and losses from the conversion of final energy (chemical or electric energy) to useful energy.

Industrial production consists of products containing chemical energy (e.g. plastics) and of products that bear energy rucksacks (e.g. steel does not contain chemical energy but the conversion of iron oxide to steel requires energy). The first kind of products is described as "material or non-energy use" in energy balances (and in the sankey diagrams above). The energy (as well as carbon) stored in these products is not lost, however, the conversion of primary energy carriers to materials incurs conversion losses (which are balanced as final energy use here).

In all scenarios discussed here, energy demand for material or non-energy use is supplied by indirect electrification (via electrolysis of the oxide water and catalysis of hydrogen and the oxide CO_2). The amounts of primary energy needed for this are assumed to be identical in all four scenarios and material use is therefore not part of the scenario comparison in Table 4.[4]

Typical energy uses in industry are the use as reducing agent (as in primary steel production), the use as a source of heat (e.g. to melt minerals) or the use as mechanical energy to transport things (pumps) or to mill materials (e.g. cement mills). Mechanical energy in industry is already typically supplied by electricity because of higher conversion efficiency and far less design complexity. However, in principle all kinds of energy input can be supplied directly by electricity.

Electrical processes to produce heat are also often less complex, they typically have lower investment costs and are more easily to control and adapt. So they can be operated in a smarter way than fuel-based systems (e.g. induction furnaces vs. combustion-based furnaces). Once primary energy supply is based

3. Diesel engine with the respective propulsion system (incl. gearbox) is the reference here.

4. See Lechtenböhmer et al. (2016) for a discussion on electrification of hydrocarbon material supply on the EU level.

Table 4. Useful, final and primary energy demand of industry, four scenarios for Germany in 2050.

	High efficiency		Frozen efficiency	
in TWh/a	indirect RES electrification	direct RES electrification	indirect RES electrification	direct RES electrification
useful energy demand	355	355	648	648
final energy demand	392	392	720	720
synfuels (synthetic methane)	*199*	*0*	*348*	*0*
electricity	*180*	*379*	*373*	*720*
ambient and solar heat	*14*	*14*	*0*	*0*
electricity demand of methane production	352	0	615	0
total net electricity demand	532	379	988	720
total losses	190	37	340	72

mainly on electricity from renewable sources – as is assumed in the scenarios discussed here, electrical energy will be cheaper on a per kWh basis than (synthetic) fuels or gases, and therefore (direct) electrification seems to be a promising strategy for economical, energetic and logistical reasons. (cp. Lechtenböhmer et al. 2016)

However, as can be seen by comparing the scenarios with direct electrification and those with indirect electrification in Table 4, energy savings through direct electrification are less evident in industry than in the transport and buildings sectors. The main reason for the smaller gap is the fact that the main share of fossil fuel use in industry is used for high temperature heat (> 100°). As conversion losses from electricity and fuels to high temperature heat are similar, savings by electrification depend on improved design of the production stock by electrification and are thus process-specific. However, there are some general advantages in electrothermal heating processes. EPRI (2009) summarizes as follows: quick start-up, faster turnaround, less material loss (through oxidation), direct heating (e.g. induction instead of indirect heating by burning fuels) and more process control – which can lead to higher efficiency.

In general, electrification of industrial applications is in the long run less of a technical but mainly an economic and energy system related challenge, as has been shown by Lechtenböhmer et al. (2016), who discuss far reaching electrification strategies for the main energy intensive industries in the EU. For reasons of simplification, no savings through electrification have been assumed here for the two "direct electrification" scenarios (same amount of useful energy as for the indirect electrification scenarios) – which is a rather conservative assumption.[5]

In spite of the smaller differences between the cases, final energy efficiency makes a huge difference compared to the frozen efficiency scenarios. Frozen efficiency requires an additional electricity supply of 90% compared to the respective base case[6].

5. However, part load operation of the production stock in a demand side management mode (which could be much more needed in a "direct electrification" future) could result in lower efficiency, compensating for other efficiency gains.

6. Direct electrification with today's efficiency is however a rather academic case: If industry's energy supply was converted completely to electricity, the production stock (at least for the heat supply) would need to be renewed to a great degree and would therefore be more efficient than today's production stock (which includes appliances that are up to 50 years old).

The transition to an energy supply system based mainly on electricity generation from renewables could lead to geographical relocation and/or smaller production units with smarter production. But also a stronger concentration, e.g. at coastal sites – due to cheap offshore wind and logistic advantages compared to existing sites that partly lose their "fossil based" locational advantages – could be the consequence, depending on the evolution of the energy system as a whole as is discussed for the steel industry in Schneider & Lechtenböhmer (2016).

Conclusion

It can be argued that energy efficiency does not lead to a decrease in CO_2 emissions if the energy supply is carbon free. However, existing deep decarbonisation scenarios all heavily rely on energy efficiency as a core strategy, suggesting that without far-reaching improvements in energy efficiency, a carbon-free energy supply is difficult to imagine. In this paper we therefore explore the role that energy efficiency can play in long-term low greenhouse gas emission development strategies assuming a future energy supply based entirely on renewable energy sources.

Our analysis of four very far reaching decarbonisation scenarios for Germany shows that without considerable energy efficiency improvements, challenges to achieve future low carbon energy systems would be significantly higher. This holds true for the amount of green electricity needed and potentially also to the required electricity grid, the storage capacity and the power-to-X infrastructure (depending on the overall energy system design).

In case of a lack of efficiency improvements there will certainly be a much higher challenge on realising a sufficient supply of energy from renewable sources. At least for Germany it is highly doubtful that the necessary renewable energy resources will be available in such a low-efficiency decarbonisation scenario, as the energy resources needed are already high in scenarios with significant efficiency improvements – and they are much higher still in scenarios without energy efficiency.

Furthermore, there will be an infrastructure and technology challenge as the capacity of the electricity system's existing infrastructure would need to be massively expanded, especially in case a lack of efficiency improvements is combined with a direct electrification strategy. In case of a strategy of indirect electrification on the other hand, massive capacities of technologies to convert electricity to gaseous and liquid fuels would need to be added, either domestically or abroad (e.g. in regions with very good conditions for renewable energy supply, so called "sweet spots"), if efficiency improvements will be lacking.

There are additional beneficial effects of efficiency improvements on the energy system. This is especially obvious in in the buildings sector, in which building insulation significantly reduces thermosensitivity of electricity demand. A high thermosensitivity of electricity demand would be a significant challenge, especially in a scenario focussing on direct electrification. Furthermore, heat pumps (which can only be deployed effectively in most existing buildings if insulation is improved), if equipped with thermal storage, can be used to buffer the fluctuations of renewable electricity supply.

To conclude, our brief analysis suggests that while far-reaching energy efficiency improvements will of course *not* be *sufficient* to achieve a zero emission energy system, it is difficult to imagine the feasibility of such a system *without* much higher energy efficiency. In fact, realizing zero emission energy systems appears to be very ambitious even if strong final energy efficiency improvements are assumed. Policymakers and society should therefore take great strides to achieve significant efficiency improvements over the coming decades.

References

AG Energiebilanzen (2016): http://www.ag-energiebilanzen.de.

Andrews, J.; Shabani, B. (2012): Re-envisioning the role of hydrogen in a sustainable energy economy. International Journal of Hydrogen Energy, 10th International Conference on Clean Energy 2010 37(2)1184–1203. doi: 10.1016/j.ijhydene.2011.09.137.

Blanck R.; Kasten, P.; Hacker, F.; Mottschall, M. (2013): Treibhausgasneutraler Verkehr 2050: Ein Szenario zur zunehmenden Elektrifizierung und dem Einsatz stromerzeugter Kraftstoffe im Verkehr. Berlin.

Bürger, V. et al. (2016): Klimaneutraler Gebäudebestand 2050. UBA series „Climate Change", No. 6/2016. Dessau/Rosslau.

Chaturvedi, V.; Shukla, P. R. (2014): Role of energy efficiency in climate change mitigation policy for India: assessment of co-benefits and opportunities within an integrated assessment modeling framework. Climatic Change 123(3–4)597–609. doi: 10.1007/s10584-013-0898-x.

Deng, Y. Y.; Blok, K.; van der Leun, K. (2012): Transition to a fully sustainable global energy system. Energy Strategy Reviews, European Energy System Models 1(2) 109–121. doi: 10.1016/j.esr.2012.07.003.

Edenhofer, O. et al. (eds.) (2014): Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, UK & New York, NY, USA.

EPRI (2009): Program on Technology Innovation: Industrial Electrotechnology Development Opportunities. Final Report, July 2009.

European Commission (eds.) (2011): Energy Roadmap 2050. Brussels: European Commission. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0885&from=EN

G7 Heads of State (2015): Leaders' Declaration, G7 Summit, 7-8 June 2015. Elmau.

Grubler, A. (2012): Energy transitions research: Insights and cautionary tales. Energy Policy, Special Section: Past and Prospective Energy Transitions - Insights from History 508–16. doi: 10.1016/j.enpol.2012.02.070.

Henning, H.-M.; Palzer, A. (2015): Was kostet die Energiewende? Wege zur Transformation des deutschen Energiesystems bis 2050. Freiburg.

IEA (eds.) (2016a): Energy Technology Perspectives 2016 - Towards Sustainable Urban Energy Systems. Paris.

IEA (eds.) (2016b): World Energy Outlook 2016. Paris: Organisation for Economic Co-operation and Development OECD.

Jeffries, B.; Deng, Y.; Cornelissen, S.; Klaus, S. (2011): The Energy Report - 100% Renewable Energy by 2050. Gland, Utrecht, Rotterdam. assets.panda.org/downloads/the_energy_report_lowres_111110.pdf

Kaya Y. (1990): Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios. Paper presented to the IPCC Energy and Industry Subgroup. Response Strategies Working Group, Paris.

Kaya Y., Yokobori K. (1997): Environment, energy, and economy: strategies for sustainability. United Nations University Press, Tokyo/New York/Paris.

Knoop, K., Lechtenböhmer, S. (2015): The potential for energy efficiency in the EU Member States – A comparison of studies, Renewable and Sustainable Energy Reviews 68 (2017) 1097–1105, doi: 10.1016/j.rser.2016.05.090.

Kriegler, E.; Weyant, J. P.; Blanford, G. J.; Krey, V.; Clarke, L.; Edmonds, J.; et al. (2014): The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. Climatic Change 123(3–4)353–367. doi: 10.1007/s10584-013-0953-7.

Lechtenböhmer S, Nilsson L.J:, Åhman M., Schneider C: (2016): Decarbonising the energy intensive basic materials industry through electrification – implications for future EU electricity demand, Energy (2016), Volume 115, Part 3, 15 November 2016, Pages 1623–1631, doi: 10.1016/j.energy.2016.07.110.

Lechtenböhmer, S., Samadi, S. (2013): The double challenge: Limiting electricity demand growth while pushing forward electrification of energy demand – Lessons from recent low-carbon roadmaps and scenarios for the EU. Proceedings of the eceee 2013 summer study, p. 59–69.

Lechtenböhmer, S., Schneider, C., Yetano Roche, M., Höller, S. (2015): Re-Industrialisation and Low-Carbon Economy – Can They Go Together? Results from Stakeholder-Based Scenarios for Energy-Intensive Industries in the German State of North Rhine Westphalia. In: Energies 2015, 8, pp. 11404–11429.

Loftus, P.J., Cohen, A. M., Long, J.C.S., Jenkins, J. D. (2015): A critical review of global decarbonization scenarios: what do they tell us about feasibility? WIREs Clim Change 2015, 6:93–112. doi: 10.1002/wcc.324.

McCollum, D.; Krey, V.; Kolp, P.; Nagai, Y.; Riahi, K. (2014): Transport electrification: A key element for energy system transformation and climate stabilization. Climatic Change 123(3–4)651–664. doi: 10.1007/s10584-013-0969-z.

Nagl, S.; Fürsch, M.; Paulus, M.; Richter, J.; Trüby, J.; Lindenberger, D. (2011): Energy policy scenarios to reach challenging climate protection targets in the German electricity sector until 2050. Utilities Policy, Infrastructure Reform in China 19(3)185–192. doi: 10.1016/j.jup.2011.05.001.

Özbek, M. (2010): Modeling, Simulation, and Concept Studies of a Fuel Cell Hybrid Electric Vehicle Powertrain. Phd thesis at Fakultät für Ingenieurwissenschaften, Abteilung Maschinenbau und Verfahrenstechnik der Universität Duisburg-Essen.

Samadi, S.; Gröne, M.-C.; Schneidewind, U.; Luhmann, H.-J.; Venjakob, J.; Best, B. (n.y.).: Sufficiency in energy scenario studies: Taking the potential benefits of lifestyle changes into account. Technological Forecasting and Social Change. doi: 10.1016/j.techfore.2016.09.013.

Schlomann, B., Rohde C., Plötz, P., (2015): Dimensions of energy efficiency in a political context. Energy Efficiency 2015; 1: 97–115.

Schneider, C.; Lechtenböhmer, S. (2016): Industrial site energy integration – the sleeping giant of energy efficiency? Identifying site specific potentials for vertical integrated production at the example of German steel production. eceee industrial summer study 2016.

SRU (2011): Pathways towards a 100 % renewable electricity system. Special Report. Berlin, Germany.

Teske, S.; Sawyer, S.; Schäfer, O. (2015): energy [r]evolution – A Sustainable World Energy Outlook 2015 - 100 % Renewable Energy for All. Hamburg. http://www.greenpeace.org/international/en/publications/ Campaign-reports/Climate-Reports/Energy-Revolution-2015/.

UBA (eds.) (2014): Umweltbundesamt. Greenhouse gas neutral Germany (Treibhausgasneutrales Deutschland). Dessau; 2014.

UNFCCC (2015): Adoption of the Paris Agreement. Paris.

Williams, J. H. (2013): The technology path to deep greenhouse gas emissions cuts by 2050: The pivotal role of electricity. Science, 335, 6064, 53-59, 2012. doi: DOI: 10.1126/science.1208365.