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Demand-side decarbonization options and the role of electrification

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Demand-side decarbonization options can be placed into four categories, as depicted in Figure 1:

- Carbon capture: capturing greenhouse gasses (GHGs) at the point of origin
- Energy and material efficiency: reducing the material and energy input at constant output
- Fuel and material substitution: substituting fossil fuels and emission intensive materials through climate friendly alternatives
- Energy and material sufficiency: reducing energy and material use by lowering the output

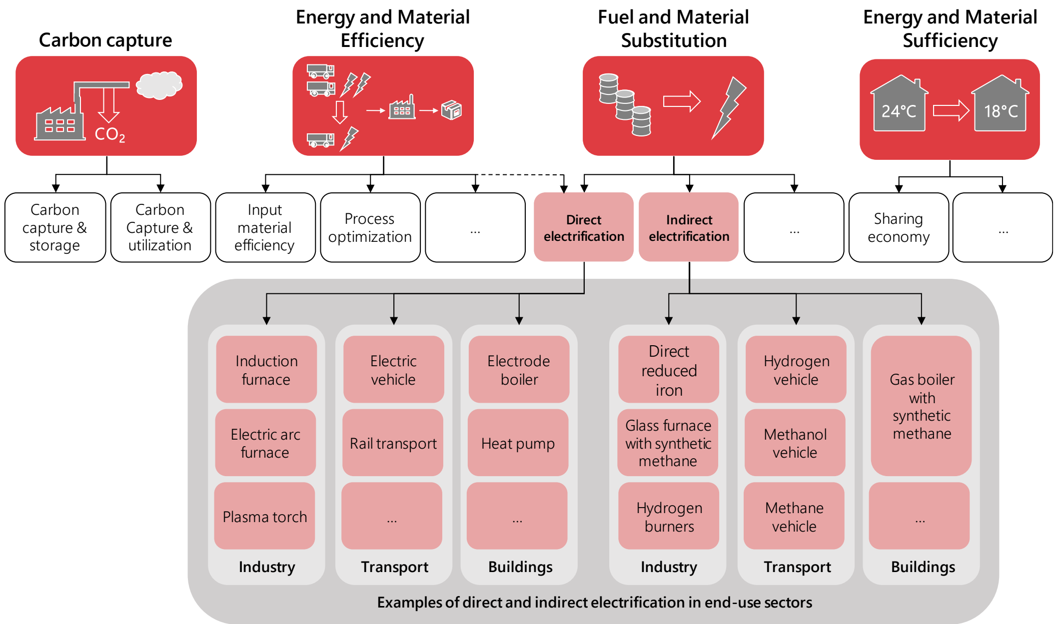

Figure 1: Categorization of demand-side decarbonization options including examples for direct and indirect electrification

Direct electrification can be part of the "Energy and Material Efficiency" and the "Fuel and Material Substitution" category. In most cases electrification also improves energy efficiency.

While all four categories are critical success factors for limiting the global temperature increase to "well below 2 °C", the substitution of fossil final energy carriers through emission-free alternatives is a prerequisite [1]. Existing emission free fossil fuel substitutes are green fuels (synthetic and bio-based fuels), solar thermal energy and electricity [2].

The future mix of fossil fuel substitutes varies strongly, depending on the scenario analysis at hand. To date, limitations on the use of bio-based fuels (sustainable biomass potential) and

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The term *sector* is also frequently used to subsume *electricity, heat* and *transport*. With increasing coupling of heat and transport to the electricity sector (sectorcoupling), this definition will gradually lose its discriminatory power. Hence, we refer to *energy end-use sectors*.

solar thermal energy (temperature level)[2] indicate that the direct and indirect electrification of energy end-use sectors (households, services, industry and transport) will assume an important role on the path towards achieving the Paris goals [3].

In this discussion paper, we will therefore summarize a variety of important aspects concerning decarbonization through electrification. Focus points are defining electrification, analyzing core electrification technologies and how it affects short and long-term energy system flexibility.

How is electrification defined and is it relevant for decarbonization?

Electrification is sub-divided into *direct* and *indirect* electrification, which are defined as follows:

Power-to-X terms, where X can be substituted by chemicals, mobility, gas, etc. are specifications of direct and/or indirect electrification.

Direct Electrification is defined as *"replacing [...] fossil-fueled end-use technologies (existing or planned) with more efficient electric end-use technologies."* [4]

Indirect Electrification is defined as the substitution of fossil fuels through "e*lectricity-based synthetic fuels."* [5]

In both cases, the CO_2-intensity of electricity supply determines, to what extent the solution is still associated with emissions. The following figure shows the European theoretical electrification potential (39 countries included) [6].

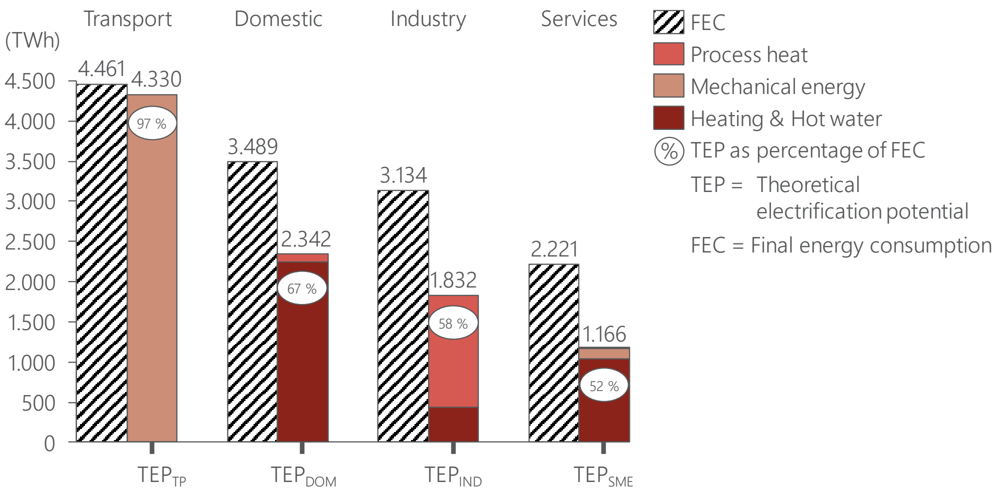

Figure 2: Sectoral final energy consumption and theoretical electrification potential 2017, in Europe, in TWh

In each of the energy end-use sectors in Figure 2 a variety of different technological solutions is required to electrify existing fossil-fueled appliances.

[2] The technology readiness level of solutions which can achieve higher temperature levels does not exceed four (Component and/or breadboard validation in laboratory environment). Example: the lab-size solar reactor PROME can reach temperatures of up to 3000 °C [21].

Which technologies are used for direct and indirect electrification?

In the domestic and services sector 96 % of the theoretical electrification potential results from heating and hot water (H&HW). Consequently, ground and air source heat pumps as well as electric resistance heaters (with or without storage) are discussed as direct electrification technologies. Examples for indirect electrification options are the use of synthetic methane or fuel oil in conventional oil/gas boilers or the use of hydrogen in solid oxide fuel cells.

In transport, 97 % of the total final energy consumption resulted from the combustion of fossil fuels. The transport sector has a variety of sub-categories: personal road, road freight, rail, air and navigation. The relevant direct electrical technologies are electric vehicles, trains, ferries and catenary trucks. Judging by the current technology landscape, electrification will not pose the dominant solution for greenhouse gas reductions of long-distance air travel and navigation. Indirect electrification measures include fuel cell vehicles of all types and sizes as well as the use of synthetic fuels such as gasoline, diesel and kerosene.

In the industry sector, heating and hot water as well as process heat can be electrified. However, when considering decarbonization through electrification in the industry sector, also process related emissions are relevant. The complexity and heterogeneity of industrial processes results in a demand for process-specific technological solutions. Hereby, the complexity of solutions usually increases with the temperature demand of the process. While the expert consensus is that direct electrification is technically possible for most processes, this has not been demonstrated in practice for all processes [7].

General rule of thumb: higher temperature demand of an industrial process, usually means that the electrification measure is also technically more demanding.

Direct electrification technologies for low temperature process heat and heating and hot water applications are immersion heaters and heat pumps (<300 °C). High temperature processes, for which direct electrification has been demonstrated on an industry production level scale, include steel, glass, steam reforming and non-ferrous metal production. The corresponding electrical technologies are electric arc and electric glass furnaces as well as electro-thermal reforming, electrolysis and inductive and conductive electrical casting furnaces (e.g. copper and aluminum). For the case of steel as well as flat and container glass production, full decarbonization through direct electrification cannot be achieved, as process related emissions resulting from the consumption of electrodes in electric arc furnaces and the dissociation of soda during glass production remain.

Indirect electrification options in the industry sector range from the substitution of fossil energy carriers through synthetic alternatives, to process specific technological solutions. A prominent example is the steel production via direct reduction of iron ore using hydrogen and subsequent processing of reduced iron in electric arc furnaces [8], [9]. The use of hydrogen as both energy carrier and feedstock for chemical processes is discussed in a variety of industries. However, the combustion of hydrogen affects flame properties, which in turn influences the product quality [10]. Moreover, further application and transport infrastructure demands come hand in hand with the use of hydrogen as a decarbonization option [11].

Direct vs. indirect electrification – what is the system-cost optimal mix?

The sectoral analyses of electrification technologies shows,

- that several application areas exist, in which direct and indirect electrification are substitute products and
- that application areas in the transport and industry sector exist, in which, to date, no viable direct electrification measures exist.

The question consequently is, which share of direct or indirect electrification solution leads to a system cost-optimal decarbonization pathway? Figure 3 shows (part) of the conceptual attempt to answer this question.

Points on the same U-shaped curve (isocarb) correspond to the same decarbonization level.

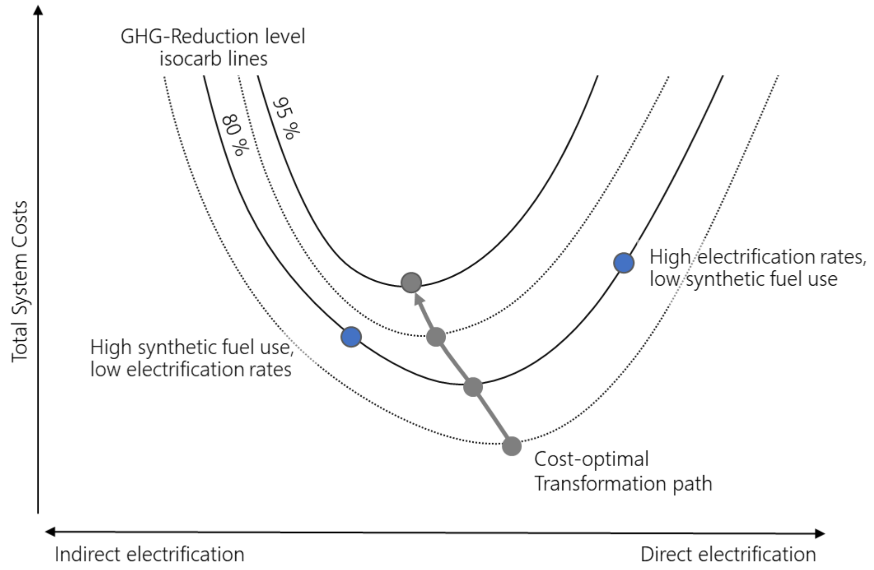

Figure 3: Conceptual visualization of the optimal mix between direct and indirect electrification measures [12]

Model simulations performed in [12] indicate that achieving high GHG emission reduction levels using only direct or indirect electrification measures results in a drastic system cost increase. The cost optimum is consequently achieved using a measure mix.

In Figure 3, the points on each U-shaped curve correspond to the same greenhouse gas reduction level (e.g. 95 % reduction with respect to the level of 1990). In most energy system studies, synthetic fuels are phased in only after 2030, in strong decarbonization scenarios (>95 %), due to high production costs [13]. This implies that the minimum of each U-shape shifts to the left, to a higher a share of indirect electrification, as the GHG emission reduction level increases.

System costs can be split into application, infrastructure and production costs of the respective solution. In the case of a sub-optimal ratio of direct and indirect electrification measures, it is likely that a tipping point in one of the three areas is reached, leading to a cost increase. For example: [14] show, that high additional inflexible electricity demand results in a demand for increased variable renewable energy source (vRES) expansion, so that decarbonization through electrification can be achieved. The combination of increased load and vRES feed-in results in additional demand for the expansion of transmission lines. In an extreme scenario, this results in high procurement and transport costs for vRES.

Are there sufficient vRES potentials to cover the additional electricity demand?

Decarbonization through electrification is contingent upon a largely emission free electricity supply. This raises the question whether the potential of the wind (on and offshore) and solar power (rooftop and offsite) is sufficient to cover the electricity consumption after electrification.

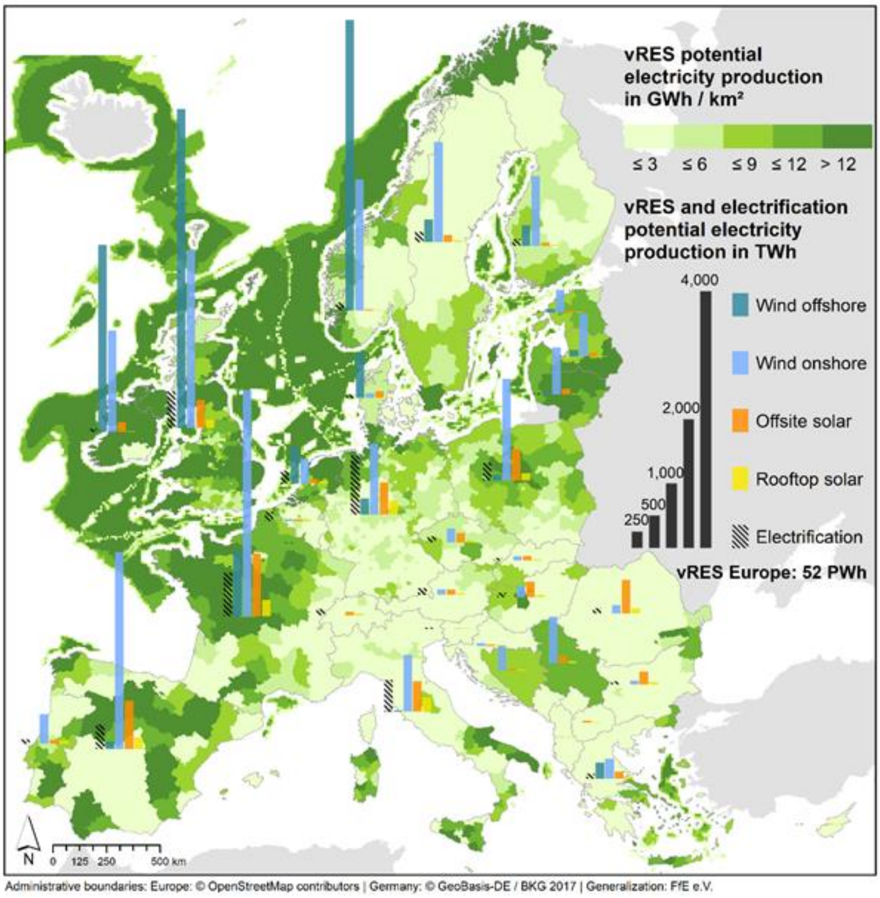

Figure 4: Comparison of vRES potentials to electrical final energy demand in a low-hanging fruits electrification scenario [15], [16]

Figure 4 shows that in most European countries the rated potential for vRES is significantly higher than the required electrical energy consumption after direct electrification.[3] However, in countries such as Belgium, Luxembourg, Slovenia and Switzerland, the electrification of large shares of the transport, industry, service and household sector results in an electricity demand which exceeds the domestic vRES potential. Reasons for this are for example: high settlement densities, topological aspects such as a hilly countryside and other site-specific aspects such as low wind occurrence.

The analysis should be viewed as a first indication on whether or not domestic vRES potentials could be sufficient for covering post-electrification electricity demand. A robust answer requires a timely and spatially resolved energy system scenario analysis.

Furthermore, [17] show, that by decreasing the geographical scope of such an analysis, emission free self-sufficiency through vRES becomes impossible in certain regions in Europe, even at current electricity consumption levels.

[3] Cf. [15] and [19] for further information about the assumptions and models used to derive vRES and electrification potentials. While the vRES potential exceeds the electricity demand in most cases, the transmission task and peak load need to undergo further analyses in order to assess the challenges of electrification holistically.

What is the effect of increased direct electrification on short and long-term flexibility in the energy system?

The discussion about electrification and flexibility includes two aspects:

1) Short-term power system flexibility: balancing supply and demand of electricity in power systems (with high shares of vRES)
2) Long-term energy system flexibility: this refers to the possibility of the energy system to adapt through new or modified assets in generation, transmission, storage and demand

High amounts of additional inflexible electrical loads can cause an increase in system costs in the short-term and can impede the integration of larger shares of vRES in future. [14] show that high direct demand-side electrification caused by additional inflexible electrical loads in combination with vRES expansion can result in an increase of curtailed energy from vRES and a generation capacity gap in certain hours of the year. The analysis highlights the need for flexible electrical loads in order to improve the short-term flexibility of the power system. In this sense, indirect and direct electrification measures can be complementary, since electrolyzers can be positioned system friendly, thereby adding flexible loads to the system. In addition, electrolyzers could also satisfy the demand for the seasonal balancing of supply and demand.

Decarbonization pressure increases the value of long-term energy system flexibility and therefore also the costs of lock-in effects.

The substitution of long-lasting infrastructure carries the risk of causing technological lock-in effects, which impede the long-term energy system flexibility. Industrial processes as well as technologies used for the procurement of heating and hot water show technical lifetimes in the range 15 to 60 years. Once the existing fossil equipment is replaced, the invested capital is bound for decades and switching to a different energy carrier could become very expensive. The risk of lock-in effects is neither avoided nor impaired through electrification measures, compared to the status-quo. Nevertheless, electrification centralizes the decarbonization challenge, by shifting the decarbonization pressure to the supply-side and hence, into a sector which is more accessible to policy and regulation. Nevertheless, the decarbonization pressure increases the value of long-term energy system flexibility and therefore also the costs of lock-in effects. This ultimately translates to a demand for technologies, which enable more demand-side fuel flexibility (e.g. the hybridization of industrial process technologies).

Are there examples of countries, which are already highly electrified?

Low electricity prices in Scandinavian countries and France lead to a comparably high share of electricity of total final energy consumption in all energy end-use sectors [18], [19]. These examples show, that the willingness to electrify depends, amongst others, on costs. Therefore it is important to understand which part of the total costs, operating or capital expenditure, are more important for different target groups. Long technology life times and high full load hours for the supply of hot water and steam in the industry sector generally result in high shares of operational expenditure compared to total costs. This highlights the sensitivity of electrification costs with respect to energy carrier price differences between electricity and fossil alternatives. In other sectors, such as personal road transport, the share of capital expenditure is often higher, resulting in stronger sensitivity towards the initial investment [20].

Electrification only?

Electrification can result in deep emission cuts across all sectors. Hereby, direct electrification is a promising solution in all sectors. However, especially in transport and industry applications the transition towards a direct all-electric system is technically and economically infeasible. Consequently, decarbonization studies view indirect electrification measures as a complementary measure. Nevertheless, depending on the status quo of the respective energy system, energy efficiency and sufficiency, carbon capture and storage/usage in combination with electrification measures will eventually pave the road to deep decarbonization.

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