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Flexibility from the electrification of energy

How heating, transport, and industries can support a 100% sustainable energy system

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Energy production and consumption activities account for 76% of global greenhouse gas (GHG) emissions, according to the *Historical GHG Emissions* database by Climate Watch. Power and heat plants cause 42% of energy-related GHG emissions while other sectors, like transport, other energy use in buildings, and industry, cause 22%, 8%, and 24% of energy-related GHG emissions, respectively. In power generation, significant carbon dioxide (CO_2) emission reductions are already underway in many countries, driven by the rapidly decreasing levelized cost of variable renewable energy (VRE) and policy measures. In contrast, CO_2 emissions from the major end-use sectors, namely transport, buildings, and industry, have remained largely unchanged or have even increased during the 2010s, according to the International Energy Agency (IEA) *CO_2 Emissions from Fuel Combustion* database. Thus, the major end-use sectors need to decarbonize as they are still mostly based upon fossil fuels as seen in Figure 1.

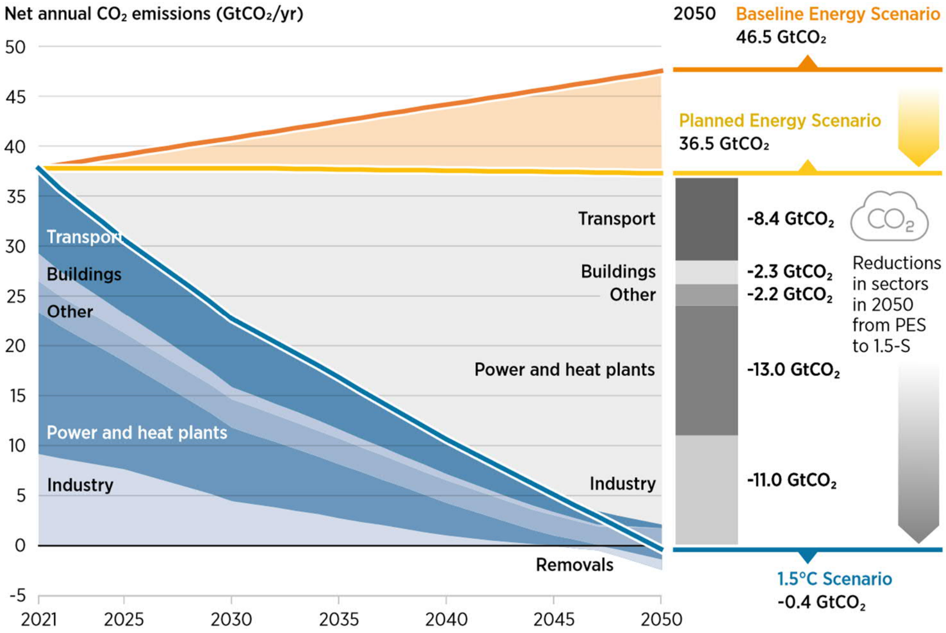
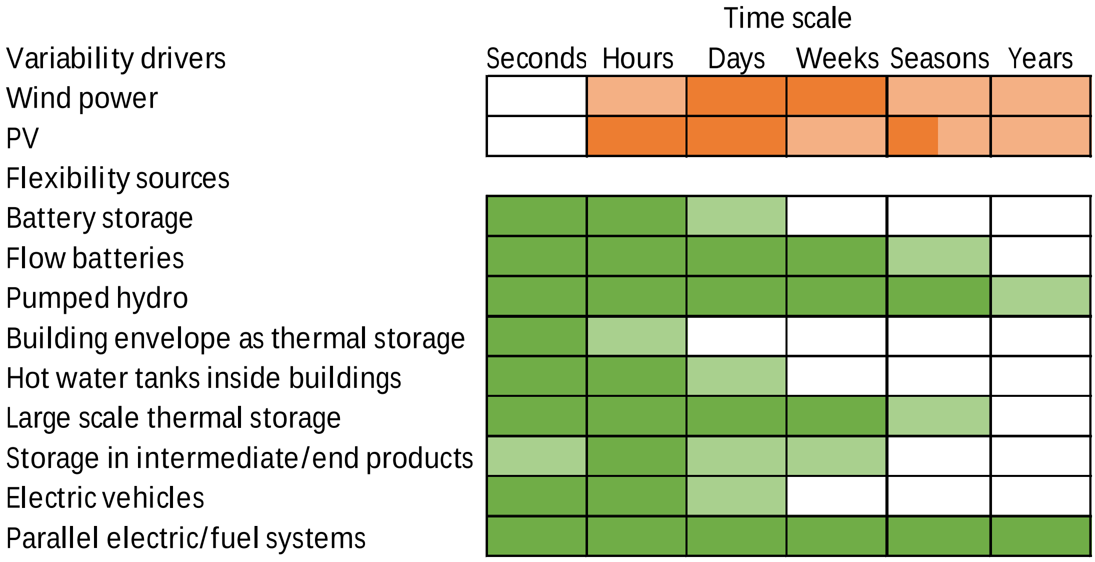


Figure 1. IRENA scenario "Target pathway to 1.5 °C" demonstrates the reduction needs of different energy sectors. Electrification is a key solution in decarbonizing transport, buildings, and industry. (World Energy Transitions Outlook: 1.5 °C Pathway, International Renewable Energy Agency 2021)

As power generation continues to decarbonize, opportunities are available to replace fossil fuel-based technologies in other energy sectors by direct or indirect use of electricity, i.e., electrification. The applications of electrification in heating, transport, and industry are likely to become the driving forces behind the global clean energy transition. For example, in the 1.5°C scenario of the IRENA World Energy Transition Outlook, global power generation increases threefold by 2050 and the share of VRE of total power generation reaches 63%. In addition to ambitious climate goals and decreasing levelized costs of VRE, the drivers for electrification include technology developments and efficiency gains for electrical storage and at the demand side, e.g., for heat pumps, electric vehicles (EVs), and use of electricity in the industrial processes.

While significant investments in VRE will be essential for the clean energy transition, a high share of variable renewables will potentially make the operation of the power system more challenging due to larger and faster variations, increased uncertainty, decreased synchronous inertia, and a reduction of available traditional sources for frequency and voltage management. A more flexible and integrated energy system is needed to manage these challenges cost-effectively and robustly. Flexibility will be needed in multiple time scales, especially from hours to seasons, since large-scale VRE can have pronounced variations in these time scales. The end-use sectors have great flexibility potential in different time scales (Figure 2), and thus electrification can be part of the solution to increase flexibility. However, many barriers need to be overcome before such flexibility potential can be confidently and efficiently utilized.



	Time scale					
Variability drivers	Seconds	Hours	Days	Weeks	Seasons	Years
Wind power	□	▨	■	■	▨	▨
PV	□	■	■	▨	■▨	▨
Flexibility sources						
Battery storage	■	■	▨	□	□	□
Flow batteries	■	■	■	■	▨	□
Pumped hydro	■	■	■	■	■	▨
Building envelope as thermal storage	■	▨	□	□	□	□
Hot water tanks inside buildings	■	■	▨	□	□	□
Large scale thermal storage	■	■	■	■	▨	□
Storage in intermediate/end products	▨	■	▨	▨	□	□
Electric vehicles	■	■	▨	□	□	□
Parallel electric/fuel systems	■	■	■	■	■	■

Figure 2. Estimated time scales for the drivers of variability and sources of flexibility (darker colour – primary impact, lighter colour – secondary impact, white – not usually relevant).

This article examines the technology status and implementation timeline for the electrification of various end-use sectors and their potential to offer flexibility. Key technologies include heat pumps that are already commercially available for space heating; EVs that are currently expanding rapidly in transport; and a growing number of industrial processes with the potential to replace fuels with electricity. The main barriers for achieving greater flexibility will be discussed, be they technological, economic, regulatory, social, and/or behavioural. The article concludes with views on pathways, opportunities, and threats related to rapid electrification. Examples mainly from the European Union (EU) and the United States are used, but the general principles should also apply to other regions.

Flexibility from hydrogen, storage, and parallel systems

Direct electrification, where electricity use directly replaces fuel combustion, is already underway. Each end-use sector has its specific needs and technologies for direct electrification. However, indirect electrification is also possible, i.e., replacement of fossil fuels by hydrogen and other synthetic fuels that are produced using electricity. Figure 3 shows an example of how these technologies can link to the overall energy system.

Hydrogen and its derivatives, storage, and parallel solutions are present in multiple sectors, and an overview is presented in the following.

In indirect electrification, hydrogen is first produced through the electrolysis of water and then possibly post-processed into different molecules required for specific purposes, such as gasoline, methane, or ammonia. These electro-fuels or synthetic fuels are associated with large conversion losses, thus direct electrification is preferred in most cases. However, some applications are difficult to electrify directly, e.g., long-range shipping and aviation. Here, synthetic fuels are promising decarbonisation options. Hydrogen would offer the lowest capital cost and least conversion losses out of the potential synthetic fuels. However, it is more difficult to store and transport than other alternatives. For example, methane and ammonia can be converted to liquids at higher temperatures and lower pressures. Furthermore, some fuels, such as synthetic gasoline and methane, could benefit from existing infrastructures, which lowers their upfront capital cost. Finally, biomass can be a source of carbon for carbon-containing synthetic fuels and it is already widely used in some applications.

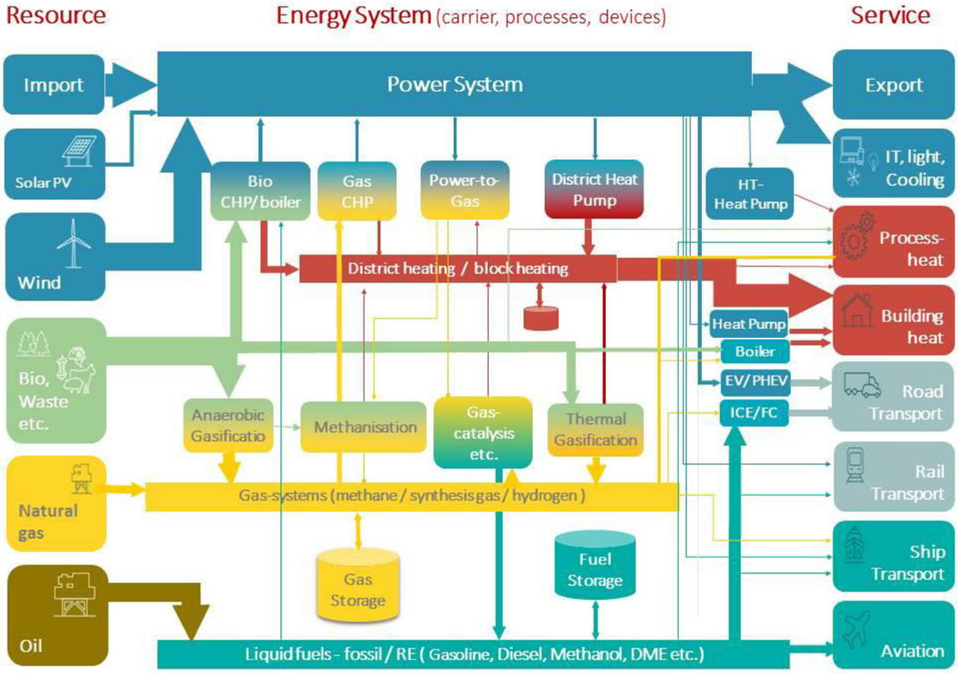


Figure 3. Energy flow in the Danish energy system for 2035 showcases sector-coupling in future energy systems. Power-to-X, storage, and parallel solutions are needed to support development towards 100% clean systems. DME: dimethyl ether; PHEV: plug-in hybrid EV; ICE: internal combustion engine; FC: fuel cell; RES: renewable energy source; PV: photovoltaic; Bio: biomass; IT: information technology; HT: high temperature. (Source: Energinet 2019; used with permission.)

Storage, in its various forms, can provide additional flexibility to the electricity system when combined with power-to-heat, electro-fuel production, and other electrification concepts. In addition to electrical storage, such as batteries, several energy storage alternatives exist, including those for thermal energy as well as gaseous and liquid fuels. However, distinct types of storage can have very different costs (Figure 4), where the cost order, from most expensive to least, on a logarithmic scale is electrical storage, heat storage, gas storage, and finally liquid storage. Overall, electro-fuels that remain liquid under atmospheric conditions are the cheapest to store and offer a potential flexibility source in the time range of days to seasons. Large-scale heat storage can also offer good cost-effectiveness in the timescale of days to weeks, possibly even seasons.

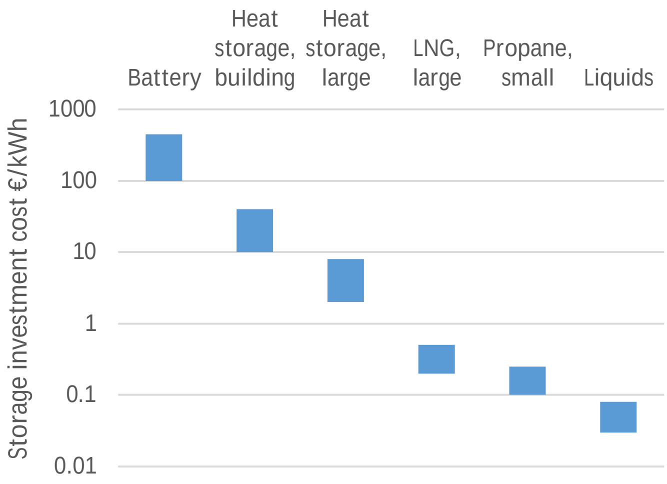


Figure 4. Approximate cost of different categories of energy storage (LNG – liquified natural gas). Logarithmic scale. Author estimate using various sources.

Parallel systems represent a cross-sector technology where an electrical energy source is complemented by a fuel-based alternative. The fuel could be initially fossil-based and, later, with more stringent 100% clean energy commitments, switched to biofuels or electro-fuels. Since the electrical resource would typically be the less costly option to operate, it should cover most of the full-load hours, but the parallel resource could support the power system during peak load periods and act as a backup during emergency conditions. Liquid or liquified storage facilities are needed for electro-fuel-based operation when there are no accessible fuel pipelines.

Heat pumps and storage key technologies in electrifying heating

Direct on-site heating and other fuel use in buildings (residential and commercial) account for only 8% of global energy-related GHG emissions. However, a large portion of emissions from power and heat generation is induced by energy use in buildings. Residential, commercial, and public sectors consumed 48% of total final electricity and 50% of heat in 2019, according to IEA World Energy Balances 2020. Consequently, IEA estimates that 10 $GtCO_2$ (20% of all global GHG emissions) is related to direct and indirect energy use in buildings. Combined with the decarbonization of power and heat generation, electrification of building heating could result in a significant reduction in both direct and indirect GHG emissions. Electric heating technologies for buildings include direct electric heating, heat pumps, and indirect methods based on synthetic fuels. While heat is often utilized on-site, it can also be distributed in district heating systems, which allow for cost-effective centralized heat generation and storage solutions. When trying to decarbonize district heating systems, electrification concepts compete mainly with bioenergy but could in the future also face competition from nuclear and carbon capture and storage-based heating solutions. In terms of public acceptance, electrification moves those questions mostly outside the cities, while the other options can have acceptability issues inside city limits. Solar heating is also a competitor for on-site applications.

District heating and cooling offer economies of scale in generation and storage, even in an electrified scenario, but at the expense of relatively costly networks. Heat pumps are already changing the heating landscape, and some forecasts expect large increases in adoption (Figure 5), although the full extent of future growth remains to be seen.

Heating technologies and their combinations each present unique considerations in terms of power system flexibility and economics:

Building envelope: Walls, roofs, and floors can store thermal energy. The rate of change of temperature depends on the temperature difference (external vs. internal), heat capacity of the building envelope, heat transfer co-efficients of the building materials involved, and the envelope insulation. Depending on those parameters, occupant comfort is impacted in the range of minutes to a couple of hours.

Heat storage: Hot water storage is the most common approach, but heat storage devices can also be in the form of solid or phase-changing materials. Typical building hot water tanks, and associated insulation, only allow time shifts that are comparatively short – from around one hour to several hours. The cost of storing heat energy falls rapidly with storage size, but it can be difficult and costly to retrofit existing buildings with larger storage systems due to space limitations. Longer storage durations could be economic if they were designed into new houses from the start and for buildings connected to district heating systems where large storage units are much more feasible.

Heat pumps and direct resistance heating: Air-source heat pumps and direct resistance heating have a pronounced impact on the peak electricity demand. Ground-source, water-source, and exhaust air heat pumps create a lesser impact, but, even here, flexibility options should be considered to improve the resiliency of individual buildings and to decrease the costs of the power system to meet demand during the peak periods.

Heating systems serving multiple houses: In addition to district heating, it may be viable to build heating systems that serve multiple nearby buildings. Such an approach would avoid the extensive heat pipelines associated with district heating but would allow for considerable economies of scale for heat pumps and heat storage. For such a system, it would also be more cost-effective to provide backup with a parallel fuel-based heating system as compared to individual buildings.

Parallel heating systems: When electric heating is supplemented by fuel-based heating, demand flexibility can be provided for an unconstrained period. However, if fossil fuels are used, then significant GHG emission reductions can only be achieved if the fuel-based operation is infrequent. The parallel approach is relevant for individual buildings also because it can also provide resiliency against long-lasting power grid failures or high prices.

New heating systems in old buildings: New heating systems are installed in old buildings not just due to technical lifetime, but also to reduce heating-related costs and/or emissions. When a building is retrofitted with electrical heating, keeping the old heating device as a parallel heating source would yield flexibility and resilience. However, this is not often done due to replacement subsidies (e.g., oil boilers need to be removed to qualify for a heat pump subsidy), lack of space, costs of maintaining two systems, and pricing structures (e.g., high annual tariff in district heating). Also, reduced operational costs from parallel devices may not be sufficient at current VRE levels but could become more valuable over the device's lifetime as the share of VRE in the power system increases.

Building heating involves several policy considerations. Energy efficiency has often been the focus of regulations related to energy use in buildings, but the regulations may fail to consider the larger system impacts of building energy use. Flexible electricity consumption can allow more cost-effective emission reductions elsewhere in the energy system. Consequently, regulation should aim to reduce emissions and not energy consumption as such. Potential flexibility for the power system cannot be exploited if appropriate incentives are not in place. For example, flexible consumption could support electricity distribution system operation and avoid network constraints, but finding such mechanisms is rare. Similarly, the electrical energy cost should be on the same footing as the cost of alternatives after emission costs are factored in. However, grid tariff structures and electricity taxes can introduce distortions that prevent cost-effective flexibility actions from taking place.

Another factor is that the potential economic benefits for buildings and their owners are often quite small. The use of “aggregators,” which operate the electric heating systems and take a share of the cost-savings from flexibility provided to the energy system, is often promoted. An alternative model would be to support standards and markets that allow buildings to benefit directly, with companies focusing on providing automatic communication and control tools compatible with related standards. Any viable model should consider how to maximize the benefit from millions of small-scale flexibility sources – requiring rapid (real-time) communication – may be too expensive. When individual devices “promise” to provide a flexibility service (e.g., a reduction of demand during high prices), many of the existing metering systems are already capable of settling the provision after the fact, although balancing and ancillary services could also be tailored for small-scale devices separately.

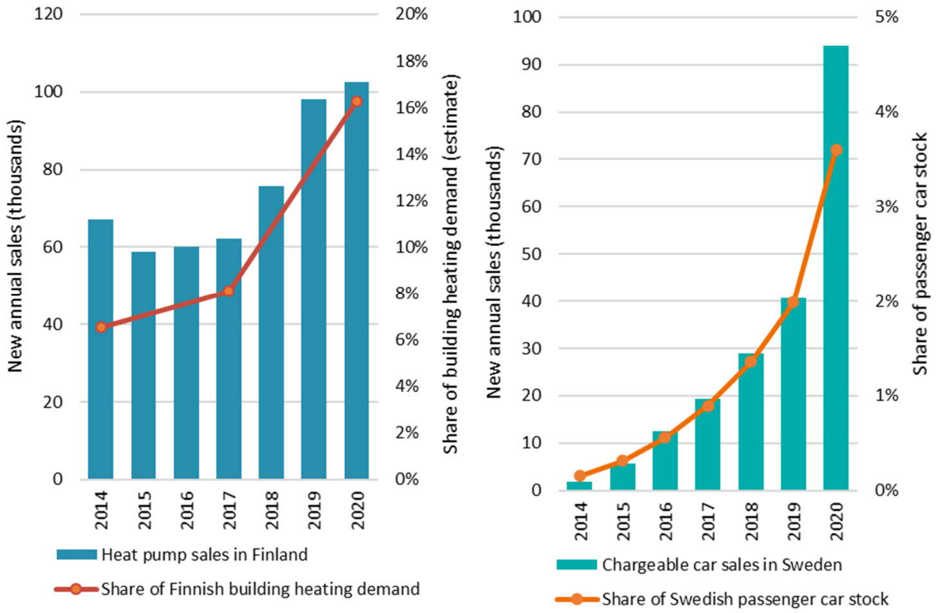


Figure 5. Annual heat pump sales and estimate on building heat generation share in Finland (left), and annual electric vehicle sales and share of car stock in Sweden (right) 2014-20. (Finnish heat pump association Sulpu / Swedish vehicle industry organization BIL Sweden)

Charging as a source of flexibility from EVs

Direct fuel consumption in road, rail, marine, and air transport emitted 22% of global energy-related GHG emissions in 2018. Road transport was responsible for 73% of transport CO_2 emissions (passenger road transport was 44% and road freight transport was 30% by IEA statistics). As of today, transport uses only 2% of total final electricity consumption. EVs have seen large year-on-year growth for the past several years (Figure 5). Global electric passenger car sales in 2020 were only 3 million out of total car sales of around 80 million. However, if the exponential growth continues, a dominant fraction of new passenger cars could be electric by the end of the decade. Battery technology has been advancing rapidly with associated price reductions and is the decisive factor driving the growth, even though climate concerns and incentives have played an important role both through direct demand for cleaner products and through policy influence. However, predicting adoption rates for technologies with strong links to society and individuals can be difficult. Figure 6 shows some of the main factors that influence the adoption speed of technology using EVs as an example. The flowchart could be adapted for other electrification technologies in heating and industry.

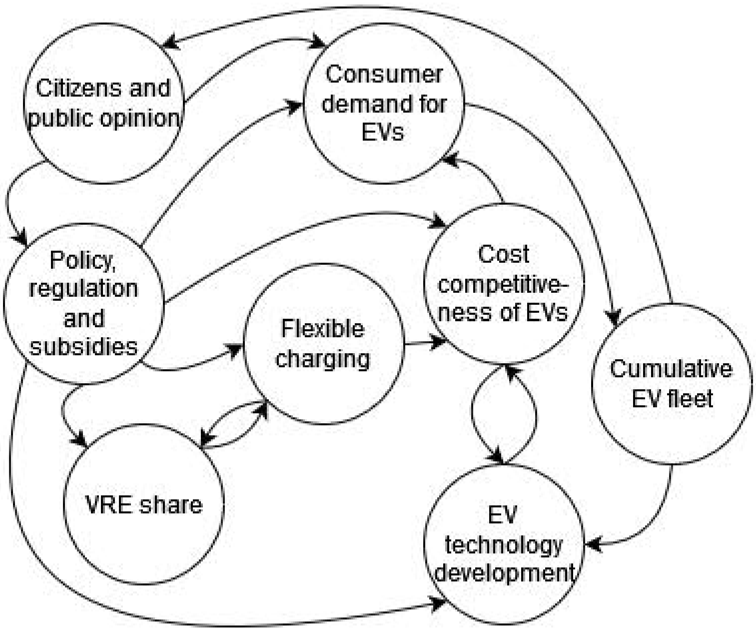


Figure 6. A web of factors influencing the adoption of EVs, including the potential impact of flexible charging.

The electrification of heavy-duty trucking is considered difficult due to the long distances over which they operate. Rapid-charging batteries could change the argument, but time-consuming charging stops would still be required. Sufficient charging infrastructure will also be required. Heavy-duty trucking, long-distance shipping, and aviation are examples where indirect electrification through hydrogen-based fuels and fuel cells, or the use of biofuels, represent viable decarbonization alternatives. Rail transport is already widely electrified, but further increasing the share of electrified tracks can provide cost-effective GHG reductions.

Comparison of decarbonization options to substitute fossil-based transport fuels indicates that direct electrification offers the highest efficiency (Figure 7). At the same time, concerns exist about carbon emissions associated with the manufacturing phase of EVs, including those of batteries. However, energy-related emissions should fall as the wider energy systems decarbonize. Consequently, it becomes important to treat transport life-cycle analysis with care – what surrounding assumptions are being made about the future?

Carbon-free electricity could power the transportation sector, but wide-scale electrification could result in large impacts on the power system. Without additional measures, vehicles could lead to pronounced charging peaks. Flexible charging and discharging of EVs are technically feasible, but the economic gains from the power markets can be small for a single vehicle (of the order of 100 €/vehicle/year), and it can be difficult to convince individual vehicle users to participate in such activities purely on a monetary basis. However, if nothing is done, many distribution grids could require costly upgrades and system-wide peak loads would be affected – and further exacerbated if electrification of heat is also considered. In many countries, distribution grid customers collectively foot the bill for distribution grid expansion such that the hidden cost of inflexibility would be paid by all customers together. Flexible charging could shift loads from the evenings to night-time periods, and even to the next day (or weekend) if the expected daily driving requirements are low – prevalent battery sizes can cover multiple days of typical driving range. Flexible discharging, so-called vehicle-to-grid, offers less system-level benefits than flexible charging, but it could also bring important benefits for distribution grids and even for buildings at certain times. Social and behavioural sciences are needed here to identify and implement those solutions that could unlock the flexibility potential of EVs at scale.

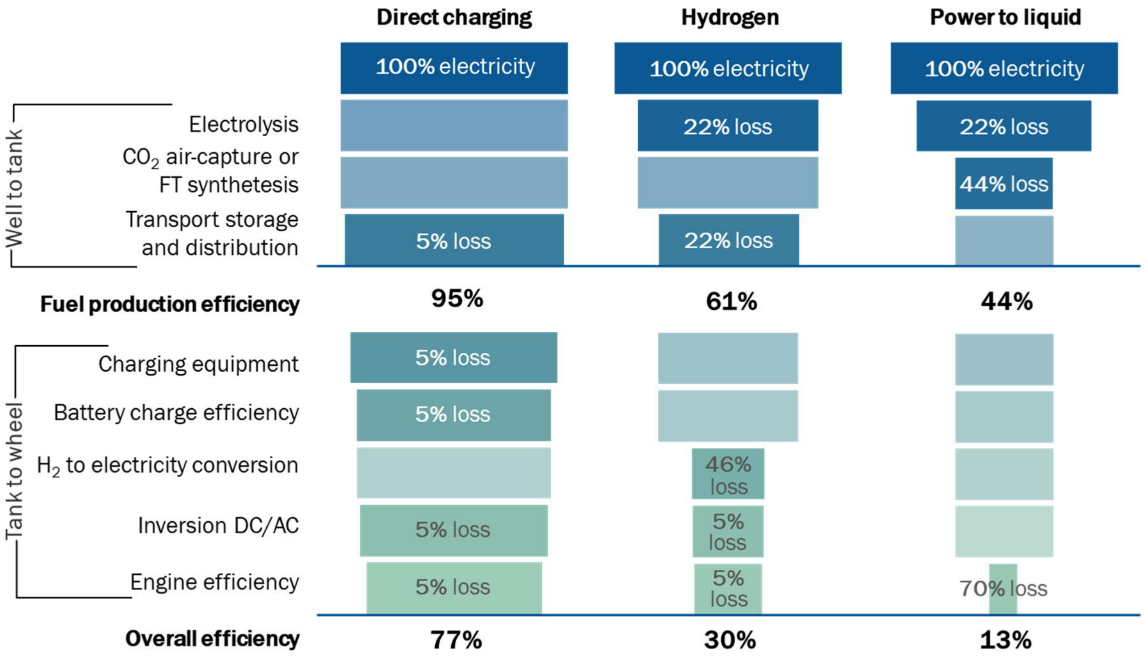


Figure 7. Comparison of different methods of decarbonizing road transport: Direct renewables-based electrification is the most efficient option (adapted from ETIPWind and WindEurope: Getting fit for 55 and set for 2050 - Electrifying Europe with wind energy, 2021. Transport and Environment.)

Industrial electrification needs a variety of solutions

The industrial sector accounted for 24% of global carbon emissions in 2018 (including industrial electricity use), and emissions were growing by 3.4% a year between 2010 and 2018, according to the Climate Watch *Historical GHG Emissions* database. As with the other sectors, sometimes electricity can substitute fuels directly, but it can also be used to produce molecules for fuels and feedstock, for example, ethylene for the chemical industry or ammonia for fertilizer use. In other cases, fuels are required to achieve high energy fluxes required by, for example, many rotary kilns. Also, carbon is part of many materials and, therefore, forms an input for some products such as ethylene.

Industrial companies are very cost-conscious, so any changes to their energy use, or raw materials, will likely require alignment with their financial incentives. It is also important to ensure good long-term predictability in policies. Uncertain future outlooks make new investments difficult to justify. For example, if fuel-based heating is perceived to remain cheaper than electrical heating, investments in electric heating will be unlikely. The relative costs of fuels and electricity can be influenced by their respective policies and regulation. Therefore, multiple sector-specific policies need to be part of investment considerations when technology options bridge energy sectors (e.g., industrial heat pumps vs. fuel-based process heating). When new policies are enacted, they should also consider the potential for flexible electricity demand in different time scales. Parallel systems, where the fuel option remains but is used only rarely, could be important to reduce the peak load burden on the power system, even though it could result in some emissions until fossil fuels are replaced with cleaner alternatives.

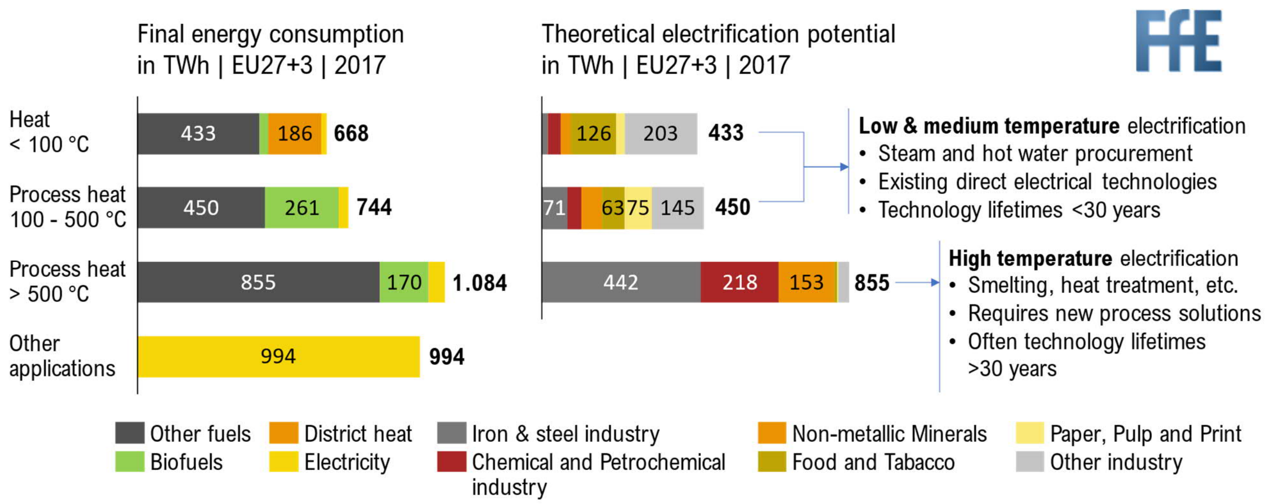


Figure 8. European final energy consumption by energy carrier (left) indicates the large energy share of industrial process heat. Theoretical electrification potential (right) differentiates low-temperature applications with existing technology solutions from high-temperature electrification where innovations are required. (FfE project eXtremOS 2017)

Figure 8 provides an overview of recent final energy consumption in European industries. The industrial energy use in Europe was approximately 3500 TWh in 2017. This means that 32% of total final energy consumption in Europe consists of electricity, higher than the global average. Electricity use in the industrial sector is dominated by electric motors, which drive pumps, fans, conveyor belts, etc. Fossil and waste-based fuels remain the dominant fuel source for energy-intensive industrial heating applications with the electricity share being only 5%, leaving much potential for electrification. Fossil fuels deliver heat for a range of processes, such as drying, evaporation, and supporting endothermic chemical reactions. Furthermore, they are used as feedstock (mainly to produce high-value chemicals and ammonia).

The right-hand side of Figure 8 shows the theoretical electrification potential (i.e., final energy consumption for fossil fuel and non-renewable waste) according to heating applications and industry sectors in Europe. Opportunities for electrification can broadly be structured into low-temperature and high-temperature electrification measures. For both, the potential for flexibility provision through parallel systems and heat or process storage should be considered in the decision-making. If industrial fuel consumption results in inflexible electricity consumption, the power system will become more costly to manage and operate.

For low-temperature (<500 °C) processes, such as drying and evaporation, industrial heat pumps, electrode and resistor boilers, as well as electrically operated mechanical vapour recompression equipment are already commercially available. The technology lifetimes of incumbent fossil technologies (e.g., gas boilers) rarely exceed 30 years, resulting in at least one investment cycle until 2050. Due to the availability of process-independent technical solutions and the lifetime of existing technologies, low-temperature electrification is often considered the “low-hanging fruit” of electrification.

The electrification of high-temperature process heat is more complex due to the need for heterogenous process-specific solutions, e.g., steel, cement, and ammonia production. Furthermore, technology lifetimes frequently exceed 30-year cycles, e.g., steam crackers and blast furnaces. For the delivery of high-temperature heat, electric furnace designs are being proposed and beginning to emerge, although they are not yet commercially available. These applications also stand in competition to indirect electrification solutions. For very high-temperature (>1,000 °C) processes, such as the melting of metals, combustion of electrolytic hydrogen instead of fossil fuels would provide an indirect method of electrification. However, hydrogen flames have different combustion properties (mixing, heat transfer) in comparison to hydrocarbon flames, which need to be considered. Also, utilising electrolytic hydrogen for high-temperature heat generation currently suffers from the low efficiency of electrolysers (60% to 70% lower heating value), increasing both the capital cost and operating cost.

Carbon capture and storage technologies can be applied to eliminate emissions from both feedstocks and energy use, and bioenergy solutions are commercially available for industrial furnaces and kilns via the gasification of biomass. However, underground storage of CO_2 is not yet widely applied or commercialized, and biomass waste or residues are not always abundantly available near industrial sites. Hence, electrification of industrial processes, if based on low-carbon energy sources, may offer greater potential for CO_2 emission reductions.

Industrial processes may be more likely to adopt new technologies if they can increase their profits. However, there is much research, design, and innovation to be completed before validated solutions across the array of industrial processes and the commercial sector are achieved (Figure 9). Due to the larger scale of activities, and the predictability of operation, many processes could potentially provide valuable sources of flexibility through parallel energy sources and storage. However, investment cycles are long, and the value of flexibility may only materialize once decarbonization is sufficiently advanced. Finding and supporting those pathways with the lowest societal costs will not be easy. At the same time, care should be taken with introducing subsidies and other incentives as they tend to remain in place even after the need has passed.

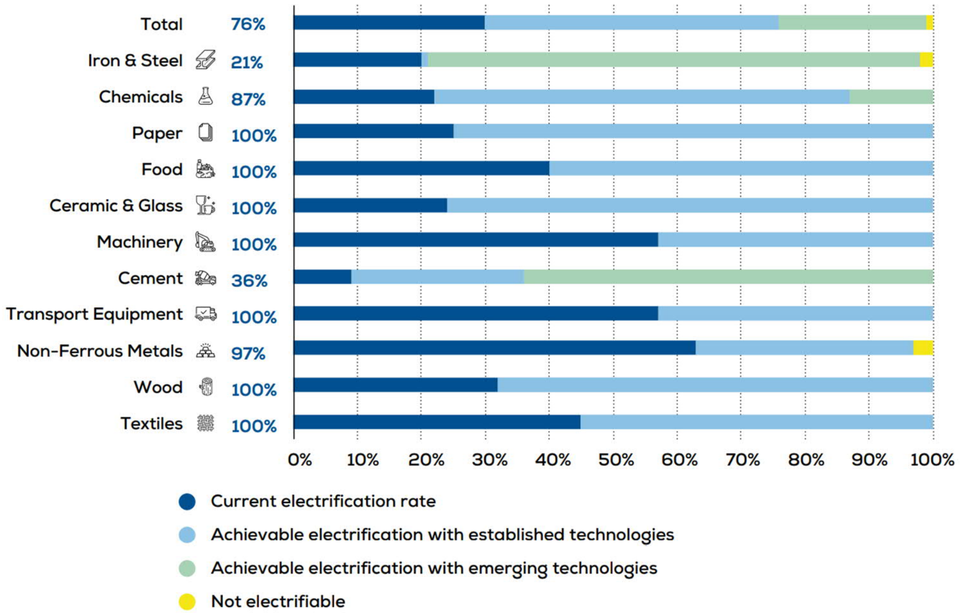


Figure 9. Comparison of different industries' electrification potential summarizes that 76% of Europe's industrial power and heat demand could be electrified with existing technology (ETIPWind and WindEurope: Getting fit for 55 and set for 2050 - Electrifying Europe with wind energy, 2021. ETIPWind based on Madeddu et al. 2020.).

Electrification timeline depends on technology, politics, and investment cycles

The adoption of new competitive technologies tends to follow an S-shaped curve as a function of time, where the initial pickup is quite slow but then accelerates rapidly until the adoption begins to saturate. Figure 10 demonstrates suggested pathways for the decarbonization and electrification in building, transport, and industrial sectors, as well as the increasing share of renewables in power generation. Space heating offers significant near-term potential, similar to low-temperature industrial processes, particularly if regulatory and tariff-related hurdles can be overcome. It is also anticipated that the transport sector will soon reach the relatively steep part of the curve once EVs become cost-competitive against gasoline vehicles. Since the average lifetime of a vehicle is only about 10 years, there could be a fairly rapid turnover of stock. The industrial sector is probably more cost-sensitive than other sectors, but it also tends to have long investment cycles and a high-risk aversity–the production process is often the primary concern. The steepness of the electrification timelines can also be strongly affected by policy, such that a well-thought-out and forward-looking suite of policies will consider the energy system as a whole, and the role of electrification in driving emission reductions.

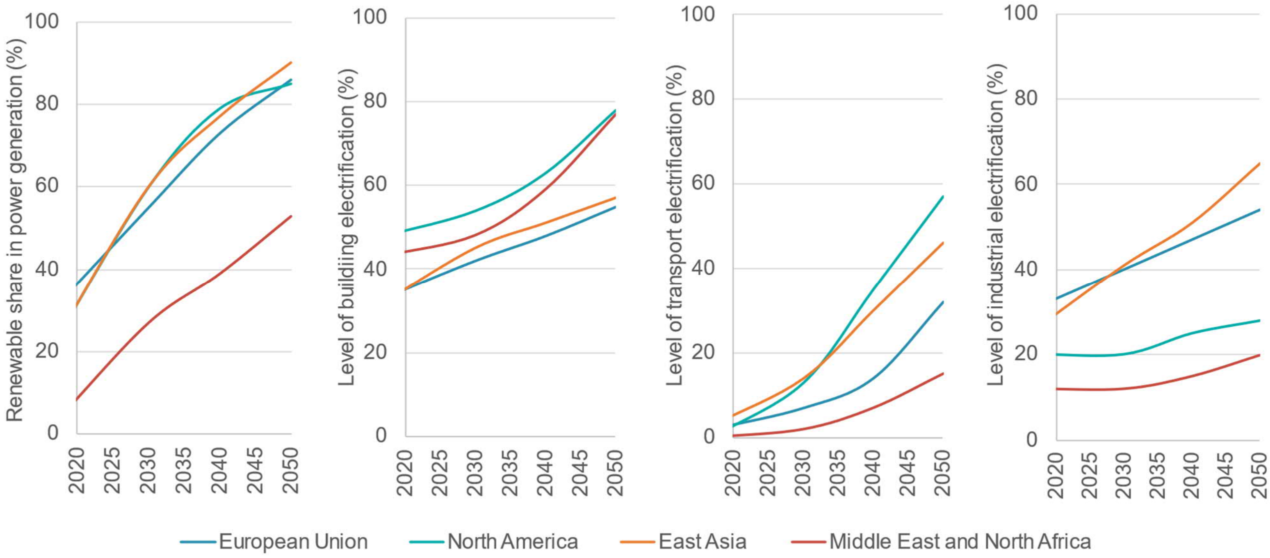


Figure 10. Suggested levels of decarbonization and electrification in selected regions to reach 2 °C global emission reduction target according to IRENA, Global Renewables Outlook 2020.

In July 2021, the European Commission proposed amendments to the EU's Renewable Energy Directive. The general objective is at least 55% of GHG emissions reduction in 2030 compared to 1990 levels, and to do so cost-effectively and sustainably, including goals for each end-use sector. One of the specific new amendments to ensure flexibility relates to small and mobile systems states: "Member States shall ensure that the national regulatory framework does not discriminate against participation in the electricity markets, including congestion management and the provision of flexibility and balancing services, of small or mobile systems such as domestic batteries and electric vehicles, both directly and through aggregation."

Electrification scenarios from the United States include the *U.S. National Electrification Assessment* led by Electric Power Research Institute and the *Electrification Futures Study* led by National Renewable Energy Laboratory, with both organizations examining the implications of high levels of end-use decarbonization on the electrical system. With the U.S. administration rejoining the Paris Agreement, it appears that the next few years will see a greater focus on decarbonizing the entire energy sector, including major fossil energy end-uses such as transportation, buildings, and industry. The United States has set a goal of achieving a clean electricity supply by 2035 and decarbonizing the complete energy system by 2050, similar to the EU goal of no net emissions of greenhouse gases by 2050.

Conclusions: Electrification seems inevitable, but sufficient flexibility is not guaranteed

One of the main uncertainties regarding the global electrification effort relates to how much of it will involve direct vs. indirect measures. The answer will certainly differ between sectors. Europe seems to be a forerunner in electrification initiatives and provides many examples of what may be coming. For example, the BloombergNEF report, "Sector Coupling in Europe: Powering Decarbonization," foresees direct electrification of more than half of energy consumption in the transport and heating sectors by 2050, but at the same time, high use of hydrogen in industry (e.g., steel, cement, ammonia, and other chemicals) especially closer to 2050. The EU is pursuing major discussions surrounding investment in hydrogen, but also encouraging energy system integration and electrification with strategies and policies that will lay the foundation for the decarbonized European energy system of the future.

Important policy decisions must be made regarding which networks and trade routes to maintain or build. Options range from developing only an electricity network, supported by fuel transportation based on trucks and ships, to designing multiple custom networks for different gaseous or liquid energy carriers, including fuel networks, and heating and cooling networks. Such opposed options need to be informed by extensive and detailed modeling of the different pathways, and their combinations, using transparent tools, data, and modeling assumptions.

The participation of electricity consumers in electricity markets has been a goal for decades, but without large-scale results. Electrification of energy will increase the stakes and, hopefully, will also lead to wider adoption of flexible power consumption. There will always be an interplay between 1) legislation, which needs to enable efficient solutions; 2) market mechanisms, which need to remunerate for all kinds of valued services; and 3) standardization, user-friendly technologies, contracting, and the means to conveniently aggregate small loads, which can help facilitate consumer-level adoption. If all that is designed and implemented well, both small- and large-scale consumers will act to increase their flexibility, much needed in 100% clean power systems.

Overall, electrification of the energy end-use sectors looks inevitable because carbon-free energy sources tend to produce electricity as opposed to heat or other energy carriers. At the same time, sufficient flexibility will not be guaranteed and requires appropriate policies, legislation, and market regulation as well as participation from energy consumers. Finding the most cost-effective flexibility sources sufficient for operating future energy systems, is not a straightforward task since many interconnected options are still emerging and evolving. Furthermore, flexibility itself is ill-defined, and power systems need flexibility in multiple time scales and for different purposes.

Such matters need to be at the forefront of policy and regulatory decisions affecting, in particular, those energy investments which typically have long lifetimes. Harmonizing and coordinating policy and regulation across the different sectors would help to simplify matters. Technical experts and engineers, together with social scientists, can contribute with robust analysis to support public and private decision-making. With these means, electrification can offer a cost-effective strategy to 100% clean and flexible energy systems.

Acknowledgements

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For further reading:

- Electrification (ed. Pami Aalto) https://www.elsevier.com/books/electrification/aalto/978-0-12-822143-3
- https://ourworldindata.org/ghg-emissions-by-sector
- World Energy Transitions Outlook: 1.5 °C Pathway, International Renewable Energy Agency (2021)

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