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ELECTRIFICATION WITH RENEWABLES

Driving the transformation of energy services

PREVIEW FOR POLICY MAKERS

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ABOUT THE REPORT

The forthcoming scoping study "Electrification with Renewables: Driving the transformation of energy services" presents recent trends and possible long-term pathways for electrification with renewables, described as "RE-electrification". It identifies key areas for further work to better understand the implications and economic impacts of those pathways.

The study is a first-of-a-kind analysis between the International Renewable Energy Agency (IRENA) and the world's largest utility, the State Grid Corporation of China. Benefitting from the perspective of a major grid operator, it synthesises recent IRENA work on technology and innovation, including findings from IRENA's forthcoming report, "Innovation landscape for a renewables-powered future: Solutions to integrate variable renewables".

This preview of the study for policy makers has been prepared for the ninth session of the IRENA Assembly, of which China will be the President.

The Chinese characters on the front cover signify the concept of "RE-Electrification".

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ELECTRIFICATION WITH RENEWABLES: DRIVING THE TRANSFORMATION OF ENERGY SERVICES

Over the course of human history, the world has made the transition from one major form of energy to another several times – from animal power and biomass to burning coal, and then to the increasing use of oil and gas. The world is already in the midst of another historic shift away from these fuels.

But to meet sustainability and climate goals, the pace of change must accelerate. **We need a vast expansion of renewables, a smarter and much more flexible electricity grid, and huge increases in the numbers of vehicles and other products and processes that run on electricity.** This report outlines the key role that those three elements – combined together to form the strategy of RE-electrification – can play along the path toward a new energy system transformation.

1. RE-ELECTRIFICATION: A VITAL PATHWAY

New technological innovations – along with policy imperatives around sustainable development and the need to combat climate change – are driving an urgent energy transition in this century. **This transition is toward clean electricity as a principal fuel, combined with "smart" digital technologies that make it possible to take full advantage of the growing amounts of cheap renewable power.** This vision, coined as RE-electrification in this report, unlocks the potential synergies between major increases in the use of electricity and renewable power generation by coordinating their deployment and use across demand sectors – power, transport, industry and buildings.

In a highly digitalised future with strong global climate policies, electrification of energy services will be pervasive. Electric or fuel cell vehicles would largely replace fossil-fuelled cars and trucks, and heat pumps and electric boilers would substitute for oil and gas furnaces in buildings and industry. Electricity from renewables could also be used to make hydrogen or synthetic gas for applications where direct electrification is difficult.

Combining widespread electrification and digital technologies on one hand and renewable power on the other can become a central pillar of energy and climate policy, given their numerous benefits. RE-electrification can make power systems more flexible and resilient, while making the wider energy system more secure and less reliant on fossil fuels. At the same time, it offers significant efficiency gains in primary energy use. It reduces pollution, leading to improved health. The modern automation and control systems that are an integral part of RE-electrification can also boost economic productivity and improve the quality of living conditions.

Unlocking synergies between electrification and renewables

In today's traditional electricity systems, demand is viewed as variable but relatively inflexible and predictable. Small variations can be covered by operational reserves at fossil fuel or hydro generators. Most flexibility to meet variable demand comes from the supply side, where dispatchable power plants can be ramped up and down.

RE-electrification creates a very different system. Overall demand for electricity will rise significantly in transport, buildings and industry, which creates new markets. Solar and wind will be key suppliers to these new markets. At the same time, the electricity they generate can vary depending on prevailing weather conditions, and having a high share of such variable renewable energy (VRE) in a power system poses increased operational challenges.

RE-electrification strategies meet emerging operational challenges by looking beyond the generation side of the power system and tapping all available sources of flexibility. This is particularly the case for flexibility of demand over a wide range of time scales. To take just one example, the charging of electric vehicles (EVs) can be ramped up or down within milliseconds or shifted by several hours.

To deliver this new system in a cost-effective manner, simply switching to electricity in end uses and building new renewable generation alone is not sufficient, however. RE-electrification strategies also require smart devices and other information technologies that offer much more flexibility and control over demand and the delivery and use of renewable electricity. The integration of smart approaches in combination with digitalisation is key to reduce the risk of rising peak loads, to expand opportunities for renewable power utilisation, and to avoid the need for massive investment in building new grid infrastructure.

Smart electrification with renewables thus creates a virtuous cycle, where electrification drives new uses and markets for renewables, which then accelerates the switch to electricity for end uses, creating more flexibility and thus driving further renewables growth and technological innovation. Growth and innovation also reduce costs and create additional investment and business opportunities.

Challenges ahead

Such a major transformation is not trivial, however. Energy systems are both complex and highly integrated, making them difficult to change. On the policy side, they are highly dependent on entrenched regulations, taxes and subsidies, which require considerable political will to adjust. **Even where there is political will, transforming markets and supply chains – *e.g.* the global car industry to EVs, or home heating to heat pumps – may still take many years**. People replace heating equipment and cars every 10-15 years, and in some parts of the world the building stock is being renovated at a rate of less than 1% per year. Any transition also creates winners and losers, and those who do not benefit may resist change. **The distribution of cost and benefits needs to be fair and just in order to achieve broad acceptance.**

On the technical side, a transition to the widespread use of renewable electricity also has considerable challenges. It requires integrating large amounts of VRE into the grid, which involves matching supply and demand in the face of varying generation and peak production that may not match peak demand. It requires improved coordination between sectors of the economy, both in planning and operation. In addition, **new infrastructure must be built or expanded for, *inter alia*, the power grid, EV charging networks and hydrogen or synthetic gas production facilities.**

The basic technologies needed for the transition already exist. Still, innovation remains critical. Innovation in technologies needs to go in hand-in-hand with improvements in new hardware, software and services. Together, all these innovations can accelerate the energy transition and lower its overall cost.

2. A PROFOUND TRANSFORMATION IN ENERGY USE

The RE-electrification transformation could be profound. With dramatic cost reductions making wind and solar cheaper than fossil-fuelled electricity generation in many regions, the prospect for low-cost renewable electricity to economically replace the direct use of fossil fuels is now in sight.

Global perspective

According to IRENA analysis underpinning the recent *Global Energy Transformation: A Roadmap to 2050* (GET2050) report, the global share of electricity in total final use of energy could rise from 20% today to nearly 45% by 2050, with some regions relying on electricity for up to 60% of their energy use by that time (IRENA, 2018a).[1] In ongoing updates to this analysis being carried out by IRENA, based on more recent data and technology trends, these figures are likely to be even higher. Meanwhile, the renewable share in power generation would climb from 26% today to 85% in 2050, with up to 60% coming from variable sources such as solar and wind. Electrification increases the demand for power, but it reduces the total energy demand, as electric heat and transport systems can be significantly more efficient at delivering energy services than those using fossil fuels.

In a future with strong RE-electrification, one billion EVs could be in use worldwide in 2050, around half of the total fleet and about the same number of all types of vehicles that are on the road today. The number of heat pumps used to provide heating for buildings could jump ten-fold, to more than 250 million. Many industrial processes could switch to electric furnaces and heat pumps, while others (along with some transport applications such as long-haul trucking) could use hydrogen or synthetic gas produced with electric power.

1 If fuels like hydrogen produced from electricity were to be included as part of electricity's share of total energy use, these figures would be even higher.

The shift to renewable energy could reduce emissions of carbon dioxide from the power sector by 64% compared to the reference case used in the IRENA GET2050 analysis, while deep electrification of the end-use sectors could reduce the emissions from buildings, transport and industry by 25%, 54%, and 16% respectively. As a result, as seen in Figure 1, the overall impact of RE-electrification would reduce total energy sector emissions by 44% compared to the reference case. Adding direct use of renewable energy (such as solar thermal for heating or biofuel for transport) and efficiency measures to RE-electrification would achieve an emissions reduction of more than 70%, which is compatible with the well-below 2°C goal established in the Paris Agreement.

IRENA's assessment agrees with other global scenarios compatible with the well-below 2°C target, which find that buildings have the highest potential for electrification (range of study outcomes between 50-80% electrification rate by 2050), followed by the industrial sector (34-52%), and then the transport sector (10-52%). A Greenpeace scenario, for example, anticipates high electrification rates for both industry and the transport sector (at 44% and 52%, respectively) (Teske, Sawyer and Schafer, 2015). Another interesting example can be seen in the 85 global scenarios underpinning the Intergovernmental Panel on Climate Change special report on limiting planetary warming to 1.5°C. Most of the scenarios feature electrification as an essential element of the overall strategy for deep decarbonisation, with the rate of electrification achieved by 2050 largely in the range of 35% to 55%, although several reach up to 70% (IPCC, 2018).

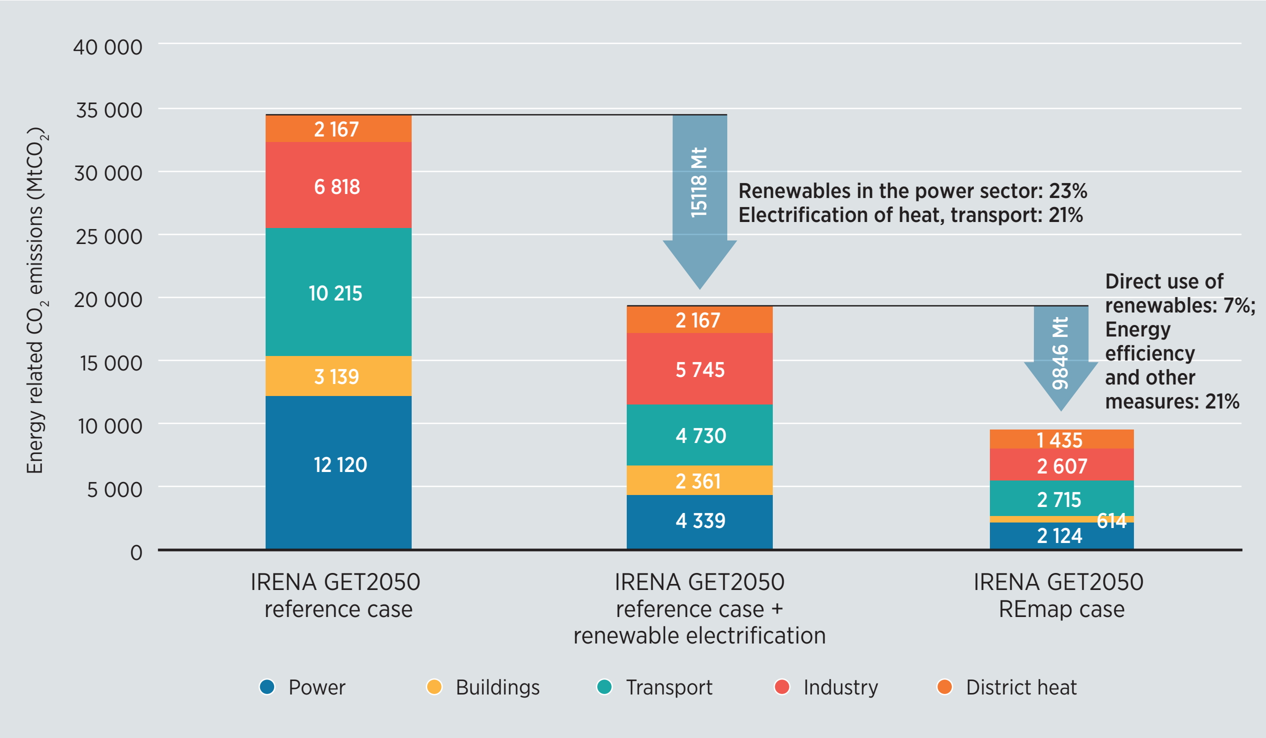
Chinese perspective

This report also features a groundbreaking assessment of future energy pathways for China, conducted by the State Grid Energy Research Institute (SGERI), which suggests that the share of electricity in the country's total final use of energy could grow from the current level of 21% up to 47% by 2050. In China, total final energy demand is expected to peak around 2030-2040 before declining, which is similar to the anticipated global trend. Between 2015 and 2050 in the analysis, the total amount of energy used would increase by around 30%, while electricity consumption would grow by 140%. There would be a structural shift away from coal towards more renewables, which would provide 66% of generation by 2050, with solar photovoltaic (PV) and wind generating 41%.

The potential for RE-electrification is particularly high in buildings, with an anticipated increase in electricity's share of energy consumption from 29% today to 63% by 2050. The share would reach 49% and 25% for industry and the transport sector, respectively (Figure 2).

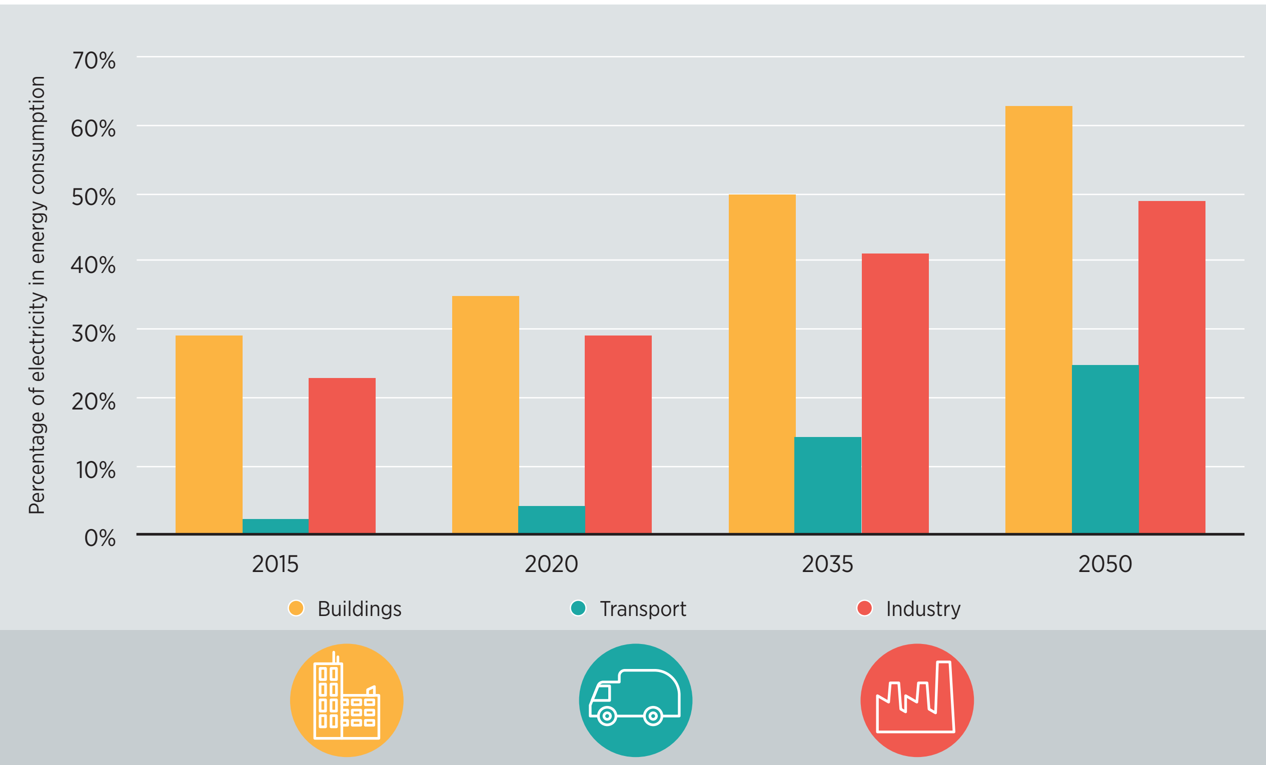
This RE-electrification would cut annual carbon emissions nearly in half by 2050 compared to the anticipated peak, which is reached after 2025. More than half of the reduction would come from the industrial sector, due to reduced demand and increased electrification. The power sector, despite an increase in total generation, would actually be responsible for more than one-third of the total emission reductions due to the switch from coal to renewables.

Figure 1 Contribution of renewable electrification to global decarbonisation needs



Notes: CO_2 = carbon dioxide; $MtCO_2$ = million tonnes of carbon dioxide.
Source: IRENA's own analysis based on IRENA (2018a)

Figure 2 Electrification rate of various sectors in 2050 in the SGERI China RE-Electrification Scenario



Source: SGERI's own analysis

3. RE-ELECTRIFICATION APPROACHES, PROSPECTS AND PRIORITIES

RE-electrification is a particularly powerful strategy because it takes advantage of potential synergies between electrification and renewable energy, and between sectors of the economy. At the same time, however, it a very complex undertaking, since **steps taken in one sector can have major impacts on other sectors and their infrastructure requirements**. The impacts will be seen not only on the power grid, but also on the gas and thermal network infrastructure, as well as on building stocks, recharging stations for EVs and other end-user infrastructure.

Each of the three major areas of the economy would play a significant role in achieving the RE-electrification transition, both through major growth in their use of electricity as a fuel, and in offering opportunities for significantly increasing the flexibility of that use.

Here are summaries of the technologies and strategies needed:

Buildings, transport and industry

1. Buildings

Buildings now use about 120 exajoules (EJ) of energy globally per year, about 30% of global final consumption (IEA, 2018). More than half of that energy is supplied by natural gas, oil, coal, or biomass. Homes and other residences consume about 70% of buildings energy, while commercial and government buildings use the rest.

Currently, electricity supplies about 24% of the energy used in residential buildings and 51% of that for commercial and public buildings. **Those shares can be increased using the following technology pathways**:

- **Switch to heat pumps for space heating and hot water.** Heat pumps are three to four times more efficient than other forms of space heating. However, they typically have higher capital costs and require major building

retrofits when applied to old properties. In some Nordic countries heat pumps already account for more than 90% of the sales of space heating equipment (European Heat Pump Association, 2017).

- **Use electricity directly for resistance heating in boilers and furnaces**, typically to heat water that is circulated to provide heating, and for space heaters. As there is no efficiency gain in this option, for economic reasons it is better suited to well-insulated buildings or mild climates. Switch to electric stoves and ovens for cooking where applicable.

In addition to the direct electrification of building energy needs, using synthetic fuels produced with clean electricity may present another pathway to reduce fossil fuel use and emissions in buildings:

- **Use electricity to produce fuels such as hydrogen or synthetic methane** that can be supplied to homes and commercial buildings through existing or new natural gas distribution pipelines.

Countries with colder winters face a particular challenge in electrifying buildings while meeting high demand for heat. In France, for example, the current typical peak demand for electricity and gas combined is four times higher in the winter than in the summer (Sauvage, 2018). A UK study showed serious electricity supply shortfalls during the winter in scenarios with high numbers of heat pumps, even when using battery storage, demand-side management and other tools to manage the demand (Fawcett, Layberry and Eyre, 2014). Solving this peak demand problem requires additional approaches and investment.

Key first steps include weatherising existing buildings to make them more energy efficient and strengthening building codes to improve the efficiency of new buildings. This reduces electricity demand and the need to build new generation capacity. Efficiency gains from heat pumps can also help to reduce the peak load.

Another important step is harnessing intelligent grid technologies and storage. These help to account for peak demand or more closely match supply from renewable generation, increasing the potential for integrating VRE. One German case study found that using smart devices on heat pumps to shut off the pumps or reduce consumption during periods of peak demand, when homes were sufficiently heated, could cut peak loads and reduce costs by 25% (Romero Rodriguez *et al.,* 2018).

A third solution is increasing the use of district heating systems, which can take advantage of waste heat, heat from sewage or water, or renewable heat as sources for heat pumps. The heat can also come from biomass and geothermal sources, combined with cogeneration to produce heat and power, and storage systems. The Heat Roadmap Europe project found that using such systems to supply half of Europe's total demand for heat (using excess industrial heat, large-scale heat pumps and cogeneration) could cut carbon emissions by 89% in 2050 compared to 2015 (Paardekooper *et al.,* 2018). District heating systems can also be combined with thermal storage systems.

In addition to existing solutions, demonstration projects are exploring even more innovative approaches. In Sweden, for example, E.ON's Ectogrid technology enables a number of buildings to be connected to a thermal grid, using heat pumps to supply the necessary heat. Heat or cooling flows as needed among the buildings, controlled by a cloud-based management system. The approach reduces heating bills by 20% (Ectogrid, 2018). In northern England, a project called HyDeploy is launching a four-year trial to inject hydrogen produced via electrolysis into a number of existing gas grids, to reduce cooking and heating emissions without the need for new end-use appliances (HyDeploy, 2018).

Achieving greater electrification of energy use with renewable power in buildings requires a careful combination of multiple approaches, which balance the needs of different infrastructure requirements. Particular attention must be paid to avoiding excessive new investment in power distribution grids to meet the winter peak demand.

2. Transport

Currently, only about 1% of total energy use in transport – which includes passenger and cargo transport by road, rail, maritime shipping and aviation – is supplied by electricity. More than two-thirds of that is used for rail transport globally, and much of the rest is used by tram and subways. The electricity consumption of the estimated four million EVs now on the road (as of June 2018) is negligible. Strong policies are therefore required to accelerate the profound transformation of the transport sector called for by decarbonisation targets and concerns over local air quality.

The technology paths for achieving a major transformation include:

- **Increase the share of EVs on the road.** Such vehicles offer a number of advantages, including improved air quality and reduced maintenance and operating costs. Adoption rates will depend heavily on both public policies and continuing declines in the cost of batteries. Bloomberg New Energy Finance estimates that battery costs will drop quickly enough to make EVs cost-competitive without subsidies by 2024 (Bloomberg NEF, 2018). Especially in urban environments, the air pollution benefits of EVs can make a decisive difference. As a result, an increasing number of cities have put in place regulations that favour electric driving. Anticipated changes in transport, such as autonomous vehicles and more shared rides, which are expected to increase the usage rates of vehicles, could reinforce the deployment of EVs.
- **Use renewable electricity to make hydrogen to power fuel cell vehicles (FCVs) and trains for use over long-distances, for example, where battery capacities limit the range of EVs, or in cases where the cost of building new overhead electric lines is high.** Though currently expensive to buy, studies show that in the long run FCVs may offer well-to-tank costs comparable to the internal combustion engine (ICE) equivalent, subject to future changes in oil prices and tax schemes.
- **Use renewable electricity to make synthetic gas or oil (hydrogen derivatives) to replace fossil-based transport fuels.** Studies show that even in the long run, the economic prospects for such fuel use in ICE vehicles may not be positive in comparison to EV or FCV options. However, such fuels can be used for applications where no alternatives exist, such as heavy-duty marine and aviation applications.

The extent to which the use of hydrogen and its synthetic fuel derivatives penetrate may largely depend on the future performance and cost of batteries. With sufficiently low battery costs, electricity can increasingly be used for rail travel and freight, and perhaps in aviation. For example, Avinor, the public operator of Norway's airports, has a goal of using electric aircraft for all flights of up to 1.5 hours long by 2040 (Avinor, 2018). Ships are being electrified and batteries have been introduced on ferries in Norway, for example, while hydrogen is being considered for Rhine River freight shipping. The future role of hydrogen for transport applications requires further debate.

The electrification of transport is in many ways an ideal use of renewable power, given the variable output of sources such as solar and wind. Road vehicles are parked about 90% of the time, allowing their charging schedules to be optimised using smart power management tools to accommodate (or even take advantage of) those variations in power generation. German research finds that adjusting charging rates up or down to match the changes in wind and solar generation, in combination with price-sensitive smart charging systems, can more than double the share of renewable energy used by EVs (Kasten *et al.,* 2016; Schuller, Flath and Gottwalt, 2015).

EVs also offer the potential of so-called vehicle-to-grid (V2G) services. When parked and connected to the grid, their batteries can help regulate voltage and frequency, or supply electricity to meet spikes in demand. The vehicle capacities are significant: car battery capacity already far exceeds the capacity of all other electricity storage. However, this V2G potential has not yet been widely taken advantage of, outside of certain pilot projects.

Flexibility can also come from using electrolysis to produce hydrogen, which then can be used in FCVs. Not only can the electrolysis process be quickly ramped up or down to match supply variations, but the resulting hydrogen also functions as a means to store temporary surpluses of energy.

Realising these potential synergies requires intelligent grids and smart power management strategies. This is especially important to avoid the massive investment in upgrading distribution networks that would be required if EV charging were uncontrolled.

Pilot projects and experiments are already demonstrating the benefits of smart electrification strategies in transport. In the Netherlands, grid operators and Renault have built 1 000 public solar-powered smart charging stations with battery storage, decreasing peak load by 27-67% (van der Kam and van Sark, 2015). In California, Pacific Gas & Electric (PG&E) and BMW have paid car owners for the right to draw power from their plugged-in cars, cost-effectively helping to meet peak loads (PG&E, n.d.).

Given the intricate interrelationships between generating power and using it for transport, and between market forces and public policy, the electrification of transport with renewable energy is a daunting and complex task. **Making the transition requires careful planning.**

For example, the necessary transport infrastructure – especially for road transport, whether it is EV charging stations or hydrogen distribution networks and fuelling stations – must be rolled out at a scale to ensure that consumers can have confidence in choosing new types of vehicle or transport. Furthermore, the implications of transport electrification for clean power demand, and for the potential need for hydrogen production capacity, need to be better understood. Some studies indicate that the full electrification of the transport sector would require renewable generation capacity several factors larger than what is currently envisaged. Expansion of electrification without the corresponding expansion of renewable energy will result in higher emissions from the power sector, even though emissions from the transport sector significantly reduce.

Photograph: State Grid Jiangsu Electric Power Co., Ltd

National goals, such as banning sales of fossil-fuelled vehicles entirely (as France, Norway, the United Kingdom and others plan to do) or setting EV targets (as in China, Germany, the Republic of Korea, and others), must therefore be complemented with clear plans for implementation of measures such as charging infrastructure and the use of smart charging. For example, to ensure that the five million zero-emission vehicles mandated to be on the road in California by 2030 can be supplied with electricity, the state has earmarked USD 2.5 billion over eight years to install 250 000 charging stations (California Air Resources Board, 2018).

3. Industry

Industry is the most challenging of the three major sectors to decarbonise because of its unique dependencies on fossil fuels for both fuel and feedstocks, and because of the lack of cost-effective substitution (in contrast to transport, where ICE vehicles can be replaced by already available EVs). For high-temperature industrial processes, there is no significant efficiency gain from a shift to electricity.

Today, electricity supplies only about 27% of the energy used in industry, powering everything from pumps and motors to heating and cooling units.

Technologies and strategies for RE-electrification include:

- **Increase the use of efficient heat pumps for low-temperature heat.** IRENA estimates that the number of such heat pumps could rise from one million today to 80 million in 2050, which would supply about 7% of the global demand for industrial heat. Combined with waste recovery, heat pumps offer significant cost reductions, as Kraft Foods in the United States found when it captured waste heat from refrigeration systems to heat water. The company saved more than 14 million gallons of water and USD 260 000 annually (Emerson, 2017).
- **Adopt electric boilers or hybrid boilers that can switch instantly between electricity and natural gas.** The hybrid boilers allow companies to not only take advantage of fluctuating electricity prices, but also to help balance supply and demand on the grid as renewable power generation varies. High-temperature electric furnaces for commercial applications are not yet available.
- **Replace natural gas fuel and feedstocks with hydrogen or its derivatives produced with renewable power.** Direct use of hydrogen as feedstock, for example in ammonia production, has good economic prospects among all the hydrogen applications.
- **Relocate industrial facilities to regions with low-cost renewable electricity**. Aluminium smelters have in some cases moved to Iceland because of inexpensive hydropower.

Switching to electricity in industry is easier and cheaper for new plants, given the high cost of retrofitting existing plants. In many cases electrification of industrial processes could be made cost-effective with a price on carbon. However, areas with good renewable sources, or industries where processes can be made flexible to better match the variable generation from these sources, could **already have potential to maximise the benefit of cheap and clean power generated by renewables**. For example, the output of an aluminium production process developed by Germany's Trimet Aluminium SE and New Zealand's Energia Potior Ltd can rise or fall by 25%, creating a virtual storage capacity of about 1 120 megawatt hours (MWh) – similar in size to a medium-sized pumped-storage plant (IEA, 2017).

Electrification permits quick and substantial reductions in industry's carbon emissions. The reason is that the bulk of energy use is in just a few energy-intensive industries, such as metals and chemicals.

Using smart public policy to target the production of the few energy-intensive commodities can have a major impact. The Swedish Energy Agency is co-financing a pilot initiative called HYBRIT that will use hydrogen from hydro and wind power to make steel, for example. The goal is to make the production of steel fossil-free by 2035, at a cost that is competitive with traditional steel production. That initiative alone has the potential to cut Sweden's total carbon dioxide emissions by 10% (HYBRIT, 2018).

Implications for network investment

To deliver electrification at scale, investment will clearly be needed to build or upgrade key infrastructure. This includes the production of electricity (and hydrogen), the energy transmission and distribution networks (such as the electricity grid and gas and thermal pipelines), and end-user infrastructure (such as information and communications technology [ICT] devices, retrofits and distribution stations).

RE-electrification strategies could bring significant cost reductions, by reducing investment needs in peak-load infrastructure, achieving higher utilisation rates of power generated by VRE, and reducing the need for investment in additional flexibility measures, such as storage.

Multiple RE-electrification technology pathways exist for a given sector. **Often the best strategy is a combination of technology pathways that balances the need for different infrastructure requirements across sectors, with a particular focus on avoiding excessive new investment in power distribution.** There is no global study that comprehensively assesses the infrastructure implications of alternative combinations of RE-electrification pathways, but various pilot projects, case studies and energy system modelling studies do offer some insights. These are used here to illustrate four important implications of RE-electrification for network investment:

1. Smart RE-electrification reduces peak-load grid costs

The most significant negative impacts of electrification could be unprecedented increases in peak demand relative to average demand. For example, EV charging may raise daily peaks substantially, while heat pumps could increase the seasonal peak (such as winter in European countries). The problem with this disproportionate increase in peak demand is that much of the grid infrastructure required to meet the peaks would be used only for short time periods. This lower utilisation of grid infrastructure would make the investment economically unviable.

This problem can be solved through smart management of demand. For example, a number of simulation studies have shown that controlling the timing of EV charging would minimise the increase in peak demand. In addition, drawing power from plugged-in vehicles (V2G) could even reduce peak demand. In simulations in five US states, in a case where EVs make up 23% of the vehicle fleet, the increase in peak demand was 3-11% without smart

Electrifying production of a few energy-intensive commodities can have a major impact

charging. With an optimised charging strategy, that dropped to 0.5-1.3% (Fitzgerald, Nelder and Newcomb, 2016). In addition, a recent pilot project in the United Kingdom with more than 200 Nissan Leaf EVs showed that such a smart charging strategy could save up to USD 3 billion in avoided investment costs in the power grid until 2050 (My Electric Avenue, n.d.).

Smart management of demand is less effective at reducing peak loads from the use of heat pumps in buildings, given the wide differences between the peak loads in summer and winter. That's because demand management strategies can typically shift loads by at most a week or two, not months. As a result, to achieve the electrification of heat demand in buildings, a balanced mix of gas networks (using hydrogen gas produced by electricity) and thermal networks (with heat pumps that use waste heat and renewable energy) may offer the best approach to cover peak demand and avoid excessive investment in the power grid.

2. Smart grid investment pays off beyond peak-load savings

Investment in smart grid infrastructure can deliver significant economic benefits in addition to addressing problems related to peak load. For example, EVs could put additional strain on the distribution network because the intensity of charging may exceed what the network is designed to handle. The extent of this problem depends not only on the charging strategies, but also on the choice of charging devices and the geographical concentration of the charging stations. **Studies show that ICT infrastructure to control and monitor the load would be a significantly cheaper solution than investing in additional wires and transformers to solve this problem**.

With electrical devices increasingly being used in daily life, and more and more generation assets (notably rooftop solar PV) being owned by private customers, the intensity of power use increases and power increasingly flows in more than just one direction. **As a result, the combination of electrification with increased penetration of distributed generation will have major impacts on the electricity distribution network**. The smart grid allows optimal control over small loads and generation assets, and can bring significant cost benefits. For example, investing USD 100 million in smart grid technologies at substations in the United Kingdom would bring savings of USD 640 million within 13 years, Northern Powergrid, a UK distribution company, estimates (Northern Powergrid, n.d.).

Digital technologies and sophisticated software also make it possible to combine distributed energy resources, including small-scale solar and storage, into what is known as a virtual power plant (VPP). **VPPs can bring additional sources of flexibility to the system and avoid the cost of building new generation and transmission infrastructure.** For example, in New Mexico a VPP is being used to provide 20-25 megawatts of flexibility, mitigating the need for expensive new power generation resources. The US Energy Information Administration also estimates that flexibility can be sourced from VPPs at the cost of USD 70-100 per kilowatt (kW) (Enbala, 2018), a small fraction of the USD 700-2 100 per kW cost of constructing a new gas-fired power plant.

3. Transmission investment needs depend on resource location

New transmission lines may need to be built to supply the additional renewable electricity, depending on the location of the renewable sources. Building wind generation offshore on the north coast of Germany, for example, would require transmission investment to bring that power to cities in the southern part of the country. And in countries such as China, renewable energy sources are typically far away from the cities that use most of the electricity, requiring new long-distance transmission lines. China has approached this issue in part with improved transmission technologies, such as ultra high-voltage direct-current transmission lines.

Electricity storage could reduce the need for new transmission. This is particularly the case in areas with congested transmission lines and a high concentration of VRE.

4. Economic case for hydrogen production infrastructure still needs to be established

The production and uses of electrified fuels through hydrogen and its derivatives are already technically feasible. A rapid scale-up could lower costs and demonstrate which applications are economically possible.

In the long run, producing hydrogen via electrolysis is cost-competitive, particularly in areas with good renewable energy resources and very low-cost renewable electricity.

Smart grids keep peak load under control and deliver economic benefits

Building hydrogen distribution networks does not seem cost prohibitive.

However, there seems to be a general consensus that, for hydrogen derivatives, additional financial incentives or a CO_2 price would be needed to improve their economic case. One possible enabling strategy would be building hydrogen production facilities near low-cost renewable electricity facilities that operate with high load factors, such as solar plants in the Middle East or North Africa, or offshore wind in the North Sea.

The Chilean government, for instance, plans to support production of hydrogen from solar power, which it expects to become cost-competitive with other fuels by 2023 as solar prices continue to decline. The first applications will be in industry and in mining transport fleets, but as production increases and costs drop, hydrogen could be exported to countries such as Japan as well (IRENA, 2018b).

4. KEY ITEMS ON THE FUTURE AGENDA

This scoping report and other recent studies suggest that the RE-electrification transition offers a path to a future with greater energy security, improved health and quality of life, and reduced risk of potentially catastrophic climate change. The pathway is difficult and complex, and so will required careful planning, political will, and detailed national energy strategies and roadmaps. But the preliminary analysis shows that it is both effective and achievable.

The advantages of widespread electrification are clear and compelling. How they are implemented, however, is crucial. Failing to coordinate all the complex and interrelated elements of the pathways would pose major issues, raise costs and potentially have unintended negative consequences. This scoping exercise has allowed the identification of the following areas where recommendations can already be made, and areas that require further investigation and debate.

Priorities for policy makers

To avoid potential problems, this report identifies important areas where countries can begin by taking the following concrete actions:

- **Develop a long-term vision of the role of electricity in the country's energy system**
- **Develop detailed roadmaps to fulfil that vision**
  - Plan for building or expanding RE-electrification infrastructure, including transmission and distribution grids, charging networks, facilities and pipelines for hydrogen production and distribution, and district heating and cooling systems.
  - Engage citizens and tailor solutions to meet the specific needs of local communities and consumers.
- **Adapt regulations**
  - Use price signals, such as time-of-use tariffs.
  - Remove barriers to innovative technologies or ownership models.
  - Provide incentives or funds for widespread adoption and use of heat pumps, electric boilers, and smart meters and appliances.
  - Strengthen building codes to require greater efficiency in buildings and support weatherisation of existing buildings.
- **Implementation**
  - Support pilot projects of digital grid technologies and solutions to manage new patterns of load, to optimise utilisation of VRE, and to explore V2G technologies that offer synergies between sectors.

   » Take advantage of opportunities for large-scale centralised solutions such as district heating and cooling.

   » Scale up smart charging infrastructure, and assess and plan electric infrastructure needs, particularly at the distribution level, to avoid bottlenecks.

   » Explore relocating energy-intensive industries to sites with low-cost renewable power.

- **Support key research areas**

   » Continue research and development on electric storage and on electrified fuel options in shipping and in aviation.

   » Support research, development and demonstrations of direct and indirect use of electricity in industry.

Gaps to bridge

There is clearly growing knowledge of the benefits that RE-electrification can provide. **However, future research is also needed to better understand uncertainties around the technical, economic and policy-related aspects of the transition.**

At a high level, the key technical and economic questions that remain are related to the effects of electrification on energy system costs, and the extent of the scope for cost-effective electrification in various contexts. This requires the following:

- The actual costs and benefits of these wider electrification aspects need to be more comprehensively analysed, for example new investment vs new options in end-use flexibility, efficiency, or operation.
- Even wider analysis needs to be conducted that takes into account the costs and benefits of electrification in other networks such as gas or thermal pipelines, or transport

More studies, including comprehensive – truly system-wide – analysis of RE-electrification pathways, with better data on supply- and demand-side options, will help to answer more complex questions. Case studies examining particular national or local contexts – rather than relying on generic figures – could become increasingly relevant.

While there is a need to conduct more detailed and more comprehensive techno-economic studies of RE-electrification, there is also a need to address outstanding policy-related questions. These include:

- What are the most effective system-wide policy frameworks to achieve the potential synergies between the deployment of renewable generation and electrification in buildings, transport and industry?
- How can policies integrate the economics of electrification as a whole, balancing costs and benefits to all sectors rather than specific options individually?
- Where and how can price signals be used to encourage electrification and renewable deployment?

Two important factors are often ignored – the behavioural and spatial dimensions in system-wide RE-electrification. There is still a limited understanding of how end-users will – or would like to – interact with the future energy system, and current operating models do not always reflect the needs of citizens or the potential role of active consumers. Spatial considerations in new investment can materially change the cost-benefit analysis of new energy supplies (e.g. location-dependant solar and wind), demand centres (e.g. remote industrial sites, or district heating extensions), and the required scale of network infrastructure that will connect them (e.g. smart grid assets, or EV charging stations/networks). In further exploring the optimal technical, economic and policy evolution of electrification with renewables, these dimensions need to be taken fully into account.

Lessons from failures, as well as from successes, should be widely shared. This applies whether such lessons relate to new technical demonstrations, pilot projects, or enabling-framework designs.

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Note: Complete references are to be listed in the forthcoming report.

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