CHAPTER 29

Disruptive Technologies

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1 Introduction

Disruption denotes an action that completely overhauls the traditional way an industry is working, for instance by introducing a new technology or new standards. The shorter the transition, the more disruptive the event is considered.

A well-known example is the telecommunications industry: for decades, the industry was mainly offering landline telephony based on copper wire networking, with great success. In the 1960s, 6 out of 100 people had a fixed-line subscription in the European Union (see World Bank 2019). By the early 2000s, this number had grown to almost 50 out of 100, reaching its historical peak. Just eight years later, in 2018, the share of people with a fixed-line subscription shrank to 40 out of 100, largely caused by the introduction and massive success of cellular phones—a technological disruption. Meanwhile, the telecommunications industry was dramatically adapting their business models in a very short time frame, by starting to offer mobile information as well as media services. And while the landline might have a future, it will surely not be copper-based, but rather use optic fibre cables, which are able to transmit large amounts of data at much higher speed.

Energy is, of course, not telecoms—despite some similarities, the most obvious one being that both industries are network industries. Yet, energy is considered far more complex in many ways, for instance because various energy carriers co-exist and have been co-existing for decades: oil, gas, coal and electricity being the most widely recognised ones. Moreover, energy is at the forefront of the battle against climate change, because energy-related emissions account for the largest share of global greenhouse gas (GHG) emissions. It is

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generally acknowledged that it is far easier to avoid energy-related GHG emissions than those related to land-use, for example in agriculture (see Umweltbundesamt 2018). For this reason, extensive policy efforts have been put in place, the best known being the push for renewables in the electricity sector, a measure adopted in many countries around the globe. Nonetheless, at least so far, historical patterns of energy consumption have proven to be surprisingly stable, despite technology advancements and policy efforts.

In the following, we aim at identifying energy technologies and energy uses that have the potential to become disruptive. To this end, the chapter is structured as follows. First, we will define suitable metrics to track significant changes in the energy system and try to understand existing patterns, analysing why some of them have been stable for decades. In the second section, we will learn more about major change events in the past and whether these can be classified as "disruptive". This is followed by a screening section of potential technology candidates that could be disruptive in the forthcoming decades. Finally, an outlook and conclusions are provided.

2 Monitoring Changes in Energy

In order to assess disruption, it is useful to define a metric that can be used to track and assess a significant change in the energy industry. To this end, we define **three main indicators** to measure structural changes in the energy sector:

1. A reduction in energy demand;
2. A change in the share of final energy carriers;
3. A change in the generation mix of final energy carriers.

The **first indicator**, a **reduction in energy demand**, is widely acknowledged as a key measure to reach long-term climate targets. In general, this can be achieved by making an existing process more efficient (e.g. for power plants by installing a new turbine with a higher conversion efficiency) or by reducing the primary needs (e.g. for houses by increasing insulation). Typically, these processes are not immediate across the whole sector, because the technical lifetime of installations in the energy sector can reach several decades. This makes the diffusion of new appliances a long process. Moreover, given the strong correlation between economic activity and energy consumption, at least until now, economic growth has always been accompanied by an increase in energy demand. To be able to measure efficiency effects, it is therefore useful to compare the evolution of energy demand to a counterfactual scenario (typically called "Business-as-Usual") without any efficiency improvements. This requires a deep-dive into technologies and energy carriers.

For this reason, the **second indicator focuses on what energy statisticians call *final energy consumption***, that is, the energy consumed by households, industries and services. Eurostat defines it as "the energy which reaches the final consumer's door and excludes that which is used by the energy sector itself". One might add that it excludes energy used by the energy sector itself for conversion, for example when transforming crude oil into oil products such as gasoline. Moreover, it is useful to decompose the total final energy consumption, both by energy carrier—oil, gas, coal, electricity—and by sector in which the energy is used, typically distinguishing between transport, households, industry and services. In other words, we are interested in the market share for different competitors (energy carriers) and different product categories (energy sectors) at the same time. This is of particular interest for consumer goods (e.g. passenger cars, boilers), first, because they are renewed more frequently than, say, housing facades, and second, because purchasing decisions are not only guided by economic principles.

The result is illustrated for Germany in Fig. 29.1 (2018 data). Despite not being 100% representative for all countries, the German case provides insight into patterns that can be observed throughout most OECD countries. Looking at this decomposition of total final energy consumption (TFC) one can note that there are **three main energy carriers: oil, gas and electricity**. In 2018, 36% of TFC was covered by oil and oil products, followed by gas (25%) and electricity (21%). The **share of electricity in final energy consumption** is also known as **degree of electrification**. Electricity is a very valuable form of energy, because it can be converted into so-called useful work (e.g. traction) at very high conversion efficiency. By contrast, the conversion efficiency is significantly lower in a combustion process, because thermal energy faces thermodynamic limits when transformed into work. For this reason, switching end-uses to electricity ("electrification") also reduces primary energy needs and contributes to increasing energy efficiency.

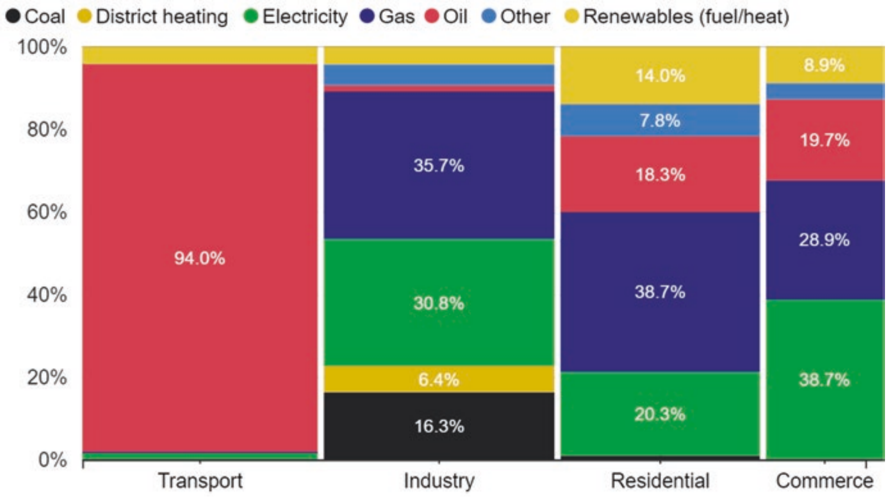

Fig. 29.1 Final energy demand by energy carrier and sector in Germany (2018). (Source: own elaboration on German Federal Energy Ministry data [2020])

Figure 29.1 also shows that significant differences across the various sectors exist. It is the **industry sector** where **coal still has a relevant share** in final energy consumption,[1] for example in primary **steelmaking** from ores. In the so-called *blast furnace route*, coke coal is needed to reduce iron ore, thereby creating molten iron, which is then refined to crude steel. In this process, carbon dioxide is emitted. An alternative is the *electric arc furnace route*, which is less diffused in Germany and most other steelmaking countries. Its main advantage is that scrap metal can be used as feedstock, which is heated up to 1800 °C through an electric arc to produce steel. The process does not generate any direct CO_2 emissions and is generally less energy-demanding than the blast furnace route, as it "recycles" end-of-life products made from steel. It is, however, a **secondary** steelmaking route, which cannot entirely replace primary steelmaking.

When looking specifically at the **transport sector**, it becomes clear that there is an elephant in the room, which is oil and oil products, which covered 94% of the transport demand in 2018. Moreover, this share has remained virtually unchanged in the last 30 years (see Fig. 29.2), when considering the combined contribution of oil products and biofuels (which made up 4% in 2018). So far, the **transport sector has proven to be resistant to disruption**, as no appropriate (and convenient) substitute for (fossil) liquid fuels in transport has yet been found. The introduction of biofuels has mainly been policy-driven and has had a limited impact, as the potential to produce additional biofuels is neither economically attractive (hence the need for continued policy support) nor

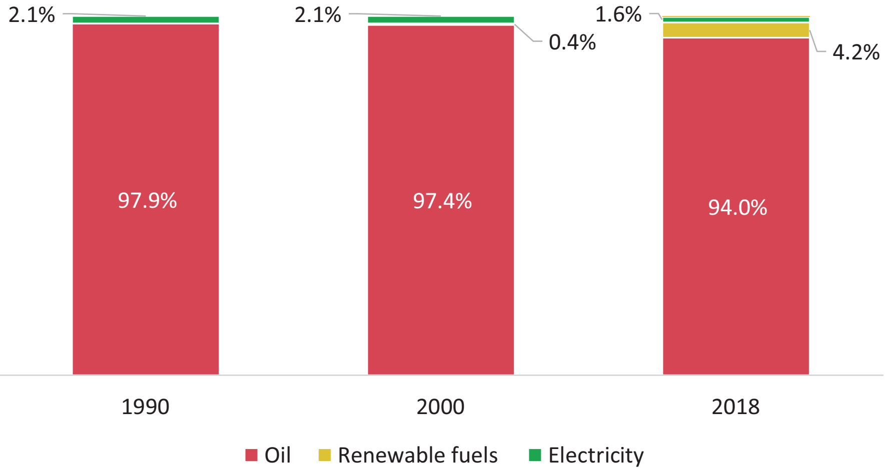

Fig. 29.2 Final energy demand of transport sector by energy carrier in Germany (1990–2018). (Source: own elaboration on German Federal Energy Ministry data [2020])

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[1] Coal is also used to generate electricity. In that case, however, it is not considered a *final* energy carrier (see third indicator, generation mix of an energy carrier).

considered particularly sustainable when food crops[2] (e.g. corn or edible vegetable oil) are used as feedstock for biofuels (see FAO 2013). Nevertheless, a key open question for the future is: **Is it possible to disrupt the dominance of oil in transport?**

The other two sectors show a more balanced mix between the three main energy carriers. For example, many households use gas for heating purposes, be it for space heating or hot water, while others rely more on electricity. As mentioned, similar patterns can be found in most OECD countries but reflecting national specificities. In fact, the French version of this graph would show a higher share of electricity in residential consumption, because of a more widespread use of direct electric heaters.

The **third indicator** refers to the **generation mix of an energy carrier**. This concept is well-known for electricity, because electricity is not an energy carrier that occurs in nature, as opposed to oil and gas that are waiting to be extracted from underground reservoirs. Instead, electricity must first be generated from other (primary) energy carriers, which can range from traditional sources (such as solid, gaseous and liquid fuels but also nuclear and hydro energy) to modern ones (like wind and solar energy). A switch from carbon-intensive fossil fuels to renewable energy sources is widely regarded as a key measure to enable a transition to a climate-neutral energy system. In fact, 38% of the electricity consumed in Germany was generated from renewable energy sources in 2018, up from 9% in 2004 and six percentage points above the average of the European Union in that year.

This concept of analysing the generation mix can be applied to all energy carriers, when aggregating energy carriers with similar characteristics. For example, let us consider oil and liquid biofuels as members of a larger energy carrier family named "liquid fuels" and calculate the overall share of renewables in this energy carrier family. For liquid fuels, the share of renewables amounted to 3% in Germany, significantly below the share of renewables in the power sector (see Fig. 29.3). Since the energy transition has primarily been focused on the electricity sector so far, it is not surprising that the share of renewables is higher in electricity than in liquid or gaseous[3] fuels.

It goes without saying that for liquid and gaseous fuels the risk of a *policy-driven* disruption is higher than ever. Policymakers could intervene if liquid and gaseous fuels continued to fail in keeping pace with electricity and in becoming greener over time. Already today it is generally acknowledged that replacing liquid and gaseous fuels with electricity is a key measure to reach climate-neutrality. To understand the feasibility of such a massive switch from one energy carrier to another—which would indeed represent a disruption—it is useful to look at previous change events in the energy industry.

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[2] To avoid this type of competition ("food vs fuel"), it has been proposed that only non-food crops such as forest residues from pulp mills be used as feedstock for biofuels. However, the economically viable potential remains limited.

[3] For gaseous fuels, biomethane is considered a renewable energy carrier. However, its share was irrelevant in the German gas mix of 2018.

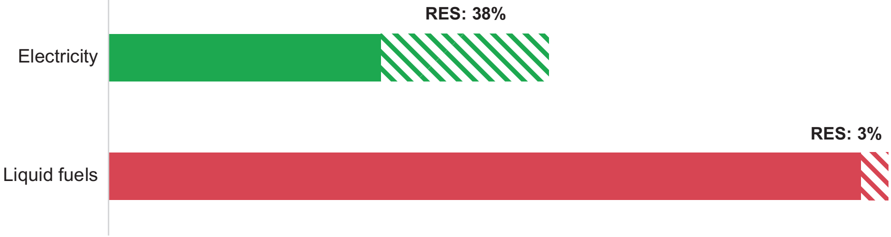

Fig. 29.3 Share of renewables in electricity and liquid fuels (Germany, 2018). (Source: own elaboration on German Federal Energy Ministry data [2020])

3 Past Disruptions in the Energy Industry

In the previous section we introduced three indicators that can be used to disclose disruptions: a reduction in energy demand, a change in the share of final energy carriers and a change in the generation mix of final energy carriers. In the following, we will apply the latter two indicators to past transitions in the energy industry and evaluate their degree of disruption.

3.1 Residential Heating in Germany: The End of Coal in the 1990s

In contrast to the transport sector that has remained virtually the same over the last thirty years, the final energy carrier mix in the residential sector has changed notably over the past two decades. Sticking to the German case (see previous section), a concrete example is the way heating of households changed in just ten years from 1990 to 2000 (see Fig. 29.4). Coal covered merely 2% of residential TFC in 2000, down from 16% in 1990. At that time, solid fuel stoves burning lignite briquettes were still widespread (especially in Eastern Germany) but were quickly replaced in the 1990s. The big winner was natural gas, responsible for more than two thirds of the loss in market share of coal, the other winners being biomass and electricity.

While substituting coal with biomass can be considered a simple "fuel switching" process, meaning that the stove was kept but only a different solid fuel is being burned, choosing natural gas and electricity required customers to install new heating devices like gas boilers—a technology disruption. Data indicates that a similar destiny awaits oil-fired heating devices, as the share of oil in German residential TFC almost halved to 18% from 1990 to 2018. Nevertheless, oil-fired central heating boilers remain fairly widespread. They function in a similar way to gas-condensing boilers but (as their name suggests) rely on oil instead of natural gas as fuel supply, which is of particular interest for households that are not connected to the gas grid. This is not uncommon: while almost every household in modern economies has access to the electricity grid, this is not the case for gas, even in OECD countries with considerable gas consumption such as Italy or Germany. A prominent example is Sardinia: despite being the second-largest island in the Mediterranean Sea, Sardinia is not

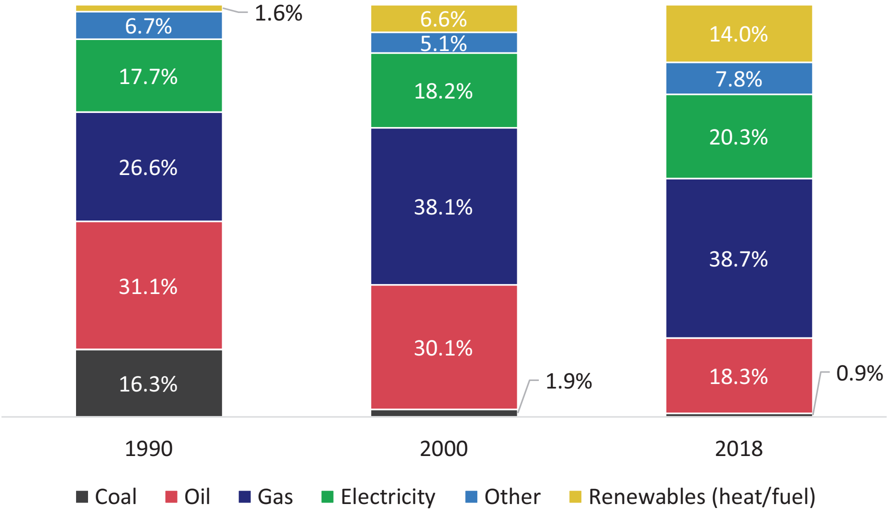

Fig. 29.4 Final energy demand of households by energy carrier in Germany (1990–2018). (Source: own elaboration on German Federal Energy Ministry data [2020])

attached to the Italian natural gas grid. As an alternative fuel, liquefied petroleum gas can be used, which is an oil product that becomes liquid at a pressure of 8 bar and ambient temperature, a physical characteristic that allows for relatively safe on-site storage in an external tank. Looking forward, many oil-fired boilers are bound to reach the end of their lifetime in the next decade. Hence, a key open question for the future is: **Which energy carrier will be able to capture oil's market share in residential heating?**

3.2 *Electricity Generation in the US: Gas Overtaking Coal*

Another example of technology disruption, well-known and thoroughly studied, is the shale gas revolution in the US (see Bellelli 2013). Shale gas (more generally: unconventional gas) is fossil natural gas that is obtained through an extraction process that was considered to be new and different in the past, because it involved hydraulic fracking and horizontal drilling. It is considered a revolution because it enabled the US to massively increase its natural gas production. The abundance of low-cost natural gas had a downward effect on US gas prices and reshuffled many markets, among which was the US power market. Electricity generation in the US had long been dominated by coal-fired power plants. In 2008, coal had a 48% share in electricity generation, with gas covering 21% (see Fig. 29.5). The shale gas revolution resulted in gas-fired production overtaking coal-fired production in 2016, merely five years after the beginning of the shale revolution.

The US case offers two insights. First, there can be quick wins even in the energy industry, despite the long technical lifetime of its assets. Driven by price

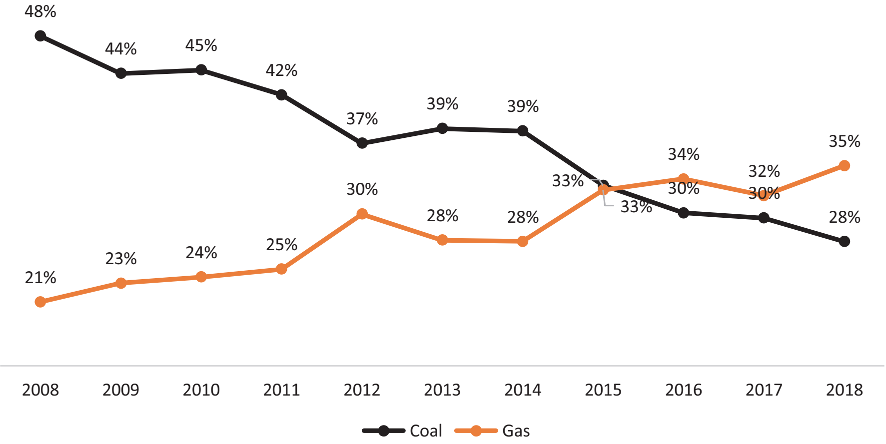

Fig. 29.5 Share of coal and gas in the US electricity generation mix (2008–2018). (Source: own elaboration on EIA data [2020])

signals, it was simply the utilisation of existing assets that was inverted, without a need to deploy new power plants. Therefore, the disruption process quickly slowed down—gas has not reached the market share coal had in 2008. This is the second insight: unless replacement capacity is built, some coal will continue to operate, despite gas being less expensive in terms of variable production costs. However, new capacity will only be built if an investor is confident about recouping total fixed costs (investment, capital and fixed maintenance costs). For existing assets, the main relevant fixed cost component is annual maintenance. Consequently, coal-fired power plants will only be closed if gross profits from annual electricity sales fail to cover these fixed costs. This decommissioning process can be slow if new-builds are rare—a quite common scenario given that investors are risk-averse and postpone their decisions to build new large-scale power plants, which typically cost more than one billion € per gigawatt of production capacity.

It goes without saying that such purely financial considerations do not apply in the same way for consumer goods, because purchasing decisions for these goods are not only guided by economic principles, especially when their price falls below a certain threshold. Thus, a key open question for the future is: **Can electricity generation assets become affordable for the masses and follow the dynamics of consumer goods?**

3.3 *Electrification of OECD Countries: The Rise of Electricity*

Another interesting but rather silent disruption in the energy industry was the process of massive electrification of modern economies (OECD countries). It can be considered silent because there were no losers: final electricity consumption simply kept increasing over the decades, that is, from 320 Mtoe in 1973

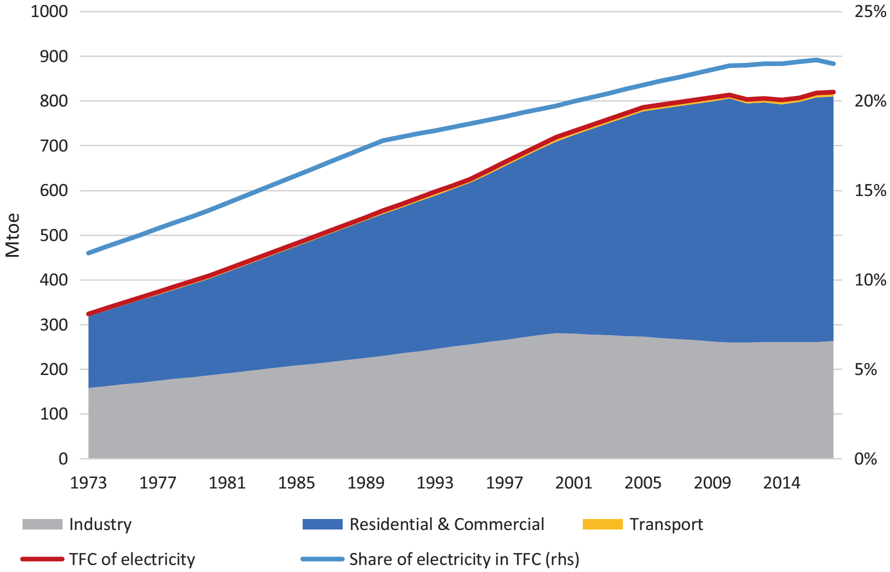

Fig. 29.6 Final consumption of electricity by sector and share in TFC (OECD countries 1973–2017). (Source: own elaboration on International Energy Agency (IEA) data [2019])

to 820 Mtoe in 2018, mostly without displacing other energy carriers but by creating new energy needs, for example due to a rising diffusion of household appliances such as fridges, TVs, washing machines, dishwashers and air conditioners (see Fig. 29.6). Data also shows that the transport sector never gained significant rates of electrification, rail transport being the only notable exception.

Massive electrification in the residential and commercial sectors was a result of technology advancements that allowed for low-cost production of household appliances but also for an ever-decreasing cost of producing, transmitting and distributing electricity. In parallel, household income and household spending in OECD countries grew at an impressive pace, for example at a compound annual growth rate of 8.3% between 1970 and 1990 for the case of Germany and almost 9% in the US (OECD 2020). As a result, household appliances became affordable for most consumers: a mass-market was created.

The latest IEA data shows that electricity has a share of 22% in total final energy consumption in OECD countries, up from 12% in 1973, and in line with German numbers shown in the previous section. What is remarkable is that this share has remained mostly stable over the last ten years. There are two possible reasons for this. First, many households in OECD countries already have a fridge, a TV, a washing machine, a dishwasher and an air conditioner. The market appears to be saturated and driven by replacement purchases, for example to substitute old or malfunctioning appliances. Second, the efficiency of new appliances appears to be increasing, because residential energy demand is not increasing, despite bullish drivers such as the increasing number of one-person households in modern economies, which—ceteris paribus—increases the number of household appliances required.

A key open question for the future is: **Will a second wave of electrification follow, if new electric appliances, affordable for the masses, are launched?**

4 Potential Future Disruptions in the Energy Industry

In the previous section, three key open questions for the future were formulated, indicating potential future disruptions. In the following, we will put these questions into a wider context, focusing primarily on technology disruptions and to a lesser extent policy-driven disruption.

4.1 Towards a Mass Market for Electricity Generation

It is generally acknowledged that electricity is a key energy carrier for energy transition, due to its intrinsic efficiency advantages and the fact that power already has a much higher share of renewables when compared to liquid and gaseous fuels (see Fig. 29.3). Costs for solar and wind, two major green electricity technologies, have declined significantly over the past decade, making them competitive vis-à-vis conventional power generation sources such as coal and gas in geographical areas where meteorological conditions (solar irradiation, wind speeds) are favourable and/or where CO_2 emissions have a price tag.

It goes without saying that policy instruments will remain key in pushing the growth of these alternative energy sources. These policy instruments certainly include CO_2 pricing but also long-term contracts, awarded by competitive bidding procedures that are organised by regulated parties such as governmental agencies.

These developments can be summarised as **regulated or policy-driven disruption**: polluting power production facilities will eventually be phased out, because they are not competitive with green electricity sources that own a long-term contract. Regulated long-term contracts will be increasingly complemented by long-term corporate power purchase agreements. These allow businesses to purchase electricity directly from renewable energy generators without being co-located. In 2018, “121 corporations purchased 13.4 GW of clean power directly from generators”, up from 6.1 GW for 2017 (Bird & Bird 2019). However, **most of these new projects tend to be large-scale assets** with an installed capacity ranging from tens to hundreds of megawatts, meaning that a typical wind or solar farm will not only cost between ten and one hundred million euros but will also **require site development and permitting procedures**. Consequently, the **development speed** will remain **by and large predictable** and manageable.

Let us also **consider a more disruptive scenario**, a complementary development, in which small-scale electricity generation assets such as rooftop solar panels would be widely installed. Already in 2018 almost half of Europe's cumulative solar PV capacity was installed on residential rooftops or commercial roofs (SolarPower Europe 2019), a result of generous feed-in tariffs that especially Germany and Italy were granting between 2008 and 2012. This period, despite being policy-driven, shows the potential dynamics of consumer-driven choices: millions of solar panels with an average size of 3 to 5 kilowatts were deployed in just a few years.

A **new disruptive wave**, this time technology-driven, would entail that **solar panels become more affordable, easier to install and fully connectable** to other digital devices. We are not far away from such circumstances. Today, solar panels for residential rooftops cost below 10,000 €, less than a passenger car. Connectivity has become a standard feature for most modern household appliances and is greatly facilitated by smartphones, because they can be used to configure appliances and how they connect to the home WiFi via dedicated apps while standing next to the appliance. The last barrier appears to be the physical installation itself, which remains labour-intensive and far from trivial, because trained workers are required to mount the panels, wire them and connect them to a power inverter. **A disruptive technology breakthrough** would therefore not be triggered by a cost reduction of the solar panels themselves but rather by the development of **do-it-yourself solar kits**.

Another aspect that could accelerate the disruption speed of solar is linked to the **efficiency of panels**, because **more electricity can be produced with the same roof area**. Technically, this can be achieved by so-called **multi-junction cells**. The efficiency limit of single-junction cells is around 33%, largely determined by spectrum losses, that is, not all the solar energy carried by solar particles (photons) can be absorbed by the cell. Any semiconductor material is characterised by a certain energy band gap—that is, the minimum amount of energy required to break free electrons of their bound state and trigger a current. When a photon does not carry enough energy to cross the band gap, it will pass through the material and its energy will remain unused. An efficiency loss can occur even when a photon carries enough energy to cross the band gap, because the amount of energy extracted will be equal to the band gap. All additional energy is lost. When picking a single band gap (as is the case for single-junction cells), there is a trade-off between extracting more energy from fewer photons and extracting less energy from more photons. The latest technology advancements show that multi-junction cells can reach an efficiency of almost 50%. The diffusion of this technology has remained limited so far, due to technical reasons (e.g. complexity of production process, lifetime) and economic competitiveness (higher cost of materials).

Instead, what appears to be a **highly unlikely scenario** is what is typically referred to as an **off-grid revolution**, that is, that consumers would massively disconnect from the grid altogether. On the one hand, it is true that the cost reduction of solar panels has been significant, insofar as auto-consumption (directly consuming the self-produced electricity rather than withdrawing electricity from the grid) already pays for many consumers, albeit at low economic returns (long payback periods). On the other hand, the limited rooftop surface and the limited energy density of batteries make it **nearly impossible to reach 100% self-sufficiency**. Therefore, people will not want to disconnect from the grid unless they are prepared to sit in the dark after two successive cloudy winter days. A minority of consumers might aim for 100% self-sufficiency by installing multiple batteries and oversizing the solar array, but this would require investments above 100,000 € per household and would therefore be unlikely to attract a mass market (see Genoese 2015).

4.2 Hydrogen and Green Gas, a Way to Keep Gas in the Game

So far, gaseous and liquid fuels have remained mostly fossil-based and thus CO_2-emitting, which is incompatible with a climate-neutral energy system. Future energy scenarios therefore indicate a rising importance of green gas and synthetic fuels in general to reach climate-neutrality. Both green gas and synthetic fuels have a common starting point: hydrogen. The molecule is highly versatile and can serve as the basis to create all sorts of synthetic hydrocarbons including jet fuel for aviation.

Like electricity, **hydrogen is not an energy carrier that occurs in nature**. Instead, hydrogen must first be generated from other (primary) energy carriers. There are several ways to produce hydrogen, the most relevant for future scenarios being water electrolysis and steam methane reforming. The former process makes use of electrical energy to split water (H_2O) into its constituent elements: hydrogen (H_2) and oxygen (O_2). Its conversion efficiency currently stands between 60 and 70%, making **water electrolysis a highly electro-intensive process**. The second production technology (steam reforming) uses methane (CH_4) as feedstock to produce hydrogen, emitting CO_2 as by-product. Hence, steam reforming needs to be accompanied by Carbon-Capture-and-Storage technologies to become climate-neutral ("blue hydrogen"), whereas hydrogen from water electrolysis is considered green, if renewable electricity is used as feedstock. Blue and green hydrogen could be highly relevant in future, as indicated in various climate-neutral future energy scenarios (e.g. European Commission 2018).

It is important to point out that already today there is demand for hydrogen as feedstock, for example in the oil industry (hydrocracking) or the ammonia industry. However, **hydrogen is not a relevant carrier for energy end-uses (e.g. heating, transport) today**: there are no H_2 boilers for space heating or hot water, and while hydrogen-fuelled passenger cars exist (known as fuel cell electric vehicles), they are not as affordable as cars with an internal combustion engine and not as mature as battery electric vehicles. In general, **hydrogen is not a cost-competitive energy carrier today**. This is not surprising given that the production of hydrogen comes at an additional cost, as it requires both costly hardware and feedstock:

- Producing H_2 from steam reforming implies H_2 having a higher cost than natural gas
- Producing H_2 from water electrolysis implies H_2 having a higher cost than electricity

At very low electricity prices and with decreasing investment costs for electrolysers, green hydrogen could at some point become less expensive than natural gas. To put it differently, one would first need further cost decreases and efficiency improvements in renewable electricity generation (solar panels, wind turbines), followed by significant cost decreases and efficiency improvements of water electrolysers. It is unlikely that both of these technology improvements will happen fast enough to represent a disruption.

Instead, the **uptake of hydrogen will depend heavily on policy choices**. Aggressive CO_2 pricing and/or regulatory decisions that require a certain share of green gas in the existing natural gas mix will trigger the deployment of hydrogen production facilities. Consequently, the **development speed** will remain **by and large predictable** and manageable.

Nevertheless, **hydrogen is a strategic energy carrier for energy transition**. Already today, green or blue hydrogen could be used as feedstock in order to **produce climate-neutral ammonia and fertilisers**. Another key industry is steelmaking. Dominated by coke coal today (blast furnace route), in the future hydrogen could be used for the direct reduction of iron ore, producing sponge iron, which can be refined to crude steel. Major global steel producers have announced the intention to build demonstration plants.

While we progressively decarbonise the energy system, the use of unabated fossil fuels such as oil, gas and coal will necessarily have to decrease, giving blue and green hydrogen a chance to move from their niche role as climate-neutral feedstock towards climate-neutral energy carriers for end-uses. Their role will be **especially relevant in sectors that require fuels with high energy density**, such as aviation, maritime and long-haul road transport. For other end-uses, such as passenger cars as well as heating and cooling of buildings, alternative decarbonisation measures exist, which fall into the broad category of electrification and are the focus of the next and final section on potential future disruptions in the energy industry running on hydrogen.

4.3 Electrification Phase Two: Transport and Heating

The rate of electrification in OECD countries has been relatively stable in the last 10 years, hovering around 22% of total final energy consumption, indicating that no major energy end-uses have been electrified in the last decade. The **next phase of electrification** consists of capturing a higher "market" share in the **transport and heating** sector, two promising developments, given the advancing technological maturity and increasing affordability of battery electric vehicles (BEVs) and electric heat pumps. Moreover, there is a **remarkable efficiency advantage of a factor of three**, as is illustrated for the case of

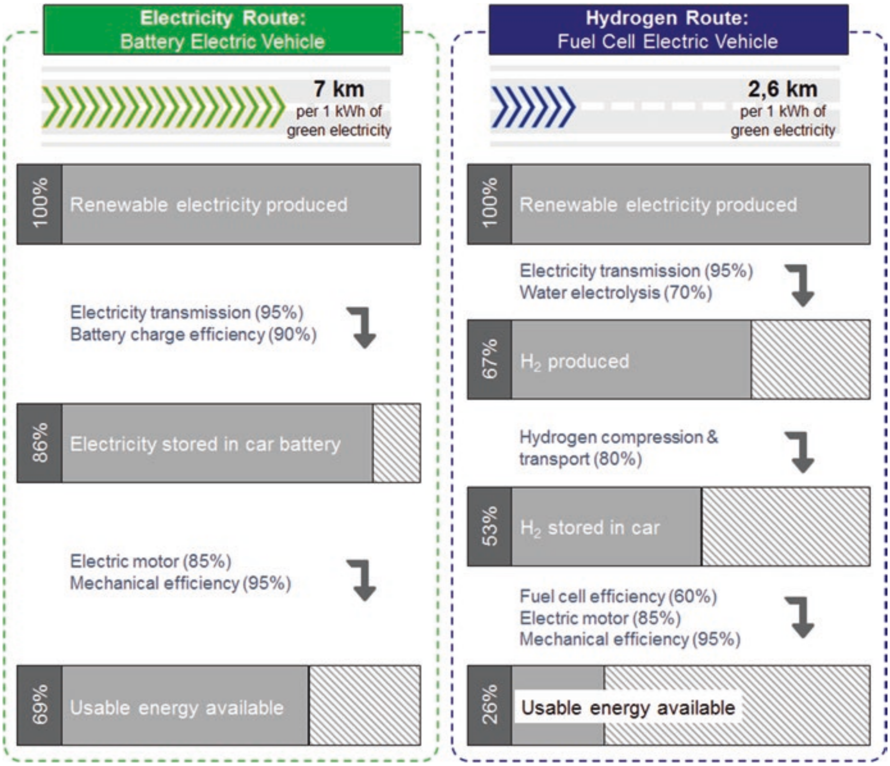

Fig. 29.7 Efficiency comparison between electricity and hydrogen in passenger cars. (Source: own elaboration based on Frontier Economics [2018])

passenger cars in Fig. 29.7. With one kilowatt-hour of electricity produced by a renewable energy plant, a BEV can drive for seven kilometres, whereas the hydrogen route would only allow for a travel distance of 2.6 kilometres. This fundamental efficiency advantage has also been recognised by major car companies such as Volkswagen and Daimler, which decided to abandon the hydrogen route for passenger cars in 2020.

In the case of heating, the efficiency advantage is even higher, because heat pumps are devices that produce heat from both ambient energy and electricity. In fact, for each kilowatt-hour of electricity consumed by a heat pump, between 3 and 5 kilowatt-hours of heat energy are produced. Modern gas-condensing boilers reach a conversion efficiency of 95%, that is, one kilowatt-hour of natural gas can be converted to 0.95 kilowatt-hours of heat energy. Heat pumps are therefore 3–5 times more efficient than gas boilers, even before considering that the production of climate-neutral gas involves additional conversion losses.

For these technological reasons and in view of the stringent EU emission standards for **new cars** and **new or heavily renovated buildings**, an uptake of demand for electric vehicles and electric heat pumps should be considered a baseline scenario in Europe. Car replacement rates range between 5 and 10%, depending on the country (see ACEA 2020), whereas less than 1% of European buildings are renovated each year. Consequently, **adoption speed** (and potential disruption) will be **much higher in passenger transport than in residential heating**, unless governments decide to incentivise the renovation of houses. Nevertheless, in view of the replacement wave of obsolete oil-fired boilers, further electrification in heating should not be underestimated. Rural areas without access to gas distribution networks today are unlikely to be served by natural gas in the future, in view of the more stringent building insulation requirements, which have a bearish effect on gas demand. Without access to gas networks, there is a limited number of technology alternatives once oil-fired boilers have to be replaced, facilitating the diffusion of electric heat pumps.

Further electrification in freight and maritime transport or aviation is less likely in the medium term. While electricity could offer tangible efficiency advantages in these transport segments, it is also true that electricity is hard to store. Current electrochemical batteries have a lower energy density than liquid fuels, too low to power airplanes, ships or trucks. The solid-state battery technology could triple energy density, making electrochemical batteries more attractive at least for long-haul road transport (trucks) but still insufficient for airplanes and ships. The technology uses a solid electrolyte, instead of the liquid electrolytes found in traditional lithium polymer batteries, which currently comes at the cost of a reduced durability and lifetime. Therefore, the solid-state technology has not been deployed at large scale, yet.

5 Summary and Conclusions

History shows that sudden disruptions are very rare in the energy industry, due to the relatively slow diffusion process of new technologies. Technological change is always ongoing but has remained manageable and predictable so far, given the long technical lifetime of assets in the energy industry.

However, in some energy sectors disruption could be imminent, largely driven by consumers, because their purchasing decisions are not only guided by economic principles. **Rooftop solar has already demonstrated its disruptive potential** between 2008 and 2012, mainly triggered by generous government incentives at that time. In the forthcoming decade, a new disruptive wave could be triggered by **easy-to-install solar kits and affordable multi-junction cells**, which increase the amount of solar energy per square metre that a panel can harvest. This will accelerate the already ongoing trend of load defection, that is, that consumers will withdraw less energy from the centralised grid. Nevertheless, people will not want to disconnect from the grid altogether, because this entails the risk to sit in the dark without electricity after two consecutive cloudy winter days.

Transport is another sector ripe for disruption: given stricter emission limits and the efficiency advantages of the electric vector, it is widely expected that **electric vehicles will capture an ever-increasing share in new passenger car registrations**, especially in the European Union, where internal combustion engine cars can no longer comply with new emission standards. Nevertheless, it is important to recall that the transport sector is much broader than just passenger cars. In fact, the passenger vehicle sector represents about a quarter of global oil demand (see IEA 2019b), while freight and maritime transport as well as aviation combined constitute about 30% of global oil demand. There is currently no viable electric alternative on the horizon for these transport means. Hence, the development of climate-neutral liquid and gaseous fuels will also be necessary to combat climate change. In this context, **hydrogen** (green or blue) could become a strategic energy carrier, being a **key measure to decarbonise the steel and ammonia industry**, as well as aviation and maritime transport. If new electrochemical battery technologies such as solid-state batteries matured, these could compete with hydrogen in long-haul transport but would still not have a sufficiently high energy density to run airplanes or ships.

After a decade of stagnation, current technology trends indicate that a **second wave of electrification is imminent**. This by itself would constitute a disruption of the energy industry. Whether hydrogen could also give rise to a disruption will mainly depend on energy policy and how seriously the fight against global warming is pursued.

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