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The global green shift: Where it comes from, how it works, and where it's heading

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Abstract

This chapter analyses the ongoing global green shift from an evolutionary (Schumpeterian) perspective. Understanding such large techno-economic shifts, their causes, dynamics, and implications, has been a recurrent theme in evolutionary economics, from Schumpeter onwards. Following this perspective, what primarily characterizes large techno-economic shifts is that the radical changes they entail concern not just one but a whole range of industries and sectors, including ways of life, the organization of work, and infrastructure. The driving forces behind such shifts, according to Christopher Freeman, Carlota Perez and other contributors to the literature, are key inputs (or factors) characterized by rapidly declining costs, almost unlimited supply, and very broad applicability. This chapter argues that the global green shift, currently unfolding, is a techno-economic shift of a similar (or even larger) magnitude as the earlier shifts discussed by Freeman and Perez and others. The analysis shows that the green shift is driven by interaction of innovations in three interrelated areas, that is, renewable energy innovation; innovation in energy-using sectors; and energy infrastructure innovation, e.g., energy storage and distribution. A number of key innovations from these three areas are identified and their development and spread during the last hundred years or so explored. Particular attention is given to the various factors, including policy, that have influenced these processes. Finally, the lessons for policymaking supporting the global green shift are considered.

Keywords

Green shift, innovation policy, climate policy, solar energy, wind energy, electric cars.

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1. Introduction

The global green shift (Mathews 2017) signifies a process of change from a technological, economic and social system powered by fossil fuels, characterized by waste, pollution, global warming and ecological problems, towards a system where fossil fuels are replaced by renewables, resources are reused, and challenges related to climate and nature are under control. Such a shift requires numerous changes, including innovation and policies supporting it, in all parts of society. However, as will be shown here, one does not have to start from scratch, as many of the required changes are associated with long-run evolutionary processes that are already well under way. These processes, we shall argue, have strong implications for how to successfully deal with the challenges confronting us.

From an evolutionary perspective long run technological, economic and social changes are outcomes of interaction between **variation**, the process through which new ideas for how to do things in better ways emerge, and **selection**, which determines the extent to which such new ideas are tried out in practice, improved, and eventually put into use on a large scale. While it is common in contemporary discourse to place emphasis on novel ideas, scientific breakthroughs, and their possible contributions to society, from an evolutionary perspective it is equally if not more essential to focus on the working of selection processes, because it is these that determine what happens in practice. As the evolutionary economist Josef Schumpeter famously pointed out a long time ago: “As long as they are not carried out into practice, inventions are economically irrelevant” (Schumpeter, 1934, p. 88). The implications of this for policy making are straightforward. Influencing selection processes is one of the most efficient ways to promote innovation-driven change. Policy makers, being part of the selection environment, have numerous ways to do this, directly as well as indirectly by influencing other actors.

The global green shift involves changes in all sectors of the economy and society, in a mutually self-reinforcing way. Understanding the dynamics of such changes has been a central theme in evolutionary economics for a long time, from Schumpeter onwards. The next section presents some of the lessons from this line of research and considers how it may help us to understand the dynamics of the global green shift. It is shown that the global green shift is driven by interaction of innovations in three interrelated areas, that is, renewable energy, energy use, and energy infrastructure. How these innovations have evolved towards their present stance is discussed in section three, which examines the development of selected core innovations from these three areas from the very beginning more than a century ago to the present. Particular attention is given to selection processes, and the role of policy makers in influencing these. The final section sums up the lessons and considers the implications for contemporary policy making.

2. The dynamics of the global green shift

That innovation, particularly radical innovation, may spur economic growth and structural change is a core proposition in evolutionary economics and innovation studies (Kline and Rosenberg 1986; Freeman and Louçã 2001, Fagerberg 2003, 2004), and how such processes unfold has been a central topic in evolutionary economics for over a century. In fact, already

Schumpeter studied this phenomenon intensively, and published a two-volume treatise on the subject (Schumpeter 1939). In this he pointed out that a single innovation, however important, should not be expected to have big macro-economic impacts. For this to happen, Schumpeter argued, constellations of different, albeit related, innovations would be necessary. However, he did not go much into detail on what might cause different innovation processes to cluster in this way, which hence became an important topic for subsequent research.

While a hotly debated topic during the first part of the previous century, the scholarly interest in large techno-economic shifts and their possible economic implications faded during the long, stable growth period that followed the end of the second world war. However, the global economic downturn in the 1970s led to renewed interest in the topic and evolutionary analyses of long run economic development. Two evolutionary economists, Christopher Freeman and Carlota Perez,¹ suggested that the “glue” in a large techno-economic shift is a “core factor” (or input) characterized by low and decreasing costs, almost unlimited availability, and very broad applicability (Freeman and Perez 1988). While the sector delivering the core factor should be expected to grow fast, of even greater importance would be the impetus that the introduction of the core factor in user sectors, so-called “carrier-branches”, gives to innovation and growth there (and feedbacks from this on the growth of the system as a whole). An example of such dynamics, highlighted by Freeman and Perez, is the introduction of cheap and abundant oil around 1900, what may be dubbed “the global fossil shift”, giving rise to numerous changes in energy using sectors; e.g., electricity production, transport (the internal combustion engine for example), textiles and clothing (e.g., synthetic fibres), and so on, and – via feedbacks – even greater demand for oil. Another example highlighted by Freeman and Perez is the introduction of cheap microelectronics from around 1980 onwards. However, as they point out, such broad systemic change is challenging, and may easily come into conflict with – and be hampered by – existing institutions, e.g., regulations. According to Freeman and Perez, a new technoeconomic shift therefore requires extensive economic, social and institutional change to deliver on its promise.²

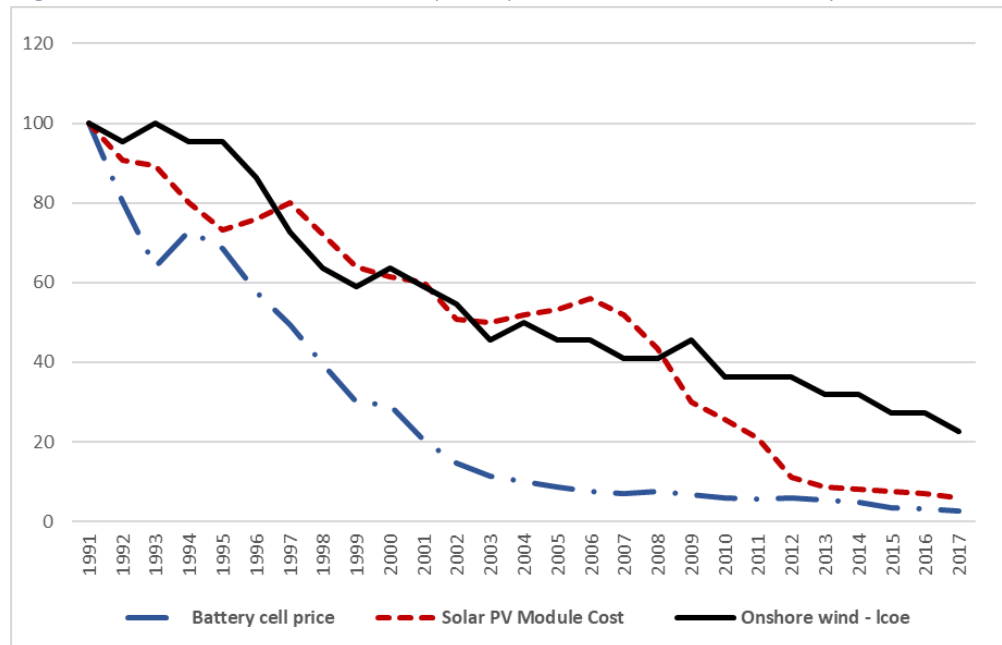
What we shall argue here, following Mathews (2013, 2014), is that the global green shift is an example of the same type of dynamics. The core factor in this case is cheap renewable energy, primarily wind and solar. Until recently, these so-called “new renewables” were considered prohibitively expensive compared to other ways to provide energy, e.g., from fossil fuels. However, during recent years the costs of renewable energy have come down considerably. The numbers are really eye-catching (Figure 1). Between 1991 and 2017 the

¹ For a more recent application of this perspective, with a focus on contemporary challenges, see Perez (2016).

² This is also an important point in the more recent social science literature on sustainability transitions. According to key contributors to this literature (Rip and Kemp 1998, Geels 2002, 2014), important sectors of society, such as the energy sector, are governed by “socio-technical regimes” adapted to dominant technologies and actors, which makes it difficult for new technologies with other characteristics to succeed. Important themes in this literature are, among other things, how such new technologies can develop in suitable “niches” (Kemp et al 1998), challenge the dominance of traditional technologies and actors, and eventually contribute to regime change. See Fagerberg (2018) for a comparison and discussion of different perspectives on how innovation - and policies affecting it - can contribute to a more sustainable society.

cost of producing electricity from onshore wind declined with 77 per cent. The similar statistics for solar, PV module cost per watt, is even more impressive, 94 per cent. In most contexts electricity from renewable energy is now the cheapest option. No surprise, perhaps, that the leading energy think-tank IEA, traditionally a close ally of the fossil fuels industry, now points to solar as “the new king of electricity supply” (IEA 2020).

Figure 1. Costs of Onshore Wind (LCOE), Solar Panels and Battery Modules, 1991-2017

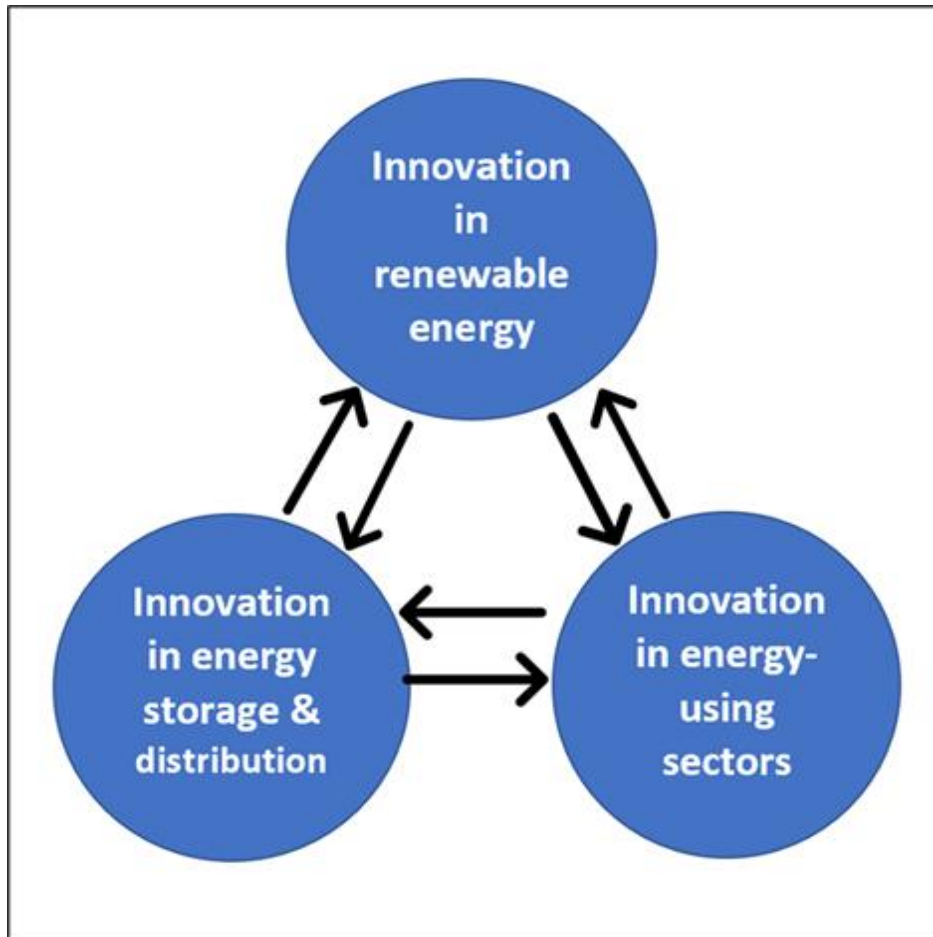


Note: The levelized cost of electricity (LCOE) from onshore wind, annual weighted average across the world, in 2016 USD per kilowatt-hour (kWh); Solar PV module cost per watt in 2019 USD; and price of lithium-ion cells(all types) per kWh in 2018 USD, in all cases with 1991=100. Own calculations on data from <https://ourworldindata.org/grapher/onshore-wind-lcoe> and <https://ourworldindata.org/grapher/solar-pv-prices>, both downloaded on February 15, 2022; and Ziegler, M. S. and Trancik, J. E., (2021a,b).

The global green shift is driven by interaction of innovations in three interrelated areas, that is, renewable energy, energy use, and energy infrastructure, e.g., storage and distribution (Figure 2). These innovation processes reinforce each other, as the two-way direction of the arrows in the figure indicates. Although the rate at which renewables have become competitive with fossil fuels is very impressive; perhaps the most important aspect is its impact on energy-using sectors, by allowing these to shift to new technologies using (green) electricity instead of polluting fossil fuels. This no doubt will require – and lead to – a lot of innovation, large and small, technological, organizational as well as institutional. This also holds for the third part of the system, energy infrastructure, which needs to change in tandem with the other parts to avoid an outcome where the entire process gets stuck. For example, electrification of energy-using sectors will require a massive increase in the capacity of the grid. Moreover, qualitative changes in the way the energy system works, for example the vast expansion in the number of energy producers that can be expected, many of which will be so-called “prosumers”, as well as the intermittent character of renewable energy, will require radical changes in how the system is organized and governed. In

addition, robust storage mechanisms will be a must. The rapid reduction in cost of batteries in recent years (Figure 1), in interaction with the fast-growing electric car industry (see later), may serve as an example of what will be needed.

Figure 2. The dynamics of the Global Green Shift



Source: <https://www.janfagerberg.org/the-global-green-shift/>

Electrification is a realistic and feasible strategy for achieving net-zero emissions in most cases. For example, green electricity can substitute for fossil fuels in power production, heating and cooling (in buildings for example), and powering of various types of machinery. This will also lead to massive energy savings, as electrical applications generally are more energy efficient than devices powered by fossil fuels. Another important way to save energy is increased re-use of materials and artefacts, that is, circular economy. Energy saving is an important element in the green shift, since it reduces the demand for renewables, and thereby frees up capacity and resources for the transition.³ Green electricity can also substitute for fossil fuels in many industrial processes, production of metals for example. In fact, in several cases – production of ammonia is a good example of that, the electric car is another - this implies a revival for electricity-based technological paths from the early part of the twentieth century, paths that were largely abandoned (or only survived in specialized

³ Energy saving may be particularly important in buildings, which currently accounts for about one third of global energy consumption (and one half of global electricity production).

niches) due to the competition from cheap and abundant fossil fuels. In other cases, electrification may be more challenging and require extensive innovation, as well as public policies supporting it. However, such innovations do not necessarily have to be very “high-tech” to contribute significantly to the green shift. For example, in heavy industries such as steel and cement (concrete), increased reuse of materials (circular economy) may substantially reduce emissions, while in the construction industry, substituting steel and cement with other materials, e.g., wood, may have a similar effect.

Box 1. Role of hydrogen in the green shift

Hydrogen is a flammable gas that can substitute for fossil fuels in most instances (Mathews 2022). It is the most common element in the universe but it does not exist naturally in pure form, so use of energy is required to split it from other substances. Deriving it from natural gas, which is composed of carbon and hydrogen, is currently the most common method (so-called grey hydrogen). But that leads to carbon emissions into the atmosphere, so to be environmentally sustainable, those emissions would have to be captured and stored somewhere, which is complicated and costly (so-called blue hydrogen). Blue hydrogen is the darling of fossil fuel producing companies and countries; however, they currently show very little appetite for undertaking the huge investments in storage and infrastructure that this would require, raising doubts about how realistic these plans are. Alternatively, hydrogen can be derived from water (hydrogen and oxygen) through electrolysis using green electricity (so-called green hydrogen), currently a rather expensive option, but which according to expert assessments (IEA 2021) is likely to become more cost-competitive over time.

However, using electricity to derive hydrogen implies a substantial loss of energy. Therefore, to use electricity directly – including via batteries - instead of indirectly in the form of hydrogen produced by electricity, will always be more economical. A key insight from evolutionary economics is that a technology, however promising, will only be selected if it offers better – and/or cheaper – solutions than competing technologies. Although hydrogen can perform a range of services in the economy that today are catered for by using fossil fuels, e.g., heating, powering machinery, or storing energy, the same can be said about electricity if used in combination with batteries and/or other complementary technologies (e.g., heat-pumps), and in most cases at a (much) lower cost.

Hence, the jury is still out with respect to the role of hydrogen in the green shift. However, hydrogen is already used in certain industrial processes, and that may well continue. Moreover, if a substantial volume of international trade in green energy develops, hydrogen may possibly play a role in facilitating that, especially over long distances and when electricity cables are not practical. In addition, hydrogen - or fuels based on it - may substitute for fossil fuels in activities for which batteries are not well suited, i.e., long haul shipping/flights, which currently stands for around 6-7 percent of global carbon emissions. A possible alternative to hydrogen-based fuels in these areas may be biofuels, however, it is doubtful whether production can be scaled up to the level required, since land suitable for producing biological materials for biofuels may also be well suited for producing food.

As recent history shows, technological change – innovation – can radically change perceptions of what’s possible to do, and what the most promising technological trajectories are. For example, some years ago, it was a common view in the car industry that battery-driven cars would never take off, and that the future was with hydrogen. The world’s leading car producer, Toyota, placed its bets on the latter. Progress in battery technology clearly invalidated that view, though, and as a consequence, production and sale of battery-driven cars has ballooned, while Toyota and other companies have struggled to find customers for their hydrogen vehicles. Moreover, electrification – with the help of batteries - is currently penetrating a range of other activities for which this was deemed very unlikely just a few years ago, such as lorries, buses, ferries, coastal shipping, and aviation on shorter routes. Arguably, the combination of rapid technological progress in renewables and innovations in complementary technologies may be expected to give rise to a range of powerful technological trajectories in different industries/sectors, processes that in many cases are still in the early stages.

Box 2. Nuclear power

An alternative to renewables, often highlighted, is nuclear energy, which currently accounts for about one tenth of global electricity production. After the second world war nuclear was widely seen as the most promising of all energy technologies. Nevertheless, safety concerns and problems related to disposal of waste (which remains radioactive for thousands of years) decreased the popular support for nuclear energy in many countries. Today, many nuclear facilities are old, and in the process of approaching the end of their lifetime. Moreover, partly as a result of attempts to respond to concerns about safety and waste, the cost of building new nuclear energy plants ballooned (Seba 2014), and nuclear is currently a much costlier way to provide electricity than through (for example) solar or wind. This arguably also holds for so-called small modular reactors (SMRs), which some see as more promising, even though they have the same safety and waste problems as conventional plants, and there are hardly any in operation yet (IEA 2022, Schlissel and Wamsted 2022). Furthermore, the economics of nuclear plants require these to run at a constant speed, which means that nuclear is not an ideal complement to highly variable energy sources such as solar and wind. It is therefore doubtful if nuclear power will play a greater role in the future global energy system than it currently does, although it cannot be ruled out that research may eventually come up with new, safer nuclear power technologies, for example fusion reactors. However, given the long time it takes for new, radical inventions to break through in practice, it is unlikely that these will contribute significantly on the road to a zero-emission society.

3. How the global green shift came about

After having laid out the dynamics of the global green shift, and identified its core elements, we will in the following trace the evolution of some of these elements from the very beginning to their present stance, with particular emphasis on the factors – including policy – that influenced their development. Since the core elements of the green shift are the new

renewables, i.e., wind and solar, we will especially focus on these. In addition, we include one energy using sector, road transport, which is currently in the process of being electrified.

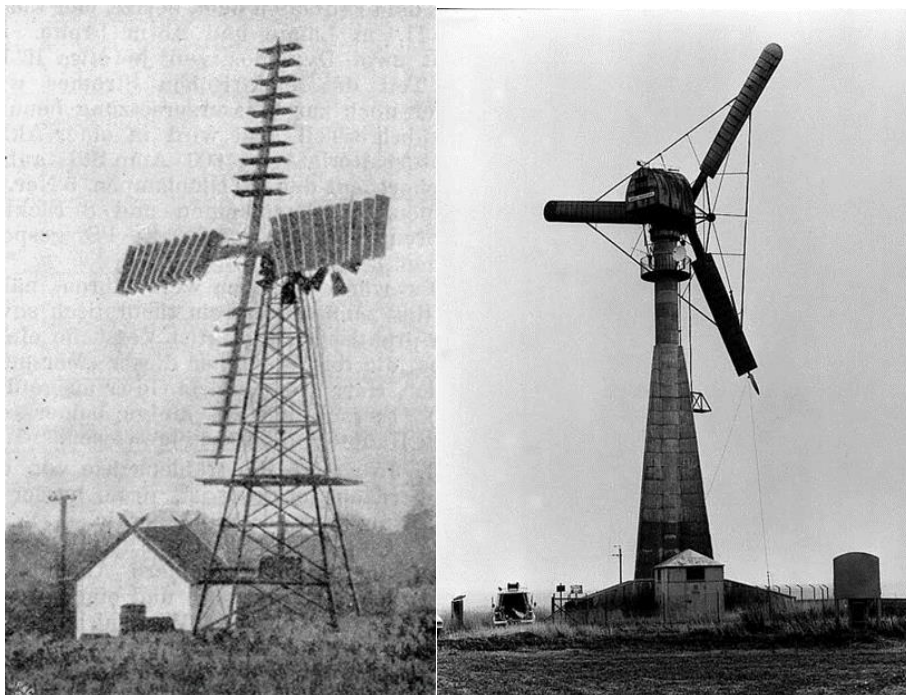
3.1 Wind

Windmills have been used to provide energy since ancient times, and it must have been tempting to try to use it to produce electricity when that came along. In fact, several attempts to do so were made by entrepreneurial individuals in different countries during the second half of the nineteenth century, and in the years that followed electricity-producing windmills, often in combination with rechargeable batteries, became quite common in several countries, particularly in rural areas (Box 3).

Box 3. Danish wind energy pioneers

During the years around 1900 the Danish inventor Paul La Cour, with economic support from the Danish state, ran what probably was the world's first R&D program on electricity-producing windmills at the Askov folk high school. In addition to constructing an electricity-producing windmill at the premises, he also founded a society for the promotion of electricity-producing windmills, started a journal promoting the spread of the technology, and organized an education program for "rural electricians" capable of installing and operating the windmills. This led to the installation of large number of electricity-producing windmills in the Danish countryside during the years that followed.

Figure 3. La Cour's windmill, Vallekilde (1905) & Juul's windmill, Gedser (1957)



Sources: *Elektrotechnische Zeitschrift* 1907, S. 902; <http://www.windpower.org/da/pictures/juul.htm>

La Cour's vision for electrification was a decentralized system based on direct current/low voltage. However, the system that came to be preferred in Denmark, as in other places, was

high voltage and alternating current, with well-developed national and regional grids and large production units using fossil fuels. Nevertheless, the experience during the second world war showed that an electricity-system dependent on (imported) fossil fuels may be quite vulnerable to disruptions. One of La Cour's students, Johannes Juul, therefore suggested – and achieved funding for – the construction of a windmill that could deliver electricity to the grid. Juul's windmill, completed in 1957, delivered electricity to the grid flawlessly for more than a decade. In spite of this, the Danish association of electricity producers decided against investing in wind energy, on the grounds that fossil fuels appeared cheap and plentiful, and that if a new technology was to be adopted, nuclear seemed to be more promising. However, Juul's efforts were not totally in vain, because when construction of electricity producing windmills resumed in Denmark a few decades later, they were based on Juul's robust three-bladed design, on the basis of which the Danish firms eventually conquered the world market (Karnøe and Garud 2012).

As electricity increasingly came to be produced in large units, powered (in most cases) by cheap and plentiful fossil fuels or nuclear energy, and grids became better developed, electricity-producing windmills gradually went out of use (i.e., they were selected against, because a seemingly superior alternative became available). Nevertheless, the 1970s and 80s saw a revival of interest in wind energy. An important reason was that the oil embargo imposed by the Organization of Oil Exporting Countries (OPEC) had created havoc in western economies, and policy makers' trust in fossil-fuel based systems was badly shaken. As a consequence, energy security rose to the top of the policy agenda⁴ in a number of countries, and this led among other things to better funding for R&D on alternatives to fossil fuels. Although most of this went to nuclear, research and experimentation with new renewables, particularly wind, also secured a boost. Moreover, there was increasing popular support for alternatives to the large scale, centralized and polluting systems that had come to dominate the energy sector, as the problems associated with the technologies adopted there, particularly nuclear, got more attention (Morris and Jungjohann 2016). This became of major importance for subsequent developments because it meant that a significant segment of the population had a positive attitude towards more environmentally friendly energy technologies, such as wind energy, and might be willing to engage with their diffusion and further development.

However, the revival of wind energy faced a number of obstacles. For example, the wind turbines that potential adopters could buy were expensive and of highly variable quality. In fact, many of the wind-turbines installed in California during the first half of the 1980s, when there was a boom in installations there, collapsed quite quickly, with negative implications for the technology's reputation. Moreover, the capacity of a wind-turbine normally exceeded the needs of a single user, and the intermittent character of electricity from wind also posed challenges. For example, strong wind might yield a lot of electricity, much above the owners' need. If this surplus had to be discarded, that would obviously create a strong disincentive

⁴ For example, in 1973 the US president Richard Nixon launched his "project independence" in response to the oil embargo and the resulting energy crisis (https://en.wikipedia.org/wiki/Project_Independence).

for potential adopters. To overcome such obstacles, not only technological innovation, but also organizational, political, and regulatory change, would be required.

To see how these various challenges were dealt with, we will here focus on the Danish case. Denmark became a hub for the emerging wind energy industry from the very beginning. As in other countries (e.g., Germany) it started with enthusiasts building their own electricity-producing windmills. Soon an association for sharing knowledge among the technology' adherents, as well as lobbying for support from policy-makers, emerged. Danish policy-makers responded by funding a technological support-centre for wind-turbines, as well as an investment subsidy for adopters, which was made contingent on approval of the design of the turbine by the support centre (Karnøe 1991). Another social innovation, which became of critical importance for the spread of the technology, was the establishment of local wind-turbine collectives – so called “vindmøllelav” - of which there were several thousands.

Eventually, a small industry supplying the necessary equipment emerged, either as startups or through migration from other, less promising industrial segments (such as the current market leader, VESTAS, originally a producer of agricultural equipment). Nevertheless, despite the investment subsidy, demand was sluggish in the early years, and several firms in the emerging industry struggled financially. The technology's supporters argued that for demand to take off, institutional change allowing owners to sell the (surplus) electricity to the grid would be required. Again, Danish policy makers responded, and as a result a so-called “feed-in tariff”, allowing wind-turbine owners to sell electricity to the grid at a “fair” price (reflecting the avoided cost for the utilities), was introduced in 1984.⁵ This regulatory innovation became of major importance for the subsequent development of wind energy in Denmark. It was subsequently adopted in several other countries, among them Germany, through a vote in the German parliament in 1990.

3.2 Solar

That sun rays exposing an appropriate medium could produce electricity had been known for a long time, long before Einstein in 1905 provided a scientific explanation for the so-called photoelectric effect (for which he received the Nobel price). In 1884 the New York - based inventor Charles Fritts had patented a working solar cell which used selenium as medium. The efficiency was very low, however, around 1 %. Nevertheless, Fritts' invention was applauded by the German industrialist Werner Siemens, who realized the technology's potential (Siemens 1885). Later the Siemens company developed plans for large scale solar cell plants in Northern Africa, using copper as medium, supplying Europe via cables, although these plans were for various reasons never realized (Nemet 2019). Instead, the torch passed to US researchers. What is commonly regarded as the first “practical” solar cell, with 6 % efficiency, was developed by three researchers at the Bell Labs in 1954, using silicon as the conducting medium.⁶ The stage was thus set for a process of further

⁵ A similar arrangement, based on new legislation to promote energy savings (PURPA – the Public Utility Regulatory Policies Act - 1978), was introduced in California at about the same time, leading to a boom in wind energy there (Nemet 2019).

⁶ The three researchers, Daryl Chapin, Calvin Fuller and Gerald Pearson, received a patent on a silicon-based solar cell, with the label "Solar Energy Converting Apparatus", in 1957. See https://en.wikipedia.org/wiki/Timeline_of_solar_cells.

improvement along this silicon-based trajectory, resulting, eventually, in a tripling if not more of the reported efficiency.

Figure 4. Vanguard 6, the first satellite with solar cells (1958)



Source: NASA

As is common for new technologies, the problem was to find an application for which solar cells had a competitive advantage. This was challenging, as solar cells were extremely expensive. The first satellite with solar cells was launched in 1958 (Figure 4). Solar cells were also used in other types of navigation equipment, and later – by Japanese firms – in such devices as portable calculators. Moreover, the increased focus among US policy makers on energy security - and alternatives to fossil fuels – during the 1970s and 1980s led to increased support for the technology's development, as well as an emerging solar energy industry in the US. In 1979 the then US president Jimmy Carter, a strong believer in the technology's potential, installed solar panels on the roof of the White House. However, his successor Ronald Reagan rolled back much of the public support to the technology's development (and spread), with the argument that such issues should be left to the markets. The return of cheap and abundant supply of fossil fuels during the latter part of the 1980s also influenced this change in the policy stance.

However, US policy makers were not alone in engaging with the technology's development. In fact, as support faded in the US, it increased in Japan, and with a comparatively stronger focus on civilian applications (solar panels). During a ten years period from the middle of the 90s onwards more than 200 000 solar panel installations were erected on Japanese roofs with public support. The purpose was to create a market with sufficient size (and growth) to stimulate the development of a dynamic domestic industry in this area, with the expectation that this would drive down the costs. Consistent with these expectations,

support levels to future installations were assumed to decrease over time. The policy worked as intended, prices on solar panels decreased by two thirds during the life time of the program, although the technology was still not competitive economically with other ways to produce electricity. Another effect was that Japanese firms, e.g., Sharp, replaced US firms as leaders in the emerging industry (Nemet 2019).

3.3 Germany's Energiewende

Germany had from 1990 a feed-in tariff for small electricity producers based on the “avoided cost” of the electricity distributors (which was tied to the price of electricity). While clearly advantageous for small producers of electricity, the policy failed to give a powerful stimulus to investments in new renewables. In fact, in 1998, when a new red-green alliance came to power, less than 1 % of German electricity came from wind and solar. To give a stronger stimulus to investments in the new renewables, the government financed several demonstration programs (Jacobsson et al 2004, Jacobsson and Lauber 2006). Moreover, and in retrospect even more significant, the new government decided to uncouple the feed-in tariff from the “avoided cost” of electricity distributors, and instead based the remuneration on the actual cost of producing electricity with the technology in question.⁷ The tariff became fixed for ten years, providing financial security for investors and, not the least, credit institutions. The cost of the scheme, that is, the difference between the remuneration to electricity producers and the “avoided cost” of electricity distributors, was financed through a surcharge on electricity consumption.⁸ This of course gave a much stronger incentive to invest in costlier, less mature technologies, such as wind energy and solar energy. Consequently, the share of wind and solar in German electricity increased very fast. As a result, by 2020 one third of German electricity consumption came from wind and solar (Fagerberg and Normann 2023).

The German push into renewables, i.e., the “Energiewende” (energy transformation), was not always plain sailing. Although supported by environmentalists, for example the anti-nuclear movements (that was very strong in Germany), and numerous local associations and municipalities, the policy also had powerful adversaries (Lauber and Jacobsson 2015). For example, it was opposed by the big electricity companies in Germany, that saw it as a threat to their established business model, involving generating power (based on nuclear energy or burning fossil fuels, especially coal) in big centralized operations, and representatives of industries and regions associated with it. Moreover, the policy was criticized by economists, and representatives of liberal and right-wing parties, for excessive intervention in markets, and for being much too expensive, thereby creating an unnecessary burden for German firms and households. The controversy lingered on for years, however, in the aftermath of the Fukushima-disaster (2011), German policymakers – led by the conservative chancellor Angela Merkel - decided to exit nuclear and continue the push into renewables. The UN

⁷ However, as in Japan in the case of solar energy, the remuneration for new vintages of a technology would be lower, due to assumed technological progress (so-called automatically decreasing tariffs).

⁸ This was relatively unproblematic as long as there was little renewable energy in the system but become more controversial as the share of renewables, and particularly solar (which for a long time was quite expensive), increased.

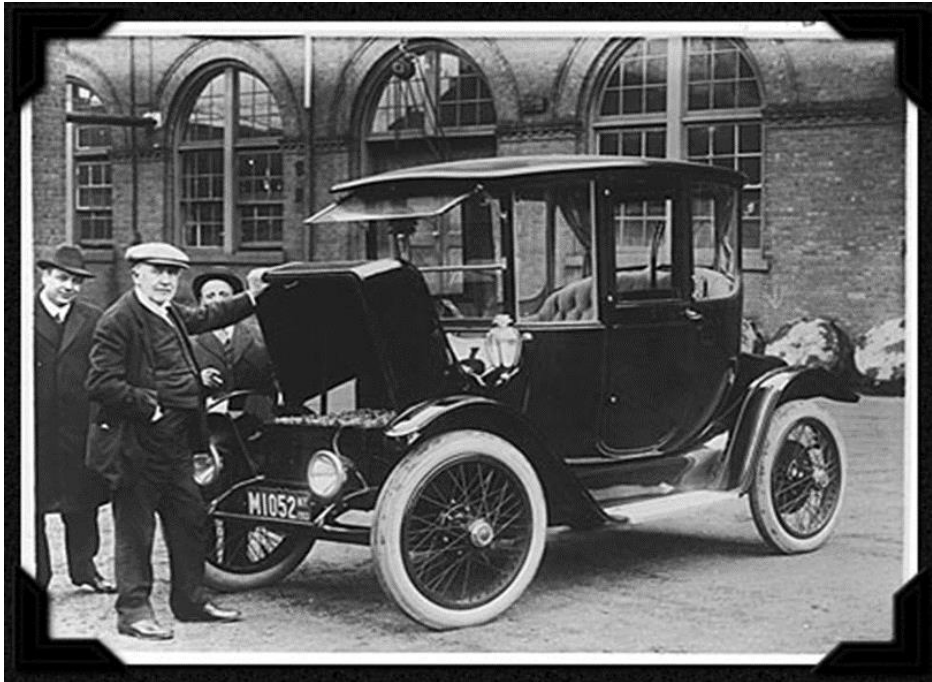
climate treaty from 2015, and the need to gradually eliminate GHG emissions, also provided legitimation to the policy.

One of the achievements of German policy in this area was to create a large and rapidly growing market for the capital goods required for producing green electricity. As expected, the prices on these goods declined over time, and as a consequence onshore wind, and eventually also solar, became the cheapest ways to expand electricity supply in most contexts. The policy became especially consequential for solar, at the outset regarded as an immature, high-cost technology, but which ended up as being the most cost-competitive option for increasing electricity production globally (IEA 2020). The policy also had favourable implications for German industry. For example, in the case of solar, German firms became global leaders, supplying solar panels and, increasingly, production equipment (e.g., turn key plants) worldwide. But the rapidly expanding German market also provided an opportunity for Chinese firms to enter the industry, initially for exports to Germany, but eventually also for the domestic market and elsewhere. Today China is by far the largest market for solar panels, and Chinese firms have replaced their German competitors as global leaders in the industry, much to the chagrin of the Germans. However, China's push into solar power has clearly contributed to speed up the green shift at the global level.

3.4 Battery-powered (electric) cars

It was the invention of rechargeable lead batteries in 1859 by the French physicist Gaston Planté that made electric cars possible, and in the early years of the automobile industry battery-powered electric cars became quite common. They had many advantages, e.g., were easy to drive, not noisy, did not pollute etc. , and were therefore quite popular. For example, the famous inventor Thomas Edison was an enthusiastic promoter of electric cars (Figure 5). However, the batteries were expensive, and, moreover, the range was quite short, up to 100 km. Edison was aware of the problem, and experimented with alkaline batteries, which had a range about twice as large, but carried an even higher price tag. And the range continued to be short compared to gasoline driven cars, which also were cheaper. As roads improved, and range became more important, electric vehicles were gradually driven out of the market (selected against), except in special niches, such as inside buildings, golf courses etc.

Figure 5. Thomas Edison with an electric car in 1913



Source: National Museum of American History

However, from the 1980s onwards there was a revival of interest for electric cars, and small entrepreneurial firms supplying electric cars emerged in several countries. This revival was not caused by a technological breakthrough in battery technology but by increasing public attention to the environmental advantages of electric cars. California's zero-emission-vehicle policy (ZEV), requiring a certain percentage of all new cars to have zero emissions, came to be particularly influential. To secure continuing presence in the lucrative Californian market, several car producers felt obliged to launch electric models, which in most cases were modified versions of existing (gasoline-driven) models and hence looked like "normal" cars. These models proved to be quite popular in certain customer segments. Nevertheless, the car producers generally withdrew them from the market following a successful challenge to California's stringent policy in US courts.⁹

The weak spot for the electric car had always been the battery, which had not improved much since Edison's time. Nevertheless, innovation in battery chemistry during the post second world war years eventually led to the development of the Li-ion battery, which was both lighter and more powerful than the alternatives. The Li-ion battery, commercialized by Sony in 1991, was initially primarily used in portable electronics of various kinds. However, it was also a potential game changer in the car industry, and in the course of a few years from 2008 onwards, several manufacturers, including newcomer Tesla but also established players

⁹ An alliance of big US car producers, backed by the Bush Administration, sued California over its Zero Emissions Vehicle (ZEV) policy, arguing among other things that it was in breach of federal law. On June 11, 2002 Judge Robert E. Coyle of the US District Court in the Eastern District of California issued an injunction against the policy, ruling it unconstitutional, and preventing the implementation of its most recent regulations. For details, see e.g., <https://www.nrdc.org/press-releases/californias-clean-cars-program-under-attack>.

such as Mitsubishi and Nissan, came up with new electric models utilizing lithium-ion batteries and, hence, operating with a much longer range than previous electric cars. It soon became clear that there was a market for electric cars, if only functionality and performance were sufficient. Due to the electric car's environmental advantages, it also benefited from various support schemes in a number of markets, and this also contributed to increasing sales. Nowhere were these support schemes more extensive than in Norway, which for that reason became a pioneer in the transition from fossil-fuel cars to electric cars (Fagerberg 2022). Strong market growth for electric cars, and continuous improvements in functionality and performance, have since gone hand in hand, and today it is a common assumption that it is only a matter of time before the fossil car is history (Box 4).

Box 4. Resource constraints?

A potential bump in the road for the global green shift often highlighted concerns possible scarcity of resources needed for the transformation. It is true that the supply of some minerals currently used in for example batteries (e.g., cobalt) is limited, and concentrated in a few locations world-wide that may give reasons for concern. Thus, if current production-methods are kept unchanged, a resource constraint on the global green shift seems likely. Nevertheless, such constraints can to a large extent be mitigated by innovation, e.g., by substituting scarce inputs with other, more readily available alternatives, and such innovations are in many cases well underway already. For instance, cobalt-free batteries for electric cars are reported to be just around the corner¹⁰. Moreover, value-chain innovation, leading to greater reuse of resources (i.e., circular economy) as well as energy savings, is another promising path, for which policy may have a large say. For example, the European Commission has recently proposed a new regulatory scheme for batteries, implying very high targets for collection and recovery of minerals (a 95% recovery rate for cobalt for instance)¹¹. Arguably, in the longer run a transition to a circular economy is a necessary condition for the global green shift to prevail.

4. Lessons for policymaking in support of the global green shift

The term “new renewables” indicates that these are regarded as fairly recent innovations. Similarly, the battery-driven car is often perceived as a novel technology. But as this chapter has shown, electricity from wind, solar cells, and electric cars, i.e., the core technologies in the global green shift, all date back to the latter part of the 1800s. Thus, the natural question is, why did it take so long for these technologies to prosper? The answer is simple: they lost out in the selection struggle during the first half of the 1900s. Alternatives based on fossil

¹⁰ <https://lmc-auto.com/news-and-insights/the-next-generation-cobalt-free-ev-battery-is-just-around-the-corner/>

¹¹ [https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI\(2021\)689337](https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2021)689337)

fuels (and later nuclear energy) were preferred because they were seen as providing the same services in a better way and/or at a lower cost. As a consequence, for many decades, ample resources were available for further developing technologies associated with fossil fuels and nuclear (Smil 2017), while the green alternatives received only minimal attention.

Nevertheless, as shown above, from the 1980s onwards there was a revival of interest in the green technologies. What were the reasons for this shift? The green shift was definitely not the result of a new wave of radical innovation, drastically increasing the competitiveness of the green technologies. In fact, improvements in the green technologies were mostly gradual, composed of many small steps, most of which took place at a later point in time.¹² Rather, the shift has to be attributed to changes in the selection environment, responding to a confluence of a number of different trends. An important source of change was no doubt the increasing attention by policy makers and society at large to “energy security”, and the perceived need to diversify energy supply, following OPEC’s embargo on oil supplies to the Western world in 1973-4. This change in the policy stance led, at least for a while, to more support to the development of energy technologies not based on fossil fuels, such as wind and solar. However, these efforts might not have been very consequential, if it hadn’t been for the increasing attention among parts of the population from the 1960s onwards to the environmental problems associated with production and use of energy, such as pollution from burning of fossil fuels and safety-issues in the case of nuclear energy. This led to increasing interest, and in many cases willingness to engage with, alternative technologies that did not harm the environment, even if this wasn’t very profitable economically. This is consistent with Elinor Ostrom’s argument that many are willing to contribute to the solution of collective problems, without necessarily gaining a lot themselves in the short run (Ostrom 2010). Being compensated for the extra costs of doing so may be more than enough. In addition, widespread scepticism towards the increasingly centralized nature of energy provision and a desire for having more local influence on this key aspect of human activity, so-called “energy democracy” (Morris and Jungjohann 2016), was another important motivation for change. The prospects for new jobs in emerging green activities also contributed to legitimate public support for initiatives in this area.

How did policymakers contribute to the green shift? In the beginning, experimentation with green technology, such as new renewables and electric cars, was often initiated by technology enthusiasts, and at a small scale. Following a process of self-organization, the adherents started to look for public support to their initiatives. Policy makers in several countries responded by supporting R&D and demonstration programs in these areas, as received thinking on innovation policy would indeed suggest (Fagerberg 2017). Nevertheless, it soon became clear that such programs, even when quite successful,¹³ were

¹² The only radical innovation worth mentioning is the switch to Li-ion batteries, which took place several decades later.

¹³ Which was not always the case, of course. For example, in the 1980s government-sponsored R&D programs in several countries aimed for a rapid scaling up wind-power technology, i.e., a classical example of so-called mission-oriented policy (Mazzucato 2013). However, the large sophisticated turbines that this research led to, such as Germany’s Growian or the MOD-turbines in the USA, all literally blew apart, and the programs were gradually abandoned (Morris and Jungjohann 2016). In contrast, the successful strategy, pioneered by Danish

not sufficient to widely diffuse the new green solutions, as the high costs of the new green technologies prevented demand from flourishing. However, to drive down costs, a large and rapidly growing market would be required.¹⁴ To address this dilemma policymakers developed support schemes compensating for the extra cost of choosing the more environmentally friendly solutions, e.g., investment-subsides, feed-in tariffs, as well as other benefits to adopters. These demand-oriented policy instruments (Edler and Fagerberg 2017) proved to be very effective, and in almost all cases led to larger – and swifter – changes than foreseen by policymakers or experts at the time (Fagerberg 2022). Hence, one of the most effective things policy makers can do to support the green shift is providing incentives for users to choose environmentally benign alternatives instead of polluting ones.

This being said, a few qualifications may be in order. The emphasis here on the effectiveness of demand-oriented policies, influencing selection, does not mean that supporting R&D and experimentation wasn't useful, or will not be required in the years ahead. Indeed, experimenting with different ways to solve challenges, in order to improve the knowledge about what the best choices are, remains an indispensable part of public policy.¹⁵ It just means that supporting such experiments will usually not be sufficient to widely diffuse new, green solutions, because the more established, polluting alternatives, having benefitted from many decades of R&D, learning, and gradual improvements, tend to be both cheaper and better aligned with the existing social and economic system.

Furthermore, although many think of demand-oriented policy as synonymous with subsidies, there is arguably more to it than that. In fact, in many cases subsidies may not suffice due to other hurdles that new green solutions face, e.g., lack of necessary infrastructure, misalignment with institutions, or regulations, requiring other types of policy interventions. For example, when policy makers in the USA, Denmark and other places in the 1980s decided to support wind energy, what they first tried was an investment subsidy. But that didn't do the trick because there were other hurdles, of an institutional nature, which could only be overcome through regulatory change (Fagerberg and Normann 2023).

Hence, successfully supporting new green technologies requires the ability to map the various factors that influence their development and spread, identifying possible factors blocking the process, and designing policy instruments (or mixes thereof) that specifically target such "blocking factors" (Bergek et al 2008), that may vary across contexts and technologies (Edler and Fagerberg 2017). Moreover, policymaking supporting the green shift is further complicated by the many actors, public and private, that influence the development and spread of the green technologies. This points to the need for effective policy coordination and alignment across different parts and levels of government, as well as with other stakeholders.¹⁶ Arguably, having a common vision for society's development

firms, was to focus on small, robust wind-turbines, based on existing designs (Box 3), and gradually improve and scale up through learning (Karnøe 1991, Karnøe and Garud 2012).

¹⁴ Arguably, several factors related to productivity growth/cost reductions depend on demand, such as learning, the development of an efficient value chain and the emergence of specialized capital goods suppliers.

¹⁵ See Kemp et al (1998), Bergek et al (2008), and Rodrik (2009, 2014) for treatments of why such policies are necessary and what it takes to succeed.

¹⁶ See, e.g., Braun (2008), Weber and Rohrer (2012), and Fagerberg and Hutschenreiter (2020).

might be of great help in this regard (Fagerberg 2018, EEA 2019). Although challenging to achieve, particularly in a democracy, the fact that the nations of the world at the UN's climate conference in Paris in 2015 agreed on working towards eliminating emissions of greenhouse-gases from human activities, committing each nation to make a plan for how to best contribute to this aim, indicates that this may indeed be possible. In fact, as documented in this paper, the process of replacing the fossil-fuel based system with a new, green system centred on renewable energy, i.e., the global green shift, is already well on its way. Embracing this shift, and adapting it to the specific national (or regional) circumstances, may be the best opportunity policy-makers have in the pursuit of net zero emissions.

The global green shift, although originating in the rich part of the world, offers great opportunities for countries at all levels for development. The centralized, capital-intensive model of electrification, based on fossil fuels or nuclear energy, never got an equally strong foothold in the developing part of the world as in present-day rich countries. In fact, a large part of the population in developing countries, particularly in Africa, do not have access to electricity and/or clean cooking facilities. Green electricity, particularly solar, offers a way out of this, since green electricity is more affordable, can be applied at all scales, and does not require access to a large, centralized grid. Electrification, combined with mobile telephony and access to the internet, may also stimulate entrepreneurship and innovation and, thereby, economic development more generally (Fagerberg et al, 2023). Thus, the global green shift is not only good for the climate, it may also be good for economic development.

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