UiO : University of Oslo

TIK **Centre for technology, innovation and culture**
P.O. BOX 1108 Blindern
N-0317 OSLO
Norway

Eilert Sundts House, 5th floor
Moltke Moesvei 31

Phone: +47 22 84 16 00
Fax: +47 22 84 16 01

http://www.sv.uio.no/tik/
info@tik.uio.no

TIK WORKING PAPERS on Innovation Studies

No. 20180216

http://ideas.repec.org/s/tik/inowpp.html

Senter for teknologi, innovasjon og kultur
Universitetet i Oslo

Mission (im)possible? The role of innovation (and innovation policy) in supporting structural change & sustainability transitions

By Professor Jan Fagerberg, Centre for Technology, Innovation and Culture, University of Oslo

Email: jan.fagerberg@tik.uio.no

Web: http://www.janfagerberg.org/

(**Version of 27.12.2017**)

Abstract

The topics addressed in this paper concern the (much-needed) transition to sustainability, the structural changes it entails and what role (innovation) policy can play in speeding up such changes. While it is easy to argue that innovation must play an important role in the transition towards sustainability, it is more challenging to provide good models for how policy may help in mobilizing innovation for this purpose. Such models, it is argued, needs to be based on the accumulated knowledge base on the role of innovation in social and economic change. The paper therefore starts by distilling some important insights on innovation from the accumulated research on this topic, and, with this in mind, discusses various policy approaches that have been suggested for influencing innovation and sustainability transitions. To allow for a more in-depth discussion the paper then goes into more detail about three cases in which policy arguably had a large impact, namely renewable energy in Denmark and Germany and electric cars in Norway. The final part of the paper sums up the discussion about the role of (innovation) policies in sustainability transitions.

Acknowledgements

This is a “scoping paper” for The Norwegian Research Council (project no. 271917). I would like to thank the many that in various ways contributed information and/or advise, in particular Jenny Chase, Tim Foxon, Peter Karnøe, Staffan Jacobsson, Rainer Kattel, Rene Kemp, Volkmar Lauber, Mariana Mazzucato, Christine Mee Lie, Sandro Mendonça, Håkon Normann, Carlota Perez, and Rannveig Røste. The responsibility for remaining errors or omissions is mine.

Introduction

The topics addressed in this paper concern the (much needed) transition to sustainability, the structural changes it entails and what role policy can play in speeding up such changes.

Economic growth has improved living standards, health and longevity across the globe, although the benefits have been far from evenly distributed. But it has also led to increasing pressure on scarce resources and ecosystems on which we depend, and continuing on the same track for ever would definitely not be sustainable.[1] The question arises if continuing economic growth is indeed possible in a world of finite resources. If so economic growth would need to be "decoupled" from its current resource-using and waste producing trajectory in the direction of a circular economy, in which scarce resources are not wasted but reused and provision of energy is based on renewable sources (Dietz and O'Neill 2013, Perez 2016). To arrive at this state, a lot innovation, and not only technological, will be necessary. That is why innovation - and policies supporting it – is essential for the transition to sustainability.

In particular, the practice of burning fossil fuels to provide energy has (in addition to local pollution) led to growing emissions of greenhouse gases into the atmosphere and, hence, steady increases in the global temperature, with potentially very negative environmental and economic consequences in the years ahead (Stern 2015). To avoid this outcome, emissions of greenhouse gases need to be reduced to almost zero before the end of this century, a goal that almost all nations now have agreed to.[2] This is a very demanding goal indeed, as 80 % percent of global energy is provided through burning of fossil fuels.[3] To reach this goal, extensive changes in technology, economic structure, governance, and ways of life will be required. Moreover, while fundamental changes of this nature historically have taken a long time to unfold, research shows that the transition to sustainability has to be well underway quite soon if very serious damage is to be avoided (Laestadius 2015). This clearly illustrates the urgency of the problem.

How can policy help in promoting such changes? In economics, the emission of greenhouse-gases is usually analysed as an unwarranted side effect of economic activity, which is allowed to go on unchecked because the polluter does not have pay for the damage. The obvious solution from such a perspective would be to introduce a price on the emissions, for example in the form of a carbon tax (or cap and trade) leading, it is argued, to less emissions and a switch from polluting to more environmentally benign activities (Nordhaus 2013). While intuitively appealing this policy approach has not worked so well in the case of greenhouse-gas emissions.[4] One reason may have to do with

---

[1] Sustainability can be defined very broadly, as in the seventeen sustainable development goals (SDG) agreed to by the United Nations (http://www.un.org/sustainabledevelopment/sustainable-development-goals/), or more narrowly as the ability of the economy to "function within the capacity provided by the earth's ecosystems" (Dietz and O'Neill 2013, p. 46). However, the latter (which is the central focus here) is obviously of vital importance for the former.

[2] The Paris climate agreement (or convention) was adopted by consensus between 196 parties at the 21st Conference of the United Nations Framework Convention on Climate Change (UNFCCC) in Paris on 12 December 2015. As of December 2017 171 parties have ratified the convention (http://unfccc.int/2860.php).

[3] See https://data.worldbank.org/indicator/EG.USE.COMM.FO.ZS, addressed on November 30, 2017.

[4] The EU European Trading System (ETS) is the world's first and biggest international emissions trading system and covers almost half of the EU's greenhouse gas emissions (Begg 2015). However, for the last five years the price for emitting a ton of $CO2$ has fluctuated around 6 Euro, only a small fraction of what would be necessary for having the desired impact on emissions (Nordhaus 2013, Laestadius 2015). Among the reasons for this are

"political economy": While the theory presupposes a powerful social planner able to impose new taxes or similar types of arrangements, in reality politicians are faced with stiff opposition when considering doing so. Furthermore, the global nature of the problem, and the lack of a similarly global governance system, also adds to the challenge (Smith 2017). Another reason may have to do with lack of affordable, environmentally benign alternatives. This is of course where innovation – and policies affecting innovation - becomes important. In fact, even a well-functioning carbon tax (or cap and trade) system would only allow for the currently most "cost effective", i.e., technologically mature, alternative, and leave the more immature (but not necessarily less promising) technologies, that we may also badly need, unsupported (Lauber and Jacobsson 2015). Moreover, as Acomoglu et al (2012) point out, without innovation - and innovation policy - the major impetus towards change would have to come through a depression of economic activity (in reaction to hefty environmental taxes) with large, negative consequences for welfare and employment. Hence, carbon pricing, while important, should be seen as a supplement to innovation policy, not an alternative.

While it is easy to argue that innovation must play an important role in the transition towards sustainability, it is much more challenging to provide good models for how policy may help in mobilizing innovation for this purpose. An important presumption for what follows is that policy advice needs to be anchored in the accumulated research on the issue at hand. We therefore start, in the next section, by distilling some important insights on innovation from the accumulated research on this topic and, with this in mind, discuss various policy approaches that have been suggested for influencing innovation and sustainability transitions. To allow for a more in-depth discussion we then go into more detail about three cases in which policy arguably had a large impact, namely renewable energy in Denmark and Germany and electric cars in Norway. The final section concludes about the role of (innovation) policies in sustainability transitions.

2. Innovation, sustainability transitions and policy

How can policy help mobilizing innovation in the transition to sustainability? An answer to this question needs to be based on our knowledge on innovation and the factors influencing it, which for half a century if not more has been the main focus of the interdisciplinary research field of innovation studies. The discussion that follows builds on the accumulated knowledge base of that field.[5]

A social theory of innovation

Innovation was for a long time a neglected topic in mainstream social science. The main exception to this rule was the Austrian-American economist Joseph Schumpeter, who already a hundred years ago developed an original theory of innovation as the driving force of long run economic and societal change.[6] The main focus was, just as in some of the more recent work on sustainability (e.g., Daly 2008), not on economic growth per se but on qualitative changes in the composition of output, the

---

a much too lax policy with respect to allocation of free emission rights and an apparent inability to tighten up the regime when the price plummeted in 2011.

[5] However, we do not aim for a complete overview, but select what we find most relevant for our discussion. For overviews of the knowledge-base on innovation see Fagerberg et al (2004) and Hall and Rosenberg (2010).

[6] Schumpeter's main works were "The theory of economic development", published in German in 1912 and in a revised English edition in 1934, and "Capitalism, Socialism and Democracy" from 1942. There is a large literature on Schumpeter's life and works, see e.g., McCraw (2007) and Andersen (2011). For a brief introduction to Schumpeterian theory and its subsequent application by others see Fagerberg (2003).

organization of economic activities, and the structure of the economy. Schumpeter made a sharp distinction between invention, i.e., new ideas for how to do things, and innovation, that is, the ability to carry these out in practice, because:

"As long as they are not carried out into practice, inventions are economically irrelevant. And to carry any improvement into effect is a task entirely different from the inventing of it, and a task, moreover, requiring entirely different kinds of aptitudes." (Schumpeter 1934, p. 88).

According to Schumpeter innovation comes in many different shapes, e.g., not only technological but also organizational, and different sizes, ranging from very radical innovations, such as railways, electricity or use of fossil fuels as a power source, that might totally revolutionize the society and the economy, to minor changes in existing products and processes. However, his main interest was in radical innovation and the conditions for getting social acceptance for it. Radical innovation was according to Schumpeter very demanding, primarily due to the fundamental uncertainty characterizing radical innovation (most innovations do indeed fail, often for reasons that cannot be foreseen), but also because of the inert nature of the social contexts into which innovations are introduced, leading to social resistance to new initiatives.[7] In his view, an important reason for the proliferation of social inertia has, in addition to "legal and political impediments" (ibid, p. 86), to do with the embedded nature of knowledge, habits and routines in society. According to Schumpeter, "this enormous economy of force" (i.e., routinized knowledge), which is essential for economic activity, also makes "every step outside the boundary of routine appear much more difficult", or as he put it:

"in the breast of one who wishes to do something new, the forces of habit raise up and bear witness against the embryonic project" (ibid).

Schumpeter also provided us with a theory of innovation as "new combinations". What is new is not necessarily the constituent parts but the way they are put together. Hence, contemporary innovations draw lessons from past innovation activity, while future innovation will be influenced by what is done here and now. This may give rise to innovation paths or trajectories influencing innovation activity and economic development for considerable periods of time (Dosi 1982, Freeman et al 1982, Freeman and Louçã 2001). Therefore, as Schumpeter repeatedly stressed, a historical perspective is essential when analysing innovation, the social conditions underpinning it and the role of policy,

In this combinatory dynamics, the innovative firm draws on various resources such as knowledge, skills, and finance, and its possibility to succeed critically depends on being able to mobilize these resources (Fagerberg 2004). The innovative firm also depends on the institutional framework into which it is embedded, and - not the least - on whether there is a market for its innovations: Innovations that are not sufficiently appreciated by potential customers, that is, are selected against, are doomed to failure. Moreover, these various factors generally are complements rather than substitutes. For example, it is of little help to have access to some potentially interesting knowledge, if you lack the skills to exploit it, the required financial backing for doing so or if demand is lacking.

---

[7] As he explains, "this resistance manifests itself most of all in the groups threatened by the innovation, then in the difficulty of finding the necessary cooperation, finally in the difficulty of finding consumers" (ibid, p. 87).

There are important lessons from this, not only for firms (that tend to learn this the hard way), but also for policy-makers that wish to encourage innovation for a specific purpose or to vitalize the economy more generally. That is, to succeed with innovation support it is not sufficient to focus one particular resource, say knowledge, because there may be other constraints that are equally or more relevant. Thus, a holistic perspective on innovation, focusing not only on supply but also demand factors, is essential for success in innovation policy (Edquist 2004, Edler and Georghiou 2007, Edler and Fagerberg 2017, Kemp 2011).

Supporting radical innovation

One of the most salient features of radical innovation is that it takes time, often several decades if not more. As Nathan Rosenberg and Stephen Kline explain:

" … most important innovations go through drastic changes in their lifetimes – changes that may, and often do, totally transform their economic significance. The subsequent improvements in an invention after its first introduction may be vastly more important, economically, than the initial availability of the invention in its original form" (Kline and Rosenberg 1986, p.283)

Hence, as they point out, the first versions of an innovation are often unpractical, costly devises that have problems in reaching out to customers in large numbers. History is replete with examples, e.g., when the first cars appeared towards the end of the 1800s they were generally regarded as expensive (and unreliable) toys for the rich. Moreover, the first computers, appearing about half a century later, were extremely large, expensive and with little computing power compared to, say, a present-day smart phone, and therefore with very limited market appeal except for the US military and a few other customers. Similarly, when solar cells were invented in the 1950s, they were very costly compared to other ways to generate energy and attracted little commercial interest except – after a while - for use in the US space missions (Jacobsson et al 2004). Thus, as in many other cases the creation of a niche market or "protected space" turned out to be essential for developing the innovation (e.g, increasing performance and reducing costs through learning and economies of scale) so that it eventually would get broader acceptance.

It is not surprising, therefore, that the creation and support of such niches have been recognized as useful tools by policy-makers that wish to support the development of a specific innovation (or innovations for a specific purpose). Particularly in the US such "mission-oriented" policies (Ergas 1986) have been carried out with great vigour by, say, military, space and health agencies (Mowery 2011) and many important innovations that eventually would have a large economic and societal impact have benefitted from these efforts (Mazzucato 2013). Support of niche-markets may thus be considered as a possible way forward in sustainability transition (e.g., strategic niche management,[8] see Kemp et al 1998). However, mission-oriented policies (or strategic niche management) require very capable policy makers (or managers) and stringent procedures to avoid the many traps that such a project easily may fall into. These include e.g., aborting the project too early; premature lock-in to a specific technological trajectory (before the pros and cons of various alternatives have been properly explored); or capture by special interests (within the private business sector for example). As Dani

[8] Kemp et al (1998, p. 186) defines it as follows: "strategic niche management is the creation, development and controlled phase-out of protected spaces for the development and use of promising technologies by means of experimentation , with the aim of (1) learning about the desirability of the new technology and (2) enhancing the further development and the rate of application of the new technology"

Rodrik[9] explains, insulating the innovation project from relevant private actors (as some might suggest) is clearly not a good idea, as it would reduce access to critically important knowledge and hamper the learning that the project was intended to achieve. Nevertheless, as he point out, it is vital that the autonomy of government is retained through appropriate project design. He suggests that a design emphasizing clear goals/targets that are enforced; transparency; and accountability may go a long way in doing so.

While potentially a very powerful tool, most successful examples of past mission-oriented policies (see, e.g., Mowery 2011, Mazzucato 2013) refer to cases where a single public agency both finances the project and is the final user, which arguably makes the governance of the process a whole lot easier. However, as Mowery et al (2010) points out, transforming the economy to sustainability is a much more complex task, involving multiple technologies, extensive structural change and a large number of users within or across sectors. Hence, as they suggest, to discuss these matters a broadening of the perspective from entrepreneurial dynamics within niches to what happens at the meso and macro levels may be required.

Changing (technological) regimes

The role of large, established firms in existing sectors for innovation and diffusion became one of the most central issues in post-war innovation studies. In a series of works, culminating with the book "An evolutionary theory of economic change" from 1982, Richard Nelson and Sidney Winter outlined a novel theory on the matter that eventually became very influential.[10] According to Nelson and Winter the central competitive asset of large firms is the organizational knowledge they posit, consisting of a set of routines for action that is reproduced (and adjusted) through practice. As a result, large, established firms are path-depended creatures and

" much better of the tasks of self-maintenance in a constant environment than they are of major change, and much better in changing in the direction of "more of the same" than they are at any other kind of change"(Nelson and Winter 1982, p. 9-10).

Thus, large firms in established sectors are analysed as highly efficient but rather inert organizations working under a common umbrella, a "technological regime" (Winter 1984), reflecting a common understanding of "how things are done" in the sector. It follows that for entrants to question such established routines and compete with the incumbents may be quite challenging indeed.

This perspective has been adapted to the analysis of sustainability transitions by Arie Rip and Rene Kemp (Rip and Kemp 1998) and other (mainly Dutch) scholars (e.g., Geels 2002, 2015, Geels and Schot 2007) under the label "multi-level perspective" (MLP).[11] Three levels are highlighted in the analysis: the macro-level (labelled "landscape") which is assumed to change slowly and for reasons that may be seen as "exogenous"; the meso-level, which is dubbed "technological" (or –

[9] Rodrik uses the term "green industrial policy" for policies that arguably might equally well have been characterized as green innovation (or technology) policy. He defines it as policies that "stimulate and facilitate the development of green technologies" (Rodrik 2014, p. 488).
[10] Nelson and Winter (1982) is the most cited work in innovation studies (Fagerberg et al 2012) and is also very popular among management scholars but receives much less attention in economics proper (Meyer 2001).
[11] This has given rise to a burgeoning literature, for overviews see e.g., Smith et al. (2010) and van den Bergh et al. (2011).

alternatively - “sosiotechnical”) regime;[12] and the micro-level, the “niches”, which is where the development of radical new technologies - the experimentation - is assumed to occur. However, a new, radical technology, even if successful in a narrow technological sense, also needs to be accepted by the broader regime structuring the relevant part of the economy, and this is seen as challenging due to the assumedly inert nature of such regimes. Therefore, much of the focus in this literature has been on the conditions under which such new, radical technologies, developed in niches, can become more broadly accepted and eventually contribute to regime change in, say, a more sustainable direction.[13]

Out of these concerns emerged an innovative policy approach, labelled “transition management” (Rotmans et al. 2001, Kemp et al 2007, Loorbach 2010), for how to address complex policy challenges of a long-term nature (such as sustainability transitions), challenges that arguably do not get the attention they deserve due to the short-term focus of traditional politics (e.g., electoral cycles). It does so by creating a separate space – a transition arena (or platform) – with the purpose of transforming general policy goals into concrete visions, which in turn are used to develop possible transition paths for how to connect the present with the future. A transition arena should according to Loorbach (2010) be led by a small number of so-called “frontrunners”, i.e., very capable and motivated people that participate in a personal capacity but with a background from “the societal pentagon: government, companies, NGOs, knowledge institutes, and intermediaries” (ibid, p.174). To explore the transition paths and facilitate learning practical experiments (e.g, strategic niche management) are suggested. Continuous monitoring and evaluation are recommended to encourage policy learning (Voss et al 2009, Loorbach 2010).

The approach was adopted by Dutch policy-makers in 2002 under the auspices of the Ministry for Economic Affairs and a number of transition platforms, composed of individuals from the private and public sector, academia and civil society, were established focusing on various issues of relevance for the transition to sustainability. The process resulted among other things in a “transition action plan”, containing ambitious goals for e.g. cuts in greenhouse-gas emissions and improvements in energy efficiency, as well as a number of concrete initiatives aimed at supporting the transition in various ways. It also led to closer cooperation between different parts of government (Nill and Kemp 2009). However, the approach has been criticized for being overly technocratic and for paying too little attention to democratic processes (Hendriks 2009, Schmitz 2015). Moreover, in practice transition management in the Netherlands proved vulnerable to capture by incumbent interests from the established oil and gas industry (Smith and Kern 2009). In 2011, following the formation of a new and more conservative government, the program was formally terminated (Kemp and Never 2017). Arguably, what this shows is, as Voss et al (2009) point out, that in a democracy there is no escape from the need for strong support from the broader polity for pursuing radical change at the societal level through dedicated policy arrangements.

---

[12] Rip and Kemp define “technological regime” as follows: “A technological regime is the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems - all of them embedded in institutions and infrastructures” (Rip and Kemp 1998, p. 338). Geels (2002) suggests the notion “sosiotechnical regime” for the same phenomenon.

[13] The interaction between the regime and the landscape levels, e.g., how differences in the pressure for change at the macro level may influence regimes and, depending also on the underlying technological dynamics, open up for different “transition pathways” is discussed by Geels and Schot (2007).

Adapting to technological revolutions

As already pointed out by Schumpeter (Schumpeter 1939), radical innovations differ with respect to how pervasive their economic effects are. While some radical innovations may influence a specific sector or industry only, others may affect a whole range of sectors or, in rare cases, the entire economy. Christopher Freeman and Carlota Perez use the term "technological revolutions" (or – alternatively – "changes in techno-economic paradigm") *for "changes in technology systems (that) are so far reaching in their effects that they have a major influence on the behaviour of the entire economy" (Freeman and Perez 1988, p. 46-7)*. The defining feature of a technological revolution, they argue, is the existence a cheap key input characterized by rapidly declining costs, almost unlimited supply and very broad applicability (ibid, p, 48). This is assumed to lead to a virtuous circle, in which both the industry producing the key input and industries using it extensively (the "carrier" branches) grow very fast, resulting in rapid productivity growth and extensive structural changes in the economy as a whole. Examples of such key inputs suggested by Freeman and Perez are oil during much of the twentieth century and microelectronics more recently.

According to Freeman and Perez, for such path-breaking innovation to come to (full) fruition, a number of complementary factors need to be in place, not only in the form of an appropriate infrastructure (although that may be essential), but also involving new ways of organizing economic activities and the society at large. However, such complementary factors take time to develop, and a mismatch between the requirements of an emerging technological revolution and the existing socio-economic framework, or "structural crises of adjustments" (Freeman and Perez 1988), may therefore occur. In the course of time, though, such technological, economic, organizational and social features would be expected to coevolve into a tightly integrated and mutually reinforcing system or, as they call it, a "dominant technological regime" (ibid, p. 47). Nevertheless, although a technological revolution may be quite dynamic for a prolonged period, sooner or later much of its extraordinary growth potential will be exhausted (Abernathy and Utterback 1978). At this stage, the technological regime will be characterized by a high degree of inertia, and consequently acts as powerful barrier to new, radical initiatives that challenge the system, as also emphasized by the MLP-literature discussed above. Unruh (2000,2002) suggests the term "techno-institutional complex" for this phenomenon , which he argues contributes to lock-in actors and resources to the existing, fossil-fuel based system ("carbon lock-in") and hamper the development and diffusion of more novel, climate-friendly technologies.

Much of the literature in this area focuses on the characteristics and delineation of successive technological (or industrial) revolutions from a historical perspective (see, e.g., von Tunzelmann 1995, Freeeman and Louçã 2001, Perez 2002). More recently, Perez (2016) has used this perspective to discuss the challenges ahead, the economic and social changes it entails, and the implications for policy. According to Perez, the global economy currently is in the middle of the ICT revolution and there are still large potential gains to be reaped. However, the prospects for succeeding in this depend in her view crucially on policy-makers' abilities to give the ICT-revolution an appropriate direction, which she suggests to call "green", implying among other things a transition to a sustainable (circular) economy,[14] all within the framework of continuing globalization, which she

[14] This includes e.g., an increasing emphasis on product quality, durability and repair; an increased share of services/intangibles in the economy; and renting (sharing) substituting for ownership, all made possible through exploitation of ICTs and policy changes (e.g., taxes).

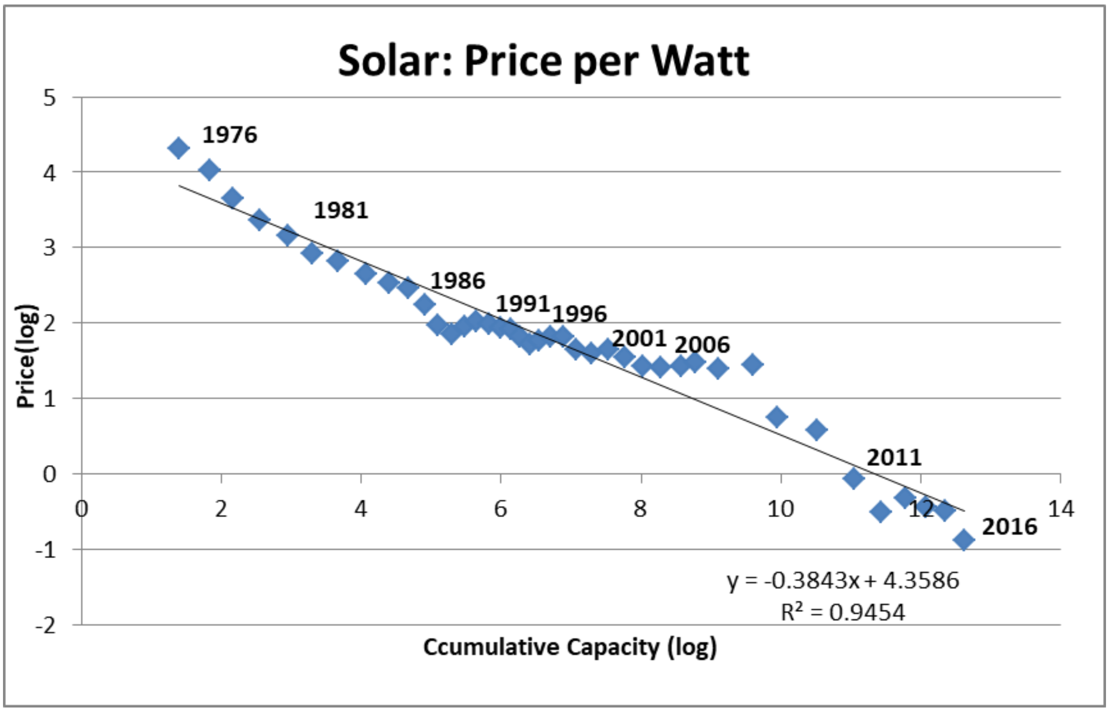
sees as “an economic necessity” (ibid, p. 203). To successfully adapt to these changes, Perez argues, a new social model based on frequent job shifts (substituting for fixed employment), increased life-long learning and some form of basic income will be required (ibid, p.212).

Perez’ insistence on seeing technological, social, institutional and political change as interrelated processes is arguably very much to the point. However, countries differ a lot in how they combine technological dynamics and social, institutional and political adaptation, and different configurations may well be equally efficient (Fagerberg 2016). Thus, it is not obvious that one social model will fit all. Moreover, while her description of the need to move in the direction of a circular economy seems well taken, there is surprisingly little attention to the unfolding revolution in renewable energy, arguably one of the most dynamic features in the global economy today, see Box 1.

Box 1 A renewable energy revolution?

The high income that we in the Western world enjoy is not only based on knowledge but also on energy provided in the form of fossil fuels (Fouqet 2016). However, burning of fossil fuels leads to climate change that threatens the very basis for our civilization. Is there a way out of this dilemma? Renewable energy may be the key to a solution.

Figure 1 A technological revolution in the making?



Note: “Price per watt” is the average price of a photovoltaic (PV) module (in real 2016 US dollars) divided by its rated DC output power in watts. “Cumulative capacity” in a specific year is the sum of the rated DC output power in watts of all PV modules produced prior to that year (starting in 1976). The regression underlying the trend-line is included in the lower right of the figure. Source: Own calculations based on data from Bloomberg New Energy Finance (with contributions from IEA and Paul Maycock).

The sun is an abundant source of energy. Only a tiny share of the sunshine that reaches earth during a year would be sufficient to cater for all human needs. The sun is the ultimate source of hydroelectric energy (rain), bio-energy (photosynthesis), wave energy, wind energy and solar energy. Hydroelectric energy, as has been important in Norway, is clean and relatively inexpensive, but the prospects for massively scaling up production of it globally are bleak. Bio-energy may not play a major role either because the photosynthesis is a relatively inefficient way to convert sunshine to other, usable forms of energy; it demands a lot of water (which is a scarce resource); and it competes with producing food (which also is in limited supply) to a growing global population (Seba 2014). Wave energy has not really caught on but wind and solar have, particularly during the last few decades (Seba 2014, Goodall 2016).

Can renewable energy from wind and solar, complemented with other renewable sources, be sufficient to cater for humanity's needs? In fact, for both wind and solar the costs of producing electricity has diminished year by year (i.e. productivity has increased) as output has expanded (Figure 1). As a result cost-levels for renewables now are substantially lower than those of e.g., nuclear energy plants (Seba 2014), and - in many if not most locations world-wide - on pair with or below plants producing electricity by burning fossil fuels (Goodall 2016) even when the social costs associated with greenhouse gas emissions are not accounted for. This pattern, i.e., rapidly falling costs, potentially almost unlimited availability and very broad applicability, is as several observers have pointed out reminiscent of previous technological (industrial) revolutions, see, e.g., Mathews (2013, 2014) and Stern (2015).

A global energy-system based on renewables, particularly wind and solar, means that the whole world will have to go electric. For example, the entire transport-sector – a major emitter of greenhouse-gases world wide - would have to be electrified, either battery-driven or by using fuels derived from renewable energy. A severe challenge, though, in an energy system based on renewables is what to do when the wind doesn't blow and/or the sun doesn't shine? To alleviate such problems energy-storage facilities and management systems will have to be improved, and this is currently a hot area for innovation world-wide.

The prospect of a renewable energy revolution raises several interesting questions. For example, what about the speed of transition, can it happen in time, so that the most damaging effects of climate change may be avoided? Energy research has shown that previous energy transitions have taken several decades if not more to unfold (Wilson 2012, Smil 2016), but also that change may occur much faster when advantages for end-users are sufficiently large (Grubler 2012, Pearson and Foxon 2012) and/or there are proactive policies in place (Sovacool 2016).

Transforming innovation systems: The role of (innovation) policy

In the aftermath of the OPEC oil crisis in the 1970s, the global economy entered a long period of slow growth, structural problems and unemployment. Traditional economic policies appeared to have little effect. It was in this context that a perspective focusing on innovation as the source of economic change, innovation systems as frameworks for shaping such dynamics (Freeman 1987, Lundvall 1992, Nelson 1993), and innovation policy as the main tool for influencing it (Rothwell 1982), started to gain currency among policy makers. This perspective - and the associated concept "national innovation systems" [15]- quickly became quite popular, not the least through the involvement of the OECD,[16] which adopted it in its analyses and evaluations of innovation policies in member-states.[17]

As pointed above, a defining feature of Schumpeterian theory is the insistence on seeing innovation as a social phenomenon, in which many different assets are combined, and a variety of actors, both inside and – not the least - outside the innovative firm, take part and influence the outcome. The innovation system approach extends this perspective by taking into account a host of empirical research[18] from the 1970s onwards on firm level innovation, highlighting the importance for successful innovation of continuous interaction between firms and their environments (e.g., customers, suppliers, various public and/or private sector organisations etc.). This led to a strong focus on the possibilities for vitalizing the system through improved interaction between its constituent parts, for example by identifying and dealing with factors hampering such interaction (Bergek et al 2008) or by improving the capabilities of system actors (including those of the policy makers themselves, see e.g., Edler and Fagerberg 2017).

Another central characteristic of the approach, consistent with its Schumpeterian origin, is a strong historical focus. National innovation systems are seen as developing over time through interaction between central economic actors, i.e., important industries and firms on the one hand and the broader "knowledge infrastructure" and political system in which they are embedded on the other hand (Fagerberg et al 2009). However, since countries specialize in different economic activities (with different needs for support etc.), and political systems differ too (for, say, historical reasons), such national systems may end up looking rather different. For example, there are large differences between otherwise quite similar countries when it comes to character of the public "knowledge infrastructure" and its interaction with the private sector (Fagerberg 2016). Such structural differences should not necessarily be regarded as a problem for policy-makers, though, as different set ups may well be equally efficient (Fagerberg 2004, 2017). Arguably, it is only through a concrete analysis of the dynamics of a system that it is possible to identify issues that require policy makers' attention (Edquist 2011).

Nevertheless, despite such (historically produced) differences in system architecture, what goes on in such systems, i.e., the various processes a system entails, may have a lot in common. Therefore, the exploration of how such processes interact in shaping the dynamics of the national innovation system has become a central focus in recent scholarly work in this area (Liu and White 2001, Edquist 2004, Bergek et al. 2008, Fagerberg 2017).[19] The implications of this for policy may usefully be

---

[15] The innovation system approach can be applied at different levels of aggregation, e.g., a specific technology (technological innovation systems, see Bergek et al. 2008), the sector or industry level (sectoral innovation systems, see Malerba 2004), the regional level (regional innovation systems, see Asheim an Gertler 2004) and, finally, the national level, which is the main focus here. For an overview and discussion see Edquist (2004).

[16] See, e.g., OECD (1997, 1999, 2002).

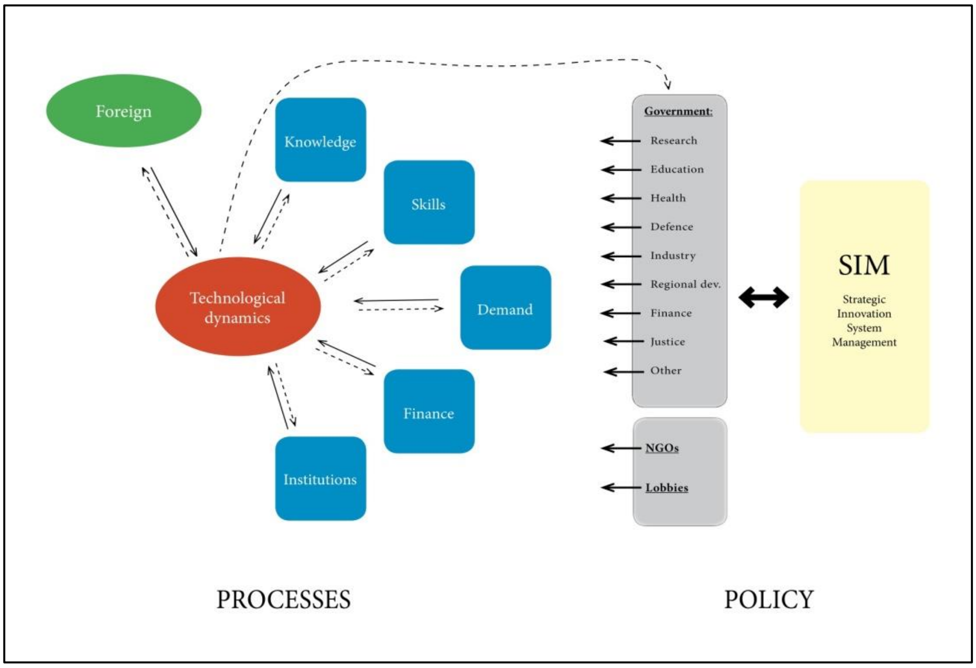
[17] For information on "OECD Reviews of Innovation Policy" see http://www.oecd.org/sti/inno/oecdreviewsofinnovationpolicy.htm.

[18] E.g., Freeman (1974), von Hippel (1988), Levin et al (1987) and, not the least, the European Union's Community Innovation Survey (CIS), conducted regularly from the early 1990s onwards, for an overview see Smith (2004).

[19] In this literature, the factors influencing innovation have invariably been called activities, processes or functions, here the term "processes" will be used. The number and description of these processes differ somewhat across the different applications, to some extent related to differences in focus, but the five

discussed in relation to Figure 2, which links the output of the national innovation system, called "technological dynamics", to five generic processes influencing it, labelled knowledge, skills, demand, finance and institutions,[20] i.e., the same as emphasized in our earlier discussion of firm-level innovation. In the Figure, the influences of these processes on the technological dynamics are indicated by solid arrows, while the possible feedbacks from this dynamics on the generic processes themselves are represented by dotted arrows.[21] However, as indicated in the right half of the Figure, these processes are also influenced by policy-makers in a multitude of ways.[22] For example, several ministries (research, education, health, industry etc.) usually engage in supporting the provision of knowledge in areas of relevance for their mandate, and similar examples may to a varying degree be found for other processes. Although many of these policies are not dubbed "innovation policies", and have traditionally not been regarded as such either, their effects on innovation may be much more important than those of more narrowly defined "innovation policies". Arguably, what matters from an innovation system perspective is not the name of a policy, but its impact.

Figure 2. The National Innovation System: Dynamics, processes and policy



Source: Fagerberg (2017)

However, since many of these policies do also (or mainly) have other motives (energy security or public health, for example), they are not necessarily aligned with other policies influencing innovation. Therefore, there is no guarantee that the total portfolio of policies influencing innovation

processes identified here are always included in one way or another. See Edquist (2004) and Bergek et al (2008) for further details.

[20] The dynamics of the system is as the Figure shows also influenced by interactions with the outside world, i.e., the global system in which national systems are embedded, but we are not going to dwell on this (arguably very important) aspect here, since the focus of our discussion is on national policy.

[21] An example of such feedback could for example be an increase in the demand for certain types of skills in an area characterized by strong innovation and growth.

[22] The framework also allows for a possible feedback from the dynamics of the system on policy-making (dotted line).

is designed so that the system as a whole gets the most out of its efforts. Hence, policy coordination (Braun 2008, OECD 2010a,b), what in the Figure is called "Strategic Innovation System Management" (SIM), becomes an important (albeit demanding)[23] part of innovation policy. One attempt in this direction, pioneered in Finland (Pelkonen 2006, Fagerberg 2016) and subsequently tried out in other countries as well, consists of establishing so-called innovation councils, typically with the prime minister in a leading role and involving major public and private actors in the deliberations (Serger et al. 2015). Such coordination (or alignment) of public policies across different sectors and levels may also give policy makers an opportunity to take into account strategic, long run goals for society's development, such as transforming society to sustainability. Nevertheless, innovation policy was invented primarily to address a different "mission", i.e., growth in income and employment, and combining such goals with sustainability is as mentioned earlier no innocent matter (Fagerberg et al 2016). What would be required is, as pointed out in a number of recent scholarly contributions [24], to give national innovation policy a clear (green) direction (see Box 2).[25]

Box 2 The fuzz about failures

The dominant approach in economics today, neoclassical economic theory, is based on the belief that free ("perfect") markets generally provide the best outcome. However, it is acknowledged that if market imperfections lead to sub-optimal outcomes, so called market-failures, tilting the economy closer to the optimal state through appropriate policies may be justified. One example of such market failure concerns so-called public goods, i.e., something that everybody can use as much as they want without paying for it, making the provision of such goods unattractive for private actors and hence justifying intervention by the government. Arrow (1962) suggested that this holds for production of knowledge.

However, while the public good/market failure argument perhaps may hold for basic science (in e.g, universities), its relevance for firm-level knowledge, much of which is "sticky" (von Hippel 1994) and not easily copied, is much less obvious (Rosenberg 1990, Soete and Arundel 1993, Fagerberg 2017). Still, the argument has become quite popular among policy-makers, probably because they see it as providing welcome moral support for their endeavours. The failure terminology has even been adopted by scholars not sharing the neoclassical framework, e.g., so-called "system failure" (Metcalfe 2005). A recent example is Weber and Rohracher (2012) who identify no less than twelve different "failures" with the hope that this intellectual effort will, as they phrase it, contribute to "legitimizing research, technology and innovation policies for transformational change" (ibid, p. 1037).

But why focusing so much on failures and not, say, on what the state is able to accomplish? Mariana Mazzucato criticizes the neoclassical approach for seriously underestimating the state's role *"for actively shaping and creating markets and systems, not just fixing them; and for creating wealth, not just redistributing it " (Mazzucato 2017, p. 15)*. The proof of this comes according to Mazzucato from the US experience with so-called mission-oriented policies, such as putting a man on the moon,

---

[23] See, e.g., the discussion of this topic in Flanegan et al (2011).

[24] See, e.g, Steward (2012), Mazzucato and Perez (2015), Mazzucato (2016, 2017), Schot and Steinmueller (2016).

[25] An interesting attempt of doing so is the "Green Growth National Strategy" adopted in South Korea from 2009 onwards (Mee Lie 2017).

policies that were not only successful with respect to their more immediate aims, but also created a range of radical innovations that fuelled growth in the private sector for decades afterwards (Mazzucato 2013). Such missions, that is innovation policies with a clear purpose (direction), carried out (as in the US) by a network of public agencies with a considerable degree of independence, may according to Mazzucato also be highly relevant in dealing with the more complex grand challenges facing contemporary societies.

Elinor Ostrom also criticizes the neoclassical approach for underestimating the potential of actors (including policy makers) at different levels to cooperate constructively in the solution of collective challenges. She argues that many collective action problems (e.g,. provision of public goods) are dealt with through cooperation between multiple actors (or agencies) at different levels that *"trust one another and …(are) willing to take on agreed action that adds to their own short term costs because they do see a long-term benefit for themselves and others " (Ostrom 2010, p. 551)*. Because of the large number of actors all over the world that necessarily will have to take part, Ostrom holds this "polycentric" approach to be particularly relevant for dealing with the climate challenge (see also Smith 2017).

Discussion

Innovation, as a problem-solving activity, is arguably as relevant for policy makers as it is for firms. There also exists a relatively well-developed knowledge base on how policy makers can engage with innovation in the solution of specific problems within their mandates. However, as pointed out above, to be effective policies for sustainability transitions need to go beyond traditional "mission oriented" policies focusing on the solution of specific problems (or specific technologies).

One reason for this is that compared to many traditional innovation policy missions, transforming society to sustainability is less about thinking and more about doing (Mowery et al 2010). For example, reducing emissions of greenhouse-gases to almost zero means that a large number of actors all over the world will have to change the way they do things. Therefore, to be effective innovation policy may need to transcend its traditional producer-oriented mode and focus more on users, that is, how to attract users (supporting deployment for example) and engage them in the collective innovation journey (von Hippel 2005). In the next section, we will focus on three examples that fit the bill.

The pervasive character of the transition also matters. For example, electrification of transport is great for reducing pollution of various kinds, but it will only lead to radically reduced GHG emissions if the electricity used to power electrical transport equipment does not come comes from, say, burning coal. Hence, for electrification of transport to be an important step in the transition to sustainability, it has to go hand in hand with a massive expansion of renewably produced electricity (as well as energy savings), which requires coordination (alignment) of policies and actors across sectors and levels, as pointed out above.

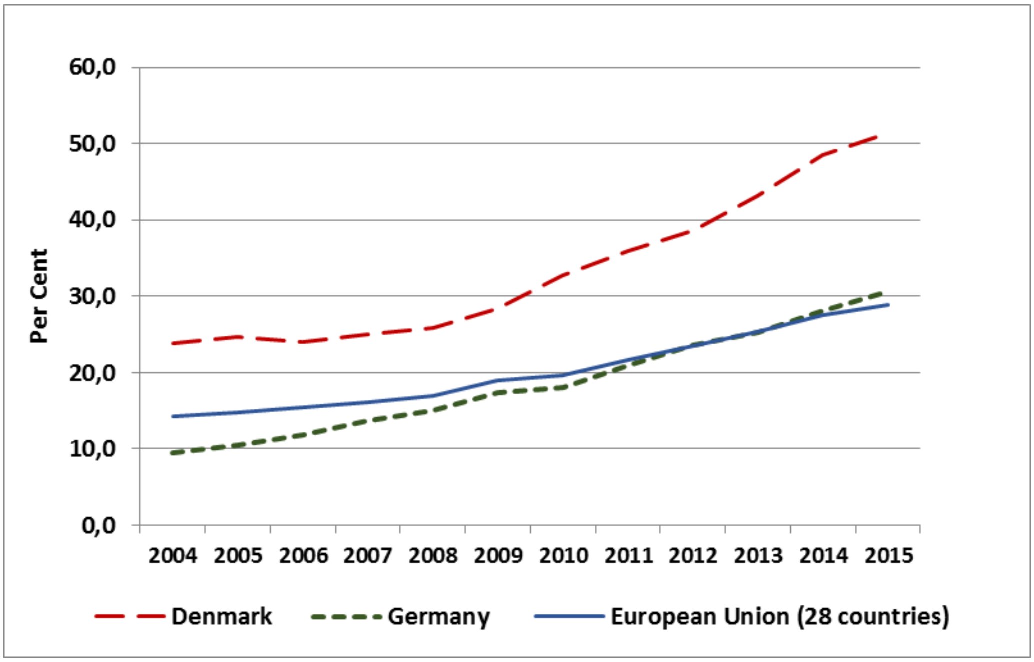
Lack of omniscience by policy-makers is often pointed to as an argument for leaving decisions about economic, industrial or technological activities to the market (Rodrik 2009). However, in the present case policy-makers know a good deal more than they used to. For the first time in history, the nations of the world have agreed on the direction for future economic development, i.e., eliminating emissions of greenhouse-gases from human activities, and each participating nation has committed to make its own plan for how best contribute towards this aim. Thus, the direction for future economic and technological change is largely already set. Moreover, not only is there agreement about where to go, it is also increasingly clear that renewable energy, electrification, energy savings and circular economy will be key features in the transition to a sustainable economy. The challenge for policy-makers, therefore, is how to - given the specific national context – adopt this agenda and combine it with other central policy goals, such as income and jobs (Fagerberg et al 2016).

The urgency of these extensive changes also constitutes a serious challenge for policy makers. As pointed out above, students of fundamental technological transformations emphasize that these usually take many decades if not centuries to unfold. However, being short of time, looking for ways to speed up change may prove essential. The three cases to be explored in the next section are chosen precisely for this reason, i.e., examples of episodes of fast, structural change in which policy has played an important role.

3. Learning from policy practice: Three cases

A core sector in this transformation concerns the provision of energy, which is a major emitter of greenhouse-gases worldwide. Exploiting the ongoing revolution in renewable energy technology, several European countries have in recent years managed to substantially increase the share of renewables in their total electricity consumption (Figure 3). The largest increase occurred in Denmark, for which the share of renewables doubled between 2005 and 2015, from 25 % to 51 % of domestic electricity consumption. In relative terms the German performance was even more impressive: the share of renewables nearly tripled, from 11 % to 31 %, during this period.

Figure 3. Share of renewable energy in electricity



Source: Own calculations based on data from Eurostat [nrg_ind_335a], accessed on August 3, 2017

However, as pointed out above, it is not sufficient to be able to produce electricity in a more environmentally friendly way, other sectors of the economy, such as transport, also have to switch from relying on polluting fossil fuels to using renewable energy. An interesting example is provided by Norway, in which the share of battery-driven electric cars increased from 1 % to 18% in just four years (2011-2015). What made these developments possible? In this section we are going to examine the evolution of policy schemes supporting these developments.

Danish windpower

In both Denmark and Germany most of this increase is due to investments in windpower. While windpower is an old technology, it did not receive much attention as a possible source of electricity production before the 1970s. However, the oil-price shocks during that decade made it clear to policy makers and the wider public that relying on imported oil and gas for electricity production may be a risky business, and that it therefore was high time to consider other options. Although in most countries nuclear energy and coal received most attention at the time, wind also attracted some interest (Box 3), particularly by the (increasing) part of the population opposing nuclear. Moreover, while nuclear and coal-fired electricity plants required huge investments, and large organizations to run and distribute the production, wind-power was small scale and hence more attractive for those that wanted, for security or other reasons, to control their own electricity supply, what Morris and Junghohann (2016) call energy democracy.

During the 1970s several initiatives were taken in Denmark, mostly by individuals, to build wind turbines and gradually a social organization of believers with regular “wind meetings”, a journal and an association evolved. The 1970s were troubled times economically, and several smaller firms with a background from other sectors of the economy (e.g., suppliers of agricultural machinery, such as Vestas) became interested in exploiting the emerging market for wind-turbines in Denmark as a way to diversify their business. The Danish government was lobbied for support and funding was secured for a small test centre at Risø, which soon became a hub for know-how, support and interaction between users and producers in the field. Moreover, to kick-start the emerging industry the Danish government introduced a 30% subsidy for windmill investments with the purpose of “creating production opportunities for Danish industry in such a way that stable batch-production could be achieved” (van Est 1999, p. 79)[26]. The subsidy was made contingent on approval of the quality of the wind-turbine by the test centre at Risø, further strengthening the role of the centre in the emerging technological innovation system for wind-power in Denmark (Karnøe and Garud 2012). Building on prior experience (see Box 3) the test-centre placed particular emphasis on solid, robust and durable designs suitable for withstanding extreme weather conditions, which became a hallmark of the Danish wind-power industry in the years that followed.

---

[26] Cited after Karnøe and Garud (2012), p. 742

Box 3. Top down or bottom up?

Following the oil-price shock in the early 1970s several countries started to devote more resources to research on other energy sources. Most of this went to nuclear energy but research in wind-energy also received some support. In the case of wind two different R&D strategies were pursued. The dominant approach was what Peter Karnøe characterizes as a top down model. This approach, adopted by for example the governments in the USA, Germany (BRD) and Denmark at the time, was a classic example of the mission-oriented innovation policies pioneered in the USA after the second world war, involving top scientists and engineers and ambitious goals for the technology's development. The research aimed for a radical scaling up of the technology (i.e. the capacity of the wind turbines) with the expectation that this would reduce costs and make wind energy more competitive. However after numerous trials none of these high-tech projects succeeded. The large sophisticated turbines that this research led to, such as Germany's Growian or the MOD-turbines in the USA, were all literally blown apart.

The alternative, bottom-up approach was particularly strong in Denmark but there too it received far less resources than the more fashionable, high-tech alternatives. In fact, most of the support to the bottom-up trajectory in the early years went to the establishment of the small test-centre for wind-turbines at Risø. However, Danish entrepreneurs in this area did not start entirely from scratch, because the Danish engineer J. Juul had already in the 1950s constructed a small-scale wind turbine, which worked flawlessly for at least a decade. The small, Danish firms that entered the then emerging industry were able to build on this design to produce small, but robust wind-turbines, which in the years that followed were gradually improved and scaled up through learning (by doing, using etc.). Eventually, it was this bottom-up approach that led to Danish firms becoming global leaders in wind technology at an early stage.

Source: Karnøe 1991.

Despite the subsidy, demand in Denmark was sluggish during the early years. However, for reasons similar to those experienced in Europe at the time, favourable policies in the USA (and in California in particular) opened up a large market for wind-turbines there during the first half of the 1980s, which Danish entrepreneurs were eager to exploit. In fact, according to one source (Karnøe and Garud 2012, p. 744), Danish firms had a market share of 65 % in the Californian market at the peak of the boom in 1986. This contributed to scale up production in Denmark, attract talent and resources (new suppliers of specialized components for instance) and increase public support for the emerging industry. Changes in US policy led in the second half of the decade to a collapse in the Californian market for wind turbines and financial problems for several Danish wind firms. However, at that point Danish firms were about to become global leaders in the emerging industry, and hence in a strong position to compete for contracts both domestically (where demand, partly as the result of policy interventions, picked up in the years that followed) and, not the least, abroad. In many ways Denmark, due to its first-mover advantage, evolved into a global hub for wind-power technology. In the decades that followed the strength of the Danish innovation system for wind-power attracted several foreign firms to locate R&D activities in Denmark, employ Danish skilled personnel or buy Danish wind-power firms (e.g., German Siemens' take-over of Danish Bonus in 2005).

Danish wind-power policy in the early years was mainly motivated by industrial and environmental policy concerns, issues particularly highlighted by parties to left of the political centre. Policy makers' attention to wind-power got a boost in the mid-1980s from the decision by the Danish parliament to refrain from developing nuclear energy. The (increasing) part of the population taking part in wind power cooperatives, particularly in the countryside, of which there are several thousand, combined with the activities of various environmental organizations (e.g., the strong anti-nuclear movement) , also contributed to keeping wind power on the political agenda. After the phasing out of the initial investment subsidy towards the end of the 1980s, the central policy instrument for supporting wind-power deployment became guaranteed access to the grid combined with a fixed price for the power supplied, i.e., a "feed-in-tariff", designed as to provide a fair (albeit not excessive) return on the investment. The first such scheme – in the form of an agreement between the government and the utilities - was introduced in 1984. However, despite the quite broad popular support for wind-power, politicians on the right were for a long time lukewarm to the idea of the state subsidizing its deployment, and this led to some volatility in policy. In fact, following a deregulation of the energy sector, economic support to wind-power deployment ceased altogether, leading to a full stop in new installations between 2004 and 2008. Nevertheless, the increasing political attention to climate change in Europe and elsewhere, particularly from around the COP 2009 onwards, eventually led to more broad-based political backing in the country for continuing ambitious policies in this area, after which the growth of renewables resumed (Irena 2013).[27]

The German "Energiewende"

As in Denmark the interest in wind energy started with a small number of enthusiasts, mostly in the country-side, many of which had a background from the anti-nuclear movement. Eventually a social organization of adherents of the technology emerged. Although in the beginning most installations were for local (off-grid) purposes, e.g., heating, gradually the interest in connecting to the grid (and getting a "fair" compensation for it) became stronger. This interest was shared by other producers of renewable energy, i.e., small, independent producers of hydro-electric power. However, grid-connection on what these local producers considered as reasonable terms was difficult to achieve at the time, as the German electricity sector was dominated a small number of large companies, with large investments in nuclear- and coal-based production and distribution of electricity, and with no interest what-so-ever in supporting the development of alternatives to their own business model. In fact, in the years that followed the large incumbents in the energy sector and their allies (such as politicians in coal producing regions) consistently opposed the development of renewable energy in Germany through media interventions, lobbying and lawsuits. This contributed to making the issue of supporting renewables very contentious politically, perhaps more so than in Denmark, which did not possess coal and where the option of developing nuclear energy was laid to rest as early as 1985. In

[27] Since 2009 the support for onshore wind is based on the market price for electricity with a "premium" added to it, financed by consumers through the price paid for electricity. For offshore wind the level of support is decided through auctions. See Irena (2013) for further details.

contrast, in Germany the controversy about nuclear energy continued to linger on until the Fukushima-disaster in 2011 eventually led Angela Merkel to replace her support for nuclear with an increased emphasis on renewables.

The controversy about nuclear energy was not only (or mainly) a traditional left-right issue. Many conservative voters (and politicians) in rural communities opposed both nuclear energy and the centralized model of economic development (and distribution of power) that it represented. A law requiring grid-access on fair terms for independent producers of renewable energy, proposed by a conservative parliamentarian, passed parliament in 1990 and came into effect the year after. The law, patterned on the Danish experience, set the feed-in tariff for new renewables to 90% of the retail price of electricity. According to Morris and Jungjohann (2016), the unanimous passing of the law came as a big surprise to the incumbents in the electricity industry, which at the time were preoccupied with taking over the East-German electricity sector.

However, while giving a boost to on-shore wind-energy, the incentives entailed by this arrangement were hardly sufficient for more immature renewable technologies, such as solar energy. As in the case of wind, there had from the late 1970s onwards been some public R&D funding for solar, followed by some demonstration programs in the decades that followed (Jacobsson and Lauber 2006). Still, by the turn of the century, solar energy accounted for only 0,01 % of Germany's electricity production, an almost negligible amount. The new "red-green" government that came to power in 1998 proposed a radical overhaul of the scheme with a technology-specific fixed feed-in tariff (independent on the electricity price) for twenty years. The extra cost of doing so was baked into the electricity price through a surcharge. While fixed for a specific installation (at a certain point in time) future installations of the same type would receive a lower support due to anticipated future technological progress/cost-reductions (automatically declining tariffs). The new scheme, introduced in 2000, led in the years that followed to a surge in investment in renewable energy, much more than foreseen by most experts. This held not only for wind-power but also (and even more so) for solar, for which the level of support through several rounds of adjustment was raised to a much higher level than in the previous decade. Accompanying this rapid increase in deployment, and in the derived demand for capital goods that it led to, a large German industry catering for these needs emerged (Lauber and Jacobsson 2015). Most of these firms, such as the successful wind-turbin supplier Enercon, were new entrepreneurial ventures as the large, established German electrical machinery firms were reluctant to engage in the new industries (or entered at a rather late stage through acquisitions, see Morris and Jungjohann 2016, p. 50).

Viewed as a means to support the transition to environmental sustainability, not only in Germany but worldwide, these policies must be regarded as being very successful. They certainly accomplished much more than anyone would have anticipated beforehand. In fact, as late as 1994, the then Minister for the Environment, Angela Merkel, said that "solar, hydro-power and wind-power will not be able to make up more than four percent of power supply even in the long term" (Morris and Jungjohann 2016, p.127). At the time of writing it is above thirty per cent and increasing. German policies in this area can also be credited with creating a global mass-market for solar panels and related equipment, leading to rapid learning, innovation and reduced costs, helping to spread the technology across the globe and contributing to less green-house gas emissions worldwide. Finally, the rapidly expanding German market for photovoltaics attracted the interest of Chinese firms, initially mainly for exports but increasingly also for domestic use, helping the much needed transition to sustainability in China itself and in other parts of the developing world (Mathews 2014, Schmitz and Lema 2015). German policy in this area thus has had very encouraging global repercussions.

Nevertheless, in Germany the Energiewende, despite continuing popular support, has become increasingly controversial.[28] First, parts of the political establishment, particularly the FDP (the liberal party), have been against the policy because they see it excessive interventionism in the working of markets. Similar views have been expressed by many economists in Germany and in the European Commission. The alternative favoured by these critics has often been more indirect measures, particularly the European Union's ETS-mechanism, which however has proven to be very ineffective (as pointed out above). Second, another faction opposing the policy consists of the large incumbents in the electricity sector and their allies in the coal industry (and affected regions) who see their economic interests threatened by the growth of renewables.[29] Third, the scheme has been criticized for being too expensive, leading to excessively high costs for consumers and undermining the cost-competitiveness of German businesses. Responding to the concern for competitiveness German governments have in successive rounds exempted a large part of the country's industrial sector from having to pay most of the surcharge financing the scheme (on the basis of their energy intensity) This has further added to the costs for ordinary consumers and the remaining part of the private business sector. Fourth, the rapid growth until recently in installed solar power added to these concerns, as more solar due its then very high cost implied a higher surcharge. Finally, a fifth factor weakening the political support in Germany for the policy was that German firms producing solar power equipment faced increasing price-competition from Chinese producers, leading to bankruptcies and a drastic reduction in employment in the part of German industry supplying such goods. Up to that point it appeared that combatting unwarranted climate change and German industrial development would go hand in hand, with the entry of China as a major supplier of technology for renewables this was no longer obvious.

Recently, a controversy arose between the German government and the European commission about the legality of the Energiewende. After a lengthy procedure the European General Court decided in 2016 that the support under the scheme was to be considered as state aid and therefore subject to EU jurisdiction[30]. While the court found the support to renewables to be justified by the purpose of the scheme, it objected to some of the wide-ranging exemptions to (energy-intensive) industry. However, rather than having to revoke (or reduce) the exemptions, the German government had already in 2014 decided to undertake a more radical change of policy, the main aim of which seems to be to reduce costs by (1) curbing future growth in renewables, particularly photovoltaics, to a level well below that of preceding years and (2) substitute politically decided feed-in tariffs with remunerations set by auctions. Whether the reduced ambitions that this policy shift entails are consistent with the long run objectives for the transition (that German politicians

---

[28] See Morris and Jungjohann (2016) for an in-depth discussion.

[29] The negative economic impact for the incumbents has to do with the so-called "merit order" in the German electricity grid, which stipulates that the cheapest sources of electricity when measured by marginal costs will be dispatched first. Since renewable power from wind and photovoltaics has close to zero marginal costs, this means that electricity plants driven by fossil fuels risk to be cut out repeatedly, i.e., only run for short periods or not at all, with predictable negative economic consequences for their owners. As the role of renewables grows, nuclear plants also risk being affected, which is a problem for their operators as production at these plants are difficult to scale up or down at short notice.

[30] See, e.g., EU General Court: Germany's 2012 Renewable Energy Source Act Involves State Aid, http://www.germanenergyblog.de/?p=19856

have agreed to) seem questionable, given that currently - despite an impressive increase - only about one third of German electricity comes from renewable sources. The policy change also implies that it has become more demanding for smaller actors, such as individuals or community-based groups, to take active part in the transition. This may be matter of concern, since most of the success of German policy in this area hitherto rests on the ability to mobilize large parts of the population for this purpose.

Electromobility in Norway

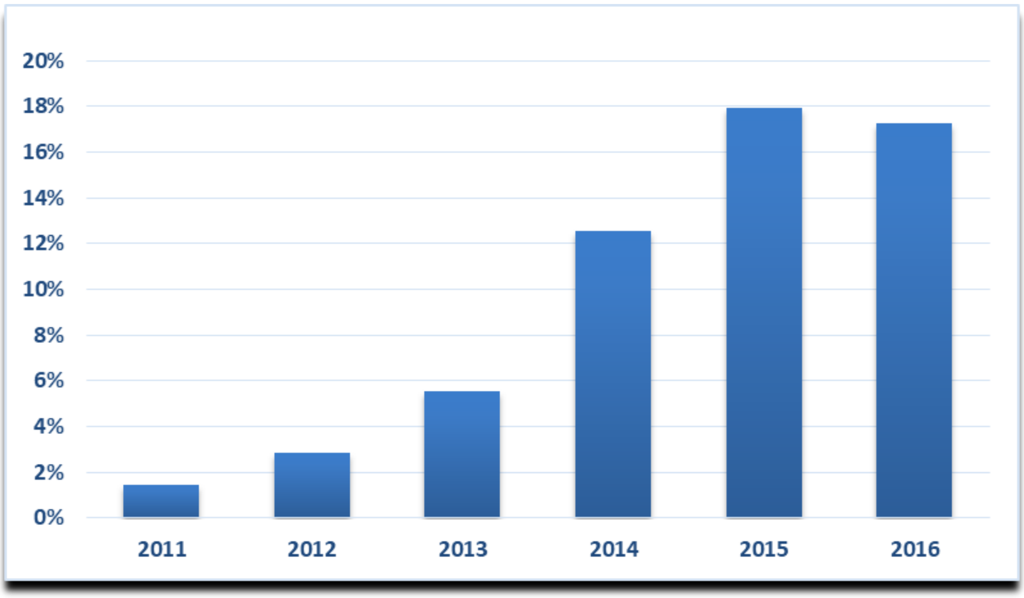
Electromobility is not a new idea. In fact, in the early years of the automobile industry electric cars were more common than petrol-driven cars but eventually the latter technology prevailed. The oil-crises of the 1970s led to a renewed interest in electric cars in several countries, and in the years that followed both new entrepreneurial firms and established incumbents started to engage with the technology on an experimental basis, leading to a small number of battery-driven electric cars being produced in a number of countries. Most of these were small city-cars, with a quite limited range but a high price-tag, thus not very attractive beyond the technology's most ardent supporters. Nevertheless, in 1990 a newly founded Norwegian environmental NGO decided to import one such car and applied successfully to the government for exemption of the (very high) Norwegian registration tax, which - based as it was on the value of the car - would have made electric cars prohibitively expensive in the Norwegian market.

However, the precedent thus set was of interest to local entrepreneurs considering joining the emerging electric car industry, and during the years that followed several such attempts were made, the most well known being the Pivco - later Think – company, which during its life time produced a few thousand electric cars (Asphjell 2013). During the early phase the company received some economic support to developing its product from various parts of government. The city of Oslo, which suffered from local air pollution, was very supportive to the spread of electric cars, and introduced several advantages for owners of electric cars early on, such as free parking and charging; its wholly owned energy company was an important actor in this respect. Over the years national policy-makers, often following up on local initiatives from Oslo, agreed to a number of additional advantages for owners of electric cars, i.e., exemptions from fees on toll roads (1997), zero value added tax (2001) and the right to use bus lanes (2003). The municipality of Oslo was also instrumental in starting up an association promoting electric cars (1995), which still exists, and currently has over 30 000 members (Figenbaum 2016). While reduction of local air pollution was often mentioned as a legitimation for these schemes, industrial policy concerns – i.e. the possibility of supporting the growth of a new industry in Norway - probably also played a role at an early stage (Røste 2001).

Despite relatively favourable public policies for buyers, sales of electric cars in Norway were sluggish during the early years and it proved difficult for Think to attract investors willing to finance the step from prototypes to regular production/marketing. However, a new market opportunity for electric cars emerged around the turn of the century due to the need for the car industry to develop "Zero Emission Vehicles" (ZEV) if they wanted to retain their presence in the lucrative Californian market. Ford acquired Think for this purpose, and for a few years the prospects looked quite rosy, but after the ZEV program was abandoned Ford rapidly lost interest and sold Think to a foreign investor who did not manage to save the firm. A final attempt to revive the company was made in the second half of the decade, just to fail once more with the emergence of the financial crisis.

However, the many incentives offered to potential users of electric cars finally resulted in increased domestic demand during the early/mid 2000s, particularly in the Oslo region. At the time, the Think company was because of its financial problems not able to deliver cars. To meet the demand some imports of used electric cars (some of which were originally produced in Norway!) from other countries took place (Figenbaum and Kolbentvedt 2013). But from the end of the decade onwards first Mitsubishi (with its I-MiEV model) and then other incumbents in the industry, such as Nissan and Volkswagen, entered the growing Norwegian market with new models, which were both more comfortable and had a longer range than what had been available hitherto, and hence had a broader appeal to consumers. As a result, sales of battery-driven electrical vehicles soared, from 1 % of all new cars in 2011 to 18% in 2015 (Figure 4), far higher than in other European countries.[31]

Figure 4. Norway: Electric cars (no emissions) as a share of all new private cars



Source: http://www.ofvas.no/, consulted on 12.03.2017

As the numbers of electric cars increased, and especially with the arrival of electric luxury cars, critics started to question the relevance of the advantages offered to the owners of such cars and instead emphasize the costs (loss of income for the state for example) and the various problems that the increasing number of such cars might lead to (such as congestion in bus lanes or increased use of cars at the expense of walking or using public transport). However, gradually climate policy goals had become more central to policy discussions in Norway, and this led to increased political support for

[31] The slight dip in the share from 2015 to 2016 was caused by a tax change that made hybrid cars (cars with two engines, one of which electric) much cheaper than before. This led to a sharp increase in sales for hybrid cars in 2016, from 12.4 per cent of total sales in 2015 to 24.5 per cent, at the expense of both fossil and zero-emission vehicles (Source: http://www.ofvas.no/, consulted on 12.03.2017).

continuing diffusion of electric cars. In fact, it had become clear to Norwegian policymakers that electrification of the transport sector was perhaps the easiest way for Norway to reduce its emissions in line with the goals European politicians and the world at large had agreed to. A broad "climate agreement" in parliament in 2012 concluded that "electrical vehicles and hydrogen incentives will be frozen until the next parliamentary term (i.e. at the end of 2017), if the number of electrical vehicles does not exceed 50 000 before that time".[32] However, although in 2012 50 000 electrical cars in Norway may have looked as a distant goal, it was attained already in April 2015. Whether this will lead to adjustments in policy remains to be seen. But at the time of writing it appears that the continuing electrification of transport has been accepted by all political parties and other relevant actors such as NGOs, major businesses etc. In fact, the responsible minister in the present (right of centre) government announced recently that policy will make sure that only ZEVs are sold in Norway in 2025.[33]

Discussion

In the three cases under scrutiny here things changed quite rapidly. In fact, if continuing at the same speed, the transition would in all three cases be complete by mid-century at the very latest. Since such fast change is what the world needs to avoid irreparable damage from climate change, it is of considerable interest to understand what made this possible.

First it is worth noting that none of these cases conform to the classic, mission-oriented model pioneered in the US of big science & advanced engineering interacting to produce path-breaking innovations as basis for subsequent commercialization. In fact, when our story begins, both wind turbines and battery-driven cars had been around for a hundred years or so. Even solar cells, invented by Bell Labs in the 1950s, had been available for almost half a century when they finally became targeted for development by German politicians through the Energiewende. The reason why wind, solar and electro-mobility did not attract more attention before was the very simple that to most observers at the time other technologies appeared more cost-effective and promising.

What changed in the 1970s and 1980s was not a sudden breakthrough in wind, solar or electric cars but that the rosy perceptions of what fossil fuels and nuclear could be expected to deliver started to crack. An important event was the OPEC oil embargo in 1973-4, leading to increased concerns all over the Western world about energy security and, hence, more public money to research on alternatives to fossil fuels. Although most of this actually went to nuclear, it also led to increased R&D on wind, solar and electro-mobility, and hence a larger knowledgebase on these technologies. However, as is apparent in all three cases, these more environmentally friendly technologies also caught the attention of the broader public, and this was to become a matter of major importance for what happened subsequently. Particularly for solar and wind this interest became much strengthened by the increasing popular resistance towards nuclear energy, fueled by events such as the Three Mile Island nuclear accident in the United States in 1979, the Chernobyl disaster in the then Soviet Union in 1986, and, closer to our own time, the Fukushima-disaster in Japan in 2011.

---

[32] Cited after Figenbaum and Kolbentvedt (2013), p. 24.

[33] Vidar Helgesen in interview with E24, 16.06.2017, http://e24.no/energi/bil/klimaministeren-skal-gjoere-bensinbiler-helt-uinteressant-aa-kjoepe/24074852

In all three countries, the driving force was not policy makers at the national level, but popular movements (or networks) composed of concerned citizens, environmental lobbies, technology enthusiasts and small entrepreneurs, united by a common interest for improving the conditions for developing and spreading the technology in question, although the motivation for doing so may have varied. For example, the motivations for advocating support for wind or solar back in the 1980s and 1990s ranged from, say, an interest in “energy democracy”, enthusiasm for the new technology, environmental issues and anti-nuclear sentiments to industrial policy concerns. Thus, while fighting climate change may be an important motive for such policies today, this was clearly not the case when the political movements (or networks) advocating these policies were formed. In the cases of wind and solar grid connection on economically acceptable terms became the central objective, while for electric cars tax exemptions and access to charging stations got most attention. The general thrust of these demands was to support deployment, by making the technology at least as attractive as the more established, less environmentally friendly, alternatives. A typical pattern was that such demands were first expressed at the local and/or regional level and, after having been accepted there, raised at the national level too.

Getting acceptance for such deployment friendly schemes at the national level was not always an easy ride though. The resistance to the suggested policy changes came from two sources in particular. One was fueled by established economic interests that, perhaps rightly, considered the new policy as threatening to them; this was especially the case in Germany. Another source of resistance, more ideological in nature, came from economists and parts of the political establishment, who looked upon such deployment friendly schemes as excessive intervention in the working of markets. The German FDP party’s criticism of Energiewende is illustrative in this regard. However, similar views were also widespread on the political right in Denmark, and for this reason support to further deployment of renewable energy in Denmark actually paused for a number of years in the 2000s. In Norway too, such ideologically charged criticisms of the current policies towards electric cars have been aired, particularly by economists, but have so far failed to influence public policy towards electrical cars significantly.

In both Denmark and Germany these policies were accompanied by a rapidly growing industry (and jobs) supplying capitals goods for producing renewable energy, increasing the legitimacy of the policy both among policy makers and the broader public.[34] However, although industrial policy concerns probably played a role in Norway too at an early stage, a similar effect, e.g., a thriving electric car industry, did not materialize there, without - it seems – hurting popular support for the policy. This may perhaps be explained by the buoyant economic conditions in Norway at the time (fueled by incomes from the oil and gas sector). In fact, policy makers did little to support the emerging industry when it ran into trouble after a few years. Arguably, lacking knowledge about car production, a solid financial backing and a sufficiently large (and growing) domestic market, the emerging industry faced an uphill struggle from day one. Nevertheless, it is possible that some of these constraints might have been addressed through innovation policy, for example by using public procurement policy to address the demand constraint, perhaps the most damaging (blocking) factor during these years. In fact, both in Denmark and Germany policy-makers had been quite clever in stimulating demand (through publicly demonstration programs for example) at similarly critical moments of their

[34] However, as noted above, more recently parts of the German solar energy industry have faced increasing competition from Chinese producers, resulting in several bankruptcies and employment losses.

emerging industries' development. However, there is no indication of policy makers in Norway at the time having an appetite for doing something of this sort.

What explains the rapid pace of change in these three cases? It probably boils down to the strong involvement of users in promoting, improving and spreading the technologies in question, in interaction with demand-oriented innovation policies supporting the deployment of these technologies (and hence continuing user involvement). This virtuous interaction did not come by itself; it was the result of a lengthy process in which a broad range of actors (including policy makers) at different levels of society, with compatible but not necessarily identical aims, took part. Hence, what happened seems broadly consistent with the "polycentric" understanding of collective action developed by Ostrom (2010), see Box 2.

Concluding remarks

The global economy is on an unsustainable course, and this needs to be changed, as almost all countries in the world have agreed. The direction of economic change is thus set, and, as envisaged in the Paris Agreement, it is now up to each country, taking into account the specific context there, to develop and implement policies that make the transition to a sustainable economy and the associated structural changes possible.[35] Innovation and policies influencing it are arguably key resources for succeeding with this aim. The purpose of this paper, therefore, has been to discuss, based on relevant theoretical work as well as lessons from policy practice, how this can be done.

The knowledge base in innovation studies provides us with a robust framework for discussions about how to make innovation policy more effective. Successful innovation depends on the ability to mobilize and combine a number of different factors, such as knowledge, skills, finance, institutions and demand. As pointed out above, having access to one such factor, knowledge for example, is of little help if for example finance is not accessible or demand not present. Thus the factors influencing successful innovation are for the most part complementarity in nature. That is why a holistic perspective on policy, taking into account not only a few but all factors influencing innovation, is a must if policy-making is going to reach its aims (Fagerberg 2017). Thus, the traditional supply-orientation of research and innovation policies, which still dominate in many settings, is - as illustrated by the three case studies included in this paper - totally deficient. Furthermore, since policy-makers in many different settings (and levels) influence the various factors that matter for innovation, coordination and alignment of policies are required, so that the various activities those policy-makers engage in complement rather than counteract each other. Therefore, to make innovation policy into the powerful instrument that a successful transition requires, innovations in innovation policy governance will be necessary (Edler and Fagerberg 2017). This an under-researched issue, theoretically as well as empirically.

One way to make innovation policy more effective is to give it a clear direction (Perez 2016, Mazzucato 2017). Previously this was regarded as an almost unsurmountable problem for policy makers: How were they to know the most promising paths to the future? However, more recently the long-run goal of transforming the economy to sustainability, an important part of which is

---

[35] See Smith (2017) and Schmitz and Lema (2015) for treatments of the international aspects of the transition to sustainability.

reducing emission of greenhouse-gases to almost zero before the end of this century, has become broadly accepted. Moreover, it appears increasingly evident that the ongoing technological revolution in renewable energy, in combination with other structural changes, will provide humanity with many the means needed to escape its current dependence on burning fossil fuels (Seba 2014, Goodall 2016). Nevertheless, following this trajectory will require a lot of innovation, in, say, energy storage and distribution, energy use (including savings), electrification of transport and so on, as well as in business models, in the organization and activities of the public sector, and in ways of life more generally. Therefore policies supporting research, innovation and real-life experiments (including deployment) along these lines will be essential.

This may sound simple but in practice it is quite challenging, due to among other things the time frame of politics: While the transition to sustainability and the structural changes it entails will take many decades, policy makers are constantly confronted with issues that require responses here and now, and which may distract attention from long-run problems. The "transition management" approach discussed above was designed to address this problem and their emphasis on the role of vision in sustainability transitions (Rotmans et al 2001) may be well worth considering. A vision is a common perception (or cognitive frame) of where we as a society would like to go (e.g., a sustainable economy), that can function a soft coordination device for the many actors, including policy makers at different levels, that need to align their actions if the transition is going to succeed. It can be made more concrete by setting up various targets that can be monitored and used to assess to what degree society's performance is in line with the long run goals. Arguably, such a vision, consistent both with the opportunities offered by, say, the renewable energy revolution and the specific context for which the vision is going to work, may be a useful tool for policy makers in pursuing the transition to sustainability. This holds not the least in Norway, which, due to its reliance on production of oil and gas, is deeply embedded in the old, fossil-based system, [36] and for which finding a workable path to a sustainable future therefore may be very challenging. However, the purpose of such a vision is not to alleviate conflict along the route, but to make the contents of possible disagreements and their relationships with long run goals more transparent. This also holds for the process of developing it, in which different ideas about the future will have to be explicated and made subject to debate.[37] Nevertheless, if this is going to work as intended, it essential that policy makers avoid the temptation to develop such a vision behind closed doors, but engage in a broad, open and transparent dialogue with stakeholders at different levels in society. Indeed, the ability to reach out to stakeholders and the broader public and engage them in the collective innovation journey towards a sustainable economic system is not only more democratic, but also more effective, as the previous section amply demonstrates.

One of the most salient features of modern societies is that users are highly knowledgeable and resourceful, and that their active involvement is essential for successful innovation (von Hippel 2005). It is probably a safe bet that without such active involvement of users, in interaction with attentive policy makers at various levels, the three transition stories discussed above would have looked very different and the speed of transition - and the technological progress it made possible - been much slower. Hence, a central lesson for policy makers is that by embracing the opportunities

[36] See Geels (2014, 2015) for a discussion of the need for policy to not only support the growth of new, green sectors but also actively reduce the old, polluting ones.

[37] Public agencies such as research councils and innovation agencies may possibly be well placed to kick-start such processes.

offered by the renewable energy revolution and actively involving users (and attracting new ones) it is possible to encourage (green) innovation, create new jobs[38] and significantly speed up the transition (which arguably is a must).

References

Abernathy, W., Utterback, J. (1978) Patterns of industrial innovation, Technology Review 80(7): 40-47

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous (2012) The Environment and Directed Technical Change, American Economic Review, 102(1): 131-66

Andersen, E.S. (2011) Joseph A. Schumpeter: A Theory of Social and Economic Evolution, Basingstoke and New York: Palgrave Macmillan

Arrow, K. (1962) "Economic Welfare and the Allocation of Resources for Innovation," in Nelson R. R. (ed.) The Rate and Direction of Inventive Activity, Princeton: Princeton University Press, p. 609-625

Asheim, B. and Gertler, M. (2004) "The Geography of Innovation" in Fagerberg, J., Mowery, D., Nelson, R. (Eds.), The Oxford Handbook of Innovation. Oxford: Oxford University Press, p. 291-317

Asphjell, A., Asphjell, Ø., Kvisle, H.H. (2013). Elbil på norsk 2013, Trondheim, Transnova

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A. (2008) Analyzing the functional dynamics of technological innovation systems: A scheme of analysis, Research Policy, 37 (3), 407–429.

Braun, D. (2008) Lessons on the political coordination of knowledge and innovation policies, Science and Public Policy 35: 289-298.

Daly, H. E. (2008). A steady state economy. Paper presented to the UK Sustainable Development Commission 24 April 2008, http://www.theoildrum.com/node/3941, consulted on 30.10.2017

Dietz, R. and D. O'Neill (2013) Enough Is Enough: Building a Sustainable Economy in a World of Finite Resources, San Francisco: Berret-Koehler Publishers

Dosi, G. (1982) Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change. Research Policy 11: 147–162

Edler, J. and Fagerberg, J. (2017) Innovation policy: what, why, and how, Oxford Review of Economic Policy 33 (1), 2-23.

Edler, J. and Georghiou, L. (2007) Public procurement and innovation – Resurrecting the demand side, Research Policy, 36 (7), 949–963.

Edler, J., Shapira, P., Cunningham, P., Gök, A. (2016) Conclusions: Evidence on the effectiveness of innovation policy intervention, in: Edler, J., Cunningham, P., Gök, A., Shapira, P. (Eds.), Handbook of Innovation Policy Impact. Edward Elgar, Cheltenham / Northampton, pp. 543-564.

[38] "Project-level data indicates that, on average, renewable energy creates more jobs than fossil-fuel technologies. Solar PV, for instance, creates more than twice the number of jobs per unit of electricity generation compared with coal or natural gas." (Irena 2017, p. 6)

Edquist, C. (2004). “Systems of Innovation: Perspectives and Challenges” in Fagerberg, J., Mowery, D., and Nelson, R (eds.) Oxford Handbook of Innovation, Oxford: Oxford University Press, p. 181-208

Edquist, C. (2011) Design of innovation policy through diagnostic analysis: Identification of systemic problems (or failures), Industrial and Corporate Change, 20 (6), 1–29.

Ergas, H. (1986), Does Technology Policy matter? CEPS papers No 29, Brussels, Centre for European Studies.

Fagerberg, J. (2003) Schumpeter and the revival of evolutionary economics: an appraisal of the literature, Journal of Evolutionary Economics 13:125-159

Fagerberg, J. (2004) Innovation: A guide to the Literature, in Fagerberg, J., Mowery, D., and Nelson, R (eds.) The Oxford Handbook of Innovation, Oxford University Press, Oxford, 2004, p 1-26.

Fagerberg, J. (2016). Innovation Systems and Policy: A Tale of Three Countries, Stato e Mercato 36 (1), 13-40

Fagerberg, J. (2017) Innovation Policy: Rationales, Lessons and Challenges, Journal of Economic Surveys 31(2), 497–512

Fagerberg, J., Fosaas, M. and Sapprasert, K. (2012) Innovation: Exploring the knowledge base, Research Policy 41: 1132-1153

Fagerberg, J., Laestadius, S. and Martin, B.R. (2016) The Triple Challenge for Europe: The Economy, Climate Change, and Governance, Challenge, 59 (3): 178-204

Fagerberg, J., Mowery, D., and Nelson, R. eds. (2004) The Oxford Handbook of Innovation, Oxford: Oxford University Press

Fagerberg, J., Mowery, D. and Verspagen, B. (2009). The evolution of Norway’s national innovation system, Science and Public Policy, 36: 431-444

Figenbaum, E. (2016) Perspectives on Norway’s supercharged electric vehicle policy, Environmental Innovation and Societal Transitions, https://doi.org/10.1016/j.eist.2016.11.002

Figenbaum, E, and M. Kolbenstvedt (2013). Electromobility in Norway - experiences and opportunities with Electric Vehicles, Report 1281/2013, The Institute of Transport Economics , (https://www.toi.no/publikasjoner/elektromobilitet-i-norge-erfaringer-og-muligheter-med-elkjoretoy-article32103-8.html, downloaded on August 21, 2017).

Flanagan, K., Uyarra, E. and Laranja, M. (2011) Reconceptualising the 'policy mix' for innovation, Research Policy, 40 (5), 702–713.

Fouquet, R. (2016) Lessons from energy history for climate policy: Technological change, demand and economic development, Energy Research and Social Science 22, 79-93

Freeman, C. (1974). The Economics of Industrial Innovation, Harmondsworth: Penguin

Freeman, C. (1987) Technology policy and economic performance: Lessons from Japan, London: Pinter

Freeman, C., Clark, J. and Soete, L. G. (1982) Unemployment and Technical Innovation: a Study of Long Waves and Economic Development, London: Pinter

Freeman, C. and Louçã, F. (2001) As Time Goes By. From the Industrial Revolutions to the Information Revolution, Oxford: Oxford University Press

Freeman, C. and Perez, C. (1988) "Structural Crises of Adjustment: Business Cycles and Investment Behaviour", in Dosi, G., Freeman, C., Nelson, R.R., Silverberg, G. and Soete, L. G. (eds.), Technical Change and Economic Theory, London: Pinter, p. 38-66.

Garud, R.; Karnøe, P. (2003) Bricolage versus breakthrough : Distributed and embedded agency in technology entrepreneurship, Research Policy, Vol. 32, No. 2, p. 277-300

Geels, F. W. (2002) Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study, Research Policy 31: 1257-1274

Geels, F. W. (2014) Regime Resistance against Low-Carbon Transitions: Introducing Politics and Power into the Multi-Level Perspective, Theory, Culture & Society 31 (5): 21 - 40

Geels, F. W. (2015)The arduous transition to low-carbon energy: A multi-level analysis of renewable electricity niches and resilient regimes, in Fagerberg, J., S. Laestadius and B. R. Martin (2015) The Triple Challenge for Europe Economic Development, Climate Change and Governance, Oxford University Press, p. 91-118

Geels, F. W. and J. Schot (2007) Typology of sociotechnical transition pathways, Research Policy 36: 399-417.

Goodall, C. (2016) The Switch: How solar, storage and new tech means cheap power for all, London: Profile Books

Grubler, A. (2012) Energy transitions research: Insights and cautionary tales, Energy Policy 50, 8-16

Hall, B.H. & Rosenberg, N. eds. (2010) Handbook of the Economics of Innovation, Amsterdam: North Holland

Hendriks, C.M. (2009) Policy design without democracy? Making democratic sense of transition management, Policy Sciences 42: 341-368

Irena (2013) 30 Years of Policies for Wind Energy – Lessons from 12 Wind Energy markets, https://www.irena.org/DocumentDownloads/Publications/IRENA_GWEC_WindReport_Full.pdf, downloaded on August 21, 2017

Irena (2017) Renewable Energy and Jobs, Annual Review 2017, http://www.irena.org/documentdownloads/publications/irena_re_jobs_annual_review_2017.pdf, downloaded on August 21, 2017

Jacobsson, S. and V. Lauber (2006) The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology, Energy Policy 34 (3), 256-27

Jacobsson, S., Sandén, B. and Bångemns, L. (2004) Transforming the Energy System—the Evolution of the German Technological System for Solar Cells, Technology Analysis & Strategic Management 16:1, 3–30

Karnøe, P. (1991) Dansk Vindmølleindustri - en overraskende international success: Om innovationer, industriudvikling og teknologipolitik, Copenhagen: Samfundslitteratur

Karnøe, P.; Garud, R. (2012) Path Creation : Co-creation of Heterogeneous Resources in the Emergence of the Danish Wind Turbine Cluster, European Planning Studies, Vol. 20, No. 5, p. 733-752.

Kemp, R. (2011) Ten themes for eco-innovation policies in Europe, S.A.P.I.EN.S , 4 (2), 1-20

Kemp, R, Loorbach, D.A, & Rotmans, J. (2007). Transition management as a model for managing processes of co-evolution towards sustainable development. The International Journal of Sustainable Development and World Ecology, 14(1), 78–91

Kemp, R. and B. Never (2017) Green transition, industrial policy, and economic development, Oxford Review of Economic Policy 33 (1), p. 66–84,

Kemp, R., Schot, J. and Hoogma, R. (1998) Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. Technology Analysis and Strategic Management 10(2): 175–198.

Kline, S.J. and Rosenberg, N. (1986) "An Overview of Innovation", in Landau, R. and Rosenberg, N. (eds.) The Positive Sum Strategy: Harnessing Technology for Economic Growth, Washington D.C.: National Academy Press, p. 275-304

Laestadius, S. (2015) Transition paths: assessing conditions and alternatives , in Fagerberg, J., S. Laestadius and B. R. Martin (2015) The Triple Challenge for Europe Economic Development, Climate Change and Governance, Oxford University Press, p. 143-169

Lauber, V. and S. Jacobsson (2015). 'Lessons from Germany's Energiewende', in Fagerberg, J., S. Laestadius and B. R. Martin (2015), The Triple Challenge for Europe: Economic Development, Climate Change and Governance, Oxford: Oxford University Press, pp.173-203.

Levin, R. C., A.K. Klevorick, R.R. Nelson and S.G. Winter (1987) 'Appropriating the Returns from Industrial Research and Development', Brookings Pap. Econ. Act: Microeconomics, p. 783–820.

Liu, X. and White, S. (2001) Comparing innovation systems: a framework and application to China's transitional context, Research Policy, 30 (7), 1091–1114

Loorbach, D. (2010) Transition Management for Sustainable Development: A Prescriptive, Complexity-Based Governance Framework, Governance: An International Journal of Policy, Administration and Institutions 23 (1), 161–183

Lundvall, B. Å. (1992) National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning, London: Pinter

Malerba, F. (2004) 'Sectoral Systems: How and why innovation differs across sectors', in Fagerberg, J., Mowery, D., Nelson, R. (eds.) The Oxford Handbook of Innovation, Oxford: Oxford University Press, pp. 380–406.

Mazzucato, M. (2013) The entrepreneurial state: debunking private vs. public sector myths. Anthem Press, London, UK.

Mazzucato, M. (2016) From market fixing to market-creating: a new framework for innovation policy, Industry and Innovation, 23 (2), 140-156.

Mazzucato, M. (2017) Mission-Oriented Innovation Policy: Challenges and Opportunities, London: RSA,https://www.thersa.org/globalassets/pdfs/reports/mission-oriented-policy-innovation-report.pdf, addressed on 30.11.2017

Mazzucato, M. and C. Perez (2015) Innovation as Growth Policy: the Challenge for Europe, in Fagerberg, J., S. Laestadius and B. R. Martin (2015) The Triple Challenge for Europe: Economic Development, Climate Change and Governance, Oxford University Press, p. 229-264

McCraw, T.K. (2007) Prophet of Innovation: Joseph Schumpeter and Creative Destruction, Belknap Press of Harvard University Press, Cambridge, Mass.

Mee Lie, C. (2017) Does green growth require a different type of policies? Exploring four recent policy frameworks, Centre for Technology, Innovation and Culture, University of Oslo

Meyer, M. (2001) Nelson and Winter's evolutionary theory – a citation analysis. Paper presented at the 2001 Nelson-Winter Conference organized by DRUID, June 12–15, 2001, Aalborg, Denmark

Metcalfe, J. S. (2005) Systems Failure and the Case for Innovation Policy, in Llerena, P. and Matt, M. (eds.) Innovation Policy in a Knowledge-Based Economy: Theory and Practice, Heidelberg: Springer, pp. 47–74.

Morris, C., Jungjohann, A. (2016) Energy Democracy - Germany's Energiewende to Renewables, Basingstoke: Palgrave MacMillan

Mathews, J. A. (2013) The renewable energies technology surge: A new techno-economic paradigm in the making? In Futures 46, p. 10-22

Mathews, J. A. (2014). Greening of Capitalism: How Asia Is Driving the Next Great Transformation, Stanford: Stanford University Press.

Mowery, D.C., R.R. Nelson and B.R. Martin (2010). 'Technology Policy and Global Warming: Why New Policy Models are Needed (Or Why Putting New Wine in Old Bottles Won't Work)', Research Policy, 39, pp.1011-1023.

Mowery, D.C. (2011), Federal Policy and the Development of Semiconductors, Computer Hardware and Computer Software: A Policy Model for Climate Change R&D?, in Rebecca M. Henderson and Richard G. Newell (eds), Accelerating Energy Innovation: Insights from Multiple Sectors, Chapter 5, Chicago, IL: University of Chicago Press, 159–88

Nelson, R. R. (ed.) (1993) National Innovation Systems: A Comparative Study, Oxford: Oxford University Press.

Nelson, R. R. and Winter, S. G. (1982) An Evolutionary Theory of Economic Change, Cambridge, Mass: Harvard University Press

Nill, J. and R. Kemp (2009) Evolutionary approaches for sustainable innovation policies: From niche to paradigm? Research Policy 38 (4), 668–680

Nordhaus, W. (2013). The Climate Casino – Risk, Uncertainty and Economics for a Warming World, New Haven & London: Yale University Press.

OECD (1997) National Innovation Systems, Paris: OECD.

OECD (1999) Managing National Innovation Systems, Paris: OECD.

OECD (2002) Dynamising National Innovation Systems, Paris: OECD.

OECD (2010a) The OECD Innovation Strategy: getting a head start on tomorrow, Paris: OECD Publishing.

OECD (2010b) 'The Innovation Policy Mix', in OECD (ed.), OECD Science, Technology and Industry Outlook 2010, Paris: OECD, pp. 251–279.

Ostrom, E. (2010) Polycentric systems for coping with collective action and global environmental change, Global Environmental Change 20 (4), 550–557

Pelkonen, A. (2006) The problem of integrated innovation policy: Analysing the governing role of the science and technology policy council of Finland, Science and Public Policy 33(9): 669–680.

Perez, C. (2002) Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages, Cheltenham: Edward Elgar

Perez, C. (2016) Capitalism, Technology and a Green Global Golden Age: The Role of History in Helping to Shape the Future, in Jacobs, M. and Mazzucato. M. (eds.) Rethinking Capitalism: Economics and Policy for Sustainable and Inclusive Growth, The Political Quarterly, Chichester: Wiley-Blackwell, p. 191-207

Pearson, P. J. G. and Foxon, T.J. (2012) A low carbon industrial revolution? Insights and challenges from past technological and economic transformations, Energy Policy 50, 117-127

Rip, A. and Kemp, R. (1998) Technological change, in Rayner, S. and Malone, E. L. (eds.) Human choice and climate change, vol. 2, Resources and technology, Washington D.C.: Battelle Press, pp. 327–399.

Rodrik, D. (2009) Industrial policy: don't ask why, ask how, Middle East Development Journal 1 (1), 1-29

Rodrik, D. (2014) Green industrial policy, Oxford Review of Economic Policy 30 (3), 469–491

Rosenberg, N. (1990). Why Do Firms Do Basic Research (with Their Own Money), Research Policy 19(2):165-174.

Rothwell, R. (1982) Government innovation policy: Some past problems and recent trends, Technological Forecasting and Social Change, 22 (1), 3–30.

Rotmans, J., Kemp, R. and van Asselt, M. (2001) More evolution than revolution: Transition management in public policy, Foresight 3(1), 15–31.

Røste, R. (2001) Næringspolitikk for konkurransedyktige nyetableringer - en casestudie av den elektriske bilen Think fra idé til marked, Master-oppgave, Universitetet i Oslo, https://www.duo.uio.no/handle/10852/13555, addressed on 15.08.2017

Rothwell, R. (1982) Government innovation policy: Some past problems and recent trends, Technological Forecasting and Social Change, 22 (1), 3–30.

Schmitz, H. (2015) Green Transformation: Is There a Fast Track?, in I. Scoones, M. Leach, P. Newell (eds.), The Politics of Green Transformations, London: Routledge

Schmitz, H. and R. Lema (2015). ‘The Global Green Economy: Competition or Cooperation between Europe and China?’, in Fagerberg, J., S. Laestadius and B. R. Martin (2015), The Triple Challenge for Europe: Economic Development, Climate Change and Governance, Oxford: Oxford University Press, pp.119-142

Schot, J and. W. E. Steinmueller (2016) Framing Innovation Policy for Transformative Change: Innovation Policy 3.0, Working-paper, http://www.johanschot.com/publications/framing-innovation-policy/, addressed on 30.11.2017

Schumpeter, J. A. (1934) The Theory of Economic Development, Cambridge, Mass: Harvard University Press.

Schumpeter J. A. (1939) Business cycles: a theoretical historical and statistical analysis of the capitalist process (2vol). New York: McGraw-Hill

Schumpeter, J. A. (1942) Capitalism, Socialism and Democracy, New York: Harper.

Seba, T. (2014) Clean Disruption of Energy and Transportation: How Silicon Valley Will Make Oil, Nuclear, Natural Gas, Coal, Electric Utilities and Conventional Cars Obsolete by 2030, Silicon Valley, California: Clean Planet Ventures

Serger, S.S., Wise, E. and Arnold, E. (2015) National Research & Innovation Councils as an Instrument of Innovation Governance: Characteristics and Challenges. Vinnova Analysis VA 2015:07. Stockholm: Vinnova

Smil, V. (2016) Examining energy transitions: A dozen insights based on performance. Energy Research & Social Science 22:194-197

Smith, A. & F. Kern (2009) The transitions storyline in Dutch environmental policy, Environmental Politics 18 (1), 78-98

Smith, A., Voss, J.-P. and Grin, J. (2010) Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges. Research Policy, 39 (4), 435-448

Smith, K. (2004) Measuring Innovation, in Fagerberg, J., Mowery, D., Nelson, R. (eds.) The Oxford Handbook of Innovation, Oxford: Oxford University Press, pp. 148–178.

Smith, K. (2017) Innovating for the global commons: multilateral collaboration in a polycentric world, Oxford Review of Economic Policy, Volume 33, Issue 1, Pages 49–65

Soete, L. and A. Arunddel (1993) An Integrated Approach to European Innovation and Technology Diffusion Policy: A MAASTRICHT MEMORANDUM, Commission of the European Communities, Dissemination of Scientific and Technical Knowledge Unit, Directorate-General Information Technologies and Industries, and Telecommunications, Luxembourg

Sovacool, B.K. (2016) How long will it take? Conceptualizing the temporal dynamics of energy transitions, Energy Research & Social Science 13, 202-215

Stern, N. (2015) Why are We Waiting?: The Logic, Urgency, and Promise of Tackling Climate Change, The MIT Press van Est, R.(1999) Winds of change : a comparative study of the politics of wind energy innovation in California and Denmark, Utrecht : International Books

Steward, F. (2012) Transformative innovation policy to meet the challenge of climate change: sociotechnical networks aligned with consumption and end-use as new transition arenas for a low-carbon society or green economy, Technology Analysis & Strategic Management Vol. 24 (4), 331-343

Unruh, G. C. (2000) Understanding carbon lock-in, Energy policy 28 (12), 817-830

Unruh, G. C.(2002) Escaping carbon lock-in, Energy policy 30 (4), 317-325

van den Bergh J.C.J.M., Truffer B. and Kallis G. (2011) Environmental innovation and societal transitions: Introduction and overview, Environmental Innovation and Societal Transitions 1 (1), 1-23

von Hippel, E. (1988) The Sources of Innovation, New York: Oxford University Press.

von Hippel, E. (1994) "Sticky Information" and the Locus of Problem Solving: Implications for Innovation, Management Science, 40 (4), 429–439.

von Hippel, E. (2005) Democratizing Innovation, Cambridge, MA: MIT Press

von Tunzelmann G.N. (1995) Technology and industrial progress: the foundations of economic growth, Aldershot: Edward Elgar

Voss, J.P., Smith, A. and Grin, J. (2009) Designing long-term policy: rethinking transition management, Policy sciences 42 (4), 275-302

van Est, R.(1999) Winds of change : a comparative study of the politics of wind energy innovation in California and Denmark, Utrecht : International Books

Weber, K. M. and Rohracher, H. (2012) Legitimizing research, technology and innovation policies for transformative change, Research Policy 41 (6), 1037-1047

Wilson, C. (2012) Up-scaling, formative phases, and learning in the historical diffusion of energy technologies, Energy Policy 50: 81-94

Winter, S. G. (1984) Schumpeterian competition in alternative technological regimes. Journal of Economic Behavior and Organization 5: 287–320