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The policy robustness and resilience trajectories of renewable energy innovation leaders

Analysing the promotion of bioenergy in Finland, wind energy in Denmark and solar power in Germany

Abstract

The policy efforts to shift energy production and consumption profiles from fossil resources towards renewables have stimulated innovation activities and economic maturing of RE technologies, most evidently the wind and solar. This has become visible not only in growing RE production shares and international technology trade volumes, but also in the numbers of issued patents. However, the economic dynamics are geographically uneven as some of the countries have emerged as *technology leaders* that in principle drive the general development and take the most advantage of it. In this paper, we focus on three suspected innovation champions - Denmark, Finland and Germany - and ask whether certain features of public policy have sustained the central role of RE technologies in their policy agendas over long periods of time. We turn to the concepts of *policy robustness* and *resilience* coined by adaptive policy scholars to achieve this. By analysing the long-term policy trajectories of the case study countries, we conclude that while all these countries have had relatively robust policy strategies, there are differences in the ways and extends that resilience is promoted. Of the case countries, Denmark's wind power policy seems to be an excellent example of how robustness and resilience building can be balanced in a fruitful way. In the end, we provide more generalisable lessons on how policy robustness and resilience could be promoted in different settings.

Key words

Renewable energy, innovations, adaptive policy, resilience, robustness, Finland, Denmark, Germany

Highlights

- Introduces a framework for studying energy policy adaptation trajectories and the policy robustness and resilience features they reflect
- Provides a meta-study on research published on energy policies in three European renewable energy champions: Finland, Denmark and Germany
- Analyses how robustness and resilience, as policy attributes, reflect e.g. commitment to certain policy goals and wider participation in politics
- Suggests that adaptive policies may also have real-world implications in terms of new innovations, installed renewable energy capacity, export surplus, etc.

1 Introduction

Increasing the share of renewable energy (RE) in the energy palette has been seen as one of the key measures to combat climate change and to promote energy security, self-sufficiency and environmental health among other things. Europe has set the target to cut at least 40% of greenhouse gas emissions (from 1990 levels) and to reach the 27% share for renewable energy by 2030 (European Commission 2017). In efforts to reach these goals, different EU member states have introduced various policies seeking to stimulate innovation and accelerate RE market penetration. The correlation between tightening RE policies and increases technology patent figures have been viewed as justification for the policy approach (e.g. Griliches 1990; Johnstone et al. 2010; Kitzing et al. 2012).

This study focuses on European RE innovation leaders - source countries for most patents - in three key RE spheres, in wind, solar and bioenergy. In these spheres, the leaders are 1) *Germany* that has been championing in solar power inventions; 2) *Denmark*, the wind energy leader; and 3) *Finland* that has been one of the prominent countries in bioenergy[1] patents (see Appendix 1). Policies and technologies often develop in interplay with each other (Mickwitz et al. 2008; Norberg-Bohm 1999), while also the wider context of policy making - 'the politics of policy' - is central in retaining, destabilising or reorienting the policy agendas (Jacobsson and Lauber 2006; Meadowcroft 2009; Shove and Walker 2007). As long-term, forceful policy efforts to drive change towards renewables seem to be common denominators for European RE technology leaders (Kivimaa & Mickwitz 2011; Lipp 2007; Meyer 2007), we are interested in the *adaptive capacities of their policy mixes, the robustness and resilience trajectories*, that show how policy aims have persisted and agendas coped over time.

Robustness and resilience are concepts that are widely applied in the climate change adaptation analyses and in other fields such as ecology, economy and computational studies (Anderies et al. 2013; Capano and Woo 2017). Robustness and resilience refer to the ability of policies to persist over time by overcoming both external shocks and internal perturbations (Capano and Woo 2017). By definition, robust systems (and policies) have a capacity to maintain their core functions at the face of external pressures, while resilient systems (and policies) have stronger tendency to self-organise over time and therefore adjust to the transformations (Anderies et al. 2013). The claim of this article is that robustness and resilience could be more frequently applied to study the features of policies, as the capacities of policies to cope and adapt can be crucially important for their success (cf. Kivimaa & Mickwitz 2011; Lipp 2007).

In RE policy studies, robustness and resilience could be useful concepts to analyse the persistence of certain policy objectives and measures over longer periods of time and in times of rapid transitions or abrupt changes. Furthermore, the RE innovation dynamics have been recently conceptualised as non-linear and multi-scalar processes (Truffer et al. 2015; Quitzow 2015), which on the one hand calls for adaptivity of policy aims and on the other for stability of policy environment. The hypotheses steering the work are i) Denmark, Finland and Germany may have certain interesting

[1] We have grouped under the umbrella of bioenergy two classes of patents: 1) Biofuels (Y02E 50/1): Combined Heat and Power turbines for biofeed, gas turbines for biofeed, bio-diesel, bio-pyrolysis, torrefaction of biomass, bio-ethanol; 2) Fuel From Waste (Y02E 50/3): Synthesis of alcohol or diesel from waste, production of methane (fermentation, land_ll gas).

robustness and resilience features in their RE policies and that ii) analysing these three country cases may render some important lessons also for other countries designing and revising their RE policies.

The robustness and resilience of the RE policy mixes of Germany, Denmark and Finland are worthwhile to analyse not only because they have been European RE innovation leaders but also because they have certain characteristics in common: All the countries feature multi-party politics and corporatist policy styles that tend to reflect the views of various interest groups and public sentiment in a relatively sensitive manner. Further, the three countries have well-established albeit varied environmental movements that demonstrate long-standing societal centrality of the environmental issues. However, there are some fundamental differences between the countries that limit the generalisability of analysis. While Denmark and Finland are small, Nordic welfare-states, Germany is one of the biggest countries in Europe with considerable political and economic power also on the global scale. Germany also features nested federation system, while Finland and Denmark have more centralised state systems.

The country cases were studied by conducting a review of recent academic literature focused on RE policies. Further, to make analysis more nuanced and reflexive, the data regarding RE installations and technology exports was gathered on each country. The triangulation of statistical analysis on patent data, review on existing policy literature and the economic and technical trends provided the solid basis for the policy lessons.

The research questions of the study are:

1) How to analyse the policy robustness and resilience profiles of the European renewable energy technology leaders?

2) What common and different features there are in the renewable energy policies of Germany, Denmark, and Finland particularly from the robustness and resilience perspectives?

3) What kind of lessons can be derived from the cases for understanding and promoting energy transitions?

In the following section (2), we will discuss robustness and resilience as policy attributes in more depth. Section (3) describes the materials and methods used in the literature review. Section (4) presents the analyses of the country cases. In sections (5) and (6), we discuss the results and draw conclusions.

2 Analysing robustness and resilience of RE policies

2.1 RE policies as focus of analysis

Most countries support the development of RE to attain the same benefits: To ensure security of supply and reduce dependence on fossil fuels, to cut greenhouse gas emissions and other environmental effects of energy production, and to foster innovation and local and regional benefits through e.g. job creation. (Lipp 2007) Previous research has revealed a clear link between environmental policies and innovation (Jaffe et al. 2002). Also in the field of renewable energy, it has been demonstrated that public policy plays a significant role in providing direction for technology innovation activities, evidenced in patent numbers (Johnstone et al. 2010). Yet, policies to promote RE differ significantly from one country to another (Rogge et al. 2017).

In practice, RE policies often take the shape of policy mixes: they emerge through processes of policy change, with changing policy goals as well as addition and subtraction of elements over time (Howlett and Rayner 2013). The policy fields that strongly affect RE patents include not only climate and energy policy but also innovation and e.g. industrial policy (Johnstone et al., 2017). There is an expanding literature on innovation policy mixes, often focused on partly overlapping goals and instruments of different policy domains and levels of governance (e.g., Kivimaa and Kern 2016; Constantini et al. 2017).

Rogge and Reichardt (2016) point out that not only instruments and goals in policy mixes should be considered but also the policy process and their broader characteristics, such as credibility, consistency of elements and coherence of policy as a whole. Likewise, policy strategies are combinations of policy objectives and the principal plans for achieving them. Analysing policy strategies highlights the outputs of policies as well as the strategic capacities. (Quitzow 2015; Rogge et al. 2017) This study analyses the RE policy trajectories of the chosen countries in a very broad manner: We focus particularly on those features of the policies, their implementation and outcomes that reflect certain robustness and resilience mechanisms (see sub-section 2.3).

2.2 Robustness and resilience as policy attributes

In a longer time perspective, many studies have shown that consistent, predictable, and reliable policy signals can induce innovations (Mickwitz et al. 2008). Also in the field of renewable energy, evidence suggests that commitment is one of the key factors for policy success (Lipp 2017). The quest towards committed, consistent and predictable policy signals in RE innovation links the discussion on effective policy mixes to that of robust and resilient policies. Robustness and resilience are attractive to researchers interested in understanding policy change and stability because they refer to the ability of policy to adapt to both external shocks and internal perturbations (Capano and Woo 2017; Nair and Howlett 2016).

In the last three decades, there has been a rising interest in resilience and robustness in several specific policy fields (climate change, environmental policy, and risk management) and among scholars of comparative politics who are interested in institutional design (e.g. Bednar 2009; Ostrom 1990). According to Anderies et al. (2013), resilience and robustness are fruitfully used in a complementary fashion. While *robustness* can be seen to reflect i) the capacity of a policy to adapt to anticipated conditions and self-adjust to linear changes in its environment, *resilience* highlights ii) the capacities to adapt to unanticipated conditions and non-linear shifts in their contexts (Nair and Howlett 2016; Swanson et al. 2010). In other words, robust policies can be described as being 'fail-safe' within a specified range of uncertainty without changing their underlying goal structure or content. Meanwhile, resilience can be considered to be an 'emergent' rather than 'static' feature of systems and policies capable of non-linear adaptation. (Nair and Howlett 2016) Thus, while robust policies may also be non-adaptive by nature, adaptiveness is the common denominator of these concepts. Figure 1 illustrates their mutual relations.

Figure 1. Robustness, resilience and adaptiveness: the mutual relationships of the concepts and their place in the stability vs. change continuum

Stability	Anticipated/linear change	Un-anticipated/non-linear change
Robustness		
	Adaptiveness	
		Resilience

Robustness has been described as the 'ability of a system to withstand perturbations in structure without change in function' (Jen 2003, p. 14). Across various disciplines, robustness is associated with a complex system's ability to remain functional in the face of shocks or disturbances (Anderies et al. 2013; Mens et al. 2011). It ensures effectiveness over time in a specific system, institutional arrangement, or policy field. However, robustness is not the same as stability: robust policies maintain the *function* of the policy, while stable policies maintain their actual state. However, due to their intrinsic ability to keep functioning, robust policies might also inhibit policy change. (Capano and Woo 2017; see also Mens et al. 2011) In policy analysis, robustness refers to the capacity of government to maintain the original definition of the problem and to control agenda setting (Green-Pedersen and Walgrave 2014; Rasch and Tsebelis 2011). Thus, policy robustness directly depends on the competence of governmental policy, as well as the configuration of socio-political interests. (Capano and Woo 2017; Wu et al. 2015). In general, robustness is proactive and design-centric as a concept (Capano and Woo 2017); it deals with designing general principles of operation as well as allocating general roles and responsibilities.

Meanwhile, *resilience* emphasizes learning by doing and multi-stakeholder engagement for policy design and implementation (Nair and Howlett 2016). Within the broad scientific domain, resilience has evolved into a framework for understanding how complex systems self-organize and change over time (Anderies et al. 2013). Compared to robustness, resilience is a more evocative and aspirational term that emphasises self-organization and learning, goal-seeking and exploration (Nair and Howlett 2016; White and O'Hare 2014). Resilience-oriented policy process facilitates more incremental adaptations to the existing policy mix, such as 'layering' or 'patching' (Howlett and Rayner 2013). In some instances, it might not be possible to 'design' resilient policies in an intentional manner (Howlett and Mukherjee 2014). Thus, it has been criticised that resilience as a policy direction or principle de-emphasizes direct policy intervention and instead emphasizes individual responsibility, as well as the role of societal actors in building up resilience (Capano and Woo 2017).

2.3 Analysis framework for studying policy adaptiveness, robustness and resilience strategies

According to Swanson et al. (2010), *robust* adaptive policies anticipate and plan for the array of conditions that lie ahead. The tools they use comprise of:

1) integrated and forward-looking analysis;

2) multi-stakeholder deliberation;

3) monitoring of key performance indicators to trigger built-in policy adjustments; and

4) formal policy review to support continuous learning.

Meanwhile, *resilient* policies are able to navigate toward successful outcomes in settings that cannot be anticipated in advance. This can be done by working in concert with certain characteristics of complex adaptive systems and thereby facilitating autonomous actions among stakeholders on the ground. Policy review and multi-stakeholder deliberation (tools 2 and 4 above) support such actions. However, most directly, such autonomous tools include:

5) enabling self-organization and social networking;

6) decentralizing decision-making to the lowest and most effective jurisdictional level; and

7) promoting variation in policy responses. (Swanson et al. 2010; see also Rammel and van den Bergh 2003)

We have built the following analysis framework (see Table 1) on the basis of the list of principles for intervention in complex adaptive systems (Swanson et al. 2010). However, as long and detailed lists are difficult to apply in policy analyses, the principles of intervention were grouped into five mechanisms that reflect *different strategies and means for promoting policy adaptiveness, robustness and resilience.*

Table 1. Analysis framework for studying policy robustness and resilience strategies (on the basis of Swanson et al. 2010)

1. Rooting
Respecting history (prevailing structures, discourses, policy goals)
Understanding local conditions, strengths and assets
Understanding interactions with the natural, built and social environment
2. Diversifying action and information
Promoting variation and redundancy

Increasing information on unknown effects
3. Broadening social capital
Enhancing public discourse and open deliberation as important elements of social learning and policy adaptation
Building trust, collaboration, consensus, identity, values, hope and capacity for social action
Using epistemic communities to inform policy design and implementation
Creating opportunities for self-organization
Enhancing and building networks for free, reciprocal interaction
4. Creating adaptive policy mechanisms
Integrating the monitoring and remedial mechanisms at the heart of the process: policies testing clearly formulated hypotheses
Making learning and adaptation of the policy explicit at the outset: policies encouraged to evolve in their implementation
Evaluating performance of potential solutions and selecting the best candidates for further support: attributing the credit carefully
5. Navigating strategically
Looking for linkages in unusual places
Determining significant connections rather than measure everything
Facilitating copying of successes
Balancing exploitation of existing ideas and strategies and exploration of new ideas

In practice, there are essentially four general tasks that a policymaker needs to undertake in order to create and implement resilient and robust policies. The tasks deal with the ability to understand the policy environment, to enable policy innovations, to monitor and to improve. These tasks feed into the iterative policy cycle at different stages, and build in adaptability (Swanson et al. 2010). The adaptive policy-making process can be passive, i.e.,operating on available 'best' scientific information till new knowledge comes up, or active, i.e., consciously experimenting with policy alternatives (Rammel and van den Bergh 2003). The next sub-section describes the materials and methods used for studying RE policy robustness and resilience of Finland, Denmark and Germany.

3 Materials and methods

The idea of the analysis was to understand how policies have affected Denmark, Germany and Finland emerging as RE innovation leaders in different areas. More specifically, the time-span over several electoral cycles and policy trends opens up the perspective over adaptation and permanence of specific policy goals regarding RE development. The analysis was conducted by a literature review on scientific publications focused on energy and climate policies of Germany, Denmark and Finland. The key literature was found by making Google Scholar searches for articles for the year 2000 onwards. The keywords used, as well as the articles that formed the core of the analysis for each country case, are listed in Table 2 below. For each keyword search, 50 best hits were read through on title, keywords and abstract level in order to pick the most suitable articles. The idea was to concentrate particularly on country cases and papers with a strong policy focus and clear relevance to the leading RE technology of each country. Thus, papers with very narrow or only e.g. engineering focus were left aside. Later on, new items were included in the list of references as the reading revealed e.g. interesting articles that had not been part of the searches. Of the most suitable papers found, 7-8 formed the core of the analysis for each country.

Table 2. Country cases, keywords and core articles of the literature review

Country case	Keywords used in searches	Core articles of the analysis
Finland	1. Finland + bioenergy + policy 2. Finland + energy policy	Aslani et al. (2013); Ericsson et al. (2004); Helynen (2004); Huttunen (2009); Huttunen (2014); Kivimaa and Mickwitz (2011); Åkerman et al. (2010)
Denmark	1. Denmark + wind energy + policy 2. Denmark + energy policy	Garud and Karnoe (2003); Klaassen et al. (2005); Lipp (2007); Meyer (2007); Munksgaard and Morthorst (2008); Möller (2010); Sperling et al. (2011); Sovacool (2013)
Germany	1. Germany + solar power + policy 2. Germany + solar energy + policy 3. Germany + energy policy 4. Germany + Energiewende	Chowdhury et al. (2014); Dinçer (2011); Frondel et al. (2008); Hoppman et al. (2014); Lauber and Mez (2006); Pegels and Lütkenhorst (2014); Quitzow (2015); Renn et al. (2016); Sahu 2015

Key justification for looking into the three technology-country pairs comes from stockpiling of innovations in recent history (Appendix 1). The leading role of Denmark in wind energy and Germany in the field of solar power patents has been clear. In bioenergy patents, Finland and Denmark have been competing on the leading position among the European countries, but the number of annually issued patents is much lower than for other RE technologies.

Patents have emerged as a valuable source of information for technological innovation, its nature and applications in modern societies (Griliches 1990). Patents are generally issued by specialized national agencies and they give the holder exclusive rights for the production of a specific good or for using a process for a defined number of years. Patent data is readily available and comparable across countries. Yet, it has some shortcomings from innovation research perspective. These shortcomings are related particularly to difficulties to differentiate between more and less 'valueble' patents and to the wide variety of patent regimes in different countries. (Johnstone et al. 2010)

The analysis and the patent data were complemented with more recent data-sets regarding the RE production levels (Appendix 2), technology exports (Appendix 3) and CO2 emission development (Appendix 4) drawn from Eurostat and UNComtrade databases. The complementary data was used to illustrate continuities and discontinuities of the trends presented in the analysis on the one hand and to track 'real world' effects of technology innovations in each country case on the other.

5 Analysis

All the countries analysed in this section, Finland, Denmark and Germany, can be considered as European renewable energy technology leaders. Certain common turning points, such as the oil crises of the 1970s or Chernobyl nuclear disaster and trajectories, like the developments of UNFCCC and EU's climate policy, have affected all these countries. At the same time, the countries have specific historical, societal and environmental conditions and distinct country-specific policy choices that have diversified their paths.

5.1 Finland's bioenergy policy

Finland is one of the countries in which RE has the highest contribution to primary energy supply (Aslani 2013). The share of bioenergy in primary energy production has risen significantly in the past 30 years and reached 51,3 % in 2016 (Statistics of Finland 2018). The development of bioenergy relates to developments in various sectors of economy including forestry and forest industry, agriculture and the food chain, energy production and consumption (particularly CHP and heating) as well as transport and waste treatment. Firewood, wood chips, pellets and briquettes are some examples of bioenergy that are usually produced from side streams and leftovers of forest industry, such as sawdust and bark. Overall, about half of the bioenergy production comes from black liquor that is the most important side product of pulp and paper industry.

While Finland has been able to reach its renewable energy targets well in time[2], the transition has been somewhat technocratic and one dimensional. The increased renewable energy shares have been mainly reached by actions of the incumbent actors: almost 90 % of bioenergy consisting of forest industry by-products (Aslani 2013; Kivimaa and Mickwitz 2011). It has been stated that biomass for energy has been able to "piggyback" on the existing forestry infrastructure (Ericsson et al. 2004). Further, in terms of policy goals and tools, new ones, such as those dealing with climate, have generally been layered on the top of the old ones dating back to oil-crises of 1970s emphasizing energy self-sufficiency, security of supply and access to inexpensive energy (Lafferty and Ruud 2008; Kivimaa and Mickwitz 2011; Ruostetsaari 2010).

[2] Finland's RE target for 2020 is 38 % of final energy consumption. That was exceeded in 2014, when 38,7 % of energy consumption was covered by renewable energy sources.

Forest industry has been a key player in the energy field from the 1970s onwards. The industrial interest groups have been active in maintaining the commanding position over the forest resources, while simultaneously lobbying for new nuclear energy production capacity (Ruostetsaari 2010; Albrecht et al. 2017). However, since the mid-1990s, the number of small-scale heating plants, utilising forest residues rather than industrial side-products as their main resource, has increased quickly (Åkerman et al. 2010). While the total amount of energy produced by these plants is small in the context of the whole bioenergy system, Åkerman et al. (2010) have shown that their existence has changed local practices in the forestry and energy sectors and the development has been important for local forest-owners and communities. Further, since the beginning of the new millennium, smaller-scale bioenergy applications such as biogas, distributed generation, and house-specific heating solutions have been taken up in policy documents, opening the floor for a more diversified set of actors such as actors of private forestry, rural population as well as farms and micro-businesses (Kivimaa and Mickwitz 2011).

Although the main instruments of Finnish bioenergy policy have stayed the same – namely, R&D and investment support, energy tax exemptions and rebates, and information provision – some new instruments, such as feed-in tariffs, have been introduced and others have been modified to be more targeted at specific bioenergy sources (Kivimaa and Mickwitz 2011). Furthermore, structural changes in pulp and paper industry as well as agriculture have been important drivers for the bioenergy policy since the early 2000s: While climate policy has given a new justification for bioenergy, the stalling of the forest industry's growth and structural changes in agriculture have opened space for alternative bioenergy options (Huttunen 2009; Kivimaa and Mickwitz 2011).

A latent rupture between industrial and communal framing of bioenergy development surfaced in 2011, when the government decided on the subsidy scheme for energy wood as key policy to achieve RED targets for 2020. In the discussion, small-scale energy producers and forest owners wanted to change 'the rules of the game', gain more access in decision making and diversify the definition of bioenergy. However, after several rounds of deliberation and intervention by the European Commission, the industrial status quo was maintained and more distributed policy goals abandoned. (Huttunen 2014)

In general, Finland has not adopted or strived for more ambitious goals than the existing EU targets (Mickwitz et al. 2009). Finnish energy policy has remained highly industry-oriented, and consequently the forest industry has actively maintained significant coordinating role as energy producer, resource provider and a developer of new bioenergy technologies - especially in bioliquids (Kivimaa 2008). Further, a remarkable feature in the Finnish research policy has been - in contrast to that in many other industrialised countries – has been continuity and competence building manifested in a relatively steady level and stable distribution of R&D support for bioenergy over the last 20 years (Helynen 2004). The development of climate and renewable energy programmes (with targets) have been important parts of the process that in practice have meant targeted support for wood-based fuels. Biogas and other non-wood biofuels have been considered but regarded as economically unviable. The literature review did not yield much material on e.g. monitoring and evaluation, which are potentially neglected areas. Further, the mechanisms of strategic navigation such as looking for linkages in unusual places and facilitating the copying of success were scarcely covered.

All in all, *Finland's bioenergy policy can be considered robust but not very resilient*. It has been well rooted in the national context as it has largely supported actions by the incumbent players (Aslani et al. 2013; Kivimaa and Mickwitz 2011). It has respected history, the prevailing structures, discourses and policy goals. It has built on the national assets and strengths. Thus, it has been able to maintain a relatively similar policy orientation for decades despite the lack of own climate policy ambition. At the same time, the policy has not encouraged nor taken advantage of the birth of resilient capacities such as varied forms of bioenergy production and use. For example, smaller scale bioenergy production has not been politically promoted at the pace that would have been technologically possible (Åkerman 2010). In addition, Finland has not sought to broaden social capital around the bioenergy cluster: While certain epistemic communities have been used to inform policy design and implementation, broader networking or deliberation have not been encouraged.

5.2 Wind energy policy in Denmark

Denmark has been a stable source in bioenergy patents but it is the clear European leader in the field of wind energy technology innovations. Wind energy is also broadly applied in Denmark (see Appendix 2). Thus, Denmark has been able to change its energy system, and also to cut its CO2 emissions drastically (Appendix 4) in a relatively short period of time. In roughly two decades, Denmark transitioned from a centralized electricity network based on large-scale fossil-fueled plants to one featuring wind turbines and CHP units (Sovacool 2013).

The Danish wind energy system is well rooted in natural conditions favorable for wind energy and social circumstances that embrace cooperative type collective action (Mendonca et al. 2009; Möller 2010). Many of the Danish wind energy facilities are owned by local actors such as municipalities and farmers All farmers and rural households have had the chance to join local cooperatives in their municipalities or neighboring municipalities, and exclusive local ownership has been a condition for the operating permits of wind power plants. Further, electric utilities could only build large wind farms in agreement with the government and if it did not violate the wishes of farmers and local residents. The access to the grid has been guaranteed and the cost of interconnection is paid by the consumers. (Sovacool 2013) This has given to a broad palette of actors, including e.g. electricity companies, wind energy developers and industry, a stake to support wind energy promotion. The broad support network has built robust basis for long term politics if favor of wind energy. Further, the system has promoted local testing of technology which has provided home market references and enabled the development of reliable small wind turbines (Klaassen et al. 2005).

In policy terms, the promotion of wind energy became important in Denmark already in the mid-1970s (Klaassen et al. 2005). The investment subsidy provided for individuals, municipalities and farming communities between 1979 and 1989 was instrumental in achieving early expansion of the capacity and familiarising actors with the technology. In the early 1990s, a feed-in-tariff (FIT) was introduced requiring utilities to buy all power produced from renewable energy technologies at a rate above the wholesale price of electricity in a given distribution area (Sovacool 2013; Klaassen et al. 2005). FIT has been considered the stimulus needed for widespread wind development that has allowed projects to move beyond wind enthusiasts and involve a bigger share of the population (Hvelplund 2005).

The Danish energy policy has been very consistent from 1973 to 1998 and from 2008 onwards. However, in 1998 - 2007, there was a period of pendulum in policy support seeking to match the liberalized energy markets with policy objectives that favour larger scale of wind turbines (Lipp 2007; Munksgaard & Morthorst 2008; Sovacool 2013). On the ground-level, the change resulted in the development of larger wind turbines with less local involvement - a phenomenon that has started to affect the overly positive attitude towards wind power among the Danes. Further, the policy change stagnated the development and domestic market of wind energy (Lipp 2007; Sovacool 2013).

The early government commitment to fostering alternative sources of energy by combining both bottom-up and top-down approaches is often named as the key to initial success in Denmark (Klaassen et al 2005; Lipp 2007; Meyer 2007; Sperling et al 2011). In addition to FIT for wind (1993), the ongoing support mechanisms through various energy acts are central for sustained top-down policy support (Lipp, 2017). Furthermore, the strong integration of the energy supply companies in developing the distributed production system and the refunding of CO2 and energy tax to wind turbine operators are considered successful policies (Klaassen et al. 2005). The Danish research policy has succeeded in balancing R&D for innovation and procurement support for diffusion of wind energy technologies. Further, it has been able to adapt: For example, the percentage of R&D funds given to small wind turbine projects has increased over time (Klaassen et al. 2005). As a result, the country has not only succeeded in promoting the utilisation of wind energy and cutting carbon emissions, but managed to turn innovations into significant technology exports (Appendix 3).

From bottom-up perspective, the Danish process has included incremental learning-by-doing through practical experience. The Danish regulators have, since the 1970s, worked with manufacturers and interested citizens to promote the development of renewable technologies and markets which has also paid dividends (Garud and Karnoe 2003; Sperling et al. 2011). Further, the Danish planning system has divided responsibilities both among national and local levels (Sperling et al. 2011). In terms of promoting wind power, national planners have offered stable financial support and developed appropriate guidelines whereas the local planners and cooperatives have drafted wind power plans and supported locally relevant projects.

Moreover, resources have been balanced between different kinds of actors in the energy field. For example, funds to empower independent lobbyists have been allocated by Parliament for technical pilot projects, energy offices and independent research centres (Hvelplund 2005). In addition, the FIT has been stimulating diversity as it allows development in a range of locations, technologies and project sizes, spreading the benefits to diverse participants (Lipp 2007). However, it should be noted that while the large amount and diversity of actors has also made the Danish policy-making more complicated (Sovacool 2013).

From perspective of robustness and resilience trajectories, the Danish policy has been quite balanced. In terms of robustness, it has built on the existing structures, respected history, the local strengths and assets. The policy has been strongly rooted and consistent over long periods of time (Lipp 2007). In terms of resilience, the Danish wind power promotion has diversified the action and actors operating on the field, enabling various players to work together. The policy has encouraged diversity in many fronts: in research and development, in policy, lobbying and planning on different levels, and in project implementation (Hvelplund 2005; Lipp 2007). However, on the creation of adaptive policy mechanisms the literature review did not provide much. There has been room for strategic navigation in terms of copying of success and balancing exploitation of existing ideas and strategies - and exploration of new ones. However, determining significant connections and looking for linkages in unusual places were not reflected in the material.

5.3 Germany's solar power policy

In the European context, Germany is one of the leading countries for the development of renewable energy (Pegels and Lütkenhorst 2014). Germany has the highest PV power installation capacity per capita in Europe and it is also the leading country of solar energy innovations (see Appendix 1). In absolute terms, Germany has been accumulating solar energy innovations and exports since 1990s (see Appendixes 2 and 3) and thus contributed significantly to the overall emergence of solar technologies in the last decade.

Many of these developments result from steps taken already long time ago as the German renewable energy policy dates back to the oil crisis of 1973 and the key policy RES-E was introduced in the renewable energy sector in 1979 (Sahu 2015). However, the promotion of renewables has got boost from *Energiewende* ('energy transformation') that the conservative government announced in 2011. In Energiewende, the decision was to reduce the amount of fossil fuels from 80% of the energy supply to 20% by 2050 (Renn and Marshall 2016). Consequently, in 2012, the new Renewable Energy Sources Act (EEG) was introduced. The purpose of this policy has been to facilitate the developments of sustainable energy by cutting environmental effects, reducing costs and promoting renewable electricity innovations (Sahu 2015).

In Germany, systematic installations of residential PV systems started under the 1000 roofs program in 1989. In the 1000 roofs program, government gave subsidies to individuals to cover the cost of installing a PV rooftop system. The aims of the program were to gain experience with solar installations, make new housing compatible with renewable electricity generation needs, and stimulate consumer usage of solar power (Chowdhury et al. 2014; Lipp 2007). However, until 1999, installations increased only slowly. In general, the political level support for RE was not widespread until the late 1990s (Lauber and Mez 2006; Lipp 2007).

A period of rapid increase started under the subsidy program 100,000 roofs (1999-2003) and the feed-in-tariff provided by the EEG of 2000 (Chowdhury et al. 2014; Quitzow 2015). The FIT was originally introduced for solar PV in

1991 was updated in 2000 and it guarantees a higher-than-market price for electricity generated by solar PV. Further, in the later version the rate has been fixed for 20 years beyond the installation date, providing investment certainty for firms and individuals. The policy has been successful. In 2000 - 2011, Germany's cumulative installed PV market increased 196 fold (Chowdhury et al. 2014; Lauber and Mez 2006; Lipp 2007). At the same time, Germany established itself as the main driver of global demand and enabled the growth of a number of German solar manufacturing start-ups, establishing a presence along the entire PV value chain. In general, the fortuitous political situation at the federal level allowed the experience gathered by numerous local initiatives in the 1990s to be translated into a strong federal market support scheme (Quitzow 2015).

The period from 2004 to 2010/2011 is considered the core growth period and is further subdivided into the periods from 2004 to 2008 and 2009 to 2010/2011. The former begins with the introduction of Germany's federal, cost-covering feed-in tariff and the removal of the previous cap on policy-supported market growth. It is the first stage of rapid growth in Germany's policy-driven market, albeit constrained by rising module prices. Meanwhile, the period from 2009 to 2010/2011 represented the steepest jump in annual installed capacity and was characterized by a drastic decline in module prices. Growing employment in the industry further bolstered the sector's political clout, so that sustaining the emergent solar industry played a central role in justifying the increase of the solar feed-in tariff in late 2013 (Quitzow 2015) Further, community level dynamics have been of key importance for enabling the later success of Germany's national feed-in tariff in driving market development (Dewald and Truffer 2012).

What is particular for the German solar power promotion is that it not only involves various domestic players but that the co-development of Chinese and German PV industries and markets has been of key importance. According to Quitzow (2015), the cheap Chinese components have enabled the rapid PV deployment in Germany: The exponential growth witnessed in the period from 2008 to 2010/2011 was strongly dependent on the sudden decline in module prices which emerged as the result of Chinese rapid development of scale economies. Thus, while the German ambitious solar PV deployment policies have not translated into the expected competitive advantages, the policy has been successful from many perspectives - enabling a global market for solar PV to take shape. (Quitzow 2015)

While the German Energiewende has become famous in Europe and globally, the share of renewable energy is still rather modest in Germany (Chowdhury et al 2014). Energiewende has been criticized for being expensive. German households are paying some of the highest electricity rates in the EU (Renn and Marshall, 2016; Sahu 2015) and it has been questioned whether Germany will be able to meet its green industrial policy aims at reasonable costs. Wind energy seems to perform better against all policy objectives (competitiveness, innovation, job creation, climate change mitigation, and cost) while the solar PV sector has come under intense pressure from international competition (Pegels and Lütkenhorst 2014).

Respectively, there is also broad commitment to the Energiewende from industry, the major players in science and technology and from environmental groups which forms a robust basis for policies (Renn and Marshall 2016). Especially domestic job creation an important success factor and justification for the permanence of the policy approach (Lipp 2007). Further, Energiewende has been a regime shift that is currently altering the German technological, political and economic system structure.

German policy push as solar power innovation champion has been, first and foremost, achieved by robust policies. On the one hand, it has involved political risk-taking and choosing powerful tools, such as significant R&D and investment funding. On the other hand, long-term commitment, such as the FIT that features guarantees for 20 years onwards (Lipp 2007). However, German solar power promotion has somewhat narrower connections to history, to social traditions, local strengths and assets than e.g. the Finnish bioenergy and Danish wind power policies.

From resilience perspective, the 1000 and 100,000 roofs programs were important as they supported the gaining of experiences with solar installations and stimulated broad consumer usage (Chowdhury et al. 2014; Lipp 2007). By the end of the 100,000 roofs program, Germany's solar PV industry had moved beyond niche markets to become capable of mass manufacture (Chowdhury et al. 2014). Further, Germany has been able to build on and maintain the strong public support on alternative energy paths (Lipp 2007; Chowdhury et al 2014). Certain level of resilience is shown by the fact that while co-evolvement of solar industries in Germany and China was not anticipated when drafting the strong policy pushes, it has still been taken advantage of.

6 Discussion and conclusions

The analysis of bioenergy promotion in Finland, wind power in Denmark and solar power in Germany revealed some interesting differences in their robustness and resilience trajectories. It showed that Denmark has striked good balance between robustness and resilience, as the wind energy policies have been well rooted in the natural and social conditions of the country. It has diversified action and information and broadened social capital by encouraging local ownership and joint testing of nationally produced wind power plants (Hvelplund 2005; Lipp 2007). The strategy has yielded high the installation capacity, steepest emission reductions and well developed technology exports. However, as evidenced by the policy pendulum of 1998-2007, the trajectories have not been thoroughly linear and uniform (Sovacool 2013).

At the same time, Finland's bioenergy policy can be considered robust but not very resilient. It has been well rooted in the prevailing structures, discourses and policy goals of incumbent forest industry actors and interest groups (Kivimaa and Mickwitz 2011). At the same time, it has taken time to start promoting diversification of action and actors such as stronger roles for forest owners, rural people and micro entrepreneurs (Åkerman et al. 2010) - and the general approach has had a technocratic flavour. Thus, as Finland has chosen to further increase the weight of bioenergy in energy palette, it has been recommended to include actors from different scales better (Huttunen 2014). In general, it can be asked whether Finland's overly robust approach on advancing bioenergy as an extension of large-scale forest industry has actually meant wasting important opportunities for structural renewal of forest and agricultural secotrs, the new market creation for new forestry and energy products and more versatile international profiling. For example, the innovation activity reflected in patent numbers is nowhere near the overall share of bioenergy in energy production palette and though the high patent count is relatively high, it does not translate into technology exports and RE production figures in bioenergy are not reflected in technology exports.

The German experiences on renewable energy and particularly solar energy promotion contradict with those of the Finns. From the start, the basis has not been as robust and there has been a need for heavy government push that has been expensive for consumers. The policy has, however, increased its resilience by bringing solar panels to the rooftops of citizens, having positive employment effects and delivering the needed emission reductions. Furthermore, by acting as a game-changer in the German energy sector, the policy's effects reach beyond the sphere of solar power promotion and over national borders (Chowdhury et al. 2014; Lipp 2007; Pegels and Lütkenhorst 2014).

Several interesting notions can be drawn on the basis of the study: First, the study shows that there are different paths to innovation leadership: European RE patent leaders have versatile policy robustness and resilience trajectories and use different mechanisms for making the policies to cope over time. All the cases highlight common elements for success, i.e. the need for clearly stated government commitment as well as consistent, predictable, and reliable policy signals over longer periods of time (cf. Lipp 2007; Mickwitz et al. 2008; Sovacool 2013).

Second, the analysis points out that energy transitions defined (narrowly) as major changes in energy palette, can be technocratic by nature. As the case of Finnish bioenergy promotion illustrates, it may strengthen existing power structures and actor constellations rather than supporting radical shift with potential unanticipated spill over effects. This supports the broader notion that climate change is often being framed as a problem that can be solved by existing energy technologies and practices rather than requiring a visionary outlook (Lovell et al., 2009; Kivimaa and Mickwitz, 2011). Yet, an intriguing question is, as discussed earlier, whether the technocratic RE policy style also means wasting some important policy opportunities.

Third, the study highlights the added value of socially and institutionally robust and/or resilient policies. It is not only about relying on suitable natural conditions and well-established technological infrastructure that makes policies to keep up on the agenda, but also about taking advantage of windows of opportunity to utilise traditions of social organisations and discourses in promoting novel technological solutions. This is an important notion as barriers to RE adoption have been shown to be in many cases socio-technical rather than merely technical (cf. McCormick and Kåberger 2007).

Last but not least, the study awakens the question whether policy robustness and resilience could add a couple of useful conceptual tools for those monitoring renewable energy policies, or other complex policy packages, for today's policy environments. In particular, robustness and resilience could inspire the formulation of rough but useful questions for policy-makers, e.g.:

a) On robustness: On what kind of natural, social, industrial and/or institutional foundations the policy rests upon? In which ways the policy utilises the existing structures? Could it be better "rooted" to increase its robustness?

b) On resilience: How does the policy add to the diversity of action, actors and information? How is learning maximised in policy design, implementation and evaluation? What kind of capacity does the policy have to act on unexpected consequences?

On the basis of the analysis, the policy robustness and resilience framework could be even simplified as in the original framework the adaptive conduct of policy was emphasized at the cost of the other features. The following type of framework could distil the main differences between the robustness and resilience profiles:

1) **Rooting** the policy on the existing structures;

2) **Diversifying** action and information;

3) **Broadening** social capital;

4) **Navigating** the policy environment by learning.

Reflecting critically this study, the learning part became the weakness in the country cases as it was more challenging to find knowledge on that than on the basis, goals and gains of the policy. The country profiles were broad enough to reveal key differences from robustness and resilience point of view. In general, our suggestion is that robustness and resilience are potentially fruitful concepts to study societal aspects of policy, reflecting both longer time-spans of policy-making and wider participation in politics. Further, the adaptive policy also has implications in innovation and economic policies, as the maturing renewable energy technologies are becoming more multi-scalar and non-linear in nature, asking also for flexible and adaptive policy capacities.

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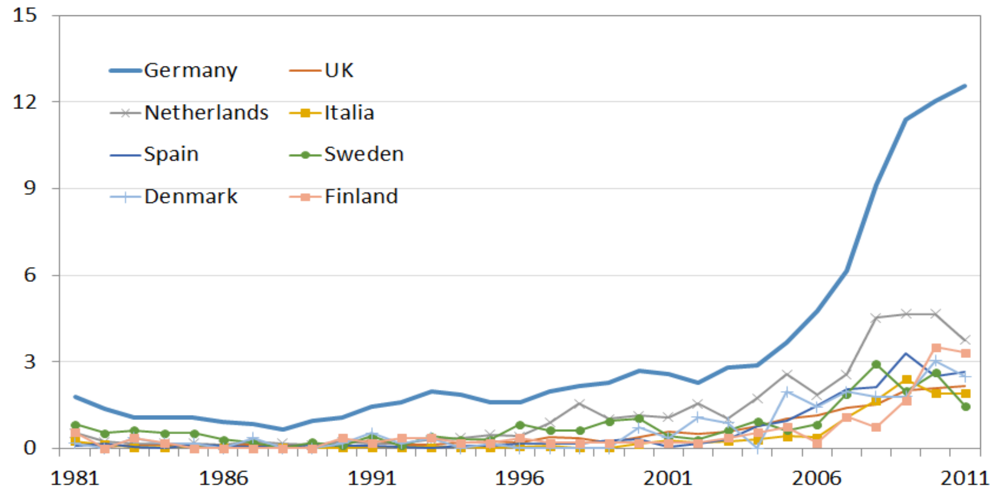
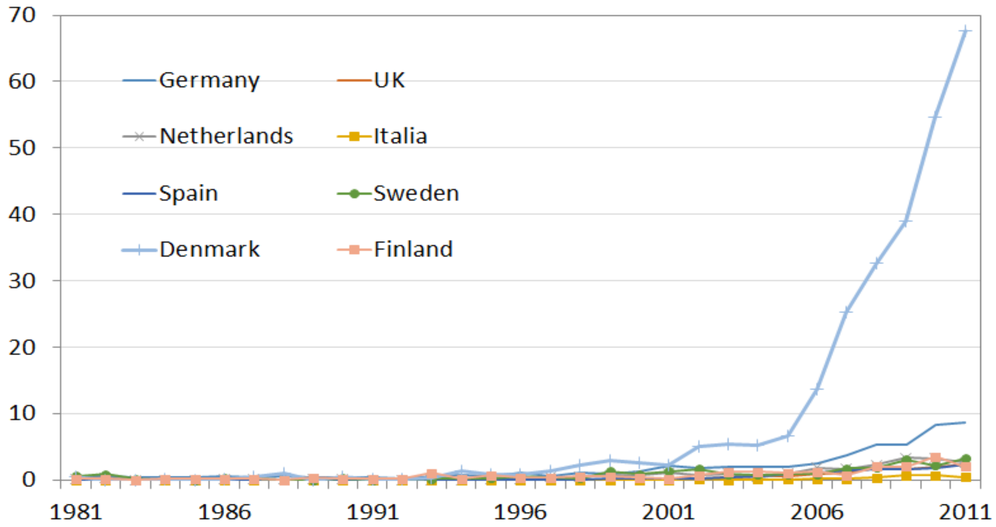
APPENDIX 1. Technology patents.(Patstat)

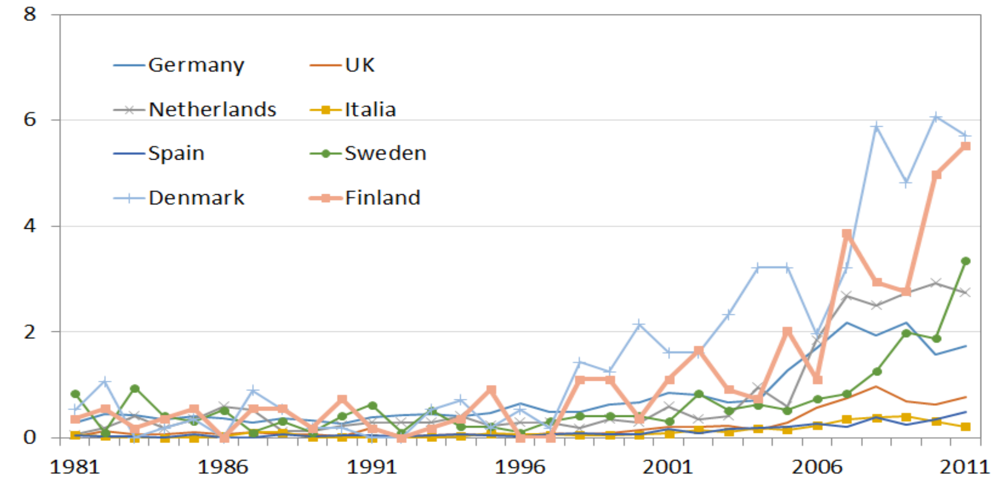
Solar power inventions per capita(million)(including PV and solar thermal and hybrid)



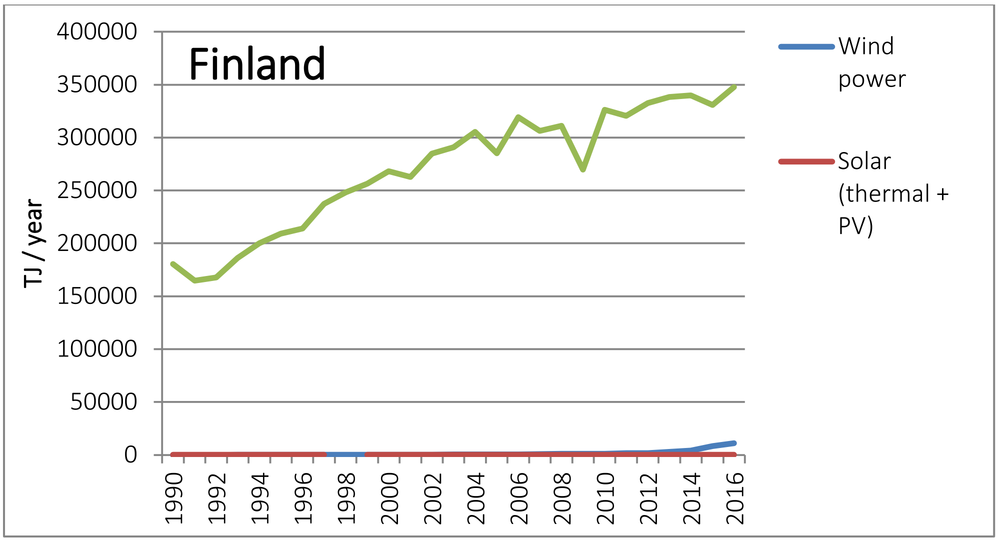
Wind energy inventions per capita(million)

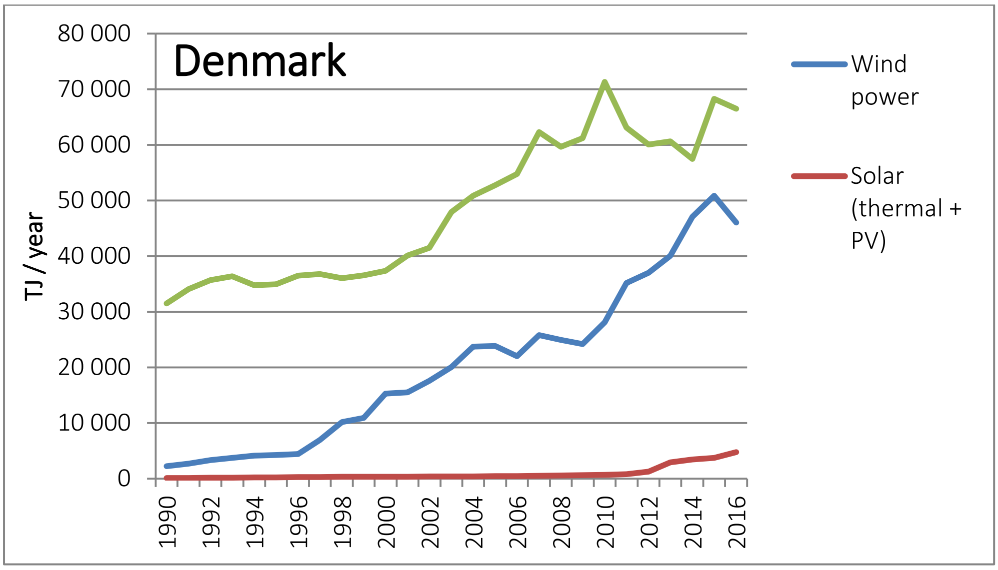


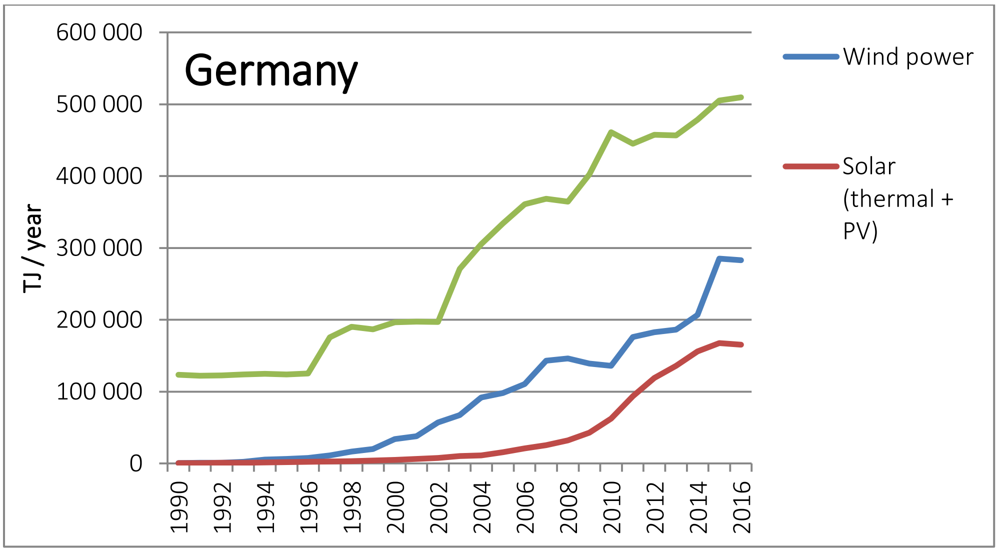
Bioenergy inventions per capita(million) (including biofuels and fuel from waste)



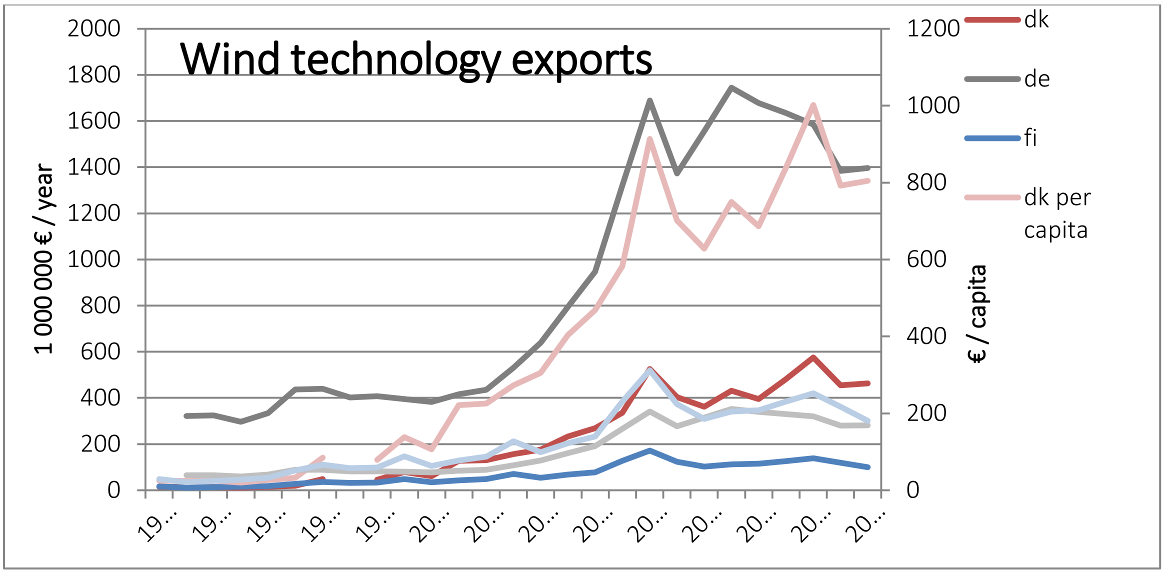
APEENDIX 2. Renewable energy production by country (Eurostat, 2018).

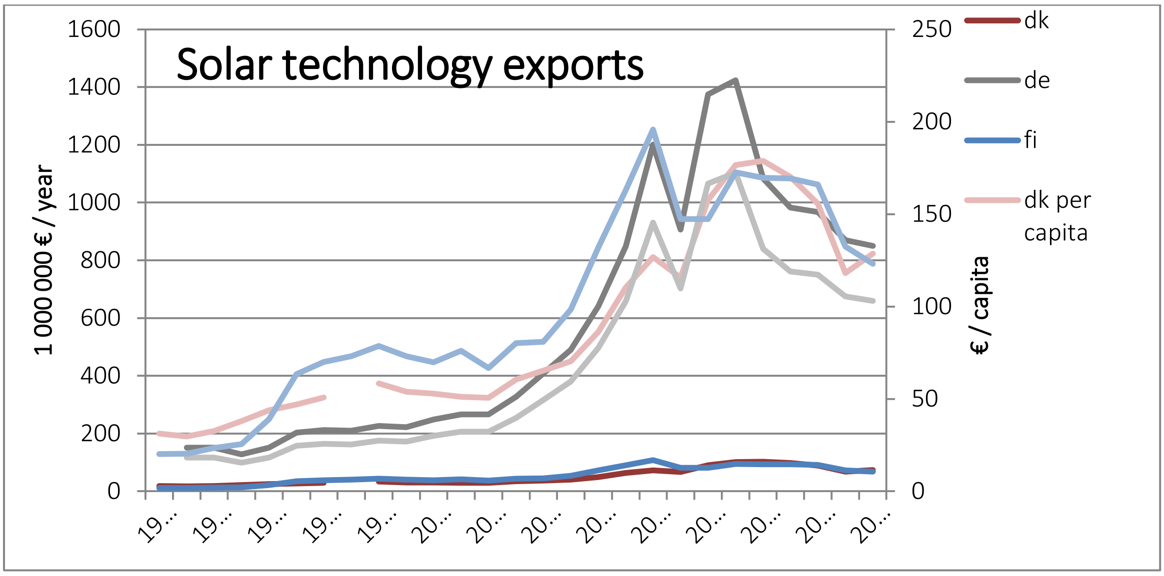


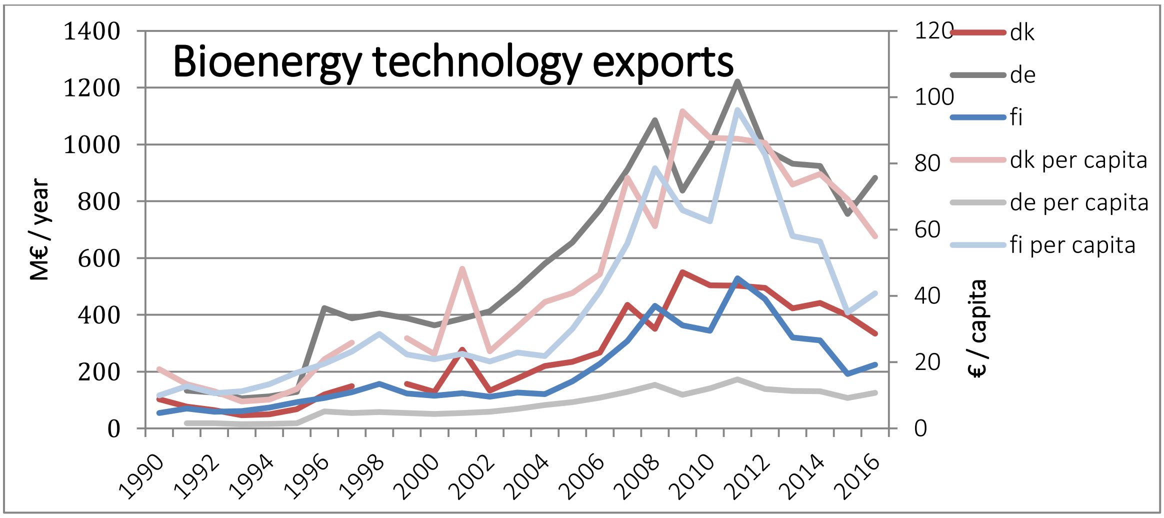




APPENDIX 3. Clean technology exports by technology (UNComtrade 2018).







APPENDIX 4. Carbon emission reductions per capita (Eurostat 2018).