EVALUATING THE EU'S ENERGY INNOVATION SYSTEM

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Abstract

The aim of this paper is to evaluate the consistency of directed innovation activity in the EU with the priority areas set out in the SET Plan. We apply the Energy Technology Innovation System framework to evaluate the distribution of directed innovation efforts between the SET Plan priority areas in 2015. First, we review relevant literature on innovation system frameworks and their application for evaluating strategic policies like the SET Plan. Second, we develop a set of indicators for measuring innovation system functioning. Third, we identify available EU-level data from a wide range of sources. Fourth, we collect data on relevant indicators to characterise the EU energy innovation system in the priority areas identified by the SET Plan. Finally, we draw conclusions about the functioning of the EU's SET Plan from an innovation systems perspective by analysing the distribution of innovation efforts. We find that EU-level innovation system activity is relatively balanced across renewables, electric vehicle and energy efficiency and unbalanced across carbon capture and storage and nuclear safety.

1. Overview

The European Commission has stated “the ambition to achieve ... a fundamental transformation of Europe’s energy system” (EC, 2015b). This transformation requires solutions and policies informed by systemic analysis of energy innovation.

Economics research on energy innovation has provided robust evidence to explain key relationships between R&D, patenting, knowledge stocks, market structure, environmental regulation, and policy uncertainty (Popp, 2002; Popp, 2003; Aghion, Bloom, Blundell, Griffith, & Howitt, 2005; Kalamova, Johnstone, & Hascic, 2012). Economists are more focused on environmental and R&D policies to incentivize the development and deployment of low-carbon technologies in the market. They put more emphasis on a narrow set of inputs and outputs for which granular data are available.

This deep causal understanding of specific innovation processes is usefully complemented by innovation systems analysis. Unlike neoclassical economics perspective on energy technological innovation, the current interdisciplinary scholars somewhat agree with the greater use of the systemic approach to energy innovation. An innovation system emphasises the actors, networks, and infrastructures which are important structural elements of innovation activity (Lundvall, 1992), as well as the necessary functions that these structural elements provide (Marko P. Hekkert & Negro, 2009). By linking these broader dimensions of innovation system functioning with specific innovation processes, a systems perspective helps explain the relative successes and failures of different historical experiences with energy innovation (Grubler & Wilson, 2014).

The EU’s Strategic Energy Technology (SET) Plan is the principal EU-level approach for achieving system transformation to meet climate, security and efficiency goals. The SET Plan was launched in 2008 to provide strategic planning and coordination of energy research & innovation activities within the EU (da Graça Carvalho, 2012) and the Commission proposed a revised SET Plan that was more targeted and used a whole systems approach to ensure better integration across sectors and technologies in 2015 (EC, 2015b). As shown in Table 1, this revised 'Integrated SET Plan' set out four priority areas (renewable energy and storage, smart systems and consumers, energy efficiency, sustainable transport) and two additional areas (carbon capture and storage, nuclear safety). The Strategic Energy Technologies Information System (SETIS) monitors the progress of impact of policy which aims to provide the most up-to-date information on the SET Plan (Corsatea, Fiorini, Georgakaki, & Lepsa, 2015). So, assessing proper indicators which represent different dimensions of energy technology innovation system is critical to understand dynamics of SET Plan better and provide policy recommendations promptly.

Table 1. SET Plan Priority Areas & Related Actions

No.	SET Plan: Six Priority Areas	SET Plan: Ten Actions
1	No.1 in Renewable Energy (RE)	Performant renewable technologies integrated into the energy system
		Reduce costs of technologies
2	Smart EU Energy System (SG)	New smart technologies & services for consumers
		Resilience, security & smartness of energy system
3	Energy Efficiency (EE)	New materials & technologies for buildings
		Energy efficiency for industry
4	Sustainable Transport (EV, Biofuels)	Competitiveness in batteries & e-mobility
		Renewable fuels
5	Carbon Capture and Storage (CCS)	Application of carbon capture with storage or use
6	Nuclear Safety (NS)	High level of safety in nuclear reactors & fuel cycles

Source: Adapted from (EC, 2015a)

2. Energy Technology Innovation System (ETIS)

Various frameworks with different emphases have been proposed for evaluating the performance of energy innovation systems. The seminal work of these scholars originated from the National Innovation System (NIS) which explains the flow of people and firms within institutions on the national level (Freeman, 1995). Subsequently, other streams of studies argue different aspects of innovation system as an important determinant of technological change. The Technology Innovation System (TIS) scholars emphasize structural elements of innovation system and analyse actors, institutions, and networks that affect a specific technological development (Hudson, Winskel, & Allen, 2011). TIS scholars have paid attention to a specific technology within borders (Hudson et al., 2011; Jacobsson & Karltorp, 2013). On the other hand, the Functional Innovation System (FIS) scholars emphasize “functions” of innovation system as a critical determinant of analysing processes of energy technology innovation (Hekkert & Negro, 2009; Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008). These “functions” can be understood as how well actors and institutions perform in various aspects of innovation system: entrepreneurial activities, knowledge development and dissemination, the guidance of search, market formation, resource mobilisation, and the creation of legitimacy (Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007).

Drawing on insights from both TIS and FIS literature, the Energy Technology Innovation System is a systemic framework for analysing energy technology innovation (Grubler & Wilson, 2014). It focuses specifically on energy technologies and draws on a wide range of historical case studies which explain how different elements of the innovation system give rise to successful innovation outcomes (Gallagher, Grübler, Kuhl, Nemet, & Wilson, 2012; Grubler & Wilson, 2014). The ETIS provides a systemic perspective on the four main dimensions of dynamic energy innovation processes: knowledge generation, resources, actors and institutions, and adoption and use. The ETIS provides insights on key drivers and processes of energy technology innovation. The concept of the ETIS emphasizes both structural and functional elements and places greater attention firstly on both end users, and secondly on processes that both accumulate and depreciate capital stocks of knowledge and resources. The ETIS collapses the somewhat arbitrary architecture between structural and functional views to focus on observable processes associated with successful or failed innovation outcomes which are specific to energy. Figure 1 illustrates the ETIS framework in terms of stocks (4 dimensions) and flows which both accumulate/generate and depreciate/erode stocks. One measure of successful energy technology innovation outcome is large-scale deployment which is not directly described in Figure 1 but is the outcome of adoption and use.

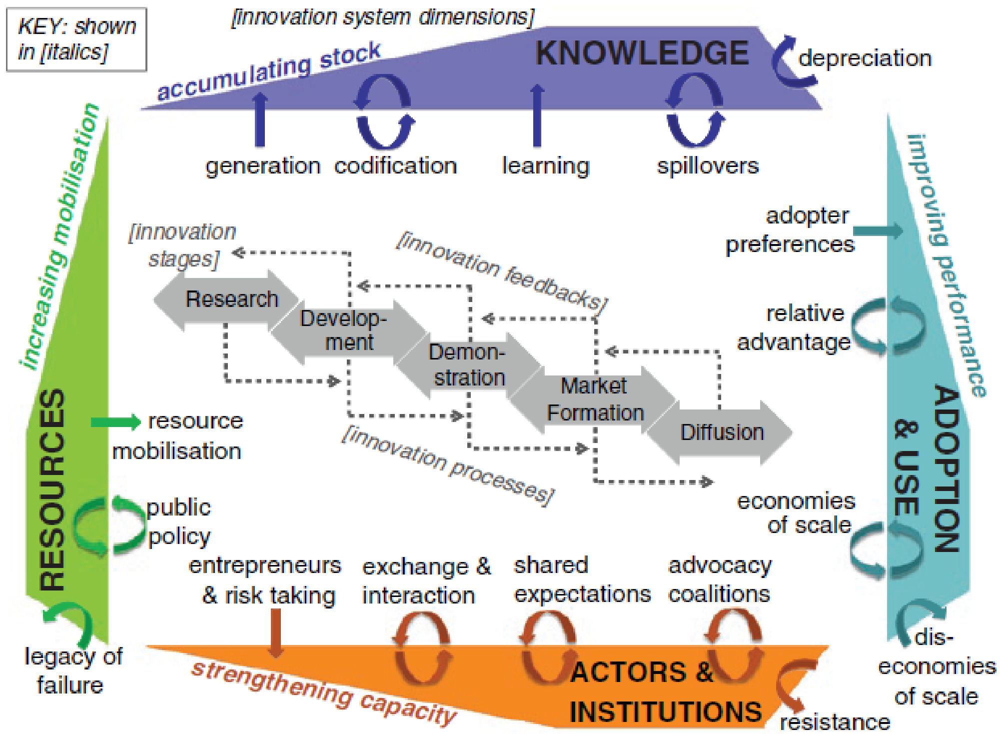

Figure 1. The energy technology innovation system (Grubler & Wilson, 2014)

The first dimension of the ETIS framework is knowledge (top of Figure 1). Knowledge generation, exchange and utilisation are engines of innovation. Scientific knowledge is generated by research and development. Knowledge can be codified as patents, blueprints, and publications, so it is readily transferrable to related sectors of the economy. Tacit knowledge is disseminated person-to-person. Knowledge stocks are depreciated due to staff turnover, business volatility or technological obsolescence. Less formal knowledge can also flow through a wide variety of mechanisms: networks of scientists and engineers, training, interactions and workshops. Learning is a key pathway of improving production processes and decreasing costs of production through the accumulation of knowledge and experience (Arrow, 1962).

The second dimension of the ETIS framework is resources (left of Figure 1). Financial investments including public research, development and demonstration (RD&D) expenditure play a crucial role in supporting energy innovation. Additionally, human capital in the form of skilled labour can generate knowledge and interact with other actors in the energy innovation system such as government officials and environmental advocacy coalitions. Market-based and non-market based policies can spur innovation. However, volatile stop-and-go policies cause uncertainty so that firms are reluctant to invest money (Löfgren, Millock, & Nauges, 2008; Barradale, 2009; Bosetti & Victor, 2011). A stable policy environment fosters long-term investment. A fragmented patchwork of resources deters energy innovation. The legacy of failure or a consumer backlash can erode policy attention and resource mobilisation.

Actors & institutions are the third dimension of the ETIS framework (bottom of Figure 1). Heterogeneous actors with different technological knowledge and resource availability can play different roles in energy innovation. Entrepreneurs take the initiative to establish the nurturing environment for energy innovation. Stability of institutions and shared expectations among actors are important to reduce the uncertainty of energy innovation processes. New technologies face resistance from actors whose interests are vested in the incumbent system. Advocacy coalitions help counteract resistance in an emerging innovation system by forming niche markets and aligning political support.

Fourth, unlike other IS approaches, the ETIS framework puts an emphasis on the adoption & use of innovations (right of Figure 1). Consumers can be both passive users of technologies but also active participants in energy innovation (Schot, Kanger, & Verbong, 2016). Consumers' preferences and experiences interact with the relative advantage of technologies by providing feedback from market settings. Economies of scale can further reduce average unit costs for technologies which up-scale. Diseconomies of scale particularly in technologies at or near the scale frontier can reverse this process. Eventually, the ultimate success of energy innovation is widespread adoption and use.

Innovation system processes associated with these four dimensions of the ETIS framework collectively generate energy innovation outcomes. Multiple components feed into an iterative innovation feedback process to generate desired outcomes. The energy technology innovation system cannot be represented by a simple model. In common with other innovation system frameworks, system performance and functioning can be evaluated using indicators as descriptive proxy measures of innovative system processes.

3. Methodology

In this paper, we used the ETIS framework to analyse whether innovation activities are balanced across the six SET Plan priority areas[1]: renewable energy, smart grid, energy efficiency, electric vehicles, carbon capture and storage, and nuclear safety (Table 1).

To characterize ETIS processes, we reviewed the related literature to identify potential indicators (Borup et al., 2013; Borup, Andersen, Jacobsson, & Midttun, 2008; Miremadi, Saboohi, & Jacobsson, 2016). Indicators allow us to monitor and evaluate the broader spectrum of energy technology innovation processes (International Energy Agency, 2011). This is more suitable for analysing ongoing strategic initiatives such as the SET Plan. This does not obviate the need for rigorous ex-post policy evaluation at a later stage of the SET Plan based on empirical data (Angrist, Dynarski, Kane, Pathak, & Walters, 2010; Angrist & Krueger, 1991).

We identified a comprehensive set of indicators as general descriptors of ETIS processes (Table 2). To select the most appropriate indicators from the wide range available in the literature, we used two selection criteria: usefulness and availability. First, indicators should be relevant for the ETIS. An indicator should be a strong predictor of ETIS processes. It should be understandable, measurable, and generalisable. Second, data for indicators should be available, drawing either on existing databases or on secondary data sets which can be readily analysed to extract or construct necessary indicators.

Building on Wilson et al. (2012)'s work, we collected technology-specific data measuring each indicator. We distinguished data measuring activity within the six SET Plan priority areas from data measuring activity in areas outside the SET plan. For activity within the SET Plan, we computed the relative

[1] https://setis.ec.europa.eu/system/files/integrated_set-plan/integrated_roadmap_energy_union_integrated_set-plan_10_actions.pdf

proportion of activity associated with each of the six priority areas. As our emphasis in this paper is a comparative assessment of innovation 'effort' across the SET Plan areas, we collected only EU-level data to describe our indicators (rather than country-specific data). We compiled technology-specific data for 2015 as the most recent year for which most data were available.

Table 2. Indicators for ETIS processes used in this study

ETIS process	Technology-specific indicators [and metrics] at the EU level
Knowledge	
Generation	Public energy RD&D expenditure [€m at 2015 prices & exchange rates] Demonstration budgets [€m at 2015 prices & exchange rates]
Depreciation	Volatility in energy RD&D expenditure [index: coefficient of variation (COV)]
Spillover	Knowledge spillover benefit from trade [€m: energy technology imports]
Codification	Scientific publications [# articles] Patents [# patents]
Learning	Learning-by-doing [index: learning rate (LR)]
Resources	
Policy Support	Innovation policy density [sum: cumulative years of all instruments] Market-based policy density [sum: cumulative years of all instruments] Regulatory policy density [sum: cumulative years of all instruments] Innovation policy durability [average: cumulative years of all instruments] Market-based policy durability [average: cumulative years of all instruments] Regulatory policy durability [average: cumulative years of all instruments] Diversity of policy mix [Shannon index: three types of policy instrument]
Policy Stability	Stability of policy mix [average: cumulative years of all instruments adjusted by revisions]
Legacy of Failure	Decline in public interest following failures, using Google search frequency as proxy [index: exponent fitted to decline function]
Actors & Institutions	
Capacity	Eco-innovation R&D organisations [# organisations] Top 100 clean-tech funds [sum: cumulative funds €]
Heterogeneity	Diversity in energy actors [Shannon index: type of organisation in European Energy Research Alliance]
Quality Control	EU testing centres & state labs [index]
Exchange & Interaction	European Energy Research Alliance activities involving different actors [# activities]
Shared Expectations	Density of strategic goals inc. targets, roadmaps, action plans [sum: cumulative years of all goals] Durability of strategic goals inc. targets, roadmaps, action plans [average: cumulative years of all goals]
Adoption & Use	
Market Size	Potential market size [€m: estimated as # of vehicles * €/vehicle, MW capacity * €/MW, etc.]
Relative Advantage	Market share [%: actual market as % of potential market]

Sources: Compiled from (Borup et al., 2013; Klitkou et al., 2012; Grubler & Wilson, 2014; Cornell University, INSEAD, & WIPO, 2015; Truffer, Markard, Binz, & Jacobsson, 2012; Speirs, Pearson, & Foxon, 2008; Park, Han, Jang, Choi, & Joo, 2016; Miremadi, Saboohi, & Jacobsson, 2016; Borup, Andersen, Jacobsson, & Midttun, 2008).

4. Data

Here we explain how we constructed each indicator shown in Table 2. Each indicator is constructed directionally so that a higher score indicates 'better' or 'more' innovation activity.

***Knowledge Generation*.** RD&D is the most readily available measure of knowledge generation. We used public energy RD&D expenditure including demonstration budgets from the International Energy Agency (IEA) RD&D database.

***Knowledge Depreciation*.** Knowledge depreciates more rapidly in stop-go environments associated with staff turnover and investment volatility. We calculated the volatility of energy RD&D expenditure based on earlier work on market volatility (Czarnitzki & Toole, 2011) applied using a method from the economics of energy innovation (Kalamova et al., 2012; Verdolini, Bosetti, & Jockers, 2015). Specifically, we used the inverse of the coefficient of variation so that lower volatility results in a higher score on the indicator:

$$PV_{i,t} = \frac{1}{Coefficient\ of\ Variation_{i,t}} = \frac{1}{Policy\ Volatility}_{i,t} = \frac{\frac{1}{5}\sum_{k=0}^{4} RD\&D_{i,t-k}}{\sqrt{\frac{1}{5}\sum_{k=0}^{4}\left[RD\&D_{i,t-k} - \left(\frac{1}{5}\sum_{k=0}^{4} RD\&D_{i,t-k}\right)\right]^2}} \quad (1)$$

with i as a country, t as a year, and k=0-4 (lagged year).

***Knowledge Spillover*.** We used imports of related goods as a simple measure of knowledge spillover into the EU energy innovation system. We obtained data on the total import of energy technologies from EU trade data since 1988 by Harmonised System (HS) 6.[3] We used the HS codes to attribute the import data to the different SET Plan priority areas (Sugathan, 2013; United Nations, Office, & Dechezleprêtre, 2015; Pasimeni, 2017).

***Knowledge Codification*.** Common measures of codified knowledge include publications and patents. We counted the number of relevant publications in 2015 using keywords search on the Web of Science Core Collection (Popp, 2015; Popp, 2016; Stojkoska & Trivodaliev, 2016; Belter & Seidel, 2013; Rizzi, van Eck, & Frey, 2014; Cindrella, Fu, & Ho, 2017; Tsay, 2008; Yesil-Celiktas, 2014; Sanz-Casado, Lascurain-Sánchez, Serrano-Lopez, Larsen, & Ingwersen, 2014). We counted the number of relevant patent applications in 2015 using Cooperative Patent Classifications (CPCs) from the U.S. Patent and Trademark Office (USPTO)[4] (Haščič, Silva, & Johnstone, 2015). We provide further details of both measures in the Appendix.

***Learning*.** Learning describes cost reductions and performance improvements as a function of cumulative experience. Learning rates are a simple measure of the % reduction in cost per doubling of cumulative capacity or production. We sourced learning rates per technology from existing literature (Nilsson & Nykvist, 2016; Rubin, Azevedo, Jaramillo, & Yeh, 2015; Weiss, Junginger, Patel, & Blok, 2010). As

[3] https://data.europa.eu/euodp/en/data/dataset/PApkoFg8zsTS5CyokPyQ
[4] USPTO's PatentsView database: http://www.patentsview.org/web/#viz/relationships

learning rates are estimated from time-series data, these are not 2015 cross-sectional data, and so not directly commensurate with our other indicators.

Policy Support. We used the International Energy Agency (IEA)'s policies and measures databases[7] to compile information on a wide variety of policy instruments. We distinguished policy instruments within the six SET Plan areas from those in the non-SET Plan areas using keywords.[8] We also categorized three types of policy instruments: innovation (e.g., RD&D funding), market-based (e.g., grant and subsidies), and regulatory (e.g., standards). We developed three sets of indicators describing the density (number and duration), durability (average duration), and diversity of policy instruments within each type. Density indicators are based on the summation of cumulative years of all policy instruments within a given type, defined as:

$$Density_{p,s} = \sum_{i=1}^{n}(Endyear_i - Startyear_i) \quad (2)$$

with *i* as one policy instrument (*i*=1,…..,n), *p* as types of policy instrument (p=innovation, market-based and regulatory) and *s* as SET Plan priority area (s=1,…,6).

Durability indicators are based on the average of cumulative years of all policy instruments within a given type, defined as:

$$Durability_{p,s} = \frac{\sum_{i=1}^{n}(Endyear_i - Startyear_i)}{n} \quad (3)$$

with *i* as one policy instrument (*i*=1,…..,n), *p* as types of policy instrument (p=innovation, market-based and regulatory) and *s* as SET Plan priority area (s=1,…,6).

The policy diversity indicator measures whether different types of policy instrument are well-balanced within each of the six SET Plan priority areas (Negro & Hekkert, 2010; Negro, Alkemade, & Hekkert, 2012). The notion of "policy mix" is emphasised in energy, environmental economics and innovation literature (Lehmann, 2012; Rogge & Reichardt, 2016). Building on the energy literature (Kruyt, Vuuren, Vries, & Groenenberg, 2009; Mccollum, Krey, & Riahi, 2011), we calculated Shannon's diversity index H (sometimes Shannon–Weiner or Shannon–Wiener index):

$$H_s = -\sum_i p_i \ln p_i \quad (4)$$

with p_i as share of a type of policy instrument in the SET Plan priority area. The higher the value of *H*, the more diverse the mix of policy instruments.

Policy Stability. As an aggregate measure of policy stability, we divided the average duration of all policy instruments by the total number of times policies had been changed, also using data from the International Energy Agency (IEA)'s policies and measures databases. Higher scores on the indicator denote fewer changes to policy instruments overall and so greater stability:

$$Stability_s = \frac{\sum_{i=1}^{n}(Endyear_i - Startyear_i)}{n \times No.of\ Changes} \quad (5)$$

[7] IEA/IRENA Global Renewable Energy Policies and Measures Database, IEA Addressing Climate Change Database, IEA Energy Efficiency Database, IEA Building Energy Efficiency Policies (BEEP) Database https://www.iea.org/policiesandmeasures/

[8] Renewable Energy: wind, solar, geo, ocean, RE, renewable; Smart Grid: storage, power; Energy Efficiency: heating, cooling, energy efficiency, combined heat and power, CHP, appliance, building, industry, small and medium sized enterprises (SMEs); Electric Vehicle: biofuel, bioenergy, hydropower, electric vehicle, fuel (conventional and alternative), transport; CCS: Carbon capture; Nuclear Safety: nuclear

with *i* as one policy instrument (*i*=1,…..,n) and *s* as SET Plan priority area (s=1,…,6).

Legacy of Failure. Innovation failure can have long lasting effects on market and regulatory confidence. As no prior measure exists in the literature, we developed a new indicator by fitting a decay function to Google search data following a peak of interest linked to a well-publicised failure. We reasoned that rapid decay in interest is a crude measure of a lasting legacy of failure. First, we identified a well-known 'failure' for each technology in each SET Plan priority area (e.g., Fukushima nuclear accident for Nuclear Safety)[10]. We then used Google Trends[11] to identify search frequencies using technology keywords.[12] We searched trends in all categories globally. We then fitted decay function to search frequencies following peak interest during the failure. For the indicator, we use the inverse of the decay function coefficient so that a higher score indicates slow or no dissipation of public interest (and so lower legacy of failure):

$$Y_{t,s} = A \times e^{-b_s \times t} \quad (6)$$

$$Ln\left(Y_{s,t}\right) = -b_s \times t \quad (7)$$

$$Coeff_s = \frac{1}{b_s} \quad (8)$$

with *t* as year and *s* as SET Plan priority area (s=1,…,6).

Capacity of Actors & Institutions. As simple measures of institutional capacity, we used data on the number of actors involved in relevant R&D. First, we calculated the number of R&D organisations in each of the SET Plan priority areas[14] from the eco-innovation R&D organisations. Second, we computed the cumulative R&D funding[15] in each of the SET Plan priority areas from a survey of the top 100 clean-tech R&D organisations in the EU collected by the European Commission.

Heterogeneity of Actors & Institutions. We calculated the diversity[18] of different types of organisations participating in the European Energy Research Alliance (EERA) within each SET Plan priority area. Higher scores a more heterogeneous mix of actors in the energy innovation system:

$$E_s = -\sum_s q_s \ln q_s \quad (9)$$

with q_s as the share of SET Plan priority area *s* in the entire SET Plan.

Quality Control. We used data on the number of EU testing centres and state laboratories from the European Commission's science and knowledge service.[19]

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[10] The high-profile innovation 'failures' in technologies across the SET-Plan priority areas from which point we estimated decay functions in Google Search interest are: RE: Solyndra bankruptcy (Sept. 2011), SG: Smart grid backlash in the Netherlands (April, 2009), EE: Cancellation of the UK Green Deal (July, 2015), EV: Roadster failure (June, 2008), 5: Several CCS cancellations (April, 2009), 6: Fukushima nuclear accident (March, 2011)
[11] https://trends.google.co.uk/trends/
[12] RE: renewable energy, SG: the smart grid, EE: the green deal, EV: electric vehicle, CCS: carbon capture and storage, NS: nuclear safety
[14] https://ec.europa.eu/environment/ecoap/about-eco-innovation/research-developments_en
[15] https://i3connect.com/gct100/the-list
[18] EERA includes associations, industries, research organisations and universities.
[19] https://ec.europa.eu/jrc/en/research-facilities?f[0]=im_field_research_areas%3A2208

***Exchange & Interaction*.** To capture the broader spectrum of actors involved in energy innovation activities beyond traditional data sets (e.g., patents, publications), we counted the number of actors and organisations participating and interacting within the European Energy Research Alliance (EERA).[20]

***Shared Expectations*.** Targets and roadmaps developed collaboratively by key stakeholders are important indications of shared expectations. We calculated both the density and durability of strategic goals, targets, roadmaps, action plans (OECD, 2015) following the method set out above for other types of policy instruments. We also relied on the IEA's policies and measures databases.

***Market Size*.** Potential market size is a measure of expectation and demand-pull for innovations. We used numerous data sources to estimate the potential market size for technologies in each SET Plan priority area. To ensure comparability across areas, we expressed market size in € terms, converting from physical units using average €/unit estimates (Table 3).

***Market Share*.** We used data on actual market penetration of technologies in each SET Plan priority area to estimate market share relative to the potential market size estimated for the previous indicator (Table 3). The market share indicator for Nuclear Safety is anomalous as it measures the share of nuclear power in the electricity mix rather than the share of *safe* reactors and fuel cycles (which is assumed and hoped to be 100%).

Table 3. Estimates of Potential and Actual Market Size in Six SET Plan Priority Areas.

	SET Plan Priority Area	**Potential Market Size (physical units)**	**Actual Market Size (physical units)**	**Market Share**	**Unit Cost**	**Potential Market Size (economic value)**
[1]	Renewable Energy (RE)	1,144,025 MW	120,716 MW	10.55%	1,995,123 €/MW	2,282 € billion
[2]	Smart Grid (SG)	241,662,532 homes	110,000,000 homes	46%	422 €/home	102 € billion
[3]	Energy Efficiency (EE)			33.34%		492 € billion
	Energy Efficiency-Buildings	241,662,532 homes	16,898 homes	0.01%	3,800 €/home	918 € billion
	Energy Efficiency Appliances	535,587,700 appliances	357,076,320 appliances	66.67%	121 €/appliance	65 € billion
[4]	Electric Vehicle (EV)	198,376,808 numbers	149,500 numbers	0.08%	32,500 €/numbers	6,447 € billion
[5]	Carbon Capture & Storage (CCS)	481,916 MW	600 MW	0.12%	2,561,875 €/MW	1,235 € billion
[6]	Nuclear Safety (NS)	1,144,025 MW	121,957 MW	10.66%	3,653,490 €/MW	4,180 € billion

* Potential Market size (RE)=current RE installed capacity/all installed capacity
* Potential Market size (SG)=current number of homes with smart meters/total number of homes
* Potential Market size (EE Building)=current number of homes with Energy Performance Certificate/total number of homes
* Potential Market size (EE Appliance)=current number of homes with A+++ rated appliances/total number of homes
* Potential Market size (EV)=current number of electric vehicles/total number of vehicles
* Potential Market size (CCS)=current CCS projects in Europe/total capacity of fossil-fuel power plant
* Potential Market size (NS)=Total current nuclear power generation capacity/total power generation capacity
* Refer to the Appendix for details.

[20] https://setis.ec.europa.eu/implementation/technology-roadmap/european-energy-research-alliance-eera

5. Results

Using 2015 data for each indicator, we applied the ETIS framework to analyse the extent to which EU-level innovation activity is balanced across the six priority areas of the SET Plan.[21] 'Balance' would see an even distribution of innovation activity in each indicator across each priority area. Our results are summarised in Figures 2; each panel shows indicators describing innovation system processes in one of the four ETIS dimensions. We first discuss observable patterns within each dimension; then we explore generalisable patterns across the four dimensions and so the innovation system as a whole.

Indicators within each ETIS dimension.

Knowledge. We found that renewable energy (RE) and electric vehicles (EV) have the consistently largest shares knowledge-related processes; energy efficiency (EE) and smart grid (SG) have large shares in some processes. Indicators show strong *balance* across the portfolio of SET Plan priority areas include learning measured by learning rates, knowledge generation measured by public energy RD&D expenditure, and knowledge depreciation measured by volatility in RD&D expenditure. Indicators showing a strong *imbalance* between SET Plan priority areas include knowledge generation measured by demonstration budgets (RE+EV=93% of the total), and knowledge codification measured by patent and publications. Publications in 2015 were dominated by electric vehicles, correlating positively with a sizable share of demonstration budgets. However, patent and publication counts need to be interpreted cautiously due to methodological issues. Knowledge spillovers measured by the value of imports were also strongly imbalanced with renewable energy (RE) accounting for about 50% of the total. This finding is in line with a recent study showing that EU has a negative trade balance in solar photovoltaics (Pasimeni, 2017) .

Resources. We found our various resource indicators to be balanced. Our indicators for policy support (density and durability) and policy stability were fairly evenly distributed between the four main areas of the SET Plan: renewable energy, smart grid, energy efficiency, and electric vehicles. The only exception was a smaller share of innovation (RD&D) policy instruments for smart grid. This is an interesting indication of broad policymaking employing a diverse mix of instruments in all domains, as shown by our additional measure of policy support (diversity). The low share of CCS and nuclear safety in our indicators could be affected by how the policy instrument databases are constructed or queried. This is an important topic for our future research. We also found that legacy of failure, measured by decline in Google Search interest following a well-publicised innovation failure, is dominated by renewable energy. In other words, following spike in interest in renewables marked by the Solyndra bankruptcy in 2011, interest did not decline as the failure was 'forgotten'. However, the ability to query Google Trends for search frequencies is limited, and it is highly likely that the search for renewables following Solyndra was also for positive reasons as the industry was growing rapidly. How we construct the legacy of failure indicator needs further work.

Actors & Institutions. We found indictors of actors and institutions active in the EU innovation system to be mostly balanced. This included exchange and interaction indicators measured using organisations participating in the EERA, and shared expectation indicators measured using targets, goals and roadmaps. Both these are core elements of the SET plan in bringing stakeholders together to plan and cooperate around strategic research objectives. However, the EERA is obviously only one of many forums and contexts for actors to exchange knowledge and collaborate, so the sampling methodology limits implications we can draw. Both our indicators of actors' capacity are strongly skewed: towards electric

[21] We do not analyse data corresponding to technologies outside the SET Plan priority areas.

vehicles for the indicator measured using top 100 clean-tech R&D funds; and towards energy efficiency for the indicator measured using eco-innovation R&D organisations. But again, the underlying datasets are small and selective, so further research is needed here.

Adoption & Use. Our two indicators relating to adoption and use are useful as outcome measures of successfully functioning innovation systems. The actual market share indicator describes the extent of successful diffusion, market penetration, and displacement of incumbents. Smart grids and energy efficiency perform strongly on this indicator. Energy efficiency in particular is arguably the most mature of the SET Plan priority areas, with the exception of nuclear. Smart grid is supported by regulated rollout of smart meters into homes across the EU. The potential market share indicator describes the extent of future possibility, market expectations, and realisable diffusion. Electric vehicles perform strongly on this indicator. The vehicle market in € terms is vast, and some modelling studies are already showing the potential for almost full electrification of the vehicle fleet in the medium-to-long term.

Overall, renewable energy, sustainable transport (electric vehicles) and energy efficiency account for the majority of innovation activity in the EU energy technology innovation system in 2015. Smart grid performs well on some indicators, but relatively weakly on knowledge. This could be explained by an emphasis in the EU on smart grid rollout rather than earlier-stage RD&D activity. Nuclear safety has the largest inconsistency across different innovation processes. Nuclear research is a very mature field, so the innovation system framework is less applicable. In addition, the nuclear industry is centralised and capital-intensive with high barriers to entry, so it involves a relatively small number of actors. Knowledge generation on CCS, measured by public energy RD&D expenditure, is not negligible but it is only weakly supported by other innovation system dimensions. This risks undermining the effectiveness of knowledge investments.

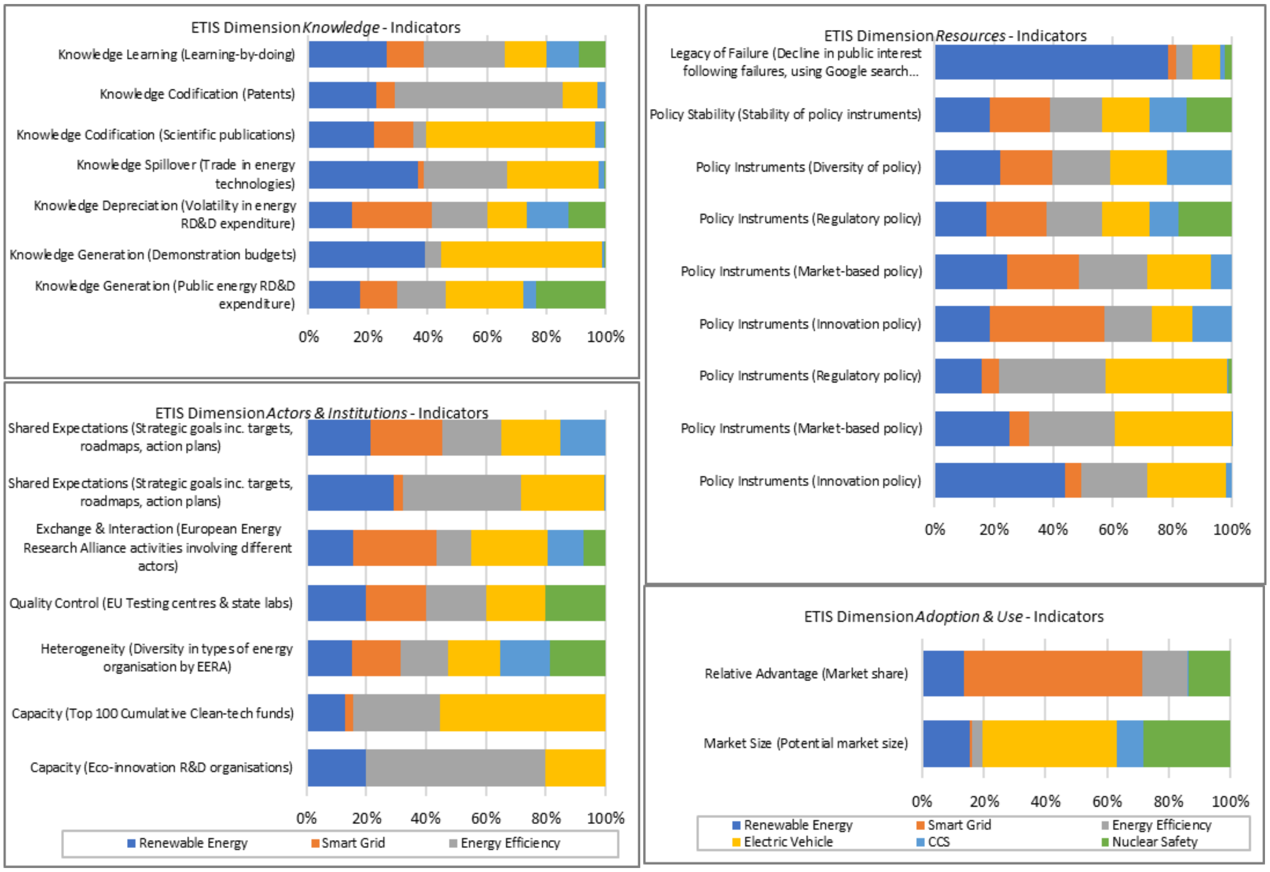

Figure 2. Proportion of innovation system processes in six SET Plan priority areas

***Indicators across all ETIS dimensions*.**

Figure 3 shows the proportions of innovation activity for each of the six SET Plan priority areas across all the indicators in each ETIS dimension. This gives an indication of consistency (low range) or inconsistency (large range) per SET Plan priority area across multiple innovation processes. *Consistency* of activity within each SET Plan priority area is strongest for the resources dimensions (policy support, policy stability, policy diversity, legacy of failure) and the actors & institutions dimensions (actors capacity, exchange & interaction, actor heterogeneity, shared expectations, quality control). *Inconsistency* of activity within each SET Plan priority area is strongest for the knowledge dimension (knowledge generation, codification, spillover, learning) particularly for electric vehicles which accounted for a large share of innovation activity in some areas and a small share in others. The adoption & use dimension only has two indicators so the plot should be interpreted cautiously. Overall these findings offer useful pointers for future SET Plan activity to rebalance imbalance and inconsistency in innovation processes both within and between ETIS dimensions.

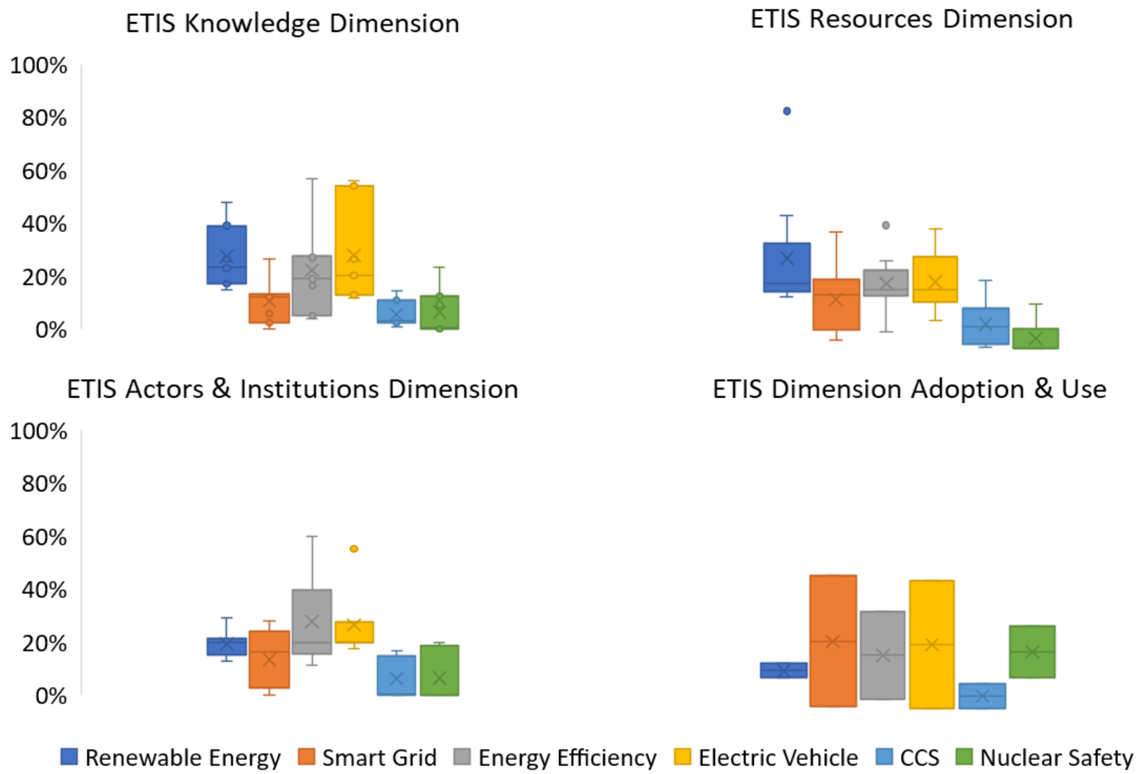

Figure 3. Proportion of innovation system processes in six SET Plan priority areas across all indicators in each ETIS dimension

6. Conclusions

This paper provides a systemic perspective on energy innovation to inform the EU's SET Plan with newly-constructed indicators of energy innovation system processes. These findings provide a valuable analytical perspective to complement insights from the economics of energy innovation about the design of effective policy environments to stimulate innovation activity that is critical for meeting ambitious energy system transformation goals.

Our findings can be briefly summarized as follows. We found that EU-level innovation system activity was unbalanced in important ways. Relatively strong progress and evidence of innovation system activity were observed in renewable energy, electric vehicle and energy efficiency. Conversely, nuclear safety and CCS are less emphasised within the portfolio of six SET Plan priority areas. We also found relatively diverse actors and organisations in the EU energy innovation system, but we need to be cautious about generalizing indicators because of the limitation of the data.

The balance or consistency in innovation system indicators between SET Plan priority areas will depend on their different maturities. Indicators describing early stage innovation processes (e.g., knowledge generation) would be expected to favour technologies still prior to widespread commercial application (e.g., electric vehicles). This can be observed for some indicators such as knowledge generation measured by demonstration budgets, but not other indicators such as knowledge codification measured by patent counts. Conversely, indicators describing late stage innovation processes (e.g., learning) would be expected to favour mature technologies (e.g., nuclear safety and energy efficiency). Again, this can be observed for some indicators such as market share but not other indicators such as durability of policy instruments.

This paper is a first effort to bring a wide range of innovation system processes into the realm of comparative, quantitative analysis using a standardised and generalisable set of indicators. There are many methodological limitations which we hope to address in further research. First, several of the indicators need refinement, particularly where we had to construct novel approaches for characterising innovation system processes which are largely analysed qualitatively (e.g., relating to actors & institutions). Second, some of the innovation system processes in our conceptual framework (Figure 1) were measured by only one indicator; others were measured by multiple indicators but treated separately. To improve robustness, we can consider compound indicators using scales. Third, we demonstrated the applicability of our indicators using only a static cross-sectional perspective. Dynamic time-series analysis of the indicators is necessary for teasing out cause and effect relationships between innovation system processes, and between innovation and innovation outcomes (e.g., successful diffusion). Fourth, we used data describing technology-specific innovation system processes at the EU level. These take place both within the context of economy-wide processes (e.g., education, training, trade) which also need taking into account. Similarly, data describing member state-level innovation activity within the EU may reveal balance or imbalance at the national level, and the extent to which there is specialisation or harmonisation between the member states in terms of their contribution to SET Plan objectives.

References

Aghion, P., Bloom, N., Blundell, R., Griffith, R., & Howitt, P. (2005). Competition and innovation: an inverted-u relationship. *The Quarterly Journal of Economics*, *120*(May), 701–728. https://doi.org/10.2307/25098750

Angrist, J. D., Dynarski, S. M., Kane, T. J., Pathak, P. A., & Walters, C. R. (2010). Inputs and impacts in charter schools: KIPP Lynn. *American Economic Review*, *100*(2), 239–243. https://doi.org/10.1257/aer.100.2.239

Angrist, J. D., & Krueger, A. B. (1991). Does Compulsory School Attendance Affect Schooling and Earnings? *The Quarterly Journal of Economics*, *106*(4), 979–2014.

Arrow, K. J. (1962). The economic learning implications of by doing. *The Review of Economic Studies*, *29*, 155–173.

Barradale, M. J. (2009). *Impact of Public Policy Uncertainty on Renewable Energy Investment : Wind Power and the PTC* (USAEE WP 08-003). Retrieved from http://ssrn.com/abstract=1085063

Belter, C. W., & Seidel, D. J. (2013). A bibliometric analysis of climate engineering research. *WIREs Clim Change*, *4*(October), 417–427. https://doi.org/10.1002/wcc.229

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. https://doi.org/10.1016/j.respol.2007.12.003

Borup, M., Andersen, D., Jacobsson, S., & Midttun, A. (2008). Nordic energy innovation systems - Patterns of need integration and cooperation. *Innovation*, (November), 129. Retrieved from http://www.nordicenergy.org/wp-content/uploads/2012/02/Nordic-energy-innovation-systems-Patterns-of-need-integration-and-cooperation.pdf

Borup, M., Klitkou, A., Andersen, M. M., Hain, D. S., Lindgaard, J., & Rennings, K. (2013). *Indicators of energy innovation systems and their dynamics: A review of current practice and research in the field*.

Bosetti, V., & Victor, D. G. (2011). Politics and economics of second-best regulation of greenhouse gases: The importance of regulatory credibility. *Energy Journal*, *32*(1), 1–24. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol32-No1-1

Cindrella, L., Fu, H., & Ho, Y. (2017). Global thrust on fuel cells and their sustainability – an assessment of research trends by bibliometric analysis. *International Journal of Sustainable Energy*, *6451*(June). https://doi.org/10.1080/14786451.2012.755185

Cornell University, INSEAD, & WIPO. (2015). *The Global Innovation Index 2016: Winning with Global Innovation*. Ithaca, Fontainebleau, and Geneva. https://doi.org/978-2-9522210-8-5

Corsatea, T., Fiorini, A., Georgakaki, A., & Lepsa, B. (2015). *Capacity Mapping: R & D investment in SET-Plan technologies Reference year 2011*. *JRC Science and Policy Reports*. https://doi.org/10.2790/751673

Czarnitzki, D., & Toole, A. A. (2011). Patent Protection, Market Uncertainty, and R&D Investment. *The Review of Economics and Statistics*, *93*(1), 147–159.

da Graça Carvalho, M. (2012). EU energy and climate change strategy. *Energy*, *40*(1), 19–22. https://doi.org/10.1016/j.energy.2012.01.012

EC. (2015a). *SET Plan actions: Implementation process and expected outcomes*.

EC. (2015b). *Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation EN. European Commission (EC)*. Brussels, Belgium. https://doi.org/10.1007/s13398-014-0173-7.2

Freeman, C. (1995). The National System of Innovation in historical perspective. *Cambridge Journal of Economics*, *19*(March 1993), 5–24. https://doi.org/Article

Gallagher, K. S., Grübler, A., Kuhl, L., Nemet, G., & Wilson, C. (2012). The Energy Technology Innovation System. *Annual Review of Environment and Resources*, *37*, 137–162. https://doi.org/10.1146/annurev-environ-060311-133915

Grubler, A., & Wilson, C. (2014). *Energy Technology Innovation: Learning from Historical Successes and Failures*. Cambridge University Press.

Haščič, I., Silva, J., & Johnstone, N. (2015). The Use of Patent Statistics for International Comparisons and Analysis of Narrow Technological Fields.

Hekkert, M. P., & Negro, S. O. (2009). Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims. *Technological Forecasting and Social Change*, *76*(4), 584–594. https://doi.org/10.1016/j.techfore.2008.04.013

Hekkert, M. P., Suurs, R. A. A., Negro, S. O., Kuhlmann, S., & Smits, R. E. H. M. (2007). Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting and Social Change*, *74*(4), 413–432. https://doi.org/10.1016/j.techfore.2006.03.002

Hudson, L., Winskel, M., & Allen, S. (2011). The hesitant emergence of low carbon technologies in the UK: the micro-CHP innovation system. *Technology Analysis & Strategic Management*, *23*(3), 297–312. https://doi.org/10.1080/09537325.2011.550396

International Energy Agency. (2011). Good practice policy framework for energy technology research, development and demonstration (rd&d), 68.

Jacobsson, S., & Karltorp, K. (2013). Mechanisms blocking the dynamics of the European offshore wind energy innovation system – Challenges for policy intervention. *Energy Policy*, *63*, 1182–1195. https://doi.org/10.1016/j.enpol.2013.08.077

Kalamova, M., Johnstone, N., & Hascic, I. (2012). Implications of Policy Uncertainty for Innovation in Environmental Technologies: The Case of Public R&D Budgets. In V. Costantini (Ed.), *The Dynamics of Environmental and Economic Systems: Innovation, Environmental Policy and Competitiveness* (pp. 83–95). Springer. https://doi.org/10.1007/978-94-007-5089-0

Klitkou, A., Borup, M., & Iversen, E. (2012). *Energy Innovation Systems*.

Kruyt, B., Vuuren, D. P. Van, Vries, H. J. M. De, & Groenenberg, H. (2009). Indicators for energy security. *Energy Policy*, *37*, 2166–2181. https://doi.org/10.1016/j.enpol.2009.02.006

Lehmann, P. (2012). Justifying a policy mix for pollution control: a review of economic literature. *Journal of Economics Surveys*, *26*(1), 71–97. https://doi.org/10.1111/j.1467-6419.2010.00628.x

Löfgren, Å., Millock, K., & Nauges, C. (2008). The effect of uncertainty on pollution abatement investments: Measuring hurdle rates for Swedish industry. *Resource and Energy Economics*, *30*(4), 475–491. https://doi.org/10.1016/j.reseneeco.2008.09.002

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

Mccollum, D. L., Krey, V., & Riahi, K. (2011). An integrated approach to energy sustainability. *Nature Climate Change*, *1*(9), 428–429. https://doi.org/10.1038/nclimate1297

Miremadi, I., Saboohi, Y., & Jacobsson, S. (2016). Adapting Innovation Indicators to Assess Performance of Energy Innovation Systems : A Framework and Categorization of Indicators.

Negro, S. O., Alkemade, F., & Hekkert, M. P. (2012). Why does renewable energy diffuse so slowly? A review of innovation system problems. *Renewable and Sustainable Energy Reviews*, *16*(6), 3836–3846. https://doi.org/10.1016/j.rser.2012.03.043

Negro, S. O., & Hekkert, M. P. (2010). Overcoming typical failures in the emergence of sustainable innovation systems – The need for a new form of innovation policy. In *Energy transitions in an interdependent world: what and where are the future social science research agenda?* SPRU, University of Sussex, UK.

Nilsson, M., & Nykvist, B. (2016). Governing the electric vehicle transition ??? Near term interventions to support a green energy economy. *Applied Energy*, *179*, 1360–1371. https://doi.org/10.1016/j.apenergy.2016.03.056

OECD. (2015). *System Innovation: Synthesis Report*.

Park, M. S., Han, K., Jang, E., Choi, W., & Joo, J. (2016). *ASEM Eco-innovation Index 2016*.

Pasimeni, F. (2017). *EU energy technology trade: Import and export*. Luxembourg. https://doi.org/10.2760/607980

Popp, D. (2002). Induced Innovation and energy prices. *American Economic Review*, *92*(1), 160–180.

Popp, D. (2003). Pollution control innovations and the Clean Air Act of 1990. *Journal of Policy Analysis and Management*, *22*(4), 641–660. https://doi.org/10.1002/pam.10159

Popp, D. (2015). *Government R&D Spending : The Case of Energy* (No. 5442).

Popp, D. (2016). *From Science to Technology: The Value of Knowledge From Different Energy Research Institutions* (No. 22573). Retrieved from http://www.nber.org/papers/w22573

Rizzi, F., van Eck, N. J., & Frey, M. (2014). The production of scientific knowledge on renewable energies: Worldwide trends, dynamics and challenges and implications for management. *Renewable Energy*, *62*, 657–671. https://doi.org/10.1016/j.renene.2013.08.030

Rogge, K. S., & Reichardt, K. (2016). Policy mixes for sustainability transitions : An extended concept and framework for analysis. *Research Policy*, *45*(8), 1620–1635. https://doi.org/10.1016/j.respol.2016.04.004

Rubin, E. S., Azevedo, I. M. L., Jaramillo, P., & Yeh, S. (2015). A review of learning rates for electricity supply technologies. *Energy Policy*, *86*, 198–218. https://doi.org/10.1016/j.enpol.2015.06.011

Sanz-Casado, E., Lascurain-Sánchez, M. L., Serrano-Lopez, A. E., Larsen, B., & Ingwersen, P. (2014). Production, consumption and research on solar energy Sanz-Casado,. *Renewable Energy*, *68*, 733–744. https://doi.org/10.1016/j.renene.2014.03.013

Schot, J., Kanger, L., & Verbong, G. (2016). The roles of users in shaping transitions to new energy systems. *Nature Energy*, *1*(5), 16054. https://doi.org/10.1038/nenergy.2016.54

Speirs, J., Pearson, P., & Foxon, T. (2008). Adapting Innovation Systems Indicators to assess Eco-Innovation. *Framework*, *44*(0), 1–19.

Stojkoska, B. L. R., & Trivodaliev, K. V. (2016). A review of Internet of Things for smart home: Challenges and solutions. *Journal of Cleaner Production*.

Sugathan, M. (2013). *Lists of Environmental Goods : An Overview*.

Truffer, B., Markard, J., Binz, C., & Jacobsson, S. (2012). *Energy Innovation Systems-Structure of an emerging scholarly field and its future research directions*. *EIS Radar Paper*.

Tsay, M.-Y. (2008). A bibliometric analysis of hydrogen energy literature , 1965 – 2005. *Scientometrics*, *75*(3), 421–438. https://doi.org/10.1007/s11192-007-1785-x

United Nations, Office, E. P., & Dechezleprêtre, A. (2015). *Climate change mitigation technologies in Europe – evidence from patent and economic data*.

Verdolini, E. B. (, & Jockers, P. (2015). *The impact of policy and uncertainty on innovation in the wind industry : evidence from European countries*. Green Growth Knowledge Platform (GGKP) Third Annual Conference.

Weiss, M., Junginger, M., Patel, M. K., & Blok, K. (2010). A review of experience curve analyses for energy demand technologies. *Technological Forecasting and Social Change*, *77*(3), 411–428. https://doi.org/10.1016/j.techfore.2009.10.009

Wilson, C., Grubler, A., Gallagher, K. S., & Nemet, G. F. (2012). Marginalization of end-use technologies in energy innovation for climate protection. *Nature Climate Change*, *2*(11), 780–788. https://doi.org/10.1038/nclimate1576

Yesil-Celiktas, O. (2014). Patenting trends in enzyme related microfluidic applications. *Biochemical Engineering Journal*, *92*, 53–62. https://doi.org/10.1016/j.bej.2014.06.017