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Knowing where to go

The knowledge foundation for investments in renewable energy

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Knowing where to go: The knowledge foundation for investments in renewable energy

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ABSTRACT

Energy policies are increasingly focused on promoting the transition towards a more sustainable energy system. Evidence-based decision-making regarding such policies needs a solid knowledge foundation. We take stock of our existing knowledge regarding the statistics and data that form the basis for research, policy and business decision-making regarding investments in renewable energy (RE). We point to several types of problems and challenges related to achieving a statistical overview of investments in the energy sector, and argue that addressing these problems is not simply a matter of intensifying existing statistical efforts and improving precision because they are caused by fundamental difficulties. We particularly emphasize the role of investors as a linkage between public policy and firm-level activity, discussing the kind of data needed to sufficiently identify investors and their activities and fulfil their particular information needs related to investing in the RE sector. This information is important not only in research and policy contexts, but also for investment behaviour.

1. Introduction

Current policy discussions on binding targets for carbon-dioxide emissions, UN global warming limits and energy policy in general are based on two types of knowledge: one is the knowledge of current rates of pollution and emissions, which is the purview of environmental scientists. A second type of knowledge regarding current and future energy production and consumption is related to where we are, in which direction we are heading and can go, and at what pace. This is the sphere of economists and statisticians. It is vital that an adequate knowledge foundation for energy policy discussions be in place for pursuing evidence-based policies in the field [1]. As an example, there is debate around subjects such as whether the EU's 2020 Energy Strategy targets can be reached if current investment levels continue, as a funding gap is likely to occur [2–4]. Another debate centres on how to induce the necessary industrial change into the energy sector, as this sector is characterised by large infrastructure investments and technological lock-in [5–8]. Furthermore, continuing government support to investments into fossil fuels (amounting to 115 billion USD in 2014, according to the OECD [4]) creates substantial inertia hindering change [5,6]. Therefore, it is argued, private investors who devote attention and resources to investments into energy investment opportunities may alleviate problems with funding gaps and lock-in [9,7,10]. However, both policy makers and investors need adequate information to pursue policies and investments. We therefore discuss the following research question: What is the status of existing statistics and other data available to policymakers, investors and professionals to inform their decisions concerning whether and how to invest in the renewable-energy (RE) sector. Further, what data and statistics is needed for these types of decision-makers to make well-informed decisions?

It is open to debate whether there already is an adequate amount of information available to investors or policymakers, and whether what is available is easy to interpret and compare. This level of information has impact on the allocation of capital to RE investments [11]. In order to identify global macro-level trends, formulate policy and assess policy impact across countries, comprehensive and comparable statistics are needed on aggregated investments, deployed capacity, energy trade, innovation and other factors. At a micro level, there is a need to understand which firms develop and deploy RE technologies, which investors provide the necessary capital, and why they do so [8]. We consequently focus the discussion

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below on investments in renewable-energy technologies, including the production, distribution and storage of electricity and heat from renewable and sustainable resources.

Our knowledge of the role of finance in transitions of RE systems is relatively sparse [12]. One possible reason for these shortcomings is that both the sub-industries and technologies deployed in RE are deeply heterogeneous, ranging from software-based smart-grid solutions, measurement and management of electricity and heat demand, to new battery solutions for energy storage and large-scale windmill production. It is additionally challenging to identify which firms are part of the RE sector [13], and to what extent their activities are related to RE. In the same vein, adequately mapping the similarly heterogeneous group of investors, including public agencies, venture capitalists, banks, project financers and large institutional investors, adds to the challenges we face in providing solid statistical evidence useful in decision-making processes.

Moreover, the knowledge foundation for policymaking should be based on good indicators and data [14,15], which is readily available [1]. Yet the current statistical system faces a number of challenges when moving from accounting for past consumption and installed capacity towards measures of technological change, as well as investments.

Such information is important not only in a research context [16], but also for political and practical reasons. Potentially, the quality and volume of statistics may create virtuous or vicious cycles of investment behaviour because investment areas covered only by weak statistical evidence may receive limited attention from investors, which may in turn render fewer incentives for producing better statistics, and vice versa. We particularly emphasise the role of investors as a link between public policy and firm-level activity, and discuss the kind of data needed to sufficiently characterise investors and fulfil their particular information needs related to investing in the RE sector.

We proceed as follows. In the next section, we examine the investor landscape of RE and point out the need for information and statistics of investors. We further discuss financial and non-financial decision-making criteria of RE investors, which are up to now inadequately understood [17]. In Section 3, we discuss how investments in energy are different from other investments and why this results in particular information on RE being of higher importance or scarcity than that of other industries. In Section 4 we provide an overview of the current primary producers of statistics on energy and of the available statistics and indicators. Section 5 focuses on the challenges in measuring energy activities. In subchapters, we discuss the problems of identifying and delimiting firms, industry dynamics and technological change. In Section 6, we summarise the deficiencies we identified during the discussion of measurement challenges in RE and discuss in Section 7 how to address these challenges. We conclude in the final section by discussing the possible implications of a lack of adequate statistics and whether producing comprehensive RE statistics covering the information needs for investments is realistic.

2. Investors and investments in renewable energy

Financial markets and their actors, such as institutional investors, banks and venture-capital firms, represent the main link between savings and investments and are pivotal to the smooth functioning of capitalistic economies, propelling economic growth [18], facilitating transition [19–21] and defining technological trajectories [22,23,80]. An investor perspective should therefore be an integral component of any strategy towards a sustainable future [24], and understanding the composition and profiles of investors and the rationales and information needs of investors is crucial to formulating meaningful RE policies [9,17,25].

Most assessments of policy measures, as well as the regional, national and global progress of CO_2 reduction and RE agendas, are illustrated by statistics on installed capacity or electricity and heat generated from RE sources (e.g. [26,27]). However, in line with earlier research in energy policy studies (e.g. [9,24,28,86]), we argue for the need to consider investment data as well. We propose this focus for several reasons. First, investment represents real-time responses of industry actors and investors, enabling us to better predict future technological progress and installed capacity. Second, investments in RE sector are subject to sector-specific particularities, as they are highly interdependent ('systemic') [29]. A lack of investments in particular technologies and infrastructure can cause bottlenecks leading to system failure, and a lack of investments in R&D and innovation can cause technological 'valleys of death' [28], which may jeopardise further development of promising technologies. Third, the investment patterns in society mediate the transfer of resources from current savings to future production, hence, investment patterns are the primary predictors of possible industrial transformation. In turn, this accentuates that mapping investors and accounting for their rationales and decision-making process becomes crucial.

The risks investors in RE commonly face are (i.) firm or project specific risks, (ii.) market risk, (iii.) technology risk, and (iv.) policy risk. These risks mainly have their origin in imperfect or asymmetric information inherent to the market for RE investments as well as the investors bounded rationality. To mitigate such information deficits and improve applied heuristics, investors in capital markets tend to specialise in certain types of investments, firms or technologies to accumulate relevant experience within these areas [30,31]. In turn, they become able and willing to take certain types of risks. For example, venture capitalists usually prefer to invest in relatively early-stage, risky technologies with high growth potential on markets where sales of products can be up-scaled, and they will often have a 7–8 year time horizon for their investment. Contrary, banks and prudent institutional investors will only invest in mature, 'safe' firms and technologies. They therefore require lower rates of returns and can cope with higher investment sums. Consequently, investors have divergent idiosyncratic information needs and reactions to policy measures. An institutional investor might be more concerned about indicators of individual and systemic investment risk, while venture capitalists might be willing to bear technological risks, but is concerned of market indicators that reflect the growth potential of a technology. Diverging capabilities and information needs, technology and risk preferences, as well as manageable investment sizes make RE investors a rather heterogeneous group. This heterogeneity further increases when considering non- or only partly profit-driven providers of capital, such as public agencies, donors, and private individuals or collectives, who act according to different rationales [93]. Consequently, a nuanced and disaggregated reflection of investors and investments in our statistical evidence is a necessary condition to understand, assess, and predict current and future RE investments.

To fulfil this objective we must deal with a couple of challenges. As discussed earlier, the RE sector stretches across various industries and deployed technologies, and this variety makes it challenging to draw its boundaries and to decide which technologies and firms should be considered part of the RE sector. Quantifying investments related to the RE sector obviously poses the same problem of ambiguity, which even amplifies when aiming to identify investors, who commonly invest in multiple industries. While some are exclusively committed to RE, the majority, such as institutional investors, devote only a small share of their portfolio to it. Consequently, the identification of RE investors can rarely be done in a binary way, since most of them invest in firms and projects, which in turn are to some extend connected to the RE sector. These investors also deploy a variety of finance vehicles to

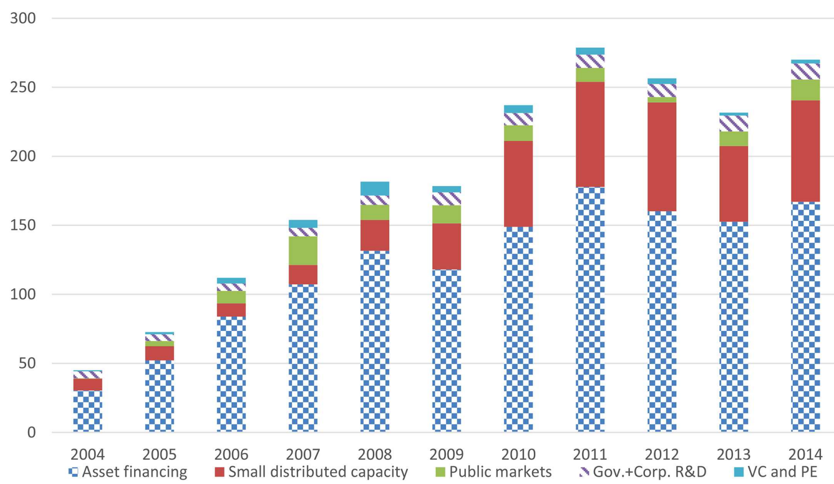

Fig. 1. Global new investments in RE by asset class, 2004–2014, $BN.

Source: UNEP [95,99].

carry out their investments, which usually can only be accessed by combining different sources of data, if possible at all. Factors such as limited mandatory disclosure of certain finance vehicles restrict available information on investments to sporadic studies and reports by national and international energy agencies (e.g. IEA, IPCC, UNEP), associations, NGOs, research institutes promoting the transition to sustainable energy sources (e.g. IIASA) and financial institutions and information providers (e.g. Bloomberg New Energy Finance, Reuters). Such reports on RE usually provide investment data at different levels of aggregation, which can be broken down by technology, asset class, region and time period. They often differ in their definition and measurement of renewable energy, and sustainable, clean or green investments, but they do provide some valuable insights. An example of such statistics is provided in Fig. 1, which depicts the development of global investments in RE by asset class and offers some broad indications on tendencies in energy investments.[1]

Even though on a high level of aggregation, Fig. 1 provides us with insights into some stylized facts and general trends in RE finance. First, public-market finance is of minor importance in RE, which is atypical for capital-intense industries. Instead, the main choice of financial vehicle for energy installations is asset financing, a form of debt financing backed by asset collateral. Furthermore, we see an increasing amount and share of small distributed capacity. Small distributed capacity is to a large extend financed by private individuals and collectives that build up own energy production capacity, for instance a community jointly investing in a collectively owned wind turbine. Such collective actions of citizens increasingly contributes to the realization of RE infrastructure [32] as well as sometimes research projects via various business models and financing concepts [33]. In recent years, the rise of online crowdfunding platforms has improved the possibilities of citizens to participate in social ventures [34]. This allows individuals to invest in RE projects with small contributions, which can be bundled to achieve large financing goals without relying on a particular local community, and make it an until now small but increasingly popular vehicle for financing RE projects [35–37].[2] Obviously, one can expect the rationales of such private "investors" to broadly diverge from the ones of professional ones, and as a result also their information need and respond to certain policies.[3] What all the above-mentioned investment types have in common is that they are mostly used to finance energy production installations hence can be seen as a proxy for near-future changes of installed capacity. Early-stage financing sources like venture capital and private and public R&D remain a small fraction of total investments. Such investments may be comparably small in volume, yet are important to consider, since they reflect the sector's effort to incrementally increase the efficiency of existing RE technologies as well as to develop radically new ones with potentially disruptive impact in the way our energy system operates. It should be noted that the financing instrument does not necessarily reflect a specific type of investor. Even if there is specialisation and division of labour in capital markets, investors may still use multiple financing instruments simultaneously.

3. What makes RE investment unique?

Understanding investments in the energy sector requires understanding its distinct characteristics [38]. Therefore, this section summarises some key features of the energy system that are particularly important for investment decisions as well as implications for measurement and interpretation of these decisions. First, the energy system cuts through many different industries, thereby displaying a huge variety of involved actors with idiosyncratic characteristics and rationales. While some industries such as windmill production have already reached a high degree of maturity and are dominated by multinational enterprises, other industries and technologies such as hydrogen, full cells, smart grid and energy storage solutions are still in experimental phases, dominated by entrepreneurial activity and offering potential for future disruptive innovation. Consequently, methods on how to identify RE firms as well as the assessment of which variables are informative varies across industries.

Another related feature of the energy sector and energy technologies is that they are usually interdependent with other, existing facilitating elements and technologies in the energy sector [29]. Consequently, the feasibility of new products and processes depends on their compatibility with other parts of the energy sys-

[1] See Geels [20] for a more comprehensive illustration of the available investment statistics produced by the above-mentioned organizations.

[2] It has to be mentioned, that investments in RE via crowdfunding are up to now not, or only very incomprehensively, included in official statistics.

[3] Hall et al. [8] call this part of the energy sector the 'civic energy sector' and argue that a corresponding decentralised banking system (as in Germany) is a more expedient financing mechanism for this area of energy production than a centralised, market-based system (as in the UK).

tem as well as its existing energy infrastructure. In many respects, it is more appropriate to talk about energy 'systems' rather than just 'sectors'. The systemic character of energy production poses challenges to investors in assessing the opportunities of new technological developments. In such complex and interdependent systems, the development and evaluation of new components is challenging, since the existing components' reactions [39,40], and thereby the new components' feasibility and profitability, is difficult to fully predict in advance. This perspective has implications for measurement, as it accentuates the importance of indicators and statistics on interaction and cooperation between components as well as actors within the system [41].

Historical studies of 'large technological systems' – such as the energy sector – have shown that they usually adapt gradually to changing internal and external needs [7,9,42]. In some cases, it has been shown that characteristics inherent to large technological systems tend to create inertia and an associated lack of ability to respond to external pressure to change. This may be due to high capital intensity and sunk costs of investments in infrastructure, centralized industry structure and governance, and a rigid institutional setup. Such characteristics can also be observed in the energy system. First, the infrastructure for energy production and distribution is enormously capital intensive [83], and consequently requires long-term capital commitment [43]. Once put into place, equipment such as power plants and transmission lines are replaced only every couple of decades [9]. High sunk costs and long amortisation periods slow down technology adaptation, and thus current energy infrastructures are still mostly organised around fossil-fuel technologies (gas, oil and coal) and the particular needs of a carbon-based energy system, such as centralised energy generation and stable system load. Modern low-carbon technologies often diverge from this paradigm, making them difficult to integrate [7]. Second, the major share of this infrastructure is controlled by large, established energy companies, state-owned, private, or semi-forms of ownership. Energy incumbents with vested interests in preserving the status quo and securing the returns on their existing investments may exercise their influence on the industry and on policy ([44]; [45], forthcoming) in a form of 'incumbent capitalism' [46], which leads to a lock-in of the energy system in its current state [5,6]. It should, though, be noted that existing incumbents within conventional energy production simultaneously invest in renewable energy projects. Examples from Scandinavian countries include Vattenfall, Statoil, DONG (Danish Oil and Natural Gas).

Regulation is a further characteristic of the energy sector. There is a heavy involvement – often even dominance and ownership – of public or semi-public organisations. For many reasons, both political and economic, energy systems are important policy targets and are subject to intense public regulation. Even in cases when their quantitative importance is limited the public investments nevertheless provides direction for technological development at both national and regional level [47]. Both direct public investments and subsidies are important parts of the total regulation of the energy sector. Consequently, investment opportunities and their returns are heavily dependent on state regulations at different levels, and private investments are thus subject to high policy risks [48]. Therefore, measures of public investment in and public procurement of energy could also be meaningfully quantified and accessible in a structured way.

From the findings of this section, it is clear that it is complex to paint a holistic picture of the dynamics of the industry as the relevant measurements encompass a wide range of factors beyond the pure energy production. This includes for example interactions between key actors in the system, carbon lock-in, identification of the firms in the industry, and the dual use of RE technologies and conventional technologies in the same product, equipment or process. A number of other problems increase the blurring of industry boundaries, such as whether energy storage, transmission and efficiency measures should be considered part of the industry statistics.

4. Our knowledge foundation today: existing energy statistics

After a period of declining quality and coverage of energy statistics resulting from the liberalisation of energy markets, budget cuts and lack of expertise [49], a recent increased interest in energy has led to rapid improvement in the empirical evidence on energy investments. Energy statistics now cover a wide range of technological fields and countries. The increased interest in measurements of energy production, consumption, and impact has been spurred by the binding targets for RE to which many countries adhere and ongoing discussions on the extent to which they should commit to such targets. Moreover, RE now makes up a substantial share of total energy production. This share is rising globally, and is much higher in some countries than in others. In this section, we identify selected important sources of information on energy consumption, energy innovation and energy production as an illustration of available energy statistics.

Energy statistics have been developed in many countries to map the development of the energy systems, especially with regard to energy consumption and energy production; energy innovation is less well covered. Harmonisation and measurement are further guided by the 'Renewable Energy Directive 2009/28/EC' [50]. In addition to national accounts, the majority of EU-28 countries also provide less aggregated data on energy produced by sources, such as RE [50].

International comparisons of such data are important for many reasons; for example, they are needed in the negotiations on climate emissions, global warming and targets for RE production and consumption. There are international organisations that collect and compare national statistics. The Eurostat data on energy R&D is valuable, but operates at a high level of aggregation, rendering analyses of renewable energy somewhat inadequate [51]. The primary statistics in the field are collected in a joint, harmonised effort by OECD/IEA[4]/Eurostat and by UNEP. The World Energy Outlook, from the International Energy Agency (IEA), is another example of statistics that cover part of the field, though they include only information from the 28 member (OECD) countries.[5] In Europe, 19 of 28 EU member states are covered in the IEA statistics; however, the coverage of the data is better than that as e.g. around 99% of investments are covered when measured in volume [51]. A third important source is the World Energy Council. They compile statistics, collect data and undertake research on global resources and technologies to support the decision-making process in policymaking and industry strategy. Since 1933 the World Energy Council has in particular produced the report World Energy Resources, which triennially survey global reserves, production and energy mix divided into 12 types of resources in the 90 member countries.

While RE production and consumption technically is possible (though difficult) to measure, the measurement of environmental impact and the application of technologies to improve energy effi-

[4] IEA, International Energy Agency, was established in 1974 as an autonomous entity within the OECD. It was established in the wake of the first oil crisis, and improving oil supply systems was among its primary objectives. However, its activities now span a wide range of analyses and data on energy and include renewable energy sources.

[5] The resulting statistical bias is illustrated by the fact that public spending on energy R&D in Brazil, Russia, China, India, Mexico and South Africa totalled 13.6 billion USD in 2009, which corresponds to the amount of all the IEA members combined [64].

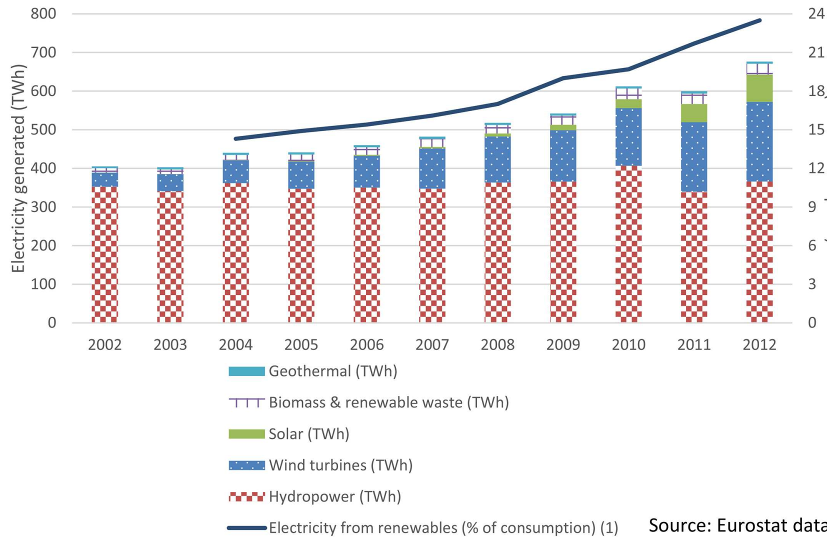

Fig. 2. Electricity generated from renewable-energy sources, EU-28, 2002–12.

ciency pose special challenges and is poorly developed [52].[6] We do not embark on the issue of energy efficiency in this article but point to that it is part of a holistic picture of the energy system. The above-mentioned decentralised production of energy in private households and the fact that a large proportion particularly of RE is not traded on a market further complicate the production of adequate statistics on energy production and usage.

For empirical evidence on sub-industries, a number of more specialised organisations compile statistics focused on specific sources of RE. For example, the Global Wind Energy Council is the international trade association for the wind-power industry and publishes statistics on global trends on topics such as installed capacity. Another example is the European Photovoltaic Industry Association, which likewise handles specialised studies, market outlooks and statistics (e.g. [53]). As an umbrella organisation for these sub-industry organisations, the European Renewable Energy Council (EREC) represents the entire renewable-energy sector and compiles statistical information based upon national statistics and Eurostat. To analyse disaggregated patterns of energy usage across countries and industries, the World Input-Output Database (WIPO [54], cf. [55,56]) can be used. Although it does not differentiate between sources of energy (RE vs. fossil) it provides data on the inter-industry input-output relationships (including energy input) of 40 major economies dating back to 1995, and thus can be utilised to capture the effects of technological changes and/or policy measures on energy usage and how these effects may differ across industries and countries.

A growing interest in more environmentally sustainable energy production has led to attempts to develop indicators and measurement of sustainable production. Studies on this include Kemp and Pearson [57], Andersen [58], OECD [59], and the Eco Innovation Observatory [60]. To take one of these examples, the OECD lists indicators for monitoring green growth, including, amongst others, GDP per unit of energy-related CO_2 emitted, share of RE in electricity production, RE in per cent of energy-related R&D and carbon market financing [59]. In total, they list 23 such groups of indicators, many of which have more than one sub-category of indicator. These may, in turn, be used in statistics, providing the capability to list exports and imports of RE, employment in energy-technology sectors and development of public Research, Development & Demonstration budgets [41]. Indicators are well developed in some areas, but often suffer from fundamental definitional problems when it comes to transferring indicators to statistics, as we shall discuss later.

As noted above, it is not the purpose of this article to detail specific numbers in the RE area. Rather, we identify what is available and what is missing, and we illustrate in Fig. 2 two selected trends regarding the European development in the electricity part of RE. First, except for a small dip in 2011, there has been a steady increase in both the production of electricity from renewable sources and the share of electricity consumption from RE sources. Second, there are vast differences in the contributions of different sources of electricity. Among sub-sources, wind energy has shown the highest growth.

Just as there is heterogeneity among energy sources, there are vast differences among countries in several respects, although this point is not illustrated in Fig. 2. They differ in the share of RE in total energy production and consumption, in the targets the countries have for RE, and in the initiatives they pursue [10,61]. Further, their policies differ, as e.g. subsidies are relatively more important in particular countries [61]. Countries also differ considerably in the relative mix of sources of RE, which is often reflected in their natural endowments. Thus, the vast majority of RE in Norway, Austria and Sweden comes from hydropower, while Denmark, Ireland and Spain has a relatively large proportion of their RE sources from wind energy. Portugal has a relatively large solar energy production and in Italy thermal heating is more common than elsewhere in Europe (due to the volcanic activity in the country). There are also differences among these countries in which RE industries and technologies dominate. For example, even if other countries may also be strong in these technology areas, Denmark is known to be strong in wind energy technologies, Scotland in wave technologies, Germany in photovoltaics and so on. The heterogeneity of energy sources and the strongholds of certain countries[7] in different forms of energy production not only results in different interests in energy statistics and energy innovation, but also has implications for how investors

[6] It is possible to partially measure energy efficiency if we measure at a high level of aggregation. The change in energy consumption compared to GDP change is a rough indicator of energy efficiency and is used as such in statistics compiled by IEA, Eurostat and the OECD. Although these statistics now follow specific guidelines (The Renewable Energy Directive 2009/28/EC), there are technologies that the statistical system is not yet geared to capture.

[7] Adding to this international heterogeneity it has been argued that also within nations there are regional differences in the development of RE technologies and production [61,100].

specialise and what types of investments are needed in the specific technologies, as discussed above. Moreover, although we do have both sub-industry and overall RE industry statistics, there are still challenges associated with identifying RE firms and measuring industry dynamics, a problem area on which we elaborate in the next section.

5. Measurement challenges in the renewable-energy system

A first prerequisite for adequate measurement and statistics is that the boundaries of the industry are clear. A second prerequisite is an understanding of the dynamics of the industry. In the following section we discuss how well policy making, statistical offices, investors and research fare in these two problem areas.

5.1. Identifying RE firms

Traditionally the boundaries of industries are defined by their industry classifications, such as NACE and SIC, which are based on the activities of firms. It should, in principle, be possible to identify the population of firms within an industry using their industry classification. However, a number of problems for the accurate identification of industries remain. Some of these problems stem from the imprecision of classifications, while others stem from more generic problems in assigning firms to specific industries [13,62,63]. One of the most severe problems relates to the cross-disciplinary and cross-industrial character of firms' activities. Such measurement problems are multiplied when considering narrow segments of industries such as RE. Many firms outside the energy industry perform activities within RE, but are classified in their main industry. Likewise, within the energy sector firms in conventional energies (oil, gas etc.) are also active in RE. The option of reporting several industry codes to account for multiple types of activities does not alleviate these problems in practice, and, generally, it is not mandatory for firms to report disaggregated levels of activities. As a consequence, register-based industry definitions of RE are highly uncertain, leaving us with problems in the production of reporting-based statistics and surveys. Shapira et al. [13] describe flaws in existing methods for identifying 'green' firms and suggest identifying the population of 'green' firms by way of a search-based method wherein textual searches of business databases produce information on firms that have 'green' products, independent of their SIC classification. However, the majority of the fundamental problems remain.

5.2. Measuring industry dynamics and technological change

In addition to collecting data on deployed capacity and investments, it is also important to measure industry dynamics in terms one measure of this being the innovation activities in the industry [16]. Some RE sub-industries are clearly more innovation driven than others. Mature sub-industries like wind and photovoltaics have relative low innovation intensities and are more exploitation dominated than exploration dominated. Observers point out that accelerated rates of technological innovation [38,64] in multiple sectors [65] are needed to cope with environmental challenges.

This highlights the need for more developed energy-innovation statistics than what is available today. National accounts measure factors like production volumes, energy sources and energy prices. These accounts are important, but are largely inadequate for energy *innovation*. Hence, we are currently in a position where the statistics on investments in innovation and the output of innovation processes in the industry are based on inadequate indicators, especially when it comes to investments beyond the Research, Development & Demonstration (RD&D) phase.

Compared to the ambitions and targets for RE in some countries the overall growth in energy production from renewable sources has been relatively slow despite rapid growth in some RE subsectors (cf. Fig. 2), and the share of RE production remains at a low level despite increased investments, due to continued investment in non-renewable installations. These installations are typically large and capital-intensive, and they have long operating life [4,20]. This potentially creates a lock-in of the existing structures wherein transition to a new system is difficult, causing some observers to term renewable-energy technologies 'niche-innovations' [66]. A lot of RE production is more in an exploitation phase than in exploration, and innovation in these sub-industries play a relative small role. However, the importance of continuous upgrading, diffusion of technologies, and incremental innovation in these sub-sectors together with the innovation activities in rapidly changing subsectors accentuates the relevance of innovation for the total RE sector. Three types of indicators are usually used in connection with industry dynamics: (i) R&D expenditures, (ii) patents and (iii) innovations.

One of the classical proxies for industry dynamics and innovation is firm level R&D expenditure. Generally, R&D expenditure measures an important source of input to the innovation process, albeit its relevance varies across industries, and it has been argued that only focussing on this indicator introduces a bias towards a narrow set of high tech industries [67]. Moreover, even if we were able to correctly identify RE related firms, in most cases only a part of firm level R&D activity will be dedicated to RE. This has led Wiesenthal et al. [51] to suggest a bottom-up approach to measuring R&D investment in low-carbon energy technologies, whereby additional information and estimations are included to produce a more reliable estimate of R&D expenditures and investments.

An also often-used source for measuring industry dynamics and innovation activities in general is the patent statistics (e.g. [68,98]). More specifically, in the RE area, organisations such as the OECD have compiled information on 'green' innovations in special studies (e.g. [69,70]) that compare data on such things as patents in 'green' technologies for member countries, as well as other measurement issues (see also [71]). Likewise, several other organisations now perform more systematic registration of 'green' patents, as illustrated by the fact that the EPO now has a patent tag covering technologies for mitigating climate change. Patents are relevant from an investment perspective because they have become an important parameter in both the decision to invest and in the subsequent ability to exit from the investment. However, they do not capture all innovation inputs and outputs, both because inputs to innovation processes span a wide range of factors beyond R&D and because only a minority of innovations are protected by patents.

Another source of information is survey-based methods aiming to measure innovation activities, output, and performance more directly. For example, in their national innovation surveys (Community Innovation Surveys, CIS), a number of countries implemented questions on environmental issues more broadly, some of which provide information on energy innovation, as well. Survey-based approaches to identifying green firms and uncovering industry dynamics in terms of innovation activities suffer from disadvantages as well, such as their general weaknesses in response rates and establishing the relevant initial sample. The empirical evidence on innovation produced from survey-based approaches also suffers from comparability problems, lacks harmonised definitions of energy innovation and fails to make a clear delineation of the energy sector [13]. Moreover, although standard questionnaires have questions on financing of investments these questions apply to all investments, not specifically RE investments.

Data on public- and private-sector energy-innovation activities is important for technology forecasting, as a basis for public authorities to decide how to allocate research grants, for investors to spot promising investment targets and for firms to allocate innovation budgets. Although the R&D statistics and patent statistics do indicate aspects of energy-industry dynamics, the measurement of industry and technology evolution poses additional challenges. We conclude that innovation statistics and other measures of industry dynamics are relatively new and not yet fine-grained enough to make them suitable for comprehensive studies of RE innovation and for establishing an adequate knowledge base for energy investments.

6. Renewable energy investment data – available sources and deficiencies

Information for policymaking targeting RE, research and investment is available from different sources. In addition to the previously mentioned reports by the IEA, UNEP, EUROSTAT, Bloomberg and others, investor organisations such as the European Venture Capital Association (EVCA) provide an overview of RE investments at different levels of aggregation. While the challenge of developing an adequate methodology to identify firms' activities and technologies deployed in the RE realm remains, there are indeed some sources of exhaustive micro-level data on investments and some means of identifying investors although they still suffer from deficiencies. Since data on equity deals is of high value for professional investors who are willing to pay for it, there exists a large variety of commercial databases for different forms of equity investments, such as venture capital, private equity, mergers and acquisitions and foreign direct investments. Popular examples are Thompson & Reuters 'VentureONE', Bureau van Dijk's 'ZEPHIR' and S&Ps 'CapitalIQ' investment databases. They contain longitudinal data on investment targets, investors and investment characteristics. In addition to common industry classifications such as SIC/NACE codes, they often contain their own sector or industry classifications, including classes such as 'RE', 'energy transmission' and the like, which can be used to get some of the way towards identify RE firms and investments, although they still suffer from the above-mentioned problems of precise classification procedures. Alternatively, free, open-access finance and business databases such as 'Crunchbase' have significantly improved in accuracy and coverage over the last few years. However, because of the structure of most private equity, these databases only contain information on the direct shareholder (general partner) and not the initial provider of capital (limited partner). Recently, however, some newer databases have started to collect information on the limited partners as well. These include the 'PreQuin' investor intelligence and the DowJones 'LP Source' database.

While there exists several types and sources of information on equity investments, limited disclosure regulations make data on debt financing very hard to obtain. One of the few databases is Thomson Reuters 'DealScanner', which provides information on the global syndicated bank-loan market; unfortunately, this database, though important, covers only a small fraction of overall debt financing. Since the major share of investments in RE actually takes place in the form of (debt-based) project financing, such data are highly needed. One exception, which provides detailed information on energy projects, installations, power plants and their investors, is the commercial 'Power' database provided by GlobalData. With respect to financial citizen participation, community funded RE projects, and crowdfunding, the local nature of this data makes measurement of a 'bigger picture' challenging. Existing data is primarily limited to isolated information on particular local initiatives, or data extracts from particular online platforms.[8]

[8] See Vasileiadou et al. [35] for one of the few studies on RE crowdfunding, analyzing investment activity in the Netherlands.

With respect to data on policy measures, researchers have utilized information archives on country specific energy policy actions provided by the 'Renewable Energy Policy Network for the 21st Century' (REN21) (e.g. [10]), the International Energy Agency (IEA) (e.g. [68]) or constructed own measurements (e.g. on the effectiveness of feed-in-tariffs in the EU: [72]). Such data is useful for research on policy impact evaluation, but could also provide a valuable source of information for professional investors, since policy risk and opportunities are among the main determinants of their investment decisions [24,73]. Yet, such data is usually limited to developed countries.

In summary, the heterogeneity of investors and investment targets calls for micro-level data able to clearly identify them. Overly aggregated statistics are likely to 'average out' possible problems and opportunities alike. Even though there is micro-level information on most types of RE investments, it usually has to be obtained from a variety of disconnected and mostly commercial data sources, and is available only for certain types of investments. The previously discussed problems with reliably identifying RE investments with respect to firm, industry and technology characteristics remain largely unsolved.

7. Some ways forward

After discussing the characteristics of the energy sector, including its particular information, we took stock of existing sources of data, and pointed towards what is still missing. We propose in this section some suggestions on how to possibly overcome the current shortcomings in terms of quality and availability of data. Here we see at least four fruitful ways forward to facilitate research as well as fact-based decision making in business and policy.

First, new, specialized surveys, or modified versions of existing surveys,could be used to deepen our understanding of up to now opaque firm and investor activities related to RE. An example of such surveys represents the 'community innovation survey' (CIS) for the EU countries as explained in Section 6. Again, in the case of RE innovation, the blurred boundaries of the sector and the varying share of Re activities within firms prevent a utilization of such data for obtaining full insights on RE activities. But extending such surveys by suitable identification mechanisms indicating if and to which extent a firm is engaged in research on or production of RE technologies has the potential to deepen our understanding of RE dynamics.

Second, and related, surveys of firms active in energy need to be complemented with similar surveys targeting investors. Such surveys could provide valuable insights on investment activities with non-mandatory disclosure, as well as their investment criteria with respect to RE technologies. Moreover, the synergies and co-investment patterns among investors are important information to avoid funding gaps. For instance, Burer and Wüstenhagen [83] survey venture capitalists on their preferences with respect to governmental RE measures to stimulate RE investments, revealing their favor for risk reducing support mechanism such as the introduction of feed-in tariffs. Including an investor perspective generally increases our awareness for their information needs, and informs data-gathering initiatives on which information facilitates investment-decision making. Third, novel data gathering techniques such as web-mining, as well as ways to make sense out of it such as natural language processing have the potential to increase the reach of countries and depth of variables covered in energy, innovation, and investment data. Such techniques just currently start to get recognized as potential valid proxy for specific variables obtained from more classical methods such as surveys [74]. To provide some examples, Jurowetzki and Hain [75] presents a method to combine web scraping of relevant twitter posts and their links with natural language processing and network analysis to map the development of emerging technologies. Curci, Y. & Ospina [76] use natural language processing techniques parents in biofuel to identify new technological trends in energy production, and Marra et al. [77] conduct a network analysis of metadata on company keywords from Crunchbase to identify metropolitan specialization pattern in RE technologies. Such methods are also useful to gather data on investments in developing economies [78]; which are often lacking exhaustive information from statistical bureaus and are outside the scope of most data gathering initiatives.

Finally, data-gathering initiatives could be done in the form of cross-national cooperation, enabling us to move beyond isolated findings limited to a particular country context. Further, as outlined above, there is also a need for cross-national cooperation in order to harmonize existing national statistics related to the production, use, distribution and storage of energy, including a breakdown of energy sources. As argued in this article, such statistics would optimally also include domestic and foreign investments in energy research, capacity and infrastructure, broken down by type of finance. A more ambitious but promising venture would be the establishment of an open database, harmonizing and pooling up to now produced research data, as called for within the community of environmental scientists [79], and the broader call for more interdisciplinary efforts within energy research [1]. Such initiatives could provide a central source of information for researchers, investors, and policy makers alike, making a step forward to bridge disciplinary and institutional silos and utilize the combined findings of energy related research and information gathering (ibid.).

8. Conclusion

In most high-income as well as many developing countries, it has high priority to spur a transition from our current fossil-fuel-dependent energy system towards a sustainable one based primarily on renewable resources. Evidence-based decision-making moving towards this transition needs a solid knowledge foundation at various levels of aggregation. The research on the role of financial institutions in changing energy systems is relatively scarce [8,12]. Policy is instrumental in such transitions, a fact underscored in several papers (e.g. [2,3,21,47,80]). Advancing towards establishing green, sustainable production is, however, dependent not only on political will, but also on whether empirical evidence in the area is commonly agreed upon and based upon data of a high standard. We particularly emphasise the role of investors as a link between public policy and firm-level activity, and we discuss the kind of data needed to sufficiently characterise them and fulfil their particular information needs for investing in the RE sector. Policies for unleashing the potential of green investments were not our primary area of focus, but the empirical evidence and available statistics are nevertheless important to policymaking, given that they provide the knowledge foundation for societal transition [1]. In this sense also, the data we produce and the statistical system we install are subject to value premises and choices based on societal interests [15]. Definitions and statistics do, in fact, also impact the allocation of investments [11]. In this article, we focused on a particular aspect of this discussion as we highlighted the current state of the field and remaining challenges in our measurement of RE and RE investments.

It was found that despite recent improvements, we are still not in a position to fully understand RE investments using existing statistical sources. Several areas of empirical evidence need improvement. We point to several types of flaws and challenges related to getting a statistical overview of investments in the energy sector, and argue they are not just a matter of intensifying existing statistical efforts and improving precision, but are caused by more fundamental difficulties.

Among the deficiencies in the currently available empirical evidence on RE, we first pointed out that the lack of historical, publicly available data addressing RE investment risks is one of the greatest challenges in engaging untapped capital. For example, there is an immediate need for publicly available performance data for investments in RE technologies both within and outside of equipment warranty periods. Additionally, historical data on default rates of RE firms are critical to assessing creditor risks.

A second general requirement for statistics is that we need to recognise and map the interdependent character of the energy system, which calls for indicators oriented towards throughput and interactions among agents in the system. We are not even sure how to delineate the energy sector, as its activities span across traditional industrial classifications, which in turn makes it difficult to produce adequate statistics [13]. For measurement purposes, it has been suggested that indicators of energy systems should consider what could be termed a carbon lock-in. This could be done by, for example, including the R&D budget for fossil fuels (e.g. [38]) or infrastructure ownership and energy cooperatives' governance structures as indicators of this lock-in. Because the development and integration of new energy technologies typically takes decades, measuring should not only focus on the current state of affairs but also include forward-looking measures that reduce the high uncertainty related to the outcomes of both present actions and technological developments [14,15].

A third and in this article most important area in which more empirical data are needed is generally investment statistics but in particular we pointed to the need to map investors in RE and which types of investments they make. A segment of much-needed information was highlighted in Section 2, ranging from the identification of investors to micro-level information on the investments. Fourth, the majority of statistics on energy production and consumption covers energy that has already been produced and consumed. Because of the intense discussions on climate change and other environmental challenges and problems, a number of scenarios for the future have been established as well. Electricity is generally characterised by limited storage possibilities; additionally, some of the renewable sources of electricity production such as wind and solar are fluctuating more than conventional sources. Therefore, statistics of such RE rarely reflect an accurate stock or potential future production. The installed capacity will, of course, reflect future production; nevertheless, more forward-looking indicators and statistics are needed. We think that new indicators should also give us a picture of how technologies are likely to evolve. Even though we are sceptical about reliance on technologies to 'save the planet', we do believe that predictions about technological evolution are important for the provision of statistics on energy. In turn, such statistics are important as a platform for informed decision-making, both for investors and policymakers. We recognize a slowly increasing effort of the research community to provide guidance for RE investors,[9] yet conclude that there is still much work to be done.

It is unlikely that the statistical profession will ever be able to cover all parts even of our non-exhaustive wish-list above. However, although it is an ambitious requirement for future standards of data to solve all of these problems, steps towards a better statistical understanding of the (financial) dynamics of the industry require that some of these issues be addressed. We would also argue that because the energy system is undergoing changes, and because it is subject to heavy political discussions and influence, the statisti-

[9] E.g. Lee & Zhong [73], who develop a three stage top-down strategy for RE investment evaluation, including the analyzis of global markets, industries and sectors, and investment vehicles.

cal system itself needs to be dynamic and capable of adapting to the needs of users. This is done by keeping information collected in tune with what is needed from policy, investors, research.[10] A balance need to be maintained here: long time-series are needed in order to benchmark over time, on the other hand statistics should be relevant, updated, and reflecting current needs. This is a classical consideration in statistics production.

References

[1] S. Pfenninger, J. DeCarolis, L. Hirth, S. Quoilin, I. Staffell, The importance of open data and software: is energy research lagging behind? Energy Policy 2 (2017) 1–215.
[2] R. Jacobsson, S. Jacobsson, The emerging funding gap for the European Energy Sector—will the financial sector deliver? Environ. Innov. Soc. Trans. 5 (2012) 49–59.
[3] World Economic Forum, The green investment report, in: The Ways and Means to Unlock Private Finance for Green Growth, 2013, Geneva, Switzerland.
[4] OECD, OECD Companion to the Inventory of Support Measures for Fossil Fuels, OECD Publishing, Paris, 2015.
[5] G. Unruh, Understanding carbon lock-in, Energy Policy 28 (2000) 817–830.
[6] G. Unruh, Escaping carbon lock-in, Energy Policy 30 (2002) 317–325.
[7] W. Blyth, R. McCarthy, R. Gross, Financing the UK power sector: is the money available? Energy Policy 87 (2015) 607–622.
[8] S. Hall, T.J. Foxon, R. Bolton, Financing the civic energy sector: how financial institutions affect ownership models in Germany and the United Kingdom, Energy Res. Soc. Sci. 12 (2016) 5–15.
[9] S. Chassot, N. Hampl, R. Wüstenhagen, When energy policy meets free-market capitalists: the moderating influence of worldviews on risk perception and renewable energy investment decisions, Energy Res. Soc. Sci. (2014) 143–151.
[10] C. Criscuolo, C. Menon, Environmental policies and risk finance in the green sector: cross-country evidenc, Energy Policy 83 (2015) 38–56.
[11] G. Inderst, C. Kaminker, F. Stewart, Defining and measuring green investments: implications for institutional investors' asset allocations, in: OECD Working Papers on Finance, Insurance and Private Pensions, No. 24, OECD Publishing, 2012.
[12] S. Hall, T.J. Foxon, R. Bolton, Investing in low-carbon transitions: energy finance as an adaptive market, Clim. Policy (2015), http://dx.doi.org/10.1080/14693062.2015.1094731.
[13] P. Shapira, A. Gök, E. Klochikhin, M. Sensier, Probing 'green' industry enterprises in the UK: a new identification approach, Technol. Forecast. Soc. Change 85 (2014) 93–104.
[14] J.E. Stiglitz, A. Sen, J.P. Fitoussi, Report by the Commission on the Measurement of Economic Performance and Social Progress, 2009 www.stiglitz-sen-fitoussi.fr.
[15] P.A. Garnåsjordet, I. Aslaksen, M. Giampietro, S. Funtowicz, T. Ericson, Sustainable development indicators: from statistics to policy, Environ. Policy Gov. 22 (2012) 322–336.
[16] H. Grubb, Foundations of the Economics of Innovation, Edward Elgar publishers, 1998.
[17] A. Masini, E. Menichetti, Investment decisions in the renewable energy sector: an analysis of non-financial drivers, Technol. Forecast. Soc. Change 80 (2013) 510–524.
[18] R. Rajan, L. Zingales, Financial Dependence and Growth National Bureau of Economic Research, 1996.
[19] A. Giddens, The Politics of Climate Change, Polity Press, Cambridge, UK, 2009.
[20] F.W. Geels, The impact of the financial-economic crisis on sustainability transitions: financial investment, governance and public discourse, Environ. Innov. Soc. Trans. 6 (2013) 67–95.
[21] R. Bolton, T.J. Foxon, A socio-technical perspective on low carbon investment challenges – insights for UK energy policy, Environ. Innov. Soc. Trans. 14 (2015) 165–181.
[22] G. Dosi, Finance, innovation and industrial change, J. Econ. Behav. Organ. (1990) 299–319.
[23] C. Perez, Technological revolutions and techno-economic paradigms, Camb. J. Econ. 34 (2010) 185–202.
[24] V. Dinica, Support systems for the diffusion of renewable energy technologies—an investor perspective, Energy Policy 34 (4) (2006) 461–480.
[25] A.B. Hargadon, M. Kenney, Misguided policy? Following venture capital into clean technology, Calif. Manag. Rev. 54 (2) (2012) 118–139.
[26] D. Toke, S. Breukers, M. Wolsink, Wind power deployment outcomes: how can we account for the differences? Renew. Sustain. Energy Rev. 12 (4) (2008) 129–1147.
[27] S. Jacobsson, V. Lauber, The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology, Energy policy 34 (3) (2006) 256–276.

[10] This is by no means easily defined and is likely to vary not only over time but also it differ what countries and different policy makers and investors require.

[28] R. Wüstenhagen, X.E. Menichetti, Strategic choices for renewable energy investment: conceptual framework and opportunities for further research, Energy Policy 40 (2012) 1–10.
[29] S. Jacobsson, A. Bergek, Innovation system analyses and sustainability transitions: contributions and suggestions for research, Environ. Innov. Soc. Trans. 1 (1) (2011) 41–57.
[30] R. Amit, J. Brander, C. Zott, Why do venture capital firms exist? Theory and Canadian evidence, J. Bus. Ventur. 13 (1998) 441–466.
[31] R. Cressy, F. Munari, A. Malipiero, Playing to their strengths? Evidence that specialization in the private equity industry confers competitive advantage, J. Corp. Finance 13 (2007) 647–669.
[32] L.W. Li, J. Birmele, H. Schaich, W. Konold, Transitioning to community-owned renewable energy: lessons from Germany, Proc. Environ. Sci. 17 (2013) 719–728.
[33] Ö. Yildiz, Financing renewable energy infrastructures via financial citizen participation – the case of Germany, Renew. Energy 68 (2014) 68–677.
[34] O.M. Lehner, Crowdfunding social ventures: a model and research agenda, Venture Cap. 15 (2013) 289–311.
[35] E. Vasileiadou, J. Huijben, R. Raven, Three is a crowd? Exploring the potential of crowdfunding for renewable energy in the Netherlands, J. Clean. Prod. 128 (2016) 142–155.
[36] P.T. Lam, A.O. Law, Crowdfunding for renewable and sustainable energy projects: an exploratory case study approac, Renew. Sustain. Energy Rev. 60 (2016) 11–20.
[37] J. Hörisch, Crowdfunding for environmental ventures: an empirical analysis of the influence of environmental orientation on the success of crowdfunding initiative, J. Clean. Prod. 107 (2015) 636–645.
[38] M. Grubb, Technology Innovation and Climate Change Policy: an overview of issues and options, Keio J. Econ. 41 (2004) 103–132.
[39] L. Fleming, O. Sorenson, Technology as a complex adaptive system: evidence from patent data, Res. Policy 30 (7) (2001) 1019–1039.
[40] K. Frenken, A fitness landscape approach to technological complexity, modularity, and vertical disintegration, Struct. Change Econ. Dyn. 17 (3) (2006) 288–305.
[41] M. Borup, A. Klitkou, M.M. Andersen, D.S. Hain, J. Lindgaard Christensen, K. Rennings, Indicators of energy innovation systems and their dynamics, in: A Review of Current Practice and Research in the Field: Radar Report, EIS, 2013.
[42] T.P. Hughes, The evolution of large technological systems, in: The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology, 1987.
[43] M. Kenney, Venture capital investment in the greentech industries: a provocative essay, in: R. Wüstenhagen, R. Wuebker (Eds.), Handbook of Research on Energy Entrepreneurship, Edward Elgar, Cheltenham, UK, 2011.
[44] T. Tsoutsos, Y. Stamboulis, The sustainable diffusion of renewable energy technologies as an example of an innovation-focused policy, Technovation 25 (7) (2005) 753–761.
[45] D.S. Hain, R. Jurowetzki, Incremental by design? On the role of incumbents in technology niches – an evolutionary network analysis, in: U. Cantner, A. Pyka (Eds.), Foundations of Economic Change – Behaviour, Interaction and Aggregate Outcomes, Economic Complexity And Evolution, Springer, Berlin, Heidelberg & New York, 2017, forthcoming.
[46] V. Khosla, Black Swan Thesis of Energy Transformation, 2011 http://www.khoslaventures.com/black-swans-thesis-of-energy-transformation.
[47] S. Dawley, D. MacKinnon, A. Cumbers, A. Pike, Policy activism and regional path creation: the promotion of offshore wind in North East England and Scotland, Camb. J. Reg. Econ. Soc. 8 (2015) 257–272.
[48] P. Astolfi, S. Baron, M.J. Small, Financing renewable energy, Commer. Lend. Rev. 23 (2008) 3–8.
[49] Eurostat, IEA, OECD, Energy Statistics Manual, 2005.
[50] Eurostat, Energy from Renewable Sources: Statistics Explained, 2013.
[51] T. Wiesenthal, G. Leduc, K. Haegeman, H.-G. Schwarz, Bottom-up estimation of industrial and public R&D-investment by technology in support of policy-making: the case of selected low-carbon energy technologies, Res. Policy 41 (2012) 116–131.
[52] K. Rennings, The challenge of energy efficiency innovations, in: M. Borup, et al. (Eds.), Indicators of Energy Innovation Systems and Their Dynamics, 2013, pp. 41–46.
[53] EPIA, Market Report 2013, European Photovoltaic Industry Association, 2013.
[54] WIPO, Patent-based Technology Analysis Report: Alternative Energy Technology, 2009.
[55] E. Dietzenbacher, B.R. Stehrer Los, M.P. Timmer, G.J. de Vries, The construction of world input-output tables in the WIOD project, Econ. Syst. Res. 25 (2013) 71–98.
[56] E. Dietzenbacher, B.R. Stehrer Los, M.P. Timmer, G.J. de Vries, An illustrated user guide to the world input–output database: the case of global automotive production, Rev. Int. Econ. 23 (August (3)) (2015) 575–605.
[57] R. Kemp, P. Pearson, Final Report: MEI Project About Measuring, eco-innovation, 2007.
[58] M.M. Andersen, Eco-Innovation Indicators, European Environment Agency, 2006.
[59] OECD, Towards Green Growth: Monitoring Progress, 2011.
[60] EIO, Methodological Report Eco Innovation Observatory, 2012.
[61] Y. Krozer, Renewable erergy in European regions, Int. J. Innov. Reg. Dev. 4 (1) (2012) 44–59.
[62] J.L. Christensen, The ability of current statistical classifications to separate services and manufacturing, Struct. Change Econ. Dyn. 26 (2013) 47–60.

[63] A. Klitkou, The challenge of classifications of technologies and products, in: Borup, et al. (Eds.), Indicators of Energy Innovation Systems and Their Dynamics, 2013.
[64] K.S. Gallagher, A. Grübler, L. Kuhl, G. Nemet, C. Wilson, The energy technology innovation system, Annu. Rev. Environ. Resour. 37 (2012) 137–162.
[65] H. Lund, B. Mathiesen, Energy system analysis of 100% renewable energy systems – the case of Denmark in years 2030 and 2050, Energy 34 (2009) 524–531.
[66] F.W. Geels, J.W. Schott, Typology of sociotechnical transition pathways, Res. Policy 36 (2007) 399–417.
[67] Jürgen Janger, T. JSchubert, P. Andries, C. Rammer, M. Hoskens, The EU 2020 innovation indicator: a step forward in measuring innovation outputs and outcomes? Res. Policy 46 (2017) 30–42.
[68] N. Johnstone, I. Hascic, D. Popp, Renewable energy policies and technological innovation: evidence based on patent counts, Environ. Resour. Econ. 45 (1) (2010) 133–155.
[69] OECD, Environmental Policy, technological innovation and patents, in: OECD Studies on Environmental Innovation, 2008, Paris.
[70] OECD, Fostering Innovation for Green Growth, OECD Green Growth Studies, OECD Publishing, Paris, 2011.
[71] UNEP, EPO, and ICTSD, Patents and Clean Energy: Bridging the Gap Between Evidence and Policy – Final Report, 2010.
[72] S. Jenner, F. Groba, J. Indvik, Assessing the strength and effectiveness of renewable electricity feed-in tariffs in European Union countries, Energy Policy 52 (2013) 385–401.
[73] C.W. Lee, J. Zhong, Top down strategy for renewable energy investment: conceptual framework and implementation, Renew. Energy 68 (2014) 761–773.
[74] C. Beaudry, M. Héroux-Vaillancourt, C. Rietsch, Validation of a Web Mining Technique to Measure Innovation in High Technology Canadian Industries OECD Blue Sky Forum on Science and Innovation Indicators, 2016, Ghent, Belguim.
[75] R. Jurowetzki, Hain, Mapping the (R-) evolution of technological fields – a semantic network approach, in: D.S, L.M. Aiello, D. McFarland (Eds.), Social Informatics, Springer International Publishing, 359-383, 2014.
[76] Y. Curci, C.A.M. Ospina, Investigating biofuels through network analysis, Energy Policy 97 (2016) 60–72.
[77] A. Marra, P. Antonelli, C. Pozzi, Emerging green-tech specializations and clusters? A network analysis on technological innovation at the metropolitan level, Renew. Sustain. Energy Rev. 67 (2017) 1037–1046.
[78] D.S. Hain, R. Jurowetzki, Silicon Savanna? Local competence building and international venture capital in low income countries. the emergence of foreign high-tech investments in Kenya, in: Globelics Working Paper Series No. 2015-09, 2015.
[79] G. Schuitema, N.D. Sintov, Should we quit our jobs? Challenges, barriers and recommendations for interdisciplinary energy, Res. Energy Policy, Elsevier 101 (2017) 246–250.
[80] C. Perez, Unleashing a golden age after the financial collapse: drawing lessons from history, Environ. Innov. Soc. Trans. 6 (2013) 9–23.
[83] M.J. Burer, R. Wustenhagen, Which renewable energy policy is a venture capitalist's best friend? Empirical evidence from a survey of international cleantech investors, Energy Policy 37 (2009) 4997–5006.
[86] IEA, World Energy Investment Outlook, International Energy Agency, 2003.
[93] L. Olmos, S. Ruester, S.-J. Liong, On the selection of financing instruments to push the development of new technologies: application to clean energy technologies, Energy Policy 43 (2012) 252–266.
[95] UNEP, Global Trends in Renewable Energy Investments, 2014.
[98] B. Verspagen, Mapping technological trajectories as patent citation networks: a study on the history of fuel cell researc, Adv. Complex Syst. 10 (2007) 93–115.
[99] UNEP, Global Trends in Renewable Energy Investments, 2015.
[100] G. Bridge, S. Bouzarovski, M. Bradshaw, N. Eyre, Geographies of energy transition: space, place and the low-carbon economy, Energy Policy 53 (2013).