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The influence of public R&D and knowledge spillovers on the development of renewable energy sources: The case of the Nordic countries

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ABSTRACT

Energy innovation is a key requirement to limit global warming and tackle climate change in the years to come. A better understanding of the public R&D mechanism is likely to improve allocation of resources for energy innovation. Thus, the present paper evaluates the impacts of public R&D and knowledge spillovers on the development of renewable energy sources. To achieve this goal, knowledge flow has been modeled as a function of public R&D expenditures, cumulative knowledge stocks and knowledge spillovers. To show the application of the model, the Nordic countries as one of the pioneers in renewable technologies have been chosen. Results show the cumulative knowledge stock will increase to 2.4 billion USD until 2030, by focusing on biofuels, solar and wind energy. Results also indicate that the knowledge spillovers reduce the domestic R&D investment and may strengthen the knowledge stock. These impacts of knowledge spillovers are more effective when the absorptive capacity of the country becomes greater. The model helps policy makers to design effective policies for creating a balance between domestic R&D expenditures and knowledge spillovers. Finally, some important policy insights and some recommendations for further research are concluded.

1. Introduction

Renewable energy sources (RES) and energy innovation play an essential role to tackle climate change and reduce GHG[1] emissions in the years to come (IPCC, 2014; Mallett, 2015). Since the cost of traditional fossil fuels is significantly lower than RES, renewable energy technologies have contributed a minor share of the total electricity generation (Semieniuk, 2016). Hence, technological breakthrough and resource mobilization in renewable energy sources are necessary to develop new technologies and to mitigate climate change (Edenhofer et al., 2014; Schmidt and Marschinski, 2009). The capability of governments to provide this financial resources is limited and usually under uncertainty (Karltorp, 2016). However, governments confirmed that their public funding for technological innovation in low-carbon energy will be increased significantly (Mission Innovation, 2016).

Analyzing the knowledge flows can help policy makers to forecast public funding in order to support energy innovation systems (Chan and Daim, 2012). Renewable energy knowledge creation is one of the main factors to develop new technologies, technological innovation systems (Bergek et al., 2008) and sustainability transition studies (Markard et al., 2012). Indeed, with respect to innovation policy at national level, knowledge flow plays a central role to create a relationship between socio-economic, environmental and energy dimensions (Aghion and Howitt, 1992). At the national-level, Bell and Pavitt (1993) and Suurs and Hekkert (2009) determined the relationship between knowledge accumulation and national R&D[2] activities.

The deep investigation about the relationship between domestic knowledge sourcing and renewable energy knowledge spillovers is a subject that has not received too much notice (Lacerda and van den Bergh, 2014). Thus, according to renewable energy innovation, determining the balance between the development of domestic knowledge (i.e. public R&D) and the advantage from knowledge developed abroad (i.e. knowledge spillover) is an important issue.

Innovation activities in the renewable energy sector have been targeted in the Nordic courtiers (i.e. Denmark, Norway, Finland and Sweden) by designing various policies to attract foreign knowledge, increasing public energy R&D and expanding energy knowledge stocks. Thanks to robust national support for energy innovation, the Nordic countries have a proper global position in this respect. Innovation in wind energy technology and bio-energy is also prominent in these

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[1] Greenhouse Gas.
[2] Research and Development.

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countries, and they have pursued to answer the environmental and economic challenges over the last three decades. Various publications such as the Nordic Energy Technology Perspectives (IEA, 2016) have illustrated that renewable energy technologies will play a central role in transition to a sustainable energy system. While these documents center on the role of investment in energy R&D activities, they do not assess the optimal resource allocation on the process of energy technologies development.

The major objective of the present study is, therefore, to identify the impact of public R&D and knowledge spillovers on the renewable energy innovation. We analyze the process of knowledge flow across the Nordic countries and investigate the potential of R&D investment saving until 2030 that helps policy makers to take critical decisions in supporting energy technologies development. The model developed in the present research enables us to estimate knowledge accumulation and knowledge spillovers. Also, it enables us to indicate how the energy knowledge stock (induced by both R&D expenditures and spillovers), can reduce the domestic R&D expenditures. Based on the data collected from IEA (2017), we have emphasized on public funding for renewable energy sources and the role of knowledge spillovers in renewable energy innovation. The target groups for the present paper are analysts, energy researchers, policy developers and energy planners.

The rest of this paper is organized as follows. Section 2, presents the literature review on the role of public R&D and knowledge accumulated in renewable energy innovation. Section 3, explains the brief model description, the sources of data and future trends in public R&D. In Section 4, results about the RES knowledge accumulated stock and the role of spillovers have been shown. Section 5 contains discussion, research limitations and some suggestions for further research and Section 6 contain our conclusions and implications for policy.

2. Literature review

2.1. The role of public R&D in renewable energy innovation

The public energy R&D expenditures play a substantial role in reducing the risk of development of new technologies, and its benefits to environmental protection, security and sustainability (Folger, 2014; Levinson, 2009; Meleddu and Pulina, 2018). The amount of public energy R&D has been object of previous investigations, however, some studies focused on climate issues and sustainable development (Carfora et al., 2018; Ghisetti and Pontoni, 2015).

Several attempts have been made to describe the impacts of government energy policy and public funding on the deployment of renewable technologies. For instance, De la Tour et al. (2011) argued the influence of technology transfer and innovation policy in solar PV[3] industry. They found that sufficient public energy R&D and effective government policies can close the technological gap in critical regions. Likewise, with respect to supply side, there is a significant impact of technology-push policy (e.g. public R&D expenditure) on the connection between market needs and social movement (Nemet, 2009; Taylor, 2008; Vega and Mandel, 2018).

Due to several reasons, governments support innovation efforts in general. First, firms and private sectors are incapable to capture the entire benefits created by their R&D investments. So, governments finance innovation activities to close the gap induced by private underinvestment (this point refers to the market failure concept) (Garrone et al., 2014; Huang et al., 2012; Koseoglu et al., 2013). Furthermore, it is important to modify the efficiency of imported technologies for domestic markets by investing on key factors of technological knowledge (Popp, 2006). In order to absorb international knowledge spillovers, the expansion of domestic absorptive capacity is required (Mancusi, 2008). Therefore, to absorb concerted technological learning and to guarantee suitable new knowledge diffusion, public R&D expenditures with more technological cooperation are needed (Anadon et al., 2014). In general, the development of a novel technological system is an uncertain and lengthy process, thus the second key reason for government interventions is the existence of barriers, market failures and uncertainty in the process of resource allocation in energy innovations (Jacobsson and Johnson, 2000).

Government energy policies are the main driver for RES development and make substantial finance for emerging technologies (Ragwitz and Miola, 2005). Governments should facilitate and support additional RES R&D in order to rise the portion of these technologies in total energy supply. Many of the government interventions arise from international agreements or national upstream documents, which apply environmental restrictions such as limits for CO_2 emissions (Popp et al., 2011). In 2016, 83% of the electricity production in the Nordic countries is carbon neutral, which 63% is renewable. Almost, the share of RES within the electricity generation in the Nordic countries is four times bigger than the level of the OECD countries.

On the whole, some problems that restrict the application of R&D investment are: financing constraints, uncertainty about future trends in R&D investment, finding the proper portfolio of R&D expenditure, market organization, infrastructure needs and lack of information. Therefore, optimal policies and appropriate portfolio of R&D investments are needed to overcome these obstacles and to develop novel energy technologies.

2.2. New green knowledge generation

Green, environmental, sustainable or eco-innovation may be defined as “new or modified processes, techniques, practices, systems and products to avoid or reduce environmental harms” (Beise and Rennings, 2005; Kemp et al., 2001). It is worth noting that this definition is based on the effect of the innovation activities independent of the initial intent and includes both incremental and radical improvements (De Marchi, 2012). In general, green technology means all technologies to improve the environment, such as renewable technologies to reduce environmental impacts (Kemp and Foxon, 2007).

Confusion exists particularly with regards to different notions that describe innovations (i.e. green innovation and innovations in general) (Fabrizi et al., 2018; Kemp and Foxon, 2007; Rennings, 2000). The main difference is that the green innovations are more complex and sophisticated than non-green innovations, especially when it comes to cleaner technologies (Cainelli et al., 2015). Indeed, with respect to the traditional technological or market domain, green innovation includes the higher levels of novelty, variety and uncertainty. As mentioned before, in the present study, we have just focused on renewable energy technologies.

The evidence of the Nordic countries' public R&D expenditures opens the question on the role of foreign renewable knowledge in domestic innovation and the effects of knowledge spillovers on renewable energy innovations. In fact, other than the internal investments in green-specific resources, the possibility to complement them with knowledge and competences coming from network partners may be a major driver for the introduction of green innovations (Andersen, 2002; Foxon and Andersen, 2009). So, international technological collaborations and interactions among countries (as a part of global innovation networks) can accelerate the rate of new technology deployment and innovation diffusion (Gassler and Nones, 2008; Li, 2010; Nemet, 2012; Simmons and Elkins, 2004). Renewable energy knowledge induced from public energy R&D, flows from a given country to other countries in various ways such as licensing, scientific cooperation, published information in patent applications, goods and services, joint ventures and foreign direct investment (Garrone et al., 2014). In general, technological knowledge can flow in two different types: explicit and tacit knowledge (Keller, 2004). Explicit knowledge such as scientific publications, refers to formal, attainable and codified knowledge that

[3] Photovoltaics.

typically, it has been documented and can be easily shared, while tacit knowledge refers to personal and experience knowledge which is hard to diffuse and formalize and is difficult to communicate to others (i.e. non-codified knowledge) (Bottazzi and Peri, 2003).

In the field of green innovation, the majority of published research (e.g. Frantzen, 2000; Keller, 2010; Lopez-Pueyo and Barcenilla-Visus, 2008; Pizer and Popp, 2008) claimed that technological knowledge could diffuse internationally when knowledge spillovers and market transactions are fully considered. Branstetter (2001) illustrated that the knowledge spillovers have a substantial effect on the innovation efforts of governments, especially on the renewable energy sector. Bento and Fontes (2015) studied the characteristics of innovation process in order to develop solar and wind technologies. They found an affirmative knowledge spillover effect for various sectors by using patent knowledge stocks. In the wind industry, Poirier et al. (2015) suggested that there are knowledge spillovers between the non-OECD and the OECD countries. They found the relationship between energy innovation resources and the cumulative knowledge stock of a country is depended on international spillovers.

Regarding knowledge spillover modeling, over the past two decades a number of researchers have sought to develop various models about the effects of spillovers and financing innovations on the development of energy technologies. According to energy efficiency technologies and climate change mitigation, Bosetti et al. (2008) modeled international knowledge spillovers in different regions. They found that the impact of knowledge spillovers depends on countries' energy R&D investments and their absorption capability. In particular, for solar and wind technologies, Kim and Kim (2015) examined the elements of innovation efforts and the role of international knowledge spillovers in OECD[4] countries. In the field of environmental issues, Verdolini and Galeotti (2011) found that larger technological and geographical distances are linked to a weak process of knowledge flows. Also, van der Zwaan et al. (2002) found that technological change is endogenous to the energy sector and thus, the knowledge production is the outcome of learning-by-doing dynamics, knowledge spillovers and public R&D expenditures.

To sum up, in order to develop new technologies at home and to absorb renewable energy knowledge developed abroad, a domestic knowledge stock with proper absorptive capacity are needed. The public R&D and spillovers have an important effect on countries' innovation efforts, specifically when it comes to green technologies. Also, the cumulative energy knowledge stock provides better vision on the long-term effects of public energy R&D expenditures. In the following, according to the objectives of the present study, we have modeled renewable knowledge flow as a function of public R&D expenditures, cumulative knowledge stocks and knowledge spillovers in the Nordic countries.

3. Methodological issues

In this section, we investigate the process of knowledge flows and then propose an analytical tool to identify the role of public R&D and knowledge accumulation in the development of renewable energy technologies. According to the Klaassen et al. (2005), Corradini et al. (2015) and Miremadi and Saboohi (2018), the process of cumulative knowledge stock has been used to measure spillovers. We have assumed the knowledge accumulated is induced by both public energy R&D expenditures and knowledge spillovers. Indeed, for limiting the scope of the paper, among three main sources for knowledge generation (i.e. R&D investment, knowledge spillovers between countries and knowledge spillovers between technologies which may be located inside the country), we have considered the first two (Emmerling et al., 2016; Grafström, 2017; Kristkova et al., 2017; Shafei et al., 2009).

[4] The Organization for Economic Co-operation and Development.

3.1. Brief model description

The developed model in the present research enables us to analyze the efficient R&D funding and knowledge spillovers. Bosetti et al. (2006) proposed that the new knowledge is developed not only by R&D investment and former cumulative knowledge stock but also by knowledge spillovers from other countries. We have focused on the seven renewable energy sources and have considered international knowledge spillovers between countries in the Nordic region. Public R&D expenditures and the cumulative knowledge stocks for each renewable technologies are the main variables in our model. Eq. (1) describes this concept and illustrates the process of knowledge creation, Z, for renewable energy technology, k, in country n at time t:

$$Z_{(n,k,t)} = a \cdot RD_{(n,k,t-x)}{}^{b} \cdot KS_{(n,k,t)}{}^{c} \cdot SPILL^{int}_{(n,k,t)}{}^{d} \quad (1)$$

where RD denotes renewable energy R&D expenditures, Z is the production of new knowledge of RES, KS is cumulative RES knowledge stock, $SPILL$ is spillover of international RES knowledge and b, c and d reflect elasticities of the production of new knowledge to the independent variables. The elasticities are between 0 and 1.

By using the annual R&D expenditures for each renewable technology in the Nordic countries and by setting the depreciation rate and time lags, the cumulative knowledge stock (KS) is estimated as below:

$$KS_{(n,k,t+1)} = (1 - \delta_{k,t})KS_{(n,k,t)} + Z_{(n,k,t)} \quad (2)$$

where δ is the depreciation rate of knowledge. Because of the obsolescence, the past knowledge is not proper for current innovation efforts. Due to rapid innovation, retirement and staff turnover, the knowledge per annum will be obsoleted (Klaassen et al., 2005). Grubler et al. (2012) examined depreciation rates for energy technologies by reviewing the literature and find ranging from 10% to 40% as the typical rates. Each renewable energy technology (e.g. PV, wind and etc.) has different rate of depreciation. For several energy technologies, Kahouli-Brahmi (2009) used a depreciation rate of 3%, for wind technology, Kobos et al. (2006) used 2.5% and Klaassen et al. (2005) indicates 5% as the rate of depreciation. In addition, there is a time lag between R&D activity and its effects. In other words, R&D investment do not lead to a gain of knowledge immediately. Many researchers found the delays of two to five years (e.g. Klaassen et al. (2005); Kobos et al. (2006); Miketa and Schrattenholzer (2004)). Already, a sensitivity analysis with regards to the time lag and the depreciation rate provided by Bointner (2014), illustrating the higher sensitivity of the cumulative knowledge with respect to the depreciation rate. Based on these studies, a 3-year time lag and a depreciation rate of 10% is assumed in the present study.

In order to estimate the RES knowledge spillovers, two main variables have been used: the knowledge pool, KP, and the absorption capacity, γ. There is well accepted that the effects of knowledge spillovers are normally measured based on a pool of accessible knowledge from other potential sources such as other firms or countries (Boschma and Wenting, 2007; Malerba et al., 2013). Countries are exposed to a pool of other countries' knowledge where a fraction of this knowledge can be absorbed by the follower country. The available knowledge for each country is illustrated by the knowledge gap between its knowledge stock and the other countries' knowledge stock (the sum of their knowledge stocks). The development of new technologies and the extent of knowledge absorption in a given country depend on its technological capability (Constantini et al., 2013; Grubb et al., 2002). It is also well-accepted that the ability of the recipient country plays a central role on knowledge spillovers (Giannoccaro and Carbone, 2017). The level of this ability that is called absorption capacity depends on various factors such as scientific bodies, laboratories, amount of R&D, industrial policy and the human resources (Murovec and Prodan, 2009). Griffith et al. (2003) illustrated that the absorption of knowledge spillovers increases by R&D investment. Absorption capacity of international knowledge spillovers represents the fraction of available pool of knowledge that each country can absorb it. In the present study, the absorption capacity is a function of total cumulative knowledge in target countries. If countries do not invest on innovation activities at the same speed of their advanced partners, their absorptive capacity will decrease over time. Eq. (3) shows international knowledge spillovers, $SPILL(n,k,t)$, for renewable technology k in country n at time t:

$$SPILL^{int}_{(n,k,t)} = \alpha_{(n,k,t)} \cdot \gamma^{int}_{(n,k,t)} \cdot KP^{int}_{(n,k,t)} = \alpha_{(n,k,t)} \cdot \frac{KS_{(n,k,t)}}{\sum_i KS_{(i,k,t)}} \cdot \left(\sum_i KS_{(i,k,t)} - KS_{(n,k,t)} \right) \tag{3}$$

Degree of spillover, α, for each renewable energy technology indicates the degree of generated knowledge by a given country for a technology that may transfer to knowledge pool which is available to other countries. This parameter is limited between 0 and 1 and it reflects the level of technology maturity and knowledge dissemination policies (Cohen and Levinthal, 1999).

Constants and coefficients have been estimated by various empirical studies (see Bosetti et al. (2008) and Markandya and Pedroso-Galinato (2007) for a review). Most of the empirical literature reflect that an elasticity of new knowledge production as in Eq. (1) and sum of elasticities are lower than one (to account for diminishing returns). The parameters b, c, d in Eq. (1) are set to be equal to 0.2, 0.55 and 0.15 respectively. For instance, the parameter d reflects that an increment of 1% of knowledge spillovers increases the output of knowledge flow and domestic ideas by 0.15%. The value of this elasticity is chosen lower than the elasticity of knowledge production to R&D investment and the cumulative knowledge (i.e. 0.2 and 0.55). Popp and Newell (2012) suggested that when spillovers are not considered, the majority of the elasticity is related to past knowledge stock (i.e. 0.55).

Given the lack of empirical evidence on the actual role of international spillovers in the development of domestic knowledge, by attributing different values to this elasticity the effects of the choice can be tested through an appropriate sensitivity analysis. The results of the sensitivity analysis are provided in Appendix A. Sensitivity analysis has revealed that the findings are robust to a range of values attributed to the elasticity of new knowledge creation to international R&D spillovers. However, there is a lack of research on the empirical foundation of main technology coefficients such as the dynamics of factor productivities and the interactions with endogenous technical change. So, further research in this issue is suggested for future agenda.

3.2. Data sources

Based on International Energy Agency (IEA) database, we have prepared a comprehensive database of public RES R&D expenditures for the Nordic countries. This database entails solely national R&D funding. It does not include the private R&D and the public funding provided by European Commission (e.g. Horizon 2020). With respect to IEA categorization (IEA, 2017), renewable energy public R&D expenditures are classified in seven technologies: solar energy (power generation from photovoltaics or solar heating and cooling), wind energy (offshore and onshore wind technologies), ocean energy (tidal and wave energy), biofuels (liquids, solids and biogases), geothermal (hydrothermal resources, hot dry rock resources and advanced drilling and exploration), hydroelectricity (power generation from falling or flowing fresh water) and other or unallocated renewable energy sources.

Since 1974, for seven renewable energy sources, the database includes public energy R&D expenditures of IEA members. Although this is the reliable source of data on energy R&D expenditures, there are some limitations. For instance, some countries do not have annual energy R&D expenditures data. In addition, for many countries the time series is not completed. For example, there is no data since 1990 for Finland. Before 1974, no R&D expenditures data are available and gradually, more detailed data were developed over time. Furthermore, this database does not include private R&D expenditures and is limited to public R&D support, thus an improved collection of such data is needed. Wiesenthal et al. (2012) investigated more information about IEA dataset limitations. In this study, the public renewable energy R&D expenditures in the Nordic countries are collected for each technology.

Table 1
The average of R&D growth rate for RES in the Nordic countries until 2030.

Renewable technologies	Denmark	Finland	Norway	Sweden	Average for the Nordic countries
Solar energy	4.3%	5.0%	4.7%	5.3%	4.8%
Wind energy	3.0%	2.1%	3.2%	2.8%	2.8%
Ocean energy	0.8%	0.1%	1.0%	1.2%	0.8%
Biofuels	4.9%	5.3%	4.4%	5.6%	5.1%
Geothermal energy	0.2%	0.1%	0.9%	0.3%	0.4%
Hydroelectricity	0.1%	1.1%	0.9%	1.1%	0.8%
Other	0.8%	0.8%	0.8%	0.8%	0.8%

In economics, in contrast with a real value, a nominal value has not been adjusted for inflation, and so changes in nominal value reflect at least in part the effect of inflation. The main difference between nominal and real values is that real values are adjusted for inflation, while nominal values are not. Indeed, in the present paper, the inflation effect has not been utilized directly. But indirectly, following scenarios would account for inflationary effects.

3.3. Future trends in public R&D expenditures

In order to estimate the annual renewable energy R&D expenditures and their knowledge accumulated, several scenarios can be proposed. It is assumed that R&D expenditures do not fluctuate sharply by radical changes of energy policy in the Nordic countries, and public R&D investment in clean energy will increase by reinforcing innovation efforts. In the present paper, therefore, we have developed two scenarios[5]: 1) based on the R&D growth rate for each renewable technology in each country and 2) based on the logical relationship between the gross domestic product (GPD) and total RES R&D.

In the first scenario, according to the Nordic Energy Technology Perspectives (IEA, 2016) the use of RES (in particular wind, solar and biofuels) is expected to continue and support by governmental energy policies. Also with respect to the R&D growth rate for each renewable technology over past years, we have proposed the average growth rate of RES R&D until 2030 (see Table 1). This pattern illustrates the path of public energy R&D investment under reinforced innovation efforts to achieve cited targets of the Nordic countries.

In order to formulate the second scenario, the research intensity of average RES R&D investment from 2008 to 2015 is considered and R&D expenditures from 2016 to the end of the time period are interpolated. The relationship between future trends in public R&D expenditures and the gross domestic product (GDP) is an important issue, because GDP development not only reflects R&D expenditures, but also economic growth and innovation efforts. With respect to Bointner et al. (2016b), Eq. (4) describes this scenario:

$$RD_{(n,k,2030)} = \frac{\overline{\sum_{2008}^{2015} RD_{(n,k)}}}{\sum_{2008}^{2015} GDP_{(n)}} * GDP_{(n,2030)} \tag{4}$$

The future trends in GDP data for the Nordic countries was derived from the OECD (2017). Under our assumptions, the supportive policies to stimulate the development of renewable technologies in the Nordic

[5] Among the long-term vision of climate and energy targets (i.e. 2050), short-term (2020) and medium-term (2030), the medium term has been selected because the Nordic countries will continue on a major transformation extending over the next 10–15 years (IEA, 2016; Mission Innovation, 2016).

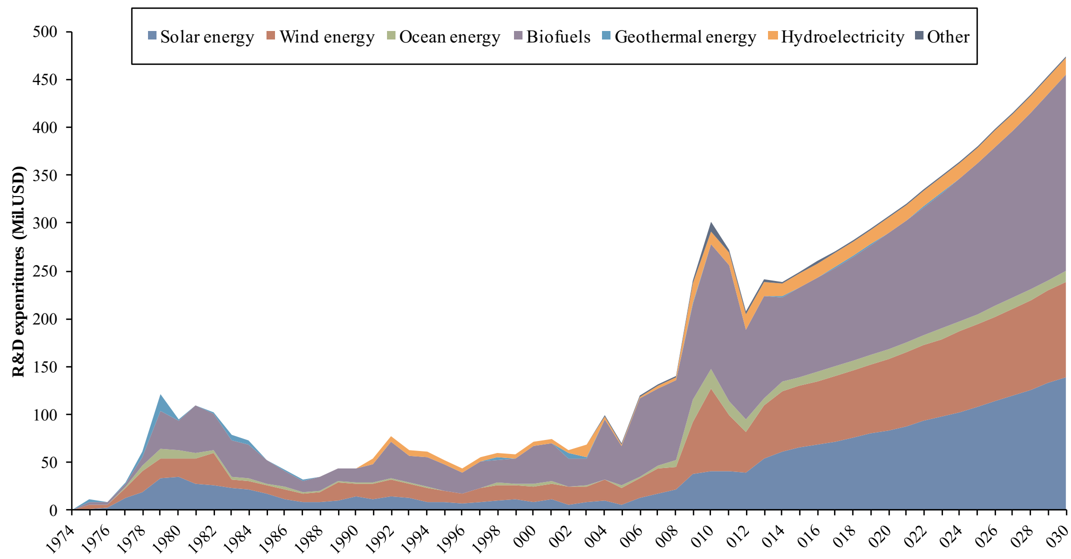

Fig. 1. Renewable energy R&D expenditures of the Nordic countries from 1974 to 2014 and estimated until 2030 (mil USD; 2014 prices and ppp), the first scenario.

countries are considered. The fundamental changes of political preferences and a technological breakthrough of immature energy technologies may be included in other types of scenarios. However, it is the reasonable assumption that until 2030 the Nordic countries would not change their energy R&D policy instantly and such radical changes are not very likely. Even if the R&D policy is changed radically in a single country, the effect may be outweighed by other countries (see Eq. (4)).

With respect to the first scenario, Fig. 1 illustrates the trends in R&D expenditures for seven renewable technologies until 2030. The total RES R&D expenditures in the Nordic countries are growing from 11.1 million USD in 1974 to 239 million USD in 2014, and then will increase to 474 million USD in 2030. According to the second scenario, Fig. 2 illustrates the total RES R&D expenditures will increase to 275 million USD in 2030 (about 2.3 million USD per year).

Regarding the historical data (from 1974 to 2014), the effects of the oil crises in 1973 and 1979 are clearly indicated in both figures by increasing RES R&D expenditures (as alternative energy sources of fossil fuels). In addition, due to the low prices of oil during the second half of 1980s, the reduction of total annual RES R&D was occurred in that time. After the Kyoto protocol in 1997, the focus in renewable sources increased significantly and culminated in 2010 by 301 million USD in total. Nowadays the largest share of RES R&D expenditures belongs to biofuels (liquids, solids and biogases), while geothermal energy was poorly financed during these years. There is a slight increase of public R&D for ocean energy and hydroelectricity compared to the main drivers of renewable sources. Furthermore, Fig. 1 illustrates fast growth in biofuels, solar and wind public R&D in renewable energy innovation.

Both figures show that the growth of RES R&D expenditures in the second scenario is much less than the first one. Indeed, the first scenario reflects that if public R&D increase based on the R&D growth rates (see Table 1), total R&D expenditures will increase near a doubling of RES R&D investment in 2014. It can be the logical assumption, because Mission Innovation (2016) also stated the doubling of present public R&D expenditures in low carbon energy technologies as a main target for related countries. Therefore, in the next section, we will select the first scenario to estimate the knowledge stock and spillovers. In addition, because specific RES have been almost full exploited, as is now the case in Norway with hydropower, in Finland and Sweden with biomass and in Denmark in respect of wind energy, future trends in RES

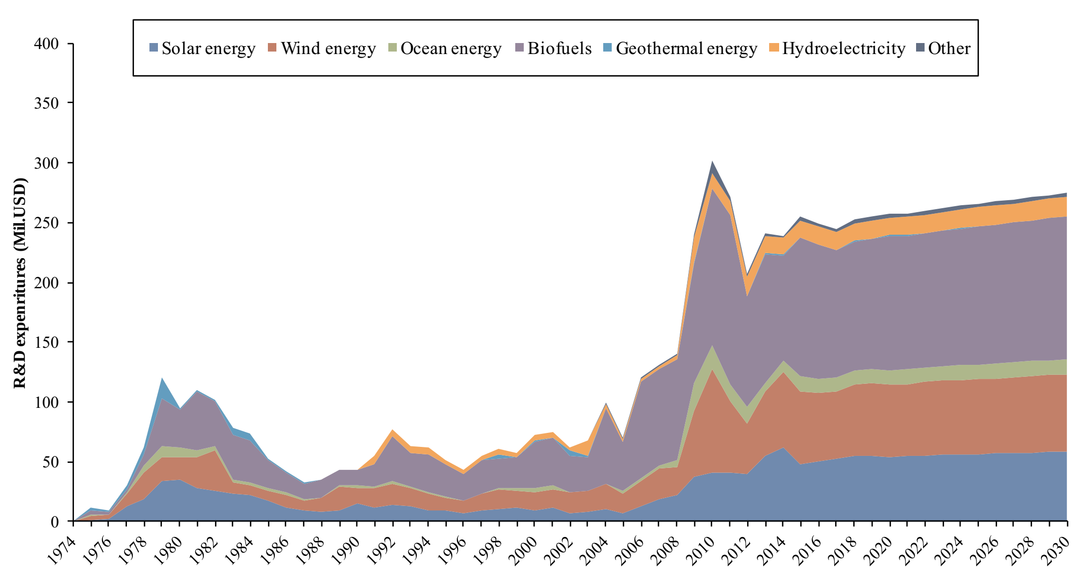

Fig. 2. Renewable energy R&D expenditures of the Nordic countries from 1974 to 2014 and estimated until 2030 (mil USD; 2014 prices and ppp), the second scenario.

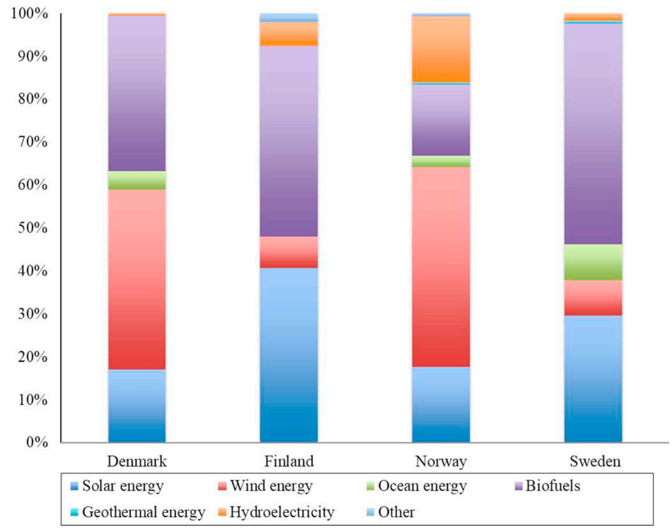

Fig. 3. The distribution of public R&D for seven energy renewable sources in 2014 between the Nordic countries.

development are expected to focus on under-exploited resources or the utilization of currently.

In order to understand more details about the share of each country, we also investigate the distribution of public R&D between the Nordic countries in 2014. Fig. 3 presents the share of total public R&D budget for RES in 2014 between the Nordic countries (IEA, 2017). As shown, Denmark and Norway are pioneers in wind energy and public R&D investment in biofuels dominates in Finland and Sweden.

In total, the energy R&D expenditures of the Nordic countries in 2014 amounted to around 1.01 billion USD, which RES accounts for about 24%. R&D expenditures on RES in 2014 consist of: 61.93 million USD on solar energy, 62.85 million USD on wind energy, 9.58 million USD on ocean energy, 88.12 million USD on biofuels, 0.52 million USD on geothermal energy, 14.38 million USD on hydroelectricity and finally 1.62 million USD on other and unallocated renewable energy sources.

4. Results

This section begins with estimating the RES knowledge accumulated stock induced by public energy R&D expenditures for each country. It proceeds with considering the effect of spillovers on the RES knowledge accumulated stock and ends with calculating R&D investment saving if spillovers fully considered.

4.1. The RES knowledge accumulated stock

In this section, we estimate the RES knowledge accumulated stock of the Nordic countries that induced only by public energy R&D expenditures (the impact of spillovers will discuss in the next section). At first we have investigated the distribution of total energy knowledge (that induced only by public energy R&D expenditures) in the Nordic countries. Fig. 4 indicates that the great majority of energy knowledge stock in the Nordic countries belongs to the renewable energy sources and energy efficiency, and then the largest share of RES knowledge belongs to biofuels, wind and solar energy. While RES counts for 25% of the cumulative knowledge stock in the Nordic countries, share of energy efficiency competes with RES by 25%.

With regard to Eq. (2), by setting the depreciation rate and time lags as described in Section 3.1, the RES knowledge accumulated stock has been estimated for each renewable technologies. Among seven types of RES, Figs. 5–8 illustrate the cumulative RES knowledge trends until 2030 for Denmark, Finland, Norway and Sweden respectively.

Fig. 5 indicates the RES knowledge stock in Denmark will grow from 386 million USD in 2014 to 700 million USD in 2030 that is mainly driven by biofuels and wind energy (40% and 38% respectively). As shown in Fig. 6, Finland started R&D investing on RES since 1990 and thus, its RES knowledge stock is less than Denmark in 2030 (reaching a level of 690 million USD). The significant portion in Finland will be biofuels and solar energy accounting by 49% and 39% respectively. In Norway, RES knowledge diversity is more homogeneous because the amount of public R&D in renewable technologies is closer together than other countries in the Nordic countries. Fig. 7 shows that the RES knowledge stock in Norway will grow to 737 million USD in 2030 (near the amount of Denmark), and it consists of wind (44%), solar (20%), biofuels (18%), hydroelectricity (13%) and other renewable energy resources (5%). With respect to Fig. 8, the first knowledge peak in Sweden is occurred in 1989 amounted to around 402 million USD. The high crude oil price between 1973 and 1979 are the main drivers for the peak in RES knowledge accumulated. The reduction of governmental incentive to support clean energy R&D and a decline of rate of knowledge flow in the 1990s is considered to be a consequence of low oil price in the 1980s (Bointner et al., 2016a). This decline continued until 2002 reaching a level of 228 million USD and then it is envisaged that it will grow to 835 million USD in 2030.

As a whole, since the very beginning of the time series, the total cumulative RES knowledge stock in the Nordic countries has a positive increment and then is expected to rise from 1.4 billion USD in 2015 to 2.9 billion USD in 2030, and Sweden ranking first in the Nordic countries in this respect. The cumulative RES knowledge stock in this year consists of biofuels by 41%, solar energy by 26%, wind energy by 24%, hydroelectricity by 5%, ocean energy by 3% and finally geothermal and other renewable energy sources by about 1%.

4.2. The impact of spillovers on the RES knowledge accumulated stock

In this section, we estimate the RES knowledge accumulated stock of the Nordic countries that induced not only by public energy R&D expenditures but also by international knowledge spillovers[6] (see Eq. (1)).

Fig. 9 shows the total RES knowledge stock of the Nordic countries after considering knowledge spillovers until 2030. When knowledge spillover is modeled, the cumulative RES knowledge stock in the Nordic countries will rise by about 29% to 3.5 billion USD in 2030. Likewise, when spillover is considered, solar energy and wind energy have been growing by 16 and 17% respectively. Due to the all Nordic countries are almost pioneer in public investment in biofuels, low spillovers are occurred for this technology and thus, the lowest increase is for biofuels by about 7%.

Knowledge spillovers play an effective role in expanding the cumulative RES knowledge stock in each country of the Nordic region. In this case, the RES knowledge accumulated for Denmark, Finland, Norway and Sweden shall raise to respectively 830, 797, 918 and 969 million USD in 2030. In addition, to analyze the process of knowledge transfer between the Nordic countries, the rate of absorption and dissemination of knowledge in each country can be investigated. Fig. 10 shows the total RES knowledge spillovers flow between countries in the Nordic region until 2030. As shown, the largest amount of RES knowledge is transferred from Denmark to Norway by 65.44 million USD. That means Norway gain more from international pool of

[6] In fact, international spillovers can also come from other countries investing in R&D. In particular, the Nordic countries (being at the frontier) would especially benefit via collaborations between them. Therefore, in the present study we assumed that absorption of renewable energy knowledge from the rest of the world would not be substantial in relation to the Nordic region's RES knowledge (which is highly realistic when they are pioneer in the development of renewable technologies).

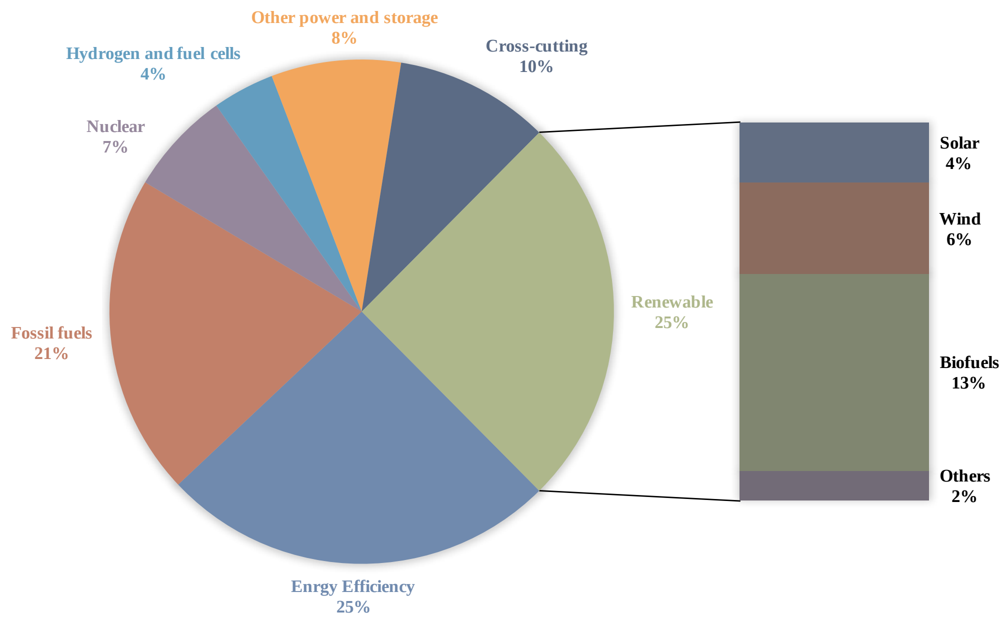

Fig. 4. Total energy knowledge distribution (that induced only by public energy R&D expenditures) for Nordic countries in 2014.

knowledge than the rest by 181 million USD, because Norway has the highest level of investment on RES R&D. It is important to point out that public R&D expenditures play a substantial role to expand the absorptive capacity (see Eq. (3)). Finland does not benefit much from the available foreign RES knowledge, because its absorption capacity is lower than others. Since Denmark is leading in RES, it doesn't absorb much knowledge from other countries. But interaction and bilateral relationship between Sweden and Denmark is appropriate and the major part of their spillovers include wind and solar technologies.

Furthermore, we can also investigate the changes of RES knowledge for each country separately over time. So, Fig. 11 illustrates the percentage changes of the future cumulative RES knowledge stock by the Nordic countries until 2030 after modeling knowledge spillover.

4.3. R&D investment saving

Countries are exposed to a pool of knowledge that can be considered as a global public good. A fraction of this knowledge is absorbed by each country and is available for use in the domestic R&D sector. So, knowledge spillovers can reduce the domestic R&D investment, facilitate the process of renewable technology diffusion and may strengthen the knowledge stock. Indeed, countries can collaborate with each other in a global knowledge environment to maximize the exploitation of this potential and reduce their R&D costs. Fig. 12 illustrates the cumulative RES knowledge stock and the potential of domestic R&D expenditure saving in the Nordic countries until 2030. Indeed, this figure shows that the Nordic countries can save R&D investment on RES around 152.6 million USD until 2030, if spillovers fully take shape between countries. This is a significant potential for technological innovation in the Nordic

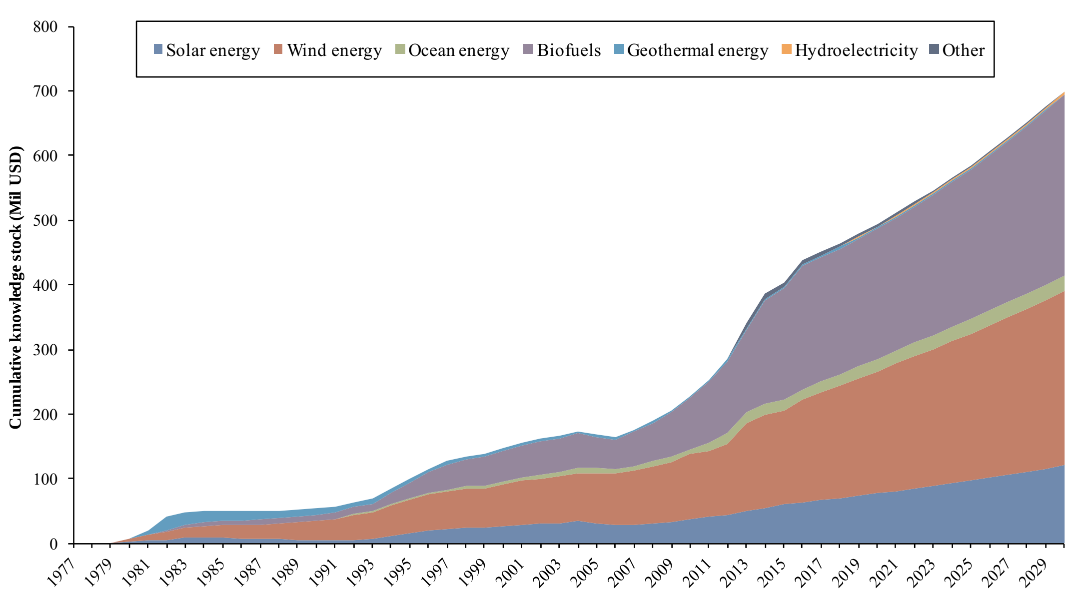

Fig. 5. The RES knowledge accumulated stock of Denmark induced by public energy R&D expenditures (mil USD; 2014 prices and ppp).

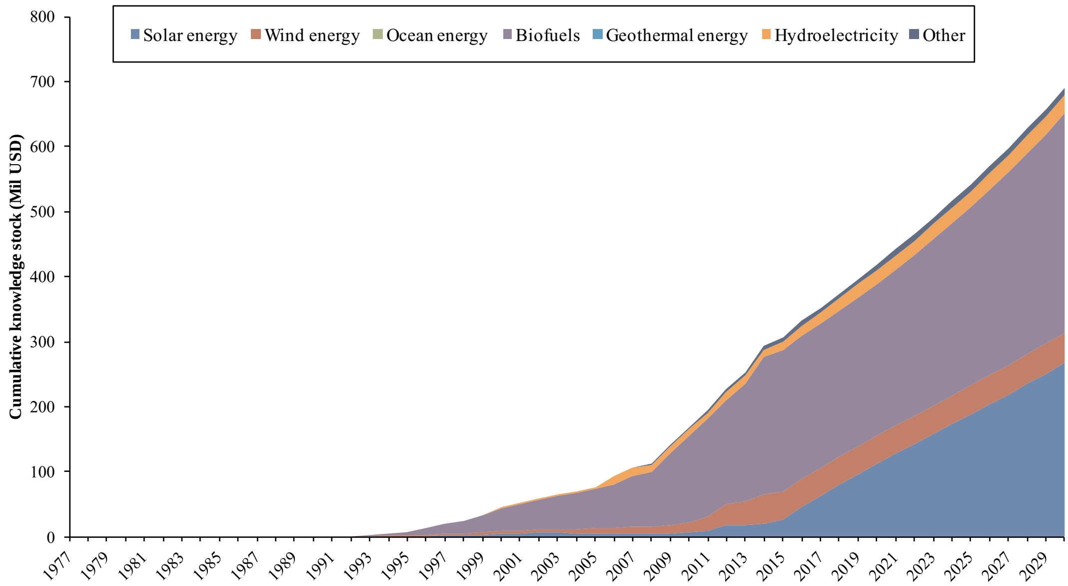

Fig. 6. The RES knowledge accumulated stock of Finland induced by public energy R&D expenditures (mil USD; 2014 prices and ppp).

region which can be considered for both energy research and energy planning. The trend in R&D investment saving has taken a bell-shaped curve, because knowledge spillovers is non-cumulative variable and are first increasing and then decreasing along (like bell-shaped). Each country starts from a very high knowledge pool and very low absorption capacity, then development of the absorptive capacity increases the knowledge spillover reaches its maximum level. At this level, the maximum saving of R&D investment occurs. In this mechanism, potential of knowledge inflows is reduced over time and spillovers rise until the knowledge stock of one country is equal to the sum of the knowledge stock of other countries in the Nordic countries (see Eq. (3)). Indeed, Fig. 12 shows how much the domestic R&D expenditures will be decreased if the knowledge stock induced not only by R&D expenditures but also by knowledge spillovers. RES R&D investment saving culminates in 2024 with accounting 15.7 million USD, and then decreases to about 7.4 million USD until 2030. As mentioned before, knowledge spillovers for RES is not too much and the highest value is around 46 million USD in 2024. In general, similar to the prior case, when spillovers are modeled three main renewable technologies (i.e. biofuels, wind and solar energy) are pioneers.

5. Discussion

The main contribution of the present study is twofold. First, it provides an analytical tool to investigate the impacts of public R&D and knowledge spillovers on the cumulative knowledge stock of renewable energy sources across the Nordic countries over a time-span until 2030. Second, it identifies the potential of R&D investment saving until 2030 that helps policy makers to take critical decisions in supporting energy technologies development.

In the Nordic countries, we modeled RES knowledge flow as a function of public R&D expenditures, cumulative knowledge stocks and knowledge spillovers. Results have highlighted, albeit preliminary, that the cumulative knowledge stock is more stable than fluctuations of R&D expenditures and will increase over time. With respect to the growth rate of RES R&D (see Section 3.3), the R&D investment for RES in the

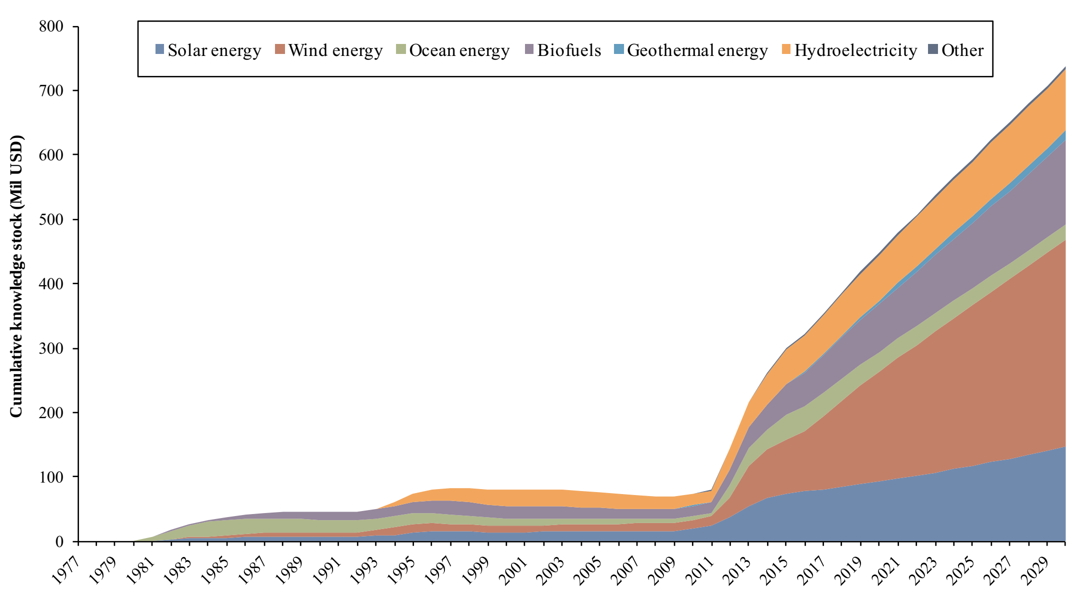

Fig. 7. The RES knowledge accumulated stock of Norway induced by public energy R&D expenditures (mil USD; 2014 prices and ppp).

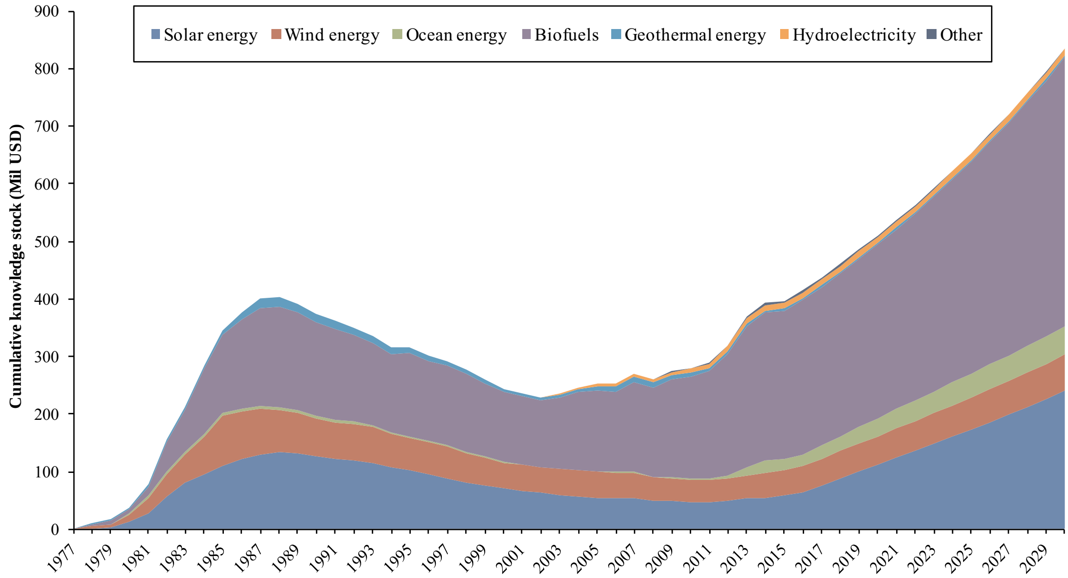

Fig. 8. The RES knowledge accumulated stock of Sweden induced by public energy R&D expenditures (mil USD; 2014 prices and ppp).

Nordic countries will probably rise to 466 million USD until 2030 with an impact of 0.12% on GDP, by focusing on biofuels, solar and wind energy. The total cumulative RES knowledge stock is expected to rise from 1.4 billion USD in 2015 to 2.9 billion USD in 2030, and Sweden ranking first in this respect.

It could be argued that the first peak in RES knowledge accumulation in 1980, principally because of high crude oil price and the oil crises between 1973 and 1979 that security of energy supply jumped to the important political agenda. In addition, due to the low prices of oil during the second half of 1980s, the reduction of total annual RES R&D was occurred in that time. Denmark chose coal to generate electricity, while nuclear power was chosen in Finland and Sweden. In Norway, due to a very large quantity of hydropower, hydro-electrical power stations were developed. After the Kyoto protocol in 1997, according to the oil price shocks and environmental concerns, a comprehensive political obligation was created after these issues, in order to increase considerably the focus of R&D investment priority on alternatives fossil fuels technologies such as RES. Renewable energy sources have gradually replaced for fossil fuels, mostly on biomass in Sweden and wind power in Denmark. Recently, once again R&D investment on RES has become desirable to reach the global energy and climate targets. Nowadays in the Nordic countries the largest share of the cumulative RES knowledge stock belongs to biofuels (liquids, solids and biogases), with an estimated 44% and then wind energy and solar energy follow with around 23 and 21%, while geothermal energy is dedicated at last situation. The abundance of paper pulp industries and developed forestry in Finland and Sweden, is the main reason that they are pioneer in biofuels. Norway has gained a reputation in hydro-based technology compared with other Nordic countries and Denmark is a pioneer in wind energy innovation which is a main exporter of wind technologies in worldwide.

The results also show that the technological capability of a given country depends on a substantial level of knowledge spillovers, even though it is lesser than domestic R&D. In a given country, RES

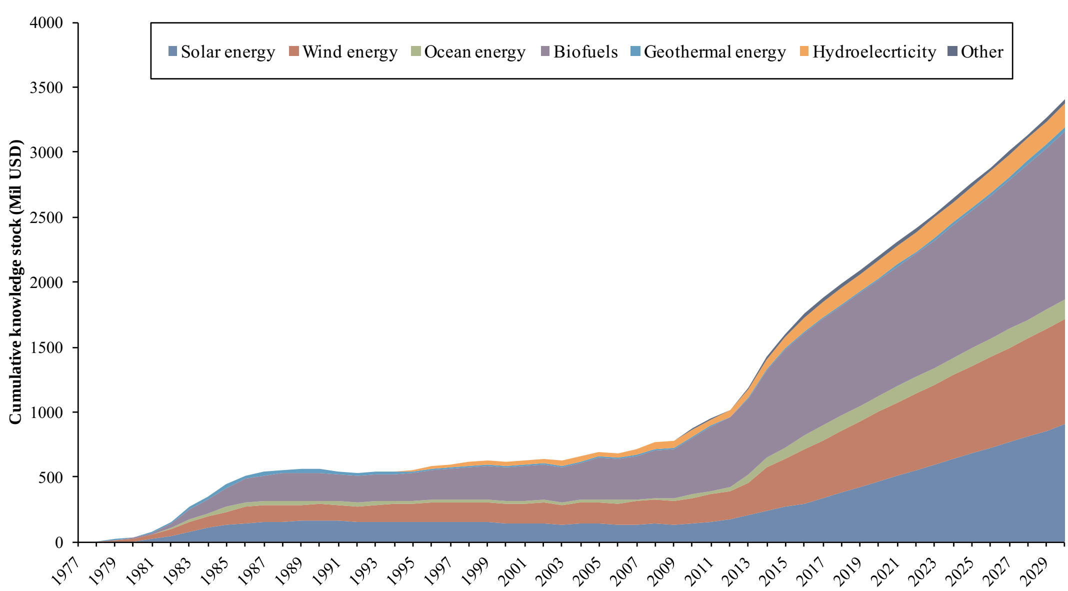

Fig. 9. The RES knowledge accumulated stock of the Nordic countries induced by both public energy R&D expenditures and spillovers (mil USD; 2014 prices and ppp).

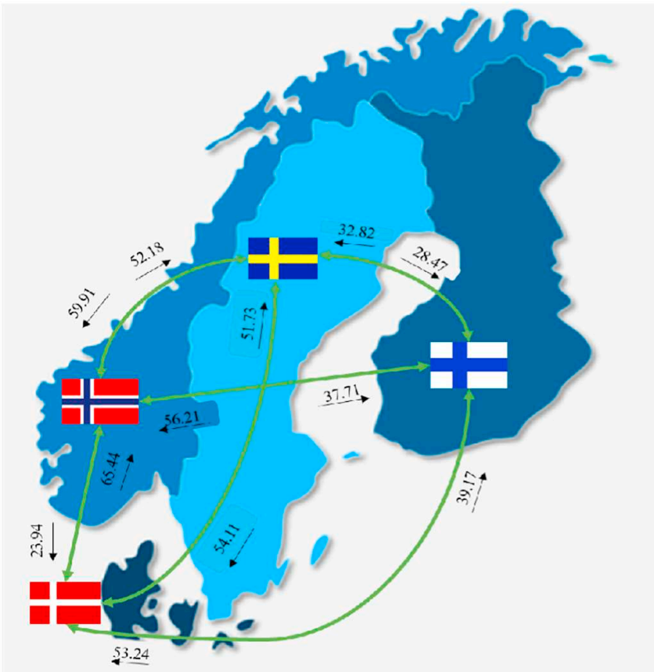

Fig. 10. The total RES knowledge spillovers flow between countries in the Nordic region until 2030. The numbers are in million USD.

knowledge spillovers have significant impact on the future potential of energy innovation in the Nordic countries. This impact is more effective when the absorptive capacity of the country becomes greater and also its relationships with other countries that have larger public R&D becomes more reliable. When knowledge spillover is modeled the cumulative RES knowledge stock will rise by about 29% to 3.5 billion USD in 2030. Among countries, Norway gained more from international pool of RES knowledge than the rest by 21% increase, because Norway has the highest level of investment on RES R&D and thus the largest absorptive capacity. If spillovers fully take shape between the Nordic countries, they can also save domestic R&D investment on RES around 109 million USD until 2030. That means the R&D intensity will be more effective and to reach a specific level of knowledge stock, lesser public R&D is required. This is a significant potential for technological innovation in the Nordic countries which can be considered as an important resource for both energy research and energy planning.

To clarify this issue, based on Cohen and Levinthal (1990), absorptive capacity is a function of two main components: prior knowledge and intensity of effort. Prior knowledge consists of accumulated knowledge available within the country. It is cited in the present study as “past knowledge stock”. Prior knowledge could increase the ability to use and assimilate new knowledge. Intensity of effort represent the amount of energy expended to facilitate knowledge conversion and/or creation. So, the outcome of knowledge creation and conversion feeds back to the prior knowledge to increase its level. Furthermore, the migratory knowledge from a country to another country or from an industry to another industry in the same country significantly affects the prior knowledge (Kim, 1998). Knowledge spillover -which is emphasized in this paper- is a sort of migratory knowledge. Thus, the influence of domestic R&D (intensity of effort) and knowledge spillover on new knowledge generation is not the same. Knowledge spillover could with any luck, improve the prior knowledge (knowledge stock) which along with domestic R&D investments (efforts) might increase the country's absorptive capacity and then its learning capabilities. Through external sourcing, countries might learn faster and less expensive than internal R&D. But R&D investment -if it results in a critical mass- could increases the absorption of acquired knowledge. Each country with effective and wise investment can thus save R&D expenditures by relying on migratory knowledge (i.e. acquired knowledge via spillover).

It should be noted that in special cases, the estimation of knowledge spillovers can be problematic. For instance, although countries can collaborate with each other in a global knowledge environment to reduce their R&D costs, coordination failures might occur if all countries at the same time rely on spillovers. So, further research in this regard would be of great help to analyze special cases in our modeling.

It has not escaped our notice that the outcomes of the present paper build on public R&D investment for RES, however the public funding provided by European Commission and the private R&D funding play an important role to strengthen knowledge flows. Hence, due to a substantial lack of data on private energy R&D expenditures, further research in this field would be of great help to understand the impact of energy R&D expenditure on the cumulative knowledge stock. For assessing the effectiveness of private and public R&D programs and future prioritization of R&D expenditures, the inclusion of patents would enhance such analysis (Miremadi et al., 2018). So, adding the patent

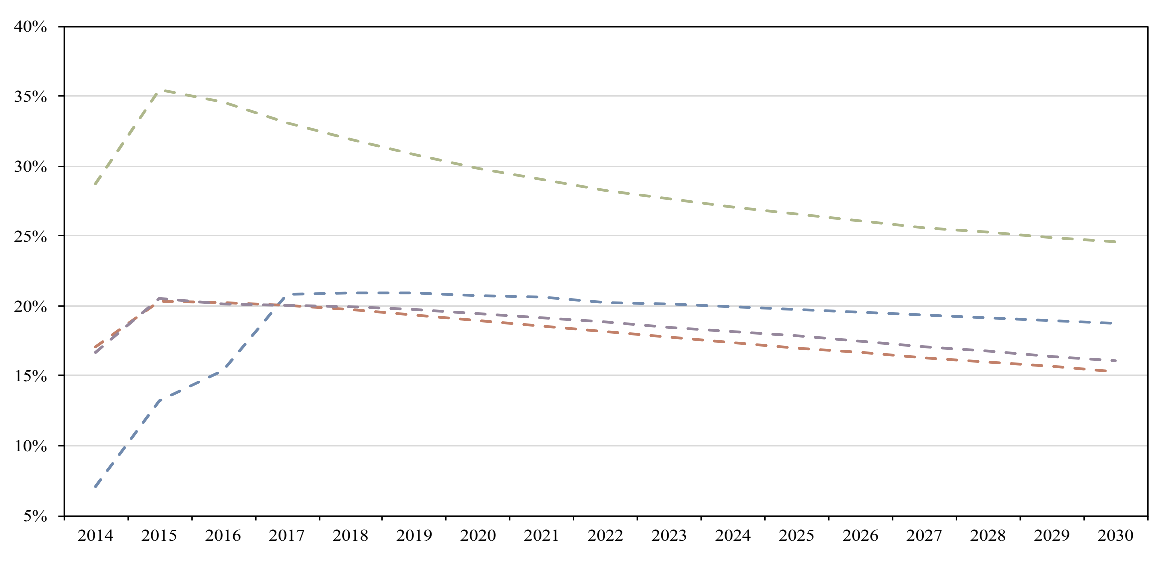

Fig. 11. Percentage changes of the future cumulative RES knowledge stock by the Nordic countries until 2030 after modeling knowledge spillover.

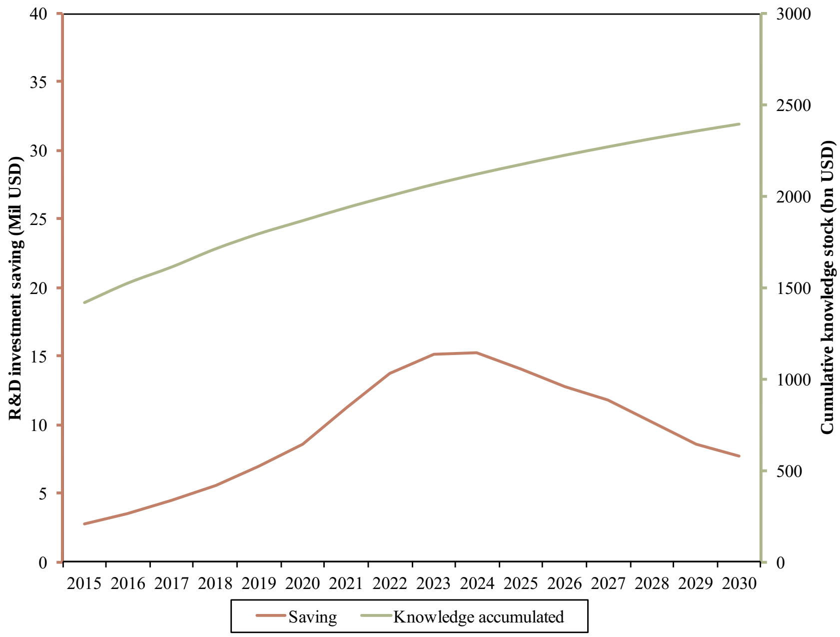

Fig. 12. The RES knowledge accumulated stock and the potential of domestic R&D expenditure saving in the Nordic countries (mil USD; 2014 prices and ppp).

analysis can improve the results of this study. Also, assessing the output of energy innovation, such as publications, licenses and patents can help to support energy technologies by increasing the accuracy in measuring the effect of cumulative knowledge stock.

Finally, given the lack of empirical evidence on the actual role of each variable in the development of domestic knowledge, it is worth concentrating the efforts in studying elasticities estimating. So, future research that may discuss how to estimate the elasticities when there are no real data over years in different countries (especially developing countries) is really valuable.

6. Concluding remark and policy implications

In the light of sustainability transitions and energy innovation, the global attention to the development of renewable technologies is rising and resource mobilization in renewable energy technologies becomes further important for policy making. It is widely agreed that an enhanced understanding of the process of technological innovation development in renewable energy sector is an essential need to tackle climate change. Hence, the Nordic countries considerably increase their public energy R&D funding for improving the development of renewable technologies over the last two decades. In addition, energy innovation is indeed significant economic activity in these countries assuming about 4–8% of total industrial exports and around 5.5% of total revenues and employment in the region.

According to our finding, the present study has three key implications for the design of energy policies in the four countries. First, innovation and spillover processes (i.e. co-operation between countries) may enable countries to utilize advantage from the experience of the other countries. Exploring the process of experience spillover among different technologies and countries, as well as assessment of its impact on global development of technologies is important. In fact, there are obstacles in a straight knowledge transfer from a country to another country but international firms can support international knowledge diffusion. Second, the heat power and generation of electricity from RES in the Nordic countries has been dependent on various public support schemes. To be more specific, green certificates, feed-in-tariffs, R&D support, CO_2 emission trading and taxation of fossil fuels in heat production are key policies in the Nordic countries. Third, renewable energy knowledge expands with more intensity between countries that have continuous alignment and significant interactions. So, international policies and finance more in public R&D can reduce the risk of investment in energy innovation that are necessary to climate co-operation and carbon reduction. Considering the promotion of open source publications and an active culture of technology transfer is important to design an effective policy on joint initiatives and knowledge transfer. Proper budget with immediate energy research policy affects the knowledge stock development and energy technology deployment, especially for renewable energy technologies.

To sum up, the proposed model in the present study assists us to assess the effects of knowledge spillovers and the reduction of domestic R&D expenditures as a main potential for energy planning. In addition, the increase in supporting innovation activities (e.g. R&D expenditures), can bring several advantages to Nordic society such as job creation, decreasing energy costs, etc. So, the appropriate budget with proper energy policy can reduce the investment of R&D, facilitate the process of renewable energy technology diffusion and may strengthen the knowledge stock.

Acknowledgement

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Appendix A. Sensitive analysis

As previously discussed, there is some uncertainty over the value to be assigned to the elasticity of knowledge creation in international R&D spillovers. Given the shortage of empirical estimates for the coefficients, we have used the values of similar variables included in the model – especially the value of elasticity of knowledge creation in domestic investments – and performed sensitivity analyses relative to this point.

So, specifically, we have used a symmetric interval around the central value of 0.15 by setting 0.20 and 0.10 as upper and lower bounds, respectively. With the upper bound value, the elasticity of knowledge creation to international spillovers is greater than 0.2, which is the value of domestic investments. According to the explanations given, 0.20 is thus a considerably high level for parameter d.

The following figures show the relationship between the coefficient d and energy R&D investment for different years (i.e. 2020, 2025, and 2030). As shown, the Nordic countries are not much sensitive to variations of the parameter. Generally, it is clear that the range of the coefficient d is very small (between 1 and 1.6%), and therefore the assumed value of 0.15 seems logical compared to the rest of values.

Sensitivity analysis shows that for all values of the parameter d, investments in energy R&D decline in the Nordic region when spillovers are explicitly modeled. This adds robustness to the results described in the Results section.

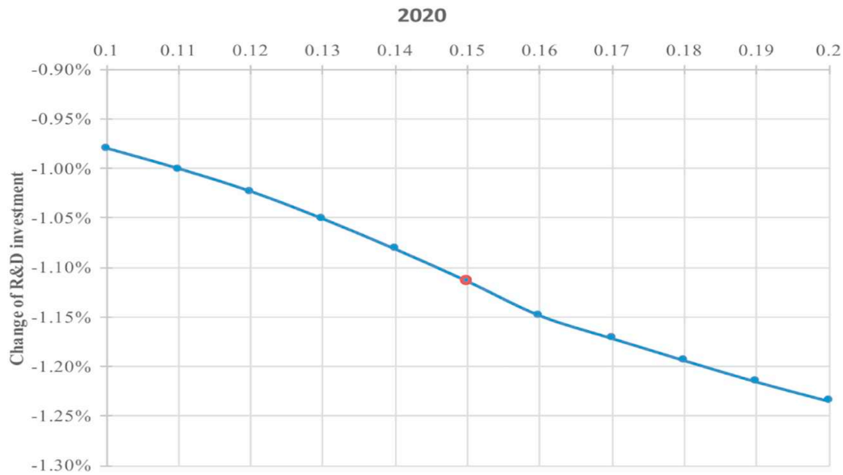

Fig. 13. R&D investments change in 2020, for different values assigned to parameter d.

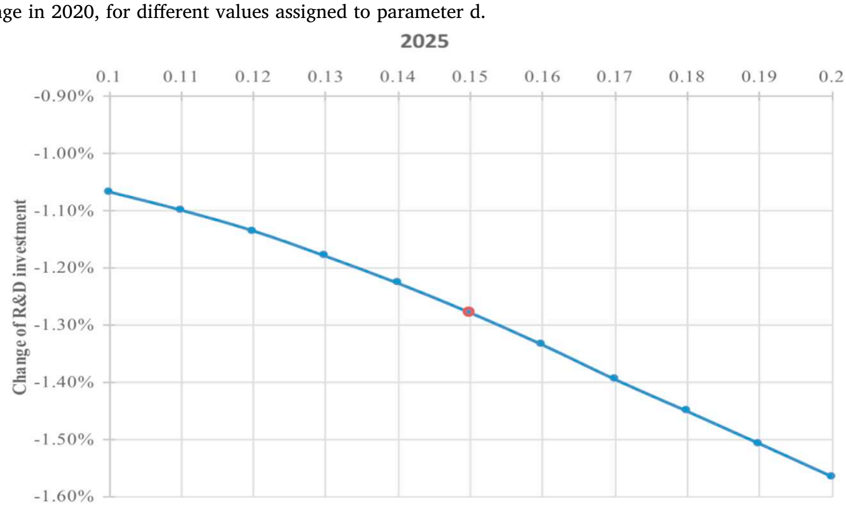

Fig. 14. R&D investments change in 2025, for different values assigned to parameter d.

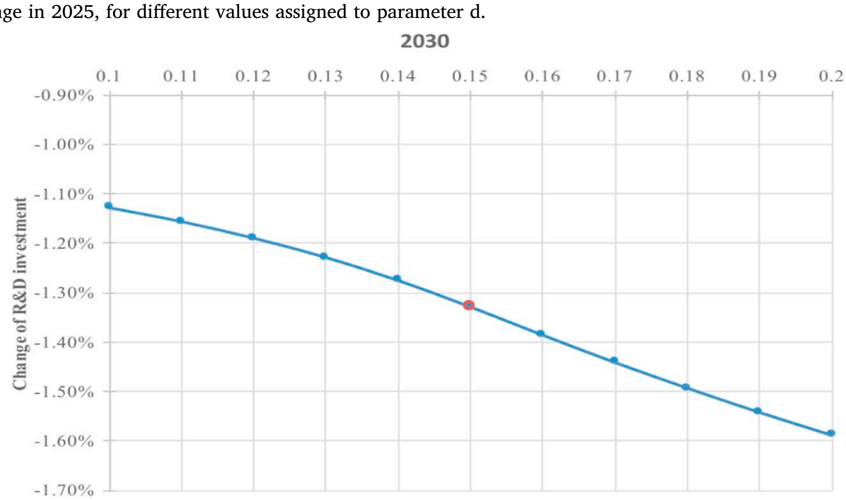

Fig. 15. R&D investments change in 2030, for different values assigned to parameter d.

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