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Article

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Planning for Investment in Energy Innovation: Developing an Analytical Tool to Explore the Impact of Knowledge Flow

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ABSTRACT

The major objective of this study is to provide an analytical tool to identify the role of investment on innovation in the process of new technologies development. To achieve this goal, a model of knowledge flow is developed and the effects of national and international knowledge spillovers are investigated. Results show that when knowledge spillovers are modelled in the Nordic countries, the required investment on domestic energy R&D decreases and the cumulative knowledge increases to 10.7 billion USD by 2030. This is a significant economic potential for technological innovation which can be considered for both energy researchers and energy planners. Finally, some important policy insights and some recommendations for further research are concluded.

Keywords: Energy Economics, R and D Expenditure, Knowledge Spillovers, Energy Policy
JEL Classifications: Q43, O3

1. INTRODUCTION

Low carbon energy technologies have received increasing notice in policy and science. According to the recent Paris agreement, diffusion of energy technologies with high efficiency will play a substantial role to tackle climate change in the near future (IPCC, 2014). To achieve the 2°C target, energy innovation to development of new energy technologies is necessary (Miremadi et al., 2018; Edenhofer et al., 2014). So, huge resources (i.e. human, financial and etc.) ought to be allocated through innovation process consists of several steps, from research and development (R and D) to large-scale deployment and commercialization (Hong et al., 2017; Bointner et al., 2016; Balachandra et al., 2010). The capability of a national system to provide these resources is limited. Therefore, to make allocation of resources more efficient, the assessment of resources allocation in different countries is required.

Public R and D has the ability to build confidence in the market by adequately demonstrating technologies; accelerate the development of new technologies; and decrease costs and takeover barriers to implementation at scale (Bozeman and Rogers, 2001; Dewald and Truffer, 2011; Folger, 2014). The cumulative energy knowledge stock enables us to estimate total energy R and D spending on energy technologies. This is more resilient and stable than fluctuations of R and D expenditures, thus, provides better vision on trends over time and on the long-term effects of public energy R and D expenditures (Bointner, 2014). The success of innovation policy at national-level can be evaluated with the knowledge stock induced by R and D expenditures (Kobos et al., 2006). Therefore, a deep understanding of how and how much the resources are allocated in energy technologies is essential for innovation policy. In addition, in order to make informed decisions, policy makers will need an understanding of the extent of the future distribution of energy R and D expenditures (Borup et al., 2013; Su and Moaniba, 2017).

In the past two decades a number of researchers have sought to develop resource allocation models in the field of energy technologies development. For instance, in order to compare the relative effects of R and D expenditures, Shayegh et al. (2017) have used learning investments and illustrated that R and D investment diverge in achieving cost effective decarbonization. To support decisions on allocation of R and D resources, Kurth et al. (2017) have demonstrated a portfolio decision analysis (PDA) approach. They stressed on coordination of R and D investment that has an important role to making the transition of the nation's energy system. Shafiei et al. (2009) have tried to determine optimal resource allocation for development of new energy technologies by focusing on a photovoltaic system. They focused on developing countries and considered the role of experience and knowledge spillovers from developed countries. To improve the R and D investment in the field of energy technologies, Akimoto et al. (2005) have developed a mixed integer programming model of the technology development. Finally, at the national-level, Wamae (2006) and Guisado-Gonzalez et al. (2017) have tried to determine the factors influencing the flow of knowledge, its relationship with knowledge accumulation and national R and D activities.

To better understanding of spreading basic science and diffusion of new technologies, the transfer of knowledge across countries and technologies is investigated in the present study. In order to develop an analytical tool for assessing innovation resources allocation (i.e. R and D investment), it would be essential to consider the knowledge spillovers between countries and between similar technologies in each country (Caniels and Verspagen, 2001; Luo et al., 2015). The knowledge diffusion appears in two domains: Time and space. Most studies investigated knowledge spillovers only over time (Kesidou et al., 2009).

Although some research has been carried out on international knowledge flows in the process of knowledge production (such as Bosetti et al. (2008), Fracasso and Vittucci (2014) and Jin (2016)), there have been few investigations into the potential of technological innovation and knowledge spillover between technologies at national-level. According to energy knowledge flow in countries, we consider both international knowledge spillovers and national knowledge spillovers.

The present paper attempts to show that with considering the process of knowledge flow and the potential of technological innovation in a specific country, domestic R and D expenditures (as the most important source of innovation) decreases. This research therefore seeks to address the following questions: How much domestic R and D expenditures will be decreased if knowledge spillovers fully considered? Do knowledge spillovers increase knowledge stock of countries? How much energy knowledge stocks will be provided for each energy technology groups? Thus, the major objective of this study is to provide an analytical tool to identify the role of knowledge accumulation and innovation investment in the process of new energy technology development. To achieve this goal, we analyze the process of knowledge flow across countries and energy technologies and the potential factors of governmental R and D investment over a certain period of time. The model developed in the present research enables us to answer the aforementioned questions. Energy planners, energy researchers and policy developers are the target groups for this paper. To show the application of the model and to illustrate energy knowledge stock and trends of public R and D expenditures over time, the Nordic countries have been chosen.

The remaining part of the paper proceeds as follows. Section 2 presents the importance of public R and D on energy technologies and also the literature on development of knowledge and spillovers. In Section 3, methodological issues and model formulation are explained. In Section 4, results have been shown in four parts. Finally, in Section 5 we present conclusions together with recommendation for further research.

2. RELEVANT LITERATURE

2.1. On the Importance of R&D Investment

Innovation activities improve the economic and social impacts of the actual R and D efforts and create new knowledge for developing novel technologies (OECD, 2002).

There are two main reasons for public R and D expenditures: Market failure and systemic failure. According to Popp (2006), market failure refers to the market that involving R and D spending in the technology, as well as users of the technology. Firms tend to underinvest, because they are incapable to capture the entire benefits created by their R and D investments. So, governments finance innovation activities to close the gap induced by private underinvestment (Garrone et al., 2014; Koseoglu et al., 2013). Systemic failure is another reason for public support to R and D. Public intervention is vital for innovation stakeholders to exploit the full potential of innovation (Baccini and Urpelainen, 2012). Therefore, to absorb concerted technological learning and to guarantee suitable new knowledge diffusion, public R and D expenditures is required (Anadon et al., 2014; Emodi et al., 2015). With more technological cooperation and filling the knowledge gap between countries, domestic energy R and D could be reduced (Wan et al., 2015). Therefore, any policy that support the transmission of world knowledge should be considered. For instance, the productivity of R and D efforts and the knowledge sharing could be increased with supporting joint development programs (Kim and Kim, 2015).

The energy R and D expenditures play an important role in the development of new technologies and its benefits to environmental protection, security and sustainability. Wong et al. (2013) have illustrated that in the OECD countries, R and D expenditure in fossil fuel improves economic growth more than the fossil fuels consumption does. To estimate the allocation of funds in energy R and D, one of the challenges for policy makers and governments is understanding the potential of knowledge spillovers across countries and energy technologies (Inglesi-Lotz, 2017).

Several attempts have been made to illustrate the vital role of R and D as a substantial contributor to development and growth. Primarily studies have determined the rate of return to R and D in the growth of productivity by measuring R and D intensity (Griliches, 1979; Jones and Williams, 1998; Corderi and Cynthia, (2011). Ho et al. (2009) and Bayarcelik and Tasel (2012) identified the effects of R and D on economic growth for Turkey and Singapore; while Gyekye et al. (2012) argued the contribution of innovation activities (i.e. R and D efforts) on the economic growth of Sub-Saharan Africa (SSA). Bointner (2014) investigated the relation between energy R and D and learning by researching as one of the major sources of learning. He also explained the four grand patterns of energy technological change as described by Grubler et al. (2012). Roper and Hewitt-Dundas (2015) have offered empirical evidence on positive and strong relationships among knowledge, R and D and firm performance. Furthermore, many countries are collaborating with each other in a global knowledge environment to reduce their R and D costs (Narula and Santangelo, 2009; Mallet, 2015; Su, 2017). Wiesenthal et al. (2012) illustrated the potential of a technology to provide a specified energy service may be even more important than its costs.

However, the severity of investment in R and D not only reflects the availability of a specific energy source and the market potential in a certain country, but also illustrates the maturity of a technology. Johnstone et al. (2010) showed that immature technologies are significantly more dependent on public R and D expenditures. Garrone and Grilli (2010) and Popp (2006) demonstrated that to increase effects of innovation activities, it is important to consider energy R and D expenditures in both supply side and demand side. Notice that R and D expenditures may be affected by knowledge spillovers and do not lead to an instantaneous gain of knowledge.

According to the energy technologies and innovations, the International Energy Agency (IEA) has categorized the energy R and D in seven groups (IEA, 2016a). For the main energy technology groups and in the Nordic countries, Figure 1 presents the share of total public energy R and D budget (IEA, 2015). Over time, the diversity of energy R and D has changed.

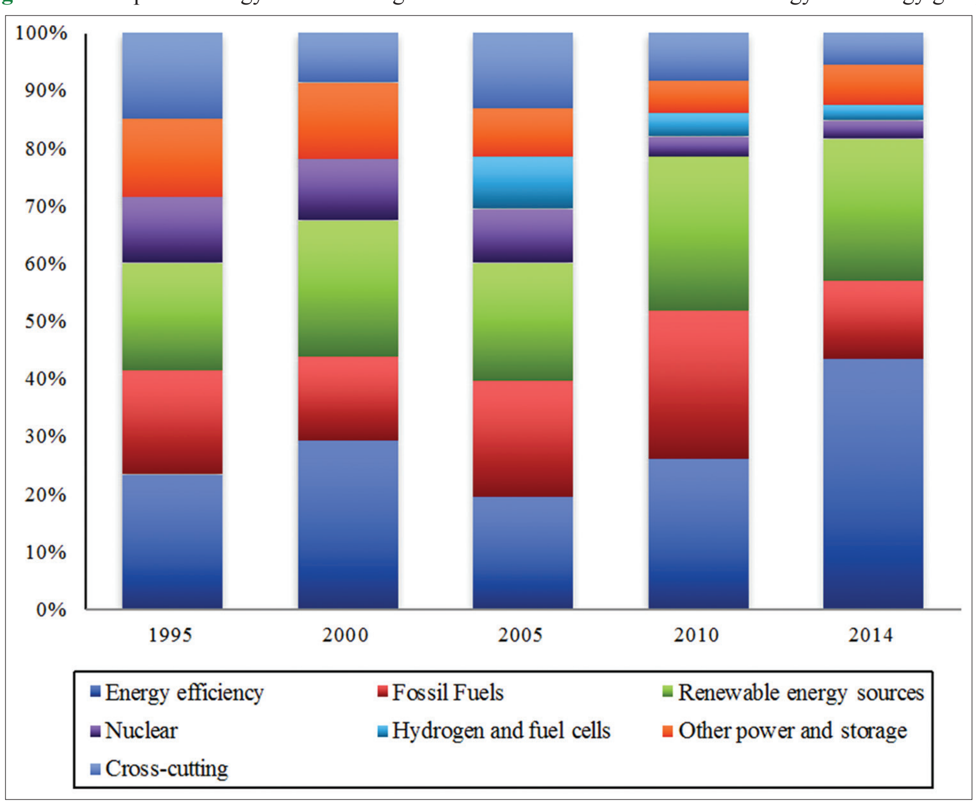
Overall, these studies highlight the need for designing suitable policies at reducing the public R and D investment. We consider knowledge flows and spillovers, because these have direct effect on the domestic public R and D expenditures.

2.2. On the Importance of Knowledge Flow

Knowledge is one of the main factors to create innovations. Between R and D expenditures and output of innovation process (e.g., knowledge stock), there is high uncertainty (Bretschger et al., 2017; Jaffe et al., 1993). Apart from public R and D expenditures, this knowledge is also influenced by other factors such as, knowledge spillovers from other countries and technologies, learning-by-doing and private R and D expenditures (Crespo-Cuaresma et al., 2008).

Several studies have investigated the role of knowledge flows in the development of technologies and also have assessed the effects of knowledge spillovers on economic growth. At the national level, numerous studies have focused on knowledge diffusion within a given sector of the economy or a country. Coe and Helpman (1995) investigated the differential impact of foreign and domestic knowledge stocks on a country's productivity. They used own R and D expenditures for measuring domestic knowledge stock. Jaffe et al. (1993) found an affirmative knowledge spillover effect for agents that are technologically similar. Bernstein and Nadiri (1988) by estimating a sample of US firms, found that inter-sectoral spillovers are really considerable. At the international level, much of the available literature focused on the role of international knowledge flows as a channel for growth (e.g. Meyer (2002)). International R and D creates more valuable outputs, because varied resources and knowledge can be synergized from several countries (Singh, 2008). Verdolini and Galeotti (2011) showed that flows of ideas and international diffusion of knowledge

Figure 1: Total public energy R and D budget in the Nordic countries for seven energy technology groups



have significant effect on higher growth rate. Finally, Aldieri and Cincera (2009) and Veldman and Gaalman (2015) illustrated that international spillovers affect significantly growing innovative activities efficiency in follower countries. In addition, for follower countries they found that absorptive capacity increases the elasticity of innovative efforts to international spillovers, while for technological leaders its marginal effect is negligible.

Furthermore, there is a large volume of published studies describing the importance of knowledge spillovers as one among the sources of technological change in formal models of energy and the environment. For instance, Buonanno et al. (2003) added international knowledge spillovers in an applied climate-economy model. A number of studies have analyzed that international knowledge flow effect on trade (Grossman and Helpman, 1991), foreign direct investment (Lee, 2006; Branstetter, 2006), and firm level innovation (Kotabe et al., 2007; Tsai, 2008). Malerba et al. (2013) studied the effect of knowledge spillovers on the factors of innovative efforts using a knowledge production function (KPF). Although the KPF is a fairly suitable tool for describing the knowledge flow and innovation process (i.e. from R and D to patents), national knowledge spillover between technologies is not concluded in this analytical tool.

To sum up, in order to develop new knowledge, there are three simultaneous options: (a) Investment on R and D on a specific technology, (b) absorbing knowledge generated abroad by other countries for a specific technology and (c) absorbing knowledge for the other similar technologies, which may be located inside the country (Shafiei et al., 2009). In the current study, we modeled all three simultaneous options to develop new knowledge.

3. METHODOLOGICAL ISSUES

Investigating the effects of energy R and D expenditures at the national level over a certain period of time, is essential for comprehensive comprehension of the process of cumulative knowledge. According to the Klaassen et al. (2005), the process of cumulative knowledge stock has been used to measure spillovers. Regarding the cumulative knowledge stock, it is important to notice that the general model is based on public R and D expenditures. The energy RD and D expenditure among seven main groups of energy technologies, reflects the amount of energy RD and D for energy efficiency, nuclear power, renewable energy sources (RES), fossil fuels, energy storage technologies, hydrogen and fuel cells, and other cross-cutting technologies denominated in million USD (IEA, 2016a).

3.1. Model Formulation

This model estimates the energy knowledge flow in each country and for each energy technology group by accounting the dynamics of cumulative knowledge, international and national spillovers. The model is formulated as follows:

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

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

$$SPILL^{int}_{(n,k,t)} = \alpha_{(n,k,t)}.\gamma^{int}_{(n,k,t)}.KP^{int}_{(n,k,t)} \quad (3)$$

$$\gamma^{int}_{(n,k,t)} = \frac{KS_{(n,k,t)}}{\sum_i KS_{(i,k,t)}} \quad (4)$$

$$KP^{int}_{(n,k,t)} = \sum_i KS_{(i,k,t)} - KS_{(n,k,t)} \quad (5)$$

$$SPILL^{nat}_{(n,k,t)} = \gamma^{nat}_{(n,k,t)}.KP^{nat}_{(n,k,t)} \quad (6)$$

$$\gamma^{nat}_{(n,k,t)} = \frac{KS_{(n,k,t)}}{\sum_{j=1}^{7} KS_{(n,j,t)}} \quad (7)$$

$$KP^{nat}_{(n,k,t)} = \sum_{j=1}^{7} KS_{(n,j,t)} - KS_{(n,k,t)} \quad (8)$$

Denoting energy R and D expenditures with RD, the cumulative knowledge with KS and knowledge spillovers with $SPILL$, the process of knowledge creation, Z, for energy technology group k in country n at time t, is modeled as Eq. (1).

A fraction δ as the depreciation rate has been assumed to estimate cumulative knowledge stock for technology group k in country n as Eq. (2). This equation indicates that the knowledge stock for each technology is developed not only by the cumulative knowledge stock in the last period but also by R&D investment, spillovers and the production of new ideas and knowledge for this technology. This methodology was investigated comprehensively by Klaassen et al. (2005) and Kobos et al. (2006). 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. Bointner (2014) indicated that the cumulative knowledge highly depends on the depreciation rate, whilst the time lags have little effect on the results. On the other hand, the time lags and depreciation rates may change over time and may also be applied for various technologies. So, based on many studies (such as Watanabe et al., 2000; Miketa and Schrattenholzer, 2004), it is the reasonable assumption that hereinafter in the present study the time lag, x, and the depreciation rate, δ, to be fixed with 3 years and 10% respectively.

Eq. (3) shows international knowledge spillovers, $SPILL(n, k, t)$, for technology group k in country n at time t that is obtained by multiplying degree of knowledge spillover, α, the knowledge pool, KP, and the absorption capacity, γ. Normally, knowledge spillovers are calculated based on a pool of accessible knowledge from other potential sources such as other firms or countries. Countries are exposed to a pool of other advanced countries' knowledge where a fraction of this knowledge can be absorbed by the follower country. It is well-accepted that the ability of the recipient country plays a central role on knowledge spillovers (Kulkarni et al., 2015). In other words, the ability of the recipient country plays a central role on knowledge spillovers and the level of this ability depends on various factors such as scientific bodies and laboratories, amount of R&D and the country's stock of human capital (Murovec and Prodan, 2009).

Eq. (4) describes the knowledge pool for energy technology group k and for the nth country at time t. Eq. (5) represents absorption capacity of international knowledge spillovers as the fraction of available pool of knowledge that each country can absorb it. The absorption parameter, γ, is a function of total cumulative knowledge of target countries. Kneller (2005) shows that for estimating the amount of knowledge transfers at the international level, absorptive capacity plays a substantial role. The lack of investments in R and D, scientific bodies and laboratories is a serious obstacle for each country to absorb new knowledge from available knowledge pool.

Eqs. (6-8) reflect national knowledge spillovers across similar technologies (i.e., a group of technologies sharing a common necessary component). In the present study, it is assumed all technologies in seven energy technology groups are similar. Again, like international spillovers, national spillovers are obtained by multiplying the knowledge pool and the absorption capacity. Indeed, in specific country each technology can benefit from other technologies in particular sector. For instance, in energy sector, the knowledge can be transferred from renewable energy technologies to energy efficiency technology group.

Constants and exogenous parameters (e.g., elasticities of the production of new knowledge) are estimated by various empirical studies (Kristkova et al. (2017) and Bosetti et al. (2008) for a review). Thus, the parameters b, c, d, e, are set to be equal to 0.2, 0.55, 0.15 and 0.05 respectively. Through a suitable calibration and sensitivity analysis based on Bosetti et al. (2008), the robustness and the effects of these setting are tested. It is further assumed that national spillover has the slightest effect in generating new knowledge and idea.

3.2. Data Sources

The Nordic countries are selected as cases for investigating the flow of technological and scientific knowledge in emerging technologies. The knowledge can be transferred between countries and technologies in the Nordic region, as well as from advanced region to the Nordic region.

The energy R and D expenditures data in this study were retrospectively collected from the International Energy Agency (IEA) database. Since 1974, for seven energy technology groups[1], this database includes public energy R and D expenditures of IEA member. Although this is the reliable source of data on energy R and D expenditures, there are some limitations. Wiesenthal et al. (2012) and IEA (2016a) investigated more information about IEA dataset limitations. In this study, the public energy R and D expenditures of the Nordic countries as the main variables are collected for each technology group.

3.3. The Scenario of Public R and D Expenditures Until 2030

In this Section, we assume a common scenario to identify the potential of technological innovation over time in the Nordic countries. The energy R and D expenditures of the Nordic countries are rising and falling over a certain period of time. Based on the concept of gross domestic product (GDP), a scenario is assumed to estimate the trend of energy R and D expenditures until 2030. The forecasts of GDP data for the Nordic countries was derived from the OECD (2017). For country n, the energy R and D expenditure at time t is based on the GDP growth and the floating average of the R and D expenditures in technology group k of the last 5 years. Thus, the energy R and D expenditure at time t is estimated as follows:

$$RD_{(n,k,t+1)} = \sum_{t-5}^{T} RD_{(n,k,t)} * \frac{GDP_{(n,t+1)}}{GDP_{(n,t)}} \tag{9}$$

Indeed, based on current pattern of R and D investment on energy technologies, this scenario shows the future potential for supporting innovation. Furthermore, it is the reasonable assumption that within the next 5 years all countries would not change their energy R and D policy instantly.

4. RESULTS AND DISCUSSIONS

4.1. Energy R and D of the Nordic Countries

In the Nordic countries, policy makers have emphasized on R and D expenditure by analyzing resource allocations for energy technology innovation (Aslani et al., 2013). Figure 2 illustrates the energy R and D expenditures in seven technology groups from 1974 to 2014 and the forecasts until 2030 (based on given scenario in Section 3.3). According to this scenario the current level of R and D expenditures grows and the distribution among energy technologies remains almost unchanged until 2030. The absolute R and D expenditures are growing by about 70 million USD per year for all energy technologies until 2030 (in total around 1.08 billion USD).

From 1974 to 2014, the energy R and D expenditures of the Nordic countries amounted to around 5.3 billion USD; about 3.3 billion USD were spent on RES and energy efficiency and around 1 billion USD on fossil fuels and nuclear. Since 2007, the energy R and D budget has increased by focusing on energy efficiency and renewable energy sources. These two groups of energy technologies culminated in 2010 (298 and 304 million USD, respectively).

Between the Nordic countries, Denmark's R and D investment on renewable energy sources is substantial, while public R and D on fossil fuels and nuclear fusion and fission is low. In Norway, energy R and D spending, due to notable domestic fossil resources, is mainly based on fossil fuels and there is little focus on RES. For Sweden and Finland, R and D investment on RES and energy efficiency dominates.

In 2013, the average public energy R and D expenditures were around 0.05% of the GDP. Figure 3 shows the total public energy R and D expenditures and the renewable energy R and D expenditures of the Nordic countries per GDP in 2013. Approximately, all countries have a similar trend between the GDP and the total R and D expenditures. Bubble size reflects renewable energy R and D expenditure, and thus as previously mentioned it's quite clear that in this respect, Denmark has the

1 Seven groups of energy technology: Energy efficiency, nuclear power, renewable energy sources (RES), fossil fuels, energy storage technologies, hydrogen and fuel cells, and other cross-cutting technologies.

largest share. However, from 1 year to another the R and D expenditures are not stable. Thus, for further investigations the cumulative knowledge stock is a proper tool which is used in the following sections.

4.2. The Cumulative Energy Knowledge Stock

In this section, at first we have estimated the cumulative energy knowledge stock of the Nordic countries that induced only by public energy R and D expenditures (without considering spillovers), as follows:

$$KS_{(n,k,t+1)} = \left(1-\delta_{k,t}\right) KS_{(n,k,t)} + RD_{(n,k,t-x)} \qquad (10)$$

According to Eq. (10) and by setting the depreciation rate and time lags as described in Section 3.1, the cumulative energy knowledge stock has been estimated for each technology groups in the Nordic countries. Among seven energy technology groups, Figures 4-7 illustrate the cumulative energy knowledge trends until 2030 that induced by public energy R and D expenditures in the Nordic countries (Denmark, Finland, Norway and Sweden).

As shown in Figure 4, in Denmark, the total energy knowledge stock will grow from 870 million USD to 1.5 billion USD in 2030 that is mainly driven by RES (44%) and energy efficiency (20%). Figure 5 reflects that the total energy knowledge stock of Finland is more than Denmark in 2030 reaching a level of 2.6 billion USD. The largest portion and the main driver in Finland will be energy efficiency accounting for 1.3 billion USD (52%). In Norway, due to notable domestic fossil resources, the knowledge is mainly based on fossil fuels. Popp and Newell (2012) investigated that countries having a high share of fossil resources do not have significant incentive to invest high values for new renewable energy technologies. Figure 6 confirms this result and indicates the contribution of fossil fuels which is far more than other technology groups (47% in 2030). The total energy knowledge stock is more than Denmark and Finland and it will grow from 1.6 billion USD to 3.5 billion USD in 2030. Regarding Figure 7, in Sweden, the first knowledge peak is occurred in 1988 amounted to around 1.3 billion USD. Baccini and Urpelainen (2012) indicated a positive influence of oil prices on the amount of public energy R and D investments. Thus, the oil crises in 1973 and 1979 and high crude oil price are the main drivers for the peak in knowledge accumulation. A decline of rate of knowledge flow in the 1990s is considered to be a consequence of low oil price in the 1980s and the reduction of governmental incentive to support energy R and D. This decline continued until 2004 reaching a level of 978 million USD and then it is envisaged it will grow to 1.6 billion USD in 2030.

Cruz-Castro and Sanz-Menéndez (2016) argued that the economic crisis had a large impact on innovative activities and consequently on R and D expenditures. Results on the cumulative renewable energy knowledge stock confirm this point in the Nordics. Indeed, the cumulative renewable energy knowledge stock increased from 632 million USD in 2008 to 1.4 billion USD in 2015.

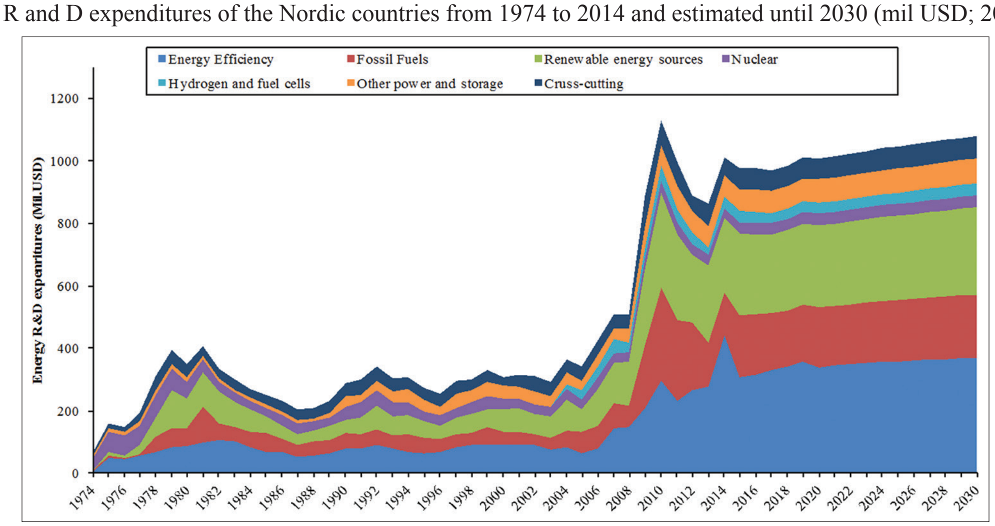
As a consequence, since 2008 the total energy knowledge stock in the Nordic countries has been increasing to 5.2 billion USD in 2014 and then it will grow to 9.2 billion USD in 2030. The cumulative energy knowledge stock in this year consists of 59% of energy efficiency and renewable energy sources and about 20% of fossil fuels (the majority of it belongs to Norway). Distribution of knowledge stock among the seven energy technology groups in the Nordic countries remains almost stable in the period 2004-2030.

4.3. The Effects of Knowledge Spillovers

In this section, we consider knowledge spillovers between countries and technologies. According to Eqs. (1-8) the new knowledge stock can be estimated. Thus, Figure 8 shows the total energy knowledge stock of the Nordic countries induced by both public R and D expenditures and spillovers until 2030.

Figure 8 illustrates that if knowledge spillovers are modeled, compared to the previous state, the cumulative energy knowledge stock will rise by 16% to 10.7 billion USD in 2030. In this case, energy efficiency with 3.5 billion USD, RES with 2.9 billion USD, and fossil fuels with 1.8 billion USD will be ranked as priorities. Other power and storage technologies will remain in the fourth position with 820 million USD, followed by cross-cutting with 796

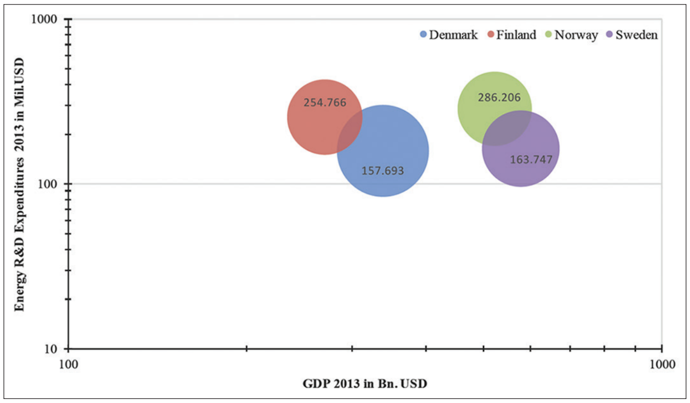
Figure 2: Energy R and D expenditures of the Nordic countries from 1974 to 2014 and estimated until 2030 (mil USD; 2014 prices and ppp)



million USD, nuclear with 410 million USD and finally hydrogen and fuel cells with 390 million USD.

When national and international knowledge spillovers are modeled, the cumulative energy knowledge stock for Denmark, Finland, Norway and Sweden shall raise to respectively 1.7, 2.9, 4.1 and 2 billion USD in 2030. This consequence indicates that between Nordic countries, Norway shall gain more than the rest (from 3.5 to 4.1 billion USD).

Figure 3: Public energy R and D expenditures per GDP in 2013 (Bubble size: Renewable energy R and D expenditures); all values in logarithmic scale



Regarding national spillovers, energy efficiency and afterward, RES in the second position play the most important role. There are two main reasons. First, according to Figure 2, more investment has been allocated to energy efficiency and renewable energy sources, and thus the absorptive capacity of these technology groups can be expanded. Second, the Nordic countries aim to further emission reductions towards 2050 (IEA, 2016b), so climate and energy policies tend toward energy efficiency and RES.

It is to note that in both cases (with and without spillovers), energy efficiency and RES are the main drivers in the Nordic countries. The energy efficiency knowledge stock will be slightly higher than RES, reaching 33% (3.5 billion USD) of the total knowledge stock in 2030, while RES reaching to 28%.

4.4. The Future Potential of Technological Innovation

As mentioned in Introduction, this section aimed to address the following question: How much the innovation resources (i.e., R

Figure 4: The cumulative knowledge stock of Denmark induced by public energy R and D expenditures (mil USD; 2014 prices and ppp)

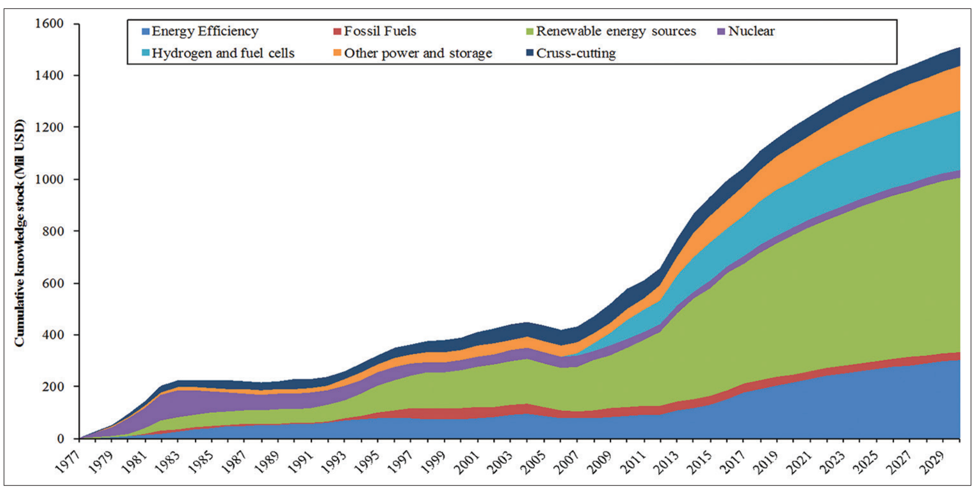
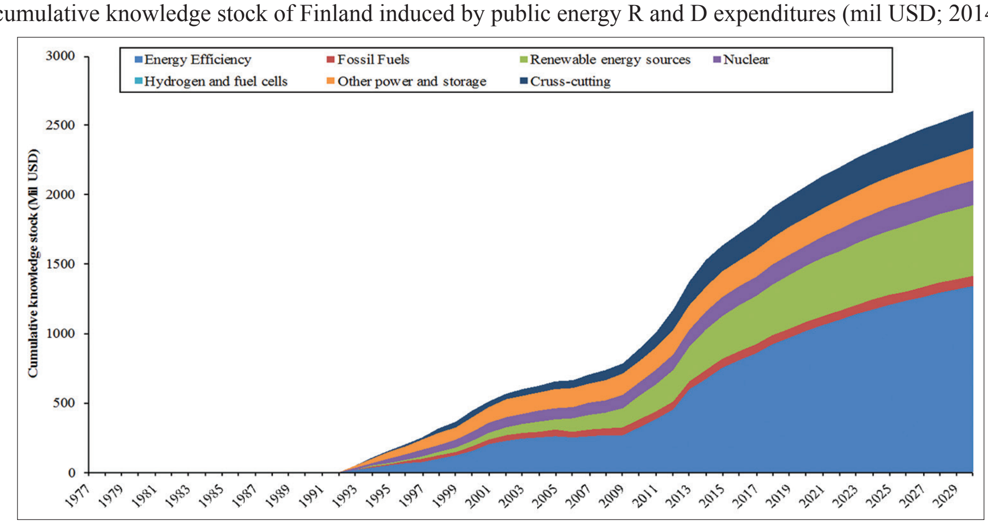


Figure 5: The cumulative knowledge stock of Finland induced by public energy R and D expenditures (mil USD; 2014 prices and ppp)



and D expenditures) for energy technologies will be saved when the energy knowledge stock induced not only by R and D expenditures but also by international and national spillovers? The answer for this question reflects the future potential of technological innovation in each country. Countries and agents can collaborate with each other in a global knowledge environment to maximize the exploitation of this potential and reduce their R and D costs. In other words, with considering the process of knowledge flow (Eq. [1]), the future potential of innovation in each country is estimated. Indeed, we show how much the domestic R and D expenditures will be decreased if the knowledge stock induced by spillovers (based on Eqs. [1 and 2]). To estimate this reduction, in first step we determined the knowledge stock that induced only by R and D expenditure until 2030 (Figures 4-7), as model inputs. In the next step and taking into account the spillovers, the model was run and new R and D expenditures were obtained.

In order to decrease the scope of the present paper, only the most leading energy technology groups in the Nordics (i.e., energy efficiency and RES) and especially in Denmark have been investigated. It is worth noting that knowledge spillovers in the figures of this section, are considered as sum of national and international spillovers.

In Denmark, for the most prominent energy technology groups, Figure 9 illustrates the future cumulative knowledge stock, the flow of spillovers and R and D investment reduction when spillovers are modeled. Figure 9 indicates that knowledge spillovers is non-cumulative variable and has taken a bell-shaped curve (are thus first increasing and then decreasing along). 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.

Since Denmark is leading in RES, it doesn't absorb much knowledge from other countries and technologies. It is apparent in Figure 9 that knowledge spillover in energy efficiency is significantly more than RES in Denmark. When spillovers are modeled, R and D expenditures in energy efficiency will be reduced up to about 6%, whilst for RES will be reduced just around 0.75%. Knowledge spillovers for energy efficiency culminates in 2023 with accounting 145 million USD, and then decreases to about 100 million USD until 2030. As mentioned before, knowledge spillovers for RES is not much and the highest value is around 40 million USD in 2022.

Figure 6: The cumulative knowledge stock of Norway induced by public energy R and D expenditures (mil USD; 2014 prices and ppp)

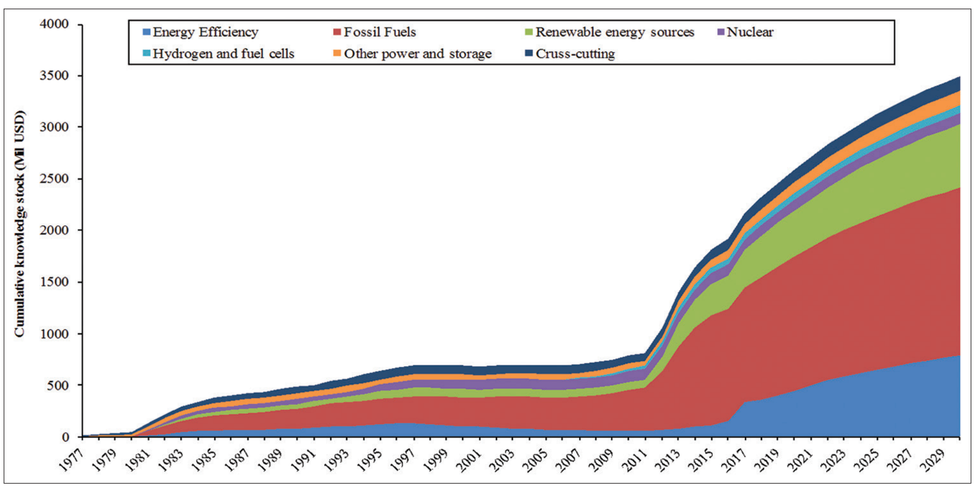


Figure 7: The cumulative knowledge stock of Sweden induced by public energy R and D expenditures (mil USD; 2014 prices and ppp)

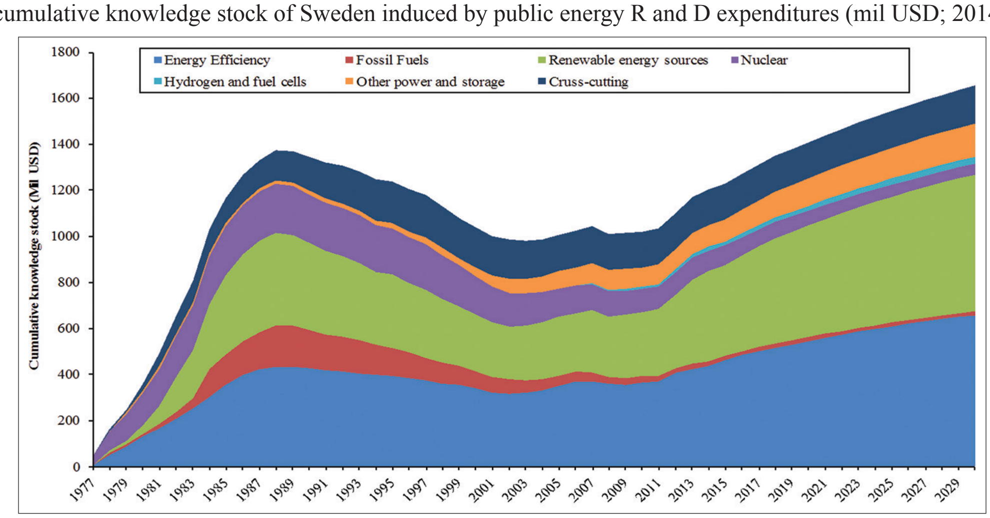


Figure 10 illustrates the cumulative knowledge stock and saving in R and D expenditure for all seven technology groups in the Nordic countries until 2030. Indeed, it reflects the future potential of technological innovation in the Nordic region, since knowledge spillovers are modeled. When the process of the cumulative knowledge fully takes shape and spillovers occur between all energy technology groups and countries, Figure 10 shows that the Nordic countries will save R and D investment around 395 million USD until 2030.

Therefore, R and D investment will be saved up to 37 million USD in 2023, and then it will decrease to about 17 million USD in 2030. Among the Nordic countries, Denmark has absorbed the most of energy efficiency knowledge from other countries and technologies, whilst Finland has absorbed the least of energy efficiency knowledge. For renewable energy sources, Denmark has disseminated the most of its knowledge, whilst Norway has disseminated the least of it.

5. CONCLUSIONS AND RECOMMENDATIONS

Energy innovation and development of clean energy technologies play a key role to constrain the growth in global temperatures and mitigate climate change. Today the Nordic countries are trying to increase their public energy R and D expenditures and energy innovation activities in order to achieve the climate and energy goals of 2030 (IEA, 2016b). New ideas and technologies freely spread across various companies, industries and countries. Knowledge spillovers between countries and technologies have a substantial role to strengthen these flows, as well as to achieve a wider diffusion of new technologies.

The present study sets out provides an analytical tool in order to investigate the cumulative energy knowledge stock, spillovers and the energy knowledge flow in the various energy technology groups in the Nordic countries over a time-span until 2030. National and international energy R and D spillovers for each energy technology group are modeled, and thus provide a proper tool to identify the role of knowledge accumulation and innovation investment in the process of new energy technology development.

The following conclusions can be drawn from the present study. First, the level of R and D expenditures in the Nordic countries will grow by about 70 million USD per year for all energy technologies until 2030 (in total around 1.08 billion USD). That's while the distribution among energy technologies remains almost unchanged until 2030. Second, since 2008 the total energy knowledge stock in the Nordic countries has been increasing to 5.2 billion USD in 2014 and then it will grow to 9.2 billion USD in 2030. The cumulative energy knowledge stock in this year consists of 59% of energy efficiency and renewable energy sources and about 20% of fossil fuels (the majority of this belongs to Norway). In Norway, Sweden, Finland and Denmark, among seven energy technology groups, the emphasis is on fossil fuels, RES, energy efficiency and RES respectively. Third, the results indicated a significant impact of knowledge spillovers on the energy knowledge flow in the Nordic countries. When national and international knowledge spillovers are modeled, the cumulative energy knowledge stock for Denmark, Finland, Norway and Sweden will raise to respectively 1.7, 2.9, 4.1 and 2 billion USD in 2030. This result indicates that between Nordic countries, Norway has increased its knowledge flow rate more than the rest (from 3.5 to 4.1 billion USD). The results show that two most important energy technology groups will be energy efficiency with 3.08 billion USD and RES with 2.4 billion USD. Forth, the Nordic countries with considering the spillovers can save in R and D investment around 395 million USD until 2030.

The findings of the developed model also show the impact of knowledge spillovers and innovation activities on the long term development of new energy technologies. Indeed, with greater national and international knowledge spillovers, domestic public R and D expenditure can be optimally reduced and becomes more efficient. Thus, this paper provided an important opportunity to advance the understanding of knowledge flows and spillovers. In

Figure 8: The cumulative knowledge stock of The Nordic countries induced by both public energy R and D expenditures and spillovers (mil USD; 2014 prices and ppp)

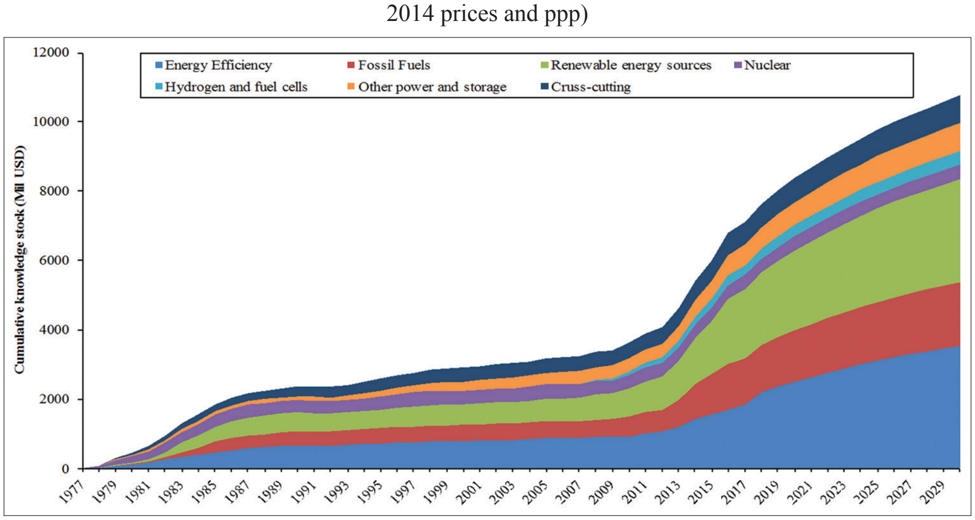


Figure 9: The cumulative knowledge stock, spillovers flow and R and D reduction of Denmark (mil USD; 2014 prices and ppp). (a) Energy efficiency. (b) Renewable energy sources

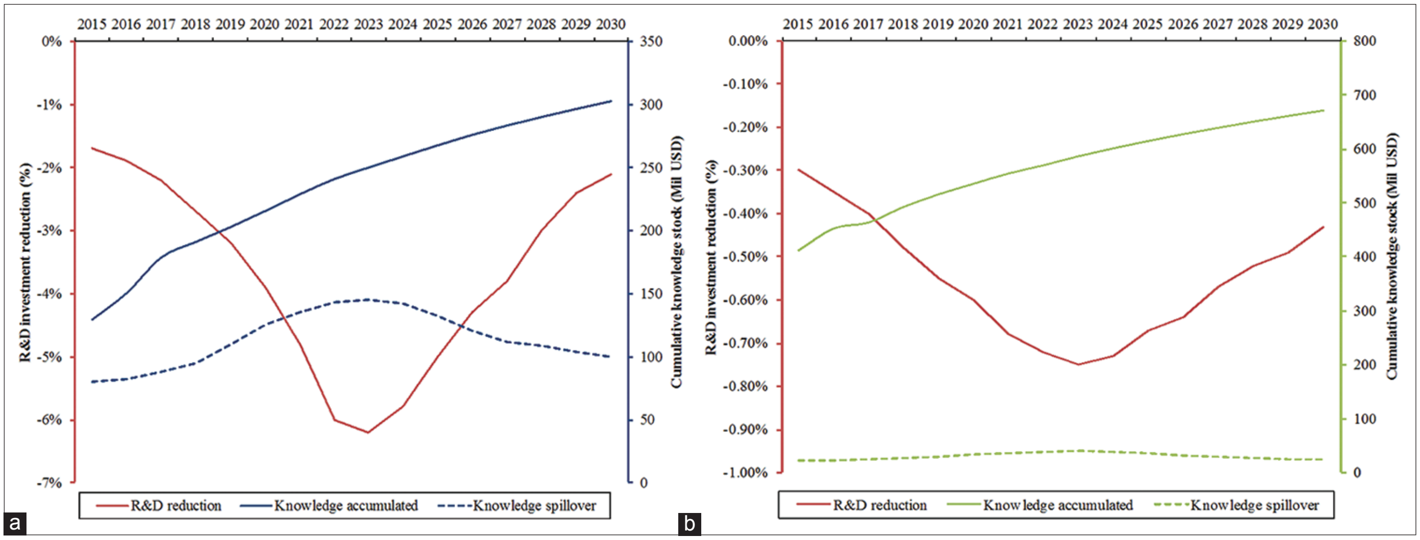
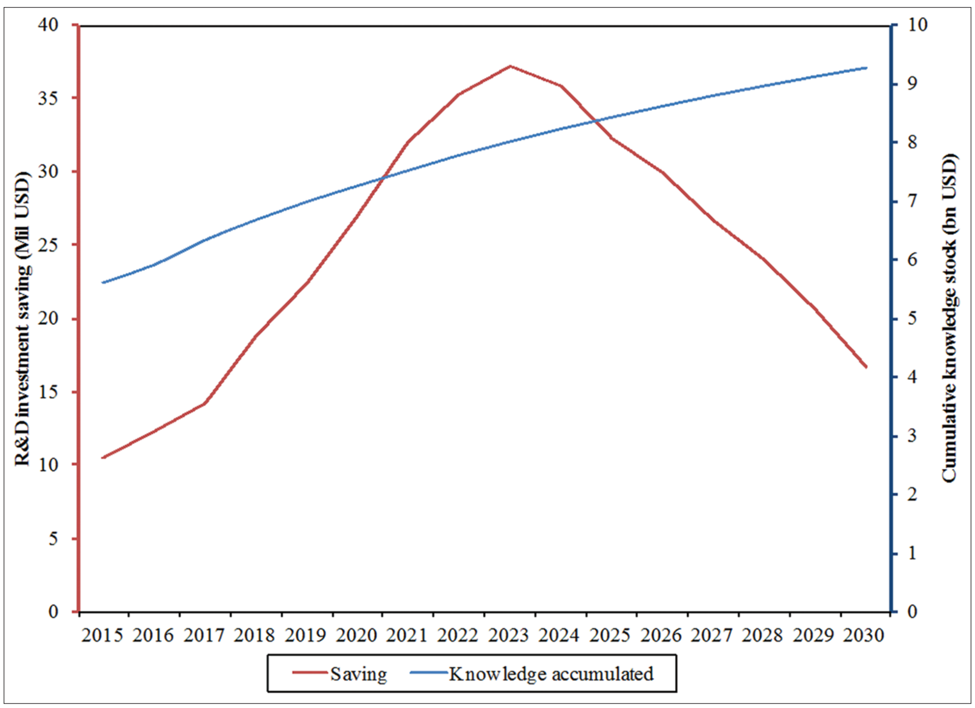


Figure 10: The cumulative knowledge stock and R and D investment saving for all seven technology groups in the Nordic countries (mil USD; 2014 prices and ppp)



general, the role of energy innovation activities such as R and D expenditures is prominent in development of new technologies.

The findings in the study are subject to at least two main limitations. First, it is worth mentioning that outcomes do depend on public energy R and D expenditures. The role of private R and D expenditures in technology development is investigated by several studies, but there is a substantial lack of data on private energy R and D expenditures, hence for these sources collection of data is required. Second, although R and D expenditures do not demonstrate all aspects of knowledge stock, it seems that some appropriate indicators are needed for monitoring the innovation process.

Further research in this field would be of great help in understanding the impact of private energy R and D expenditure on the cumulative knowledge stock. For assessing the effectiveness of private and public R and D programs and future prioritization of R and D expenditures, the inclusion of patents would enhance such analysis (Miremadi et al., 2018). It is possible to assess structural changes among time by investigating the time series of the cumulative knowledge stock. Future research should therefore concentrate on the investigation of the appropriate strategies on transfer of energy technology and evaluating the interactions between agents in energy systems to maximize the societal benefits of energy technology R and D.

To sum up, the model that presented in the present study assists us to answer the questions addressed in the introduction. National and international knowledge spillovers reduce domestic R and D expenditures, as well as the knowledge flow and spillovers have an important effect on countries' innovation efforts and new technology development. For a transition towards renewable energy, a long-term program and strategy in both side of energy system (i.e., supply side and demand side) is needed. In addition, the increase in supporting innovation activities (e.g., R and D expenditures), bring also several advantages to Nordic society such as job creation, decreasing energy costs, etc.

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