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Understanding the development trends of low-carbon energy technologies: A patent analysis ☆

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HIGHLIGHTS

- Governments' strategies set important frameworks to develop and sustain low-carbon energy technologies.
- Commercial activities play a key role in the low-carbon energy technologies' development.
- The number of patents that are based upon basic research is growing.

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ABSTRACT

Eco-innovations are being recognized as fundamental means to foster sustainable development, as well as to create new business opportunities. Nowadays, the eco-innovation concept is gaining ground within both academic and practitioner studies with the attempt to better understand the main dynamics underlying its nature and guide policymakers and companies in supporting its development. This paper contributes to the extant literature on eco-innovation by providing a comprehensive overview of the evolution of a specific type of eco-innovations that are playing a crucial role in the current socio-economic agenda, namely low-carbon energy technologies. Accordingly, we focus our attention on the related patenting activity of different countries and organizations over time, as well as on influencing policy initiatives and events. Hence, we collected 131,661 patents granted at the United States Patent and Trademark Office (U.S.PTO.) between 1971 and 2010, and belonging to the "Nuclear power generation", "Alternative energy production", and "Energy conservation" technological classes, as indicated by the International Patent Classification (IPC) Green Inventory. Our findings report the development trends of low-carbon energy technologies, as well as identify major related environmental programs, historical events, and private sector initiatives explaining those trends, hence revealing how these different circumstances have significantly influenced their development over time.

1. Introduction

Since the Brundtland Report [1], where the concept of sustainable development was first presented, an increasing demand for a new vision of innovation was claimed [2–4]. In addition, environmental protection is not considered as a limit to the economic growth, but rather a necessary condition for a long term development. Consequently, during the last years, the concept of eco-innovation (e.g., [5]) has attracted an increasing attention across many countries all over the world due to its potential to address both economic and environmental priorities [2]. Specifically, technology is deemed at the basis of eco-innovation, since it positively influences economic growth, as well as provides the means to act smarter and more sustainably. Hence, it can foster the transition toward an environment-oriented lifestyle and more efficient low-carbon systems in industrial sectors such as transport, energy, waste management, and water treatment [1,2,6–9]. Thereby, technology seems to play a strategic role by influencing environmental impacts, risks, and costs [2,10–12], as also revealed by a number of initiatives undertaken by international organizations, such as the Organisation for Economic Co-operation and Development (OECD), the International Energy Agency (IEA), and the United Nations (UN), which have recently introduced programs to deeply

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study eco-innovations and particularly their related technological developments. For instance, in 2008 the OECD launched the "Green Growth and Eco-innovation" project, with the aim to better understand how innovation can result into new technological and systemic solutions in order to face global challenges and leading the industrial system toward a sustainable growth [4,13,14].

According to the foregoing discussion, we aim at studying the development trends of a specific type of technological solutions, which have been demonstrated to be of foremost importance in the eco-innovation context, namely low-carbon energy technologies [4,7,15]. Nowadays, these technologies are recognized as fundamental means to reduce the cost of stabilizing atmospheric carbon dioxide concentrations and lower the final cost of meeting environmental policy objectives [7,16], as well as to improve energy security, emission reduction, environmental protection, and economic growth [17–19]. Nevertheless, although the number of environmental programs and initiatives is increasing, the development and diffusion of low-carbon energy technologies still remain limited, being largely dependent on public interventions [20]. In this context, while several scholars have devoted a significant attention to define, classify, and measure eco-innovations more in general (e.g., [21–23]), to our knowledge, a complete picture of the eco-innovative efforts undertaken by both companies and countries over time to develop low-carbon energy technologies is still lacking. Thereby, this paper aims at presenting a comprehensive overview of the low-carbon energy technologies' evolution, in the attempt to characterize their development over time, as well as how it is in turn dependent on a number of governmental, geopolitical, and commercial events and strategies. To this aim, we contribute to the extant literature by building a unique database of 131,661 patents granted at the U.S.PTO. from 1971 to 2010 and belonging to the green technological classes "Nuclear power generation", "Alternative energy production", and "Energy conservation", as described by the IPC Green Inventory classification. For each patent, we retrieve several data, such as assignees and inventors details, backward and forward citations, technological classes, and scientific references. Then, we present an overview of patents' development trends and identify countries and organizations mainly engaged in these innovative activities, as well as describe the most relevant public interventions and geopolitical circumstances that have influenced these trends. Finally, we provide some insights on the most relevant patented inventions in the field, in terms of technological impact on subsequent related innovations.

The paper is structured as follows. In the next section, we discuss the use of patent data as a proxy to study technological eco-innovative efforts in the energy field and present a brief literature review on the relationship between eco-innovation and low-carbon energy technologies. Then, the third section presents the data collection methodology and the sample. The fourth section contains descriptive analyses on the patenting activity and possible explanations for these results. Finally, discussion, implications, and conclusion are presented.

2. Theoretical background

2.1. Patents as a measure of innovation

Innovation indicators can be divided into two categories, namely input-based indicators and output-based indicators [24–26]. The former refers to those measures that look at the inputs of innovation processes, such as research and development (R&D) expenditures. Past studies have widely used them as a proxy to assess innovation activity efforts. Nevertheless, these data are available only for specific industries or general applications, and have not a direct relationship with the innovation outcomes [27]. Consequently, output-based indicators, which take into account the results of innovation activities (e.g., patents and new products), have emerged as valuable sources of information for studying innovative dynamics. Particularly, patent data have much attracted both researchers and practitioners [28]. A patent is an intellectual property right granted for an invention in the technical field to a company, public organization, or individual by a national patent office, hence giving the owners the right to exclude others from the industrial exploitation of the patented invention for a defined number of years [29]. The invention must be novel, non-obvious, adequately described, and claimed by the inventor in clear and definite terms [29].

The use of patent data in innovation studies is however not straightforward, hence presenting both limitations and benefits. On the one hand, patents do not portray the whole innovative portfolio. Indeed, some innovations are not patentable and patents do not always represent the most suitable mechanism to protect innovations [29–32]. In addition, the value of patents can vary across countries and the characteristics of appropriation regimes may affect the propensity to patent. Accordingly, different organizations may put different value in patenting activity [29,32]. Moreover, the rate at which innovations are patented varies across industries and technological fields, which is reflected in unobserved heterogeneity [31,33]. Finally, not all patented inventions are actually implemented in market applications [29]. Nevertheless, on the other hand, first, patents gained much consensus because of the availability of data at global scale and at different levels of analysis (e.g., national, organizational, and individual levels), thus allowing to perform diverse types of comparative study and, in turn, to have a more general picture of the nature underlying innovation phenomena [34]. Second they present a close (if not perfect) link to economic relevant inventions [35,36]. For instance, they have been recognized to be strongly correlated with other indicators of innovative activity, such as R&D expenditures and the introduction of innovative products (e.g., [28,37,38]). Third, patent data are publicly available for a long time series and provide a number of valuable information on the technological content, geographical location of assignees and inventors, and citations made and received by the patent. Thereby, academics and policymakers have made an increasing use of patents as sources of information for analyzing innovation development trends over time, countries' and organizations' technological capabilities, relationship between polices and technological innovation, geographic dispersion of R&D activities [39], and pace of technological development and diffusion [14,28,40–46]. In addition, citations received by patents have been extensively adopted to account for their impact on the subsequent creation of related innovations [47–51], here defined as technological impact. In line with this reasoning, despite the limitations above mentioned, patents are still the most commonly used proxy for the study of innovations' trends and dynamics in the scientific literature (e.g., [28,29,45,52–55]).

2.2. Eco-innovation and low-carbon energy technologies

The big global challenges posed by the growth rate of the human-induced climate change, as well as the sustainability goals recently set, such as Europa 2020 targets [56], have led to the need to redefine the concept of innovation [3–5]. In fact, the term "innovation" is generally referred to the implementation of new products, processes, or organizational methods [57] without focusing on the related environmental impacts. Differently, policymakers, companies, and international organizations (OECD, UN, etc.) have significantly increased their efforts to boost innovative activities toward sustainability objectives [5,58]. Indeed, although it has been widely recognized that innovation is still the central issue in economic prosperity [59], nowadays it is also more and more considered as the key factor to reach sustainable development targets [4,5,58]. Accordingly, the concept of eco-innovation has rapidly gained much attention across both policymakers and researchers [60].

The literature has proposed different definitions of eco-innovation and different terms have been adopted interchangeably (e.g., eco, green, environmental, or eco-friendly innovation) (e.g., [60]). Nevertheless, despite the wide range of definitions, some common features have emerged, highlighting that an eco-innovation is an innovation that primarily contributes to reduce environmental impacts and opens new sustainable pathways in the market [61–65].

In particular, several debates on eco-innovation have so far focused on topics that directly address environmental technologies [66,67], recognized as the keys to guarantee the co-existence of economic growth and environmental progress [11,68], in turn defined by the European Commission [67, p. 2] as "[...] all technologies whose use is less environmentally harmful than relevant alternatives. They include technologies to manage pollution (e.g., air pollution control, waste management), less polluting and less resource-intensive products and services (e.g., fuel cells) and ways to manage resources more efficiently (e.g., water supply, energy-saving technologies)". More in detail, past studies argued that eco-innovations range on a spectrum from more incremental innovations (e.g., end of pipe technologies) to more radical innovations that are supposed to sensibly modify the system where they are introduced (e.g., energy and transportation infrastructure) [21,62,69]. Further, their development and adoption involve firms, institutions, and individuals [69]. Accordingly, eco-innovation is "seen as an overarching concept which provides direction and vision for pursuing the overall societal changes needed to achieve sustainable development" [69, p. 359]. In particular, in this paper we analyze a specific type of technological eco-innovations that has been deemed to play a crucial role in fostering sustainable growth and business innovation (e.g., [70–73]), namely low-carbon energy technologies. These represent technologies aimed at reducing greenhouse gas (GHG) emissions, energy consumption, and environmental impacts, as well as devoted to redesign the global energy system (e.g., solar cells, electric engines) [7,15,74]. Specifically, in the present research, we discuss their development trends across countries and organizations, as well as the influences exerted by related policy initiatives and events on their emergence and development.

2.3. Patents as a measure of low-carbon energy technologies' evolution

As per innovation in general, technological advancements in the energy field can be measured by employing different types of data. One example is represented by the R&D expenditures devoted toward environmentally friendly innovative activities (e.g., energy efficiency or renewable energy initiatives). However, in addition to the drawbacks related to these input-based indicators highlighted in Section 2.1, this type of data is only available at the country level for the last ten years.[1] Therefore, it limits the possibilities to depict historical analyses and conduct in depth inquiries at the organizational level. Furthermore, another proxy may be described by a number of well-developed energy statistics that show how widespread the use of low-carbon energy technologies is.[2] Nevertheless, similarly to R&D expenditures, these data do not allow to assess the role played by single organizations. In addition, they reflect the extent to which certain types of technology are actually applied over time, which is however often dependent on public interventions (e.g., incentive schemes) and public opinions [20], rather than solely on the actual evolution of energy-related eco-innovative solutions. Finally, it is difficult to correctly assess whether the application of those technical solutions is explained by countries' and organizations' internal innovative efforts or, rather, it is the result of other factors (e.g., technology transfer mechanisms). Thereby, employing these statistics does not allow to capture important aspects of the low-carbon energy technologies' evolution, such as when and where technologies have been invented, the extent of innovative efforts made over time, and whether those efforts are merely incremental or have involved radical changes.

Differently, according to the advantages proposed in Section 2.1 (albeit recognizing their limitations), there are many examples of using patent data to study the development trends of technological eco-innovations in the energy field [13,46]. For instance, Pilkington [75] used a sample of 268 U.S. patents in the IPC class "Electric propulsion with power supplied within the vehicle" (IPC code B60L/11) in order to analyze the development of the electric vehicle. Similarly, based on a sample of U.S. patents granted between 1970 and 1994, Popp [43] showed the positive relationship between energy prices and energy-efficient innovations. Further, Oltra and Saint Jean [76] used patent applications in order to understand the competition among companies in the development of engine technologies for low emission vehicles. Johnstone et al. [20] employed patent data measures to assess the effectiveness of renewable energy policies (e.g., feed-in tariffs) on technological innovation. The OECD [58] included patent data to analyze environmental technologies' diffusion and transfer. Liu et al. [41] employed a patent growth analysis to study the development trajectories of technological solutions in the photovoltaic industry. Leu et al. [53] studied the eco-innovative activity in the field of bio-fuel and bio-hydrogen energy from 2000 to 2011 through the use of patent bibliometric analysis. Finally, by adopting a sample of 707 patents granted at the U.S.PTO., Park [55] provided descriptive analyses of the evolutionary trends of technologies devoted to reuse wastes derived from coal combustion.

These studies, however, offer a partial scenario to policymakers and companies in explaining the main dynamics underlying the evolution of low-carbon energy technologies. Indeed, they mainly refer to small samples of patents, which could be not so relevant to bring out significant results. Moreover, they refer to a bounded geographic area or a limited time period, which cannot allow to depict a complete scenario of the low-carbon energy technologies' development. Finally, most studies focus their attention to a specific sector or technological class, so limiting the generalizability of their outcomes.

Thereby, our paper aims at extending these previous studies through the creation of a wide and unique database that collects all patents related to low-carbon energy technologies, by including all the main energy-related categories and their subclasses. Hence, this allows us to more deeply analyze the differences across various types of technological eco-innovations in this specific sector. In addition, our database collects patents filed from 1971 to 2010, hence giving us the possibility to trace the entire history of low-carbon energy technologies' evolution over the last 39 years. Furthermore, the considered patents are granted to organizations spread all over the world, thus making us able to capture differences among countries' and organizations' technological eco-innovative capabilities in the energy field. Finally, we also offer a nuanced picture of most relevant technical solutions, as represented by their technological impact.

3. Data and methodology

We employ patent data to investigate the main dynamics characterizing the development trends of low-carbon energy

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[1] See http://www.iea.org/statistics/RDDonlinedataservice/.

[2] See for instance the energy statistics provided by the OECD/IEA (available at http://www.iea.org/W/bookshop/649-World_Energy_Statistics_and_Balances_2014) and Eurostat (available at http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/main_tables).

Table 1
First-level subclasses with related IPC codes. (*Source*: http://www.wipo.int/classifications/ipc/en/est/.)

Subclasses	IPC codes
Nuclear power generation	
Nuclear engineering	G21, G21B, G21C, G21D
Gas turbine power plants using heat source of nuclear origin	F02C 1/05
Alternative energy production	
Bio-fuels	C10L 5/00, 5/40–5/48, C10B 53/02, C10L 5/40, 9/00, C10L 1/00, 1/02, 1/14, C10L 1/02, 1/19, C07C 67/00, 69/00, C10G, C10L 1/02, 1/19, C11C 3/10, C12P 7/64, C10L 1/02, 1/182, C12N 9/24, C12P 7/06–7/14, C02F 3/28, 11/04, C10L 3/00, C12M 1/107, C12P 5/02, C12N 1/13, 1/15, 1/21,5/10, 15/00, A01H
Integrated gasification combined cycle (IGCC)	C10L 3/00, F02C 3/28
Fuel cells	H01M 4/86–4/98, 8/00–8/24, 12/00–12/08, H01M 4/86–4/98, H01M 2/00–2/04, 8/00–8/24, H01M 12/00–12/08
Pyrolysis or gasification of biomass	C10B 53/00, C10J
Harnessing energy from manmade waste	C10L 5/00, C10L 5/42, 5/44, F23G 7/00, 7/10, C10J 3/02, 3/46, F23B 90/00, F23G 5/027, B09B 3/00, F23G 7/00, C10L 5/48, F23G 5/00, 7/00, C21B 5/06, D21C 11/00, A62D 3/02, C02F 11/04, 11/14, F23G 7/00, 7/10, B09B 3/00, F23G 5/00, B09B, B01D, 53/02, 53/04, 53/047, 53/14, 53/22,53/24, C10L 5/46, F23G 5/00
Hydro energy	E02B 9/00–9/06, E02B 9/08, F03B, F03C, F03B 13/12–13/26, F03B 15/00–15/22, B63H 19/02, 19/04
Ocean thermal energy conversion (OTEC)	F03G 7/05
Wind energy	F03D, H02K 7/18, B63B 35/00, E04H 12/00, F03D 11/04, B60K 16/00, B60L 8/00, B63H 13/00
Solar energy	H01L 27/142, 31/00–31/078, H01G 9/20, H02N 6/00, H01L 27/30, 51/42–51/48, H01L 25/00, 25/03, 25/16, 25/18, 31/042, C01B 33/02, C23C 14/14, 16/24, C30B 29/06, G05F 1/67, F21L 4/00, F21S 9/03, H02J 7/35, H01G 9/20, H01M 14/00, F24J 2/00–2/54, F24D 17/00, F24D 3/00, 5/00, 11/00, 19/00, F24J 2/42, F03D 1/04, 9/00, 11/04, F03G 6/00, C02F 1/14, F02C 1/05, H01L 31/058, B60K 16/00, B60L 8/00, F03G 6/00–6/06, E04D 13/00, 13/18, F22B 1/00, F24J 1/00, F25B 27/00, F26B 3/00, 3/28, F24J 2/06, G02B 7/183, F24J 2/04
Geothermal energy	F01K, F24F 5/00, F24J 3/08, H02N 10/00, F25B 30/06, F03G 4/00–4/06, 7/04
Other production or use of heat, not derived from combustion, e.g., natural heat (OPoUH)	F24J 1/00, 3/00, 3/06, F24D 11/02, F24D 15/04, F24D 17/02, F24H 4/00, F25B 30/00
Using waste heat	F01K 27/00, F01K 23/06–23/10, F01N 5/00, F02G 5/00–5/04, F25B 27/02, F01K 17/00, 23/04, F02C 6/18, F25B 27/02, C02F 1/16, D21F 5/20, F22B 1/02, F23G 5/46, F24F 12/00, F27D 17/00, F28D 17/00–20/00, C10J 3/86
Devices for producing mechanical power from muscle energy	F03G 5/00–5/08
Energy conservation	
Storage of electrical energy	B60K 6/28, B60W 10/26, H01 M 10/44–10/46, H01G 9/155, H02J 3/28, 7/00, 15/00
Power supply circuitry	H02J, H02J 9/00
Measurement of electricity consumption	B60L 3/00, G01R
Storage of thermal energy	C09K 5/00, F24H 7/00, F28D 20/00, 20/02
Low energy lighting	F21K 99/00, F21L 4/02, H01L 33/00–33/64, 51/50, H05B 33/00
Thermal building insulation, in general	E04B 1/62, 1/74–1/80,1/88, 1/90, E04C 1/40, 1/41, 2/284–2/296, E06B 3/263, E04B 2/00, E04F 13/08, E04B 5/00, E04F 15/18, E04B 7/00, E04D 1/28, 3/35, 13/16, E04B 9/00, E04F 13/08
Recovering mechanical energy	F03G 7/08, B60K 6/10, 6/30, B60L 11/16

technologies, as well as their technological impact. Differently from previous studies, we refer to the IPC Green Inventory in order to collect patented technologies providing environmental benefits, rather than adopting other less rigorous approaches as those based on keywords [53,76]. These, in fact, may suffer from a number of drawbacks, as unobserved heterogeneity and failure to capture the dynamism of the technologies under investigation, making these search strategies less reliable than the employment of wide and largely accepted technological classifications. The IPC Green Inventory was launched in 2008 by the World Intellectual Property Organization (WIPO) in the attempt to create a concordance between the IPC classification and Environmentally Sound Technologies (ESTs), as defined during the Rio Earth Summith in 1992 [77]. Accordingly, the IPC Green Inventory takes into account seven different technological classes, in turn divided into hierarchical sets of subclasses. Each subclass has then been linked to the most relevant IPC code(s) by a panel of experts.[3] In particular, we considered the classes related to the energy field, namely, "Nuclear power generation", "Alternative energy production", and "Energy conservation" (see Table 1). This approach allows us to rely upon consistent and rigorous criteria to identify low-carbon energy patents and provides a large sample upon which conducting our analyses.

As the first step of the data collection process, we selected the U.S.PTO. database to retrieve the patents associated to low-carbon energy technologies. We rely upon the use of the U.S.PTO., since it "is supposed to have one of the lowest home biases as more than 50% of the patents that are issued in the U.S. goes toward non-U.S. entities" [78, p. 45]. Accordingly, previous researches have argued that it "represents the largest body where patents are filed from all over the world" [79, p. 205], thus allowing them to focus on U.S. patents instead of analyzing all patents granted in different patent office [78–80]. Then, we searched for patents granted at the U.S.PTO. between 1971 and 2010 and belonging to the selected energy-related technological classes, thus yielding a final sample of 131,661 patents. The year 1971 has been chosen as the starting time period for two main reasons. First, the IPC classification first appeared after the Strasbourg Agreement (1971).[4] Second, the technological classes reported in most of the previous granted patents have not been updated according to the new classification system, hence patents registered before 1971 cannot be effectively retrieved by employing query strings based on the IPC codes. Successively, for each of the retrieved patents we collected relevant bibliographic data, such as title, filing date, issue date, number of claims, number of backward, forward and scientific citations, inventors' and assignees' details (name, city, state, and country), and technological fields. Finally, in order to identify patents' technological impact we used the number of patent forward citations. Indeed, the most cited patents have been proven to be important precursors of new

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[3] See http://www.wipo.int/classifications/ipc/en/est/.

[4] See http://www.wipo.int/treaties/en/text.jsp?file_id=291858.

technological trajectories and paradigms, since a wide number of subsequent technological advancements are based upon those innovations [47–51]. Thereby, patent citations have been largely employed to evaluate the technological impact of patented innovations, especially in large datasets where in-depth qualitative evaluations of individual patents are very difficult to be conducted [47–51,81]. Nevertheless, the literature has questioned the use of forward citations by noticing that older patents are more likely to be cited than younger ones (e.g., [50]), hence calling for solutions to avoid such a bias. Accordingly, we calculated the citation rate per year in order to reduce the effect of patent age. Furthermore, comparing the samples sorted by citation rate and number of forward citations (top 1, 3, and 5 percent of our sample), we found no significant differences, thus increasing our confidence in the selection criteria. Hence, we considered the most cited patents as the highly impacting innovations (e.g., [52,54,81]).

In addition, since our aim is to link the trends depicted by the patent analysis to related influencing policy initiatives and events, we selected two main sources to identify these types of information. First, we referred to the outcomes of the international conferences on sustainable development and climate change organized by the UN (e.g., the 1992 Rio Earth Summit and the 2002 World Summit of Sustainable Development held in Johannesburg). Accordingly, we analyzed all the various conferences reported on the UN website.[5] Indeed, those meetings represent important occasions where leaders from all over the world, as well as thousands of participants from the private sector and non-governmental organizations come together to discuss about how to reach the goals for a sustainable growth, hence tracing the route toward future environmental initiatives. Second, we referred to major policy interventions and geopolitical circumstances related to the energy sector, most of which can be found in the specific governments' and international organizations' websites and reports. In particular, we mainly considered information from the U.S. Department of Energy, Japanese Ministry of Economy, Trade and Industry (METI), European Commission, OECD, and IEA. These, in fact, allowed us to avoid the risks to incur in misleading information provided by non-official sources, and to collect data about almost all the geographic areas covered by patent data. If complementary data and information were needed, we relied on additional authoritative sources, as scientific publications in peer-reviewed journals and reports drawn up by associations specifically devoted to the field of energy (e.g., the World Nuclear Association).

4. Analysis and results

In this section, we provide a comprehensive overview of the development trends of patented low-carbon energy technologies in each technological class. Specifically, we used patent count as a measure of the innovative effort [20,39,43,55,82], the average number of scientific citations to approximate the willingness of inventors to build upon science (e.g., [83,84]), the number of forward citations as a proxy for the technological impact of an invention (e.g., [47–51,81]), the main assignee information to analyze development trends at organization level, and, finally, the main inventor state in order to locate the geographical origin of an invention [85,86]. As time scale, we used the filing year, since it captures the invention development period better than the issue year [87]. However, the time lag between application and issue may be even large. Hence, patents filed more recently generally have less likelihood to be granted at the time of data retrieval. Thus, the last ten year analysis is used more for comparison than for an actual analysis of development trends. Finally, we also referred to major environmental programs and geopolitical circumstances, since national and international policies, historical events, and private sector initiatives may have fostered low-carbon energy technologies' evolution.

4.1. Nuclear power generation

This main class is divided into two different subclasses (see Table 2). However, the second subclass ("Gas turbine power plants using heat source of nuclear origin") has only a negligible contribution in explaining the nuclear energy eco-innovations' evolution, as revealed by the low share of patents (0.3% of the total amount in the field). Thereby, we analyze "Nuclear power generation" technologies without differentiating the two subclasses.

Fig. 1 presents the patenting application activity since 1971, as measured by patent count per year, both globally and per different geographic regions (U.S., Europe, Japan, and BRIC – Brazil, Russia, India, and China). The global trend (indicated by "ALL") shows a sharp growth of the number of patents in the 1970s. Furthermore, almost all the analyzed countries contribute in the "Nuclear power generation" technological development in its first coming, except for BRIC. Despite the potential bias resulting from the Strasbourg Agreement, this trend can be largely explained by examining geopolitical issues occurred in those years. In fact, while nuclear energy and nuclear weapons technologies were closely related to military aspirations during World War II, since late 1950s some governments started to reorient countries' resources toward the development of nuclear power plants for commercial purposes. Thus, such commercialization efforts promoted the protection of nuclear technologies in order to gain greater profits. In addition, during the 1970s the Arab–Israeli War (also known as Kippur War) caused a serious petrol crisis, which began with the 1967 oil embargo proclaimed by the Organization of Arab Petroleum Exporting Countries (OAPEC). Thereby, Western countries increased their investments in nuclear power, in order to face such an energy crisis. As a result, the most intensive growth phase of nuclear energy started from the mid-1970s [89]. Accordingly, a several number of nuclear plants came about all over the world. To name few examples, in 1971 diverse commercial nuclear power plants were in full operation in the U.S. In 1972 the world's first fast neutron reactor (the BN-350) started up in Kazakhstan. Also European countries, such as France, Italy, Germany, and UK, saw the birth of many reactors in those years. Particularly relevant was the action made by the French Prime Minister Pierre Messmer in 1974, when he declared the so named "Messmer Plan'" with the aim to generate the whole France's electricity need by employing nuclear power.

Furthermore, the graph reflects an alternate patenting activity trend across the countries during the period from 1976 to the mid-1990s. Particularly, it depicts that the patenting activity in Europe fell down immediately after 1988, whereas it grew in the U.S. and especially in Japan, which assumed a predominant innovative role in this field. Explanations may be identified in a number of different reasons that caused some concerns in the use of nuclear power, such as the reduction of the oil price in the early 1980s and some nuclear accidents, like the 1979 Three Mile Island

Table 2
"Nuclear power generation" subclasses.

Subclasses	Description
Nuclear engineering	It includes technologies for generating electricity by using fusion reactors, nuclear (fission) reactors, and nuclear power plant [88]
Gas turbine power plants using heat source of nuclear origin	It includes those technologies that use the heat generated by nuclear energy production process [88]

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[5] See http://www.un.org/en/events/.

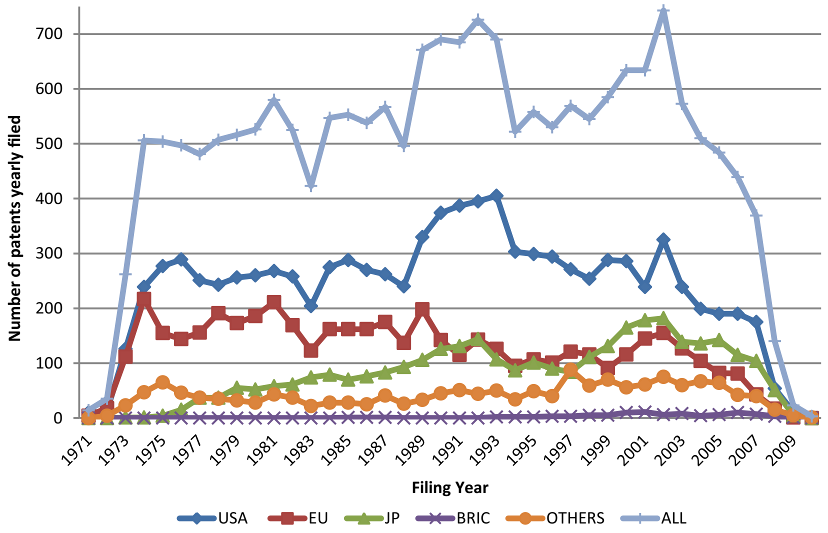

Fig. 1. Trend of "Nuclear power generation" patent applications.

incident in Pennsylvania and the well-known Cernobyl disaster in 1986. Nevertheless, at global level the effects produced were not the same. In fact, while some countries drastically reduced their attention toward nuclear power and R&D efforts in the field, others continued to invest in it. For instance, despite Italy was a pioneer of civil nuclear power and accounted for several reactors, nuclear energy was totally abolished by a public referendum in 1987. Moreover, at the end of 1989 the UK government stopped the build of nuclear stations until a review of UK nuclear policy would have been carried out, and in August 1986 Germany approved a resolution to abandon nuclear power within ten years. Differently, other nations still promoted nuclear energy. The International Thermonuclear Experimental Reactor (ITER) project represents an important signal in that direction. The ITER was a research and engineering project signed in 1985 by Soviet Union, the U.S., Japan, and European Union with the aim to have a full scale production of electricity from power plants. Nowadays, the project is still working and includes also South Korea (since 2003), India (since 2005), and China (since 2007).

Finally, Fig. 1 depicts another increase in patenting activity starting from 1996, which seems to highlight a renewed interest in the nuclear power in Europe, Japan, and some other countries (e.g., South Korea and Israel). This probably finds its roots in the rise of developing economies, which have started investments in such a direction. Indeed, that period is recognized as "nuclear renaissance" just because of a new interest in the nuclear power industry driven by the rising of fossil fuel prices and environmental concerns [90]. Consequently, despite some incidents happened around the world, a third generation of reactor was developed during these years. The first of such reactors was commissioned in Japan [91]. In addition, in 1999 the Nuclear Energy Research Initiative (NERI) was established in the U.S. in order to foster collaborative researches in innovative technological nuclear solutions. Further, President George W. Bush signed the Energy Policy Act in 2005 [92], which made significant changes in nuclear policy, fostering utility companies to establish more nuclear plants to cope with the country's growing energy demand [93]. More recently, other countries started nuclear energy programs, such as China, South Korea, and India, which, as above mentioned, joined the ITER project. Finally, several states, particularly from Africa, are currently carrying on nuclear power programs in this "nuclear renaissance" scenario. In fact, according to a joint report by OECD and IAEA [94], Africa has the 18% of the world's known recoverable uranium resources, hence making nuclear power as a valuable option.

In Fig. 2, we examined the global patent share across countries by trying to highlight the other relevant contributors. As noted in the previous graph, the three main actors are represented by the U.S., Japan, and European countries. Within European countries, France and Germany are the most innovative. Looking for other contributors, we checked for the BRIC innovative efforts, due to their significance in the current and future economic scenario. However, the analysis points out that their R&D activities in this specific field are still not so relevant. Finally, we highlighted two other important actors, namely South Korea and Israel. While it is reasonable that South Korea may be involved in developing nuclear technologies due to its entry in the ITER project, Israel has no nuclear power plants, hence making these technologies mainly originated from researches conducted in the military field.

By analyzing the citations rate made to scientific documents by all patents, it turned out an interesting aspect of the innovation activity. Specifically, by looking at the graph shown in Fig. 3, where the *y*-axis reports the average number of scientific citations made by all patents in a specific year, it is possible to note that, before 1995, inventors tend to cite only patent documents. Differently, more recently, references made to scientific literature have grown. Thus, it is possible to observe how organizations have changed their approach in research activities since 1995, shifting to a closer relationship between theoretical and applied research than in the past. In turn, this may depend on the strengthening of the link between science and technology. This is in accordance with

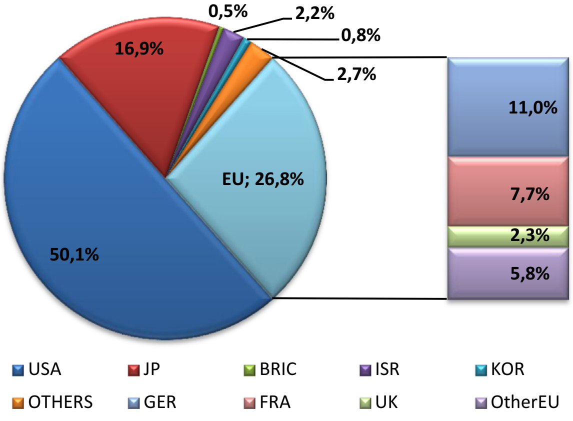

Fig. 2. "Nuclear power generation" patent share by geographic area.

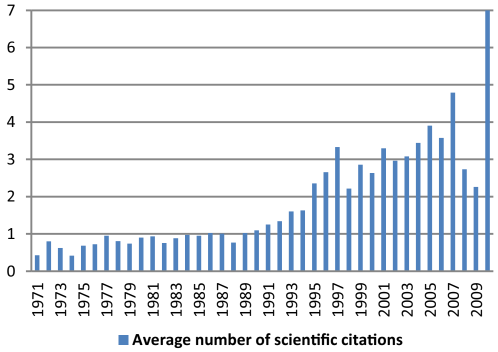

Fig. 3. "Nuclear power generation" scientific citations analysis.

previous studies that highlighted the positive influence of basic science for economic growth [95,96] and new technologies' development [83]. Accordingly, science fosters technological advances by providing new technological ideas [97], as well as by expanding firms' absorptive capacity [98], hence underscoring how the interplay between science and technology can significantly impact both individuals' and organizations' capability to successfully innovate (e.g., [83,98–101]). In particular, looking at nuclear energy technologies, this linkage can be referred to the need of new materials and chemical processes that can meet safety and efficiency goals. Indeed, basic research on materials science, chemistry, and physics can provide significant opportunities for the future of nuclear power [102,103].

Fig. 4 reveals the top ten organizations in terms of number of granted patents, operating both in the public and private sectors. Each bubble identifies an organization and its dimension represents the number of its successfully filed patents. Furthermore, in each bubble it is inserted the flag of the country where the organization is located. In addition, other two measures were employed to enrich the analysis. In particular, the first one (*x*-axis) aims at indicating when an organization has undertaken the major efforts in developing nuclear technologies. Thus, we calculated the average year in which each company has filed its patents. The second one (*y*-axis), instead, indicates the technological impact of organizations' innovative efforts as measured by the average number of forward citations. Results point out two main aspects. First, as we mentioned earlier in the paragraph, the public sector, mainly represented by the U.S. government and the Commissariat à l'énergie Atomique, has a significant role in supporting and pushing these types of power generation method. The efforts undertaken by public organizations are largely confined in the first period of nuclear power commercial use, whereas later in time private companies have assumed a major role. This trend confirms the importance of public research in exploring innovative technological solutions, hence opening the doors toward their subsequent exploitation by the private industrial sector (e.g., [95,104–108]). Second, highly impacting patents are mainly owned by actors located in the U.S., and their related innovative activity is concentrated before the 1990s. After this cut-off point (maybe related to the Cernobyl accident), the development of nuclear solutions is quite homogeneous across Europe, U.S., and Japan, but their technological impact seems to decrease.

Finally, we also showed the geographical and temporal distribution of highly impacting low-carbon energy technologies in the "Nuclear power generation" class. Specifically, Fig. 5a reveals that these innovations are owned almost totally by the U.S. and European countries, being these pioneers in the adoption of nuclear plants mainly for commercial purposes. Furthermore, Fig. 5b shows that highly cited patents were mainly filed between

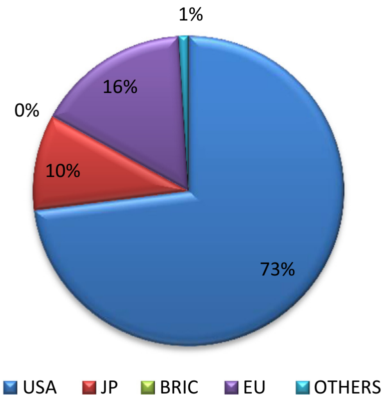

Fig. 5a. Geographical distribution of the highly impacting patents in the "Nuclear power generation" class.

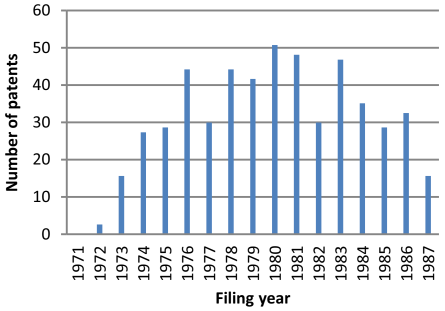

Fig. 5b. Development trend of the highly impacting "Nuclear power generation" patents.

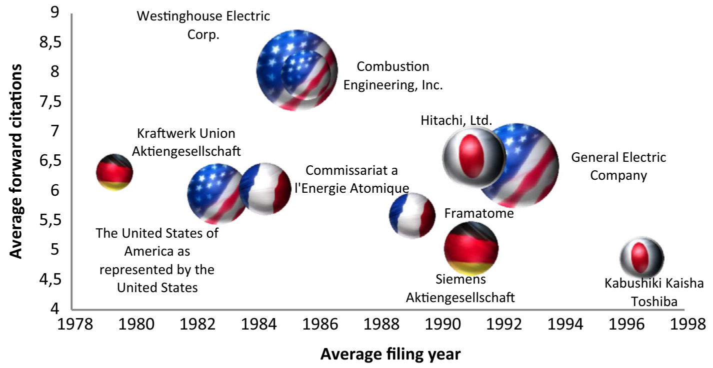

Fig. 4. Top ten organizations in the "Nuclear power generation" class in terms of patent intensity (as represented by bubble size), period of the highest patenting activity (*x*-axis), and outcome quality (*y*-axis).

Table 3
"Alternative energy production" subclasses.

Subclasses	Description
Bio-fuels	Bio-fuels are those types of fuel whose energy mainly derived from carbon fixation. They include fuels derived from any plant or animal-based feedstock conversation and various biogases. Bio-fuels technology focuses on every stage of bio-fuels production, from feedstock through processing to distribution [110]
Integrated gasification combined cycle (IGCC)	IGCC refers to those devices aimed at producing electricity from a solid or liquid fuel by merging gasification with gas cleaning, hence producing clean and affordable energy. First, the fuel is converted to synthetic gas (or syngas), which is a mixture of hydrogen and carbon monoxide, in order to eliminate emissions like SO_X and particulate matter. Second, the syngas is converted to electricity in a combined cycle power block consisting of a gas turbine process and a steam turbine process, which includes a heat recovery steam generator [111]
Fuel cells	A fuel cell is a device that generates electricity through a chemical reaction with an oxidizing agent. Hydrogen is the most common fuel. In particular, fuel cell systems do not involve combustion, thus producing few emissions [112]. They prevent the formation of oxides of nitrogen and other pollutants, such as NO_X and SO_X
Pyrolysis or gasification of biomass	This subclass refers to the mechanisms and thermo-chemical processes of pyrolysis and gasification of biomass. In particular, biomass pyrolysis has been attracting an increasing attention due to its high efficiency and good environmental performance [113]. It also provides an opportunity for the processing and transformation of agricultural residues, wood wastes, and municipal solid waste into clean energy
Harnessing energy from manmade waste	These sets of technologies refer to all the devices developed to reduce manmade waste. They incorporate technologies to address agriculture waste, gasification waste, chemical waste, industrial waste, hospital waste, and municipal waste [114]
Hydro energy	This category collects different technologies with the aim to generate energy from water sources, namely water-power plants, tide power plants, and propulsion of marine vessels by using energy derived from water movement. Although not yet widely used due to high costs and limited availability of production sites, these solutions could be really important for future energy generation, especially considering that they are a continuous source of energy, differently from solar or wind technologies [115]
Ocean thermal energy conversion (OTEC)	Ocean thermal energy conversion includes all those technologies that convert the ocean's natural thermal gradient to drive a power-producing cycle. The higher the difference between the warm surface water and the cold deep water, the more OTEC system can produce energy [115]
Wind energy	Wind energy is a source of renewable energy that converts the kinetic energy of the wind into mechanical energy. Nowadays, the most common use refers to wind turbines for producing electricity. Furthermore, this energy source can be used for the electric propulsion of vehicles and marine vessels by wind-powered motors. Its environmental impact is much lower than fossil fuel sources' one, since these solutions consume no fuel and have no emissions [116]
Solar energy	Solar power harnesses the sun's energy to produce electricity. The amount of solar radiation reaching the earth's surface is estimated to be more than the total amount of energy currently consumed by all the human activities annually [117]. The two most famous solar technologies for electricity are solar photovoltaic (PV), which use semiconductor materials to convert sunlight into electricity, and concentrating solar power (CSP), which concentrates sunlight on a fluid to produce steam and drive a turbine to produce electricity [118,119]. The production of electricity by using solar energy emits neither GHGs nor other pollutants. Nevertheless, as with any electricity-generating resource, the production of the PV systems themselves requires energy that may come from sources that emit GHGs and other pollutants
Geothermal energy	Geothermal energy can be used for electricity generation, heat pumps, production of mechanical power, or direct uses. Differently from other renewable energies, such as wind and solar, geothermal power generation can operate steadily during its life cycle. Continuous production of energy makes geothermal an ideal candidate for providing nearly zero-emission renewable power [120]
Other production or use of heat, not derived from combustion, e.g., natural heat (OPoUH)	Many colder countries consume more energy for heating than electrical power. Thus, the generation or production of heat, rather than electrical power, can play an important role in reducing energy consumption. In particular, this section refers to heat pump technologies. Heat pumps force the heat flow from a lower temperature to a higher temperature, by employing a relatively small amount of energy. Two common types of heat pump are air-source heat pumps (ASHP) and ground-source heat pumps (GSHP). Heat pumps consume less primary energy than other conventional heating systems, hence becoming an important technology for reducing gas emissions [121]
Using waste heat	Waste heat refers to heat losses that arise from machines, electrical equipment, and industrial processes inefficiencies. Methods for waste heat recovery include transferring heat between gases and/or liquids (e.g., combustion air preheating and boiler feedwater preheating), treating water, waste water or sewage, producing mechanical and/or electrical power, or using waste heat with a heat pump for heating or cooling facilities. Recovery of waste heat has different environmental benefits. Specifically, it reduces the inefficiency of processes in the utility consumption, hence contributing to the reduction of pollution level, fuel consumption, and auxiliary energy consumption [122]
Devices for producing mechanical power from muscle energy	This subclass refers to all the devices that convert muscle energy derived from human or animal motion into mechanical power. However, it has not been analyzed since only five patents have been granted in this category

1970 and 1987, hence recognizing a reduction of the technological impact after this period. Likely reasons may be related to the necessity to make previous solutions safer, rather than developing really new ones. Indeed, organizations tended to be more focused on the exploitation of existing nuclear technological solutions in order to extend their life and reliability, enable nuclear energy to meet climate change goals, manage nuclear waste [109], and develop more efficient nuclear fuel cycles [103] .

4.2. Alternative energy production

Table 3 shows the "Alternative energy production" subclasses, as recognized by the IPC Green Inventory. Firstly, we present the patenting activity as a whole without discerning the different categories. Then, we provide a brief analysis for each subclass.

As shown in Fig. 6, the global patenting activity (indicated by "ALL") in the alternative energy field presents three clear different

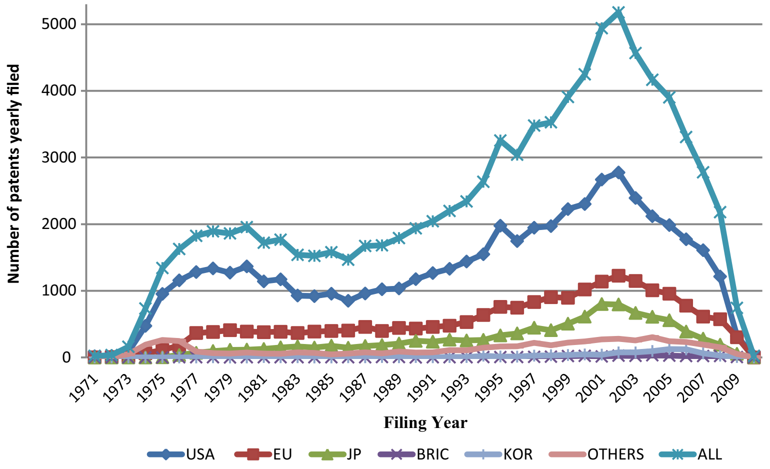

Fig. 6. Trend of "Alternative energy production" patent applications.

trends. It grew in the early 1970s. Then, it decreased till the end of 1980s, after which a still growing trend is visible. In addition, Fig. 6 depicts a common trend for each country under analysis. As we noted in Section 4.1, the initial growing trend could be associated with the oil price shock caused by the OAPEC oil embargo, which contributed to create awareness about the limits of global resources in respect of energy. Indeed, this concern attracted funds and triggered efforts to develop new solutions through which untapped renewable resources may be harnessed in a large scale to partially replace the use of fossil fuels, such as solar air heating [123]. The R&D expenditures for renewable resources were, in fact, equal to $65 million in 1974, while they reached a peak of about $2 billion in 1980 [124].

Nevertheless, the enthusiasm toward renewable energy went on through the mid-1980s, but after the oil prices fall, a season of stagnation lasted for almost two decades. As a result, R&D efforts collapsed to less than a third by 1987 [124]. Furthermore, as we also showed in Section 4.1, the period from the mid-1980s to mid-1990s saw the pursuit of the investments made in nuclear power [125]. Thereby, the innovative efforts toward alternative energy solutions drastically decreased. Finally, the increasing trend characterizing the last two decades can be reasonable explained by the perceived growing economic opportunities and the rising attention on climate change, as well as by the scarcity of crude oil in the West countries. Indeed, several actions were made by different countries and organizations. For example, in 1988, the UN established the International Panel on Climate Change in order to assess the scientific, technical, and socio-economic information required to understand the risks of the human-induced climate change. Furthermore, following what emerged during the UN Conference on the Human Environment (1972) on global environmental problems, several subsequent conferences took place in order to address the challenges of sustainable development and foster new innovative efforts regarding the improvement and renewal of national energy systems. To name some examples, the UN Conference on Environment and Development (1992) addressed issues related to environmental, social and economic sustainability. Particularly, as an outcome of the conference, it was signed the Agenda 21, which highlighted the relevance of conservation and management of resources, as well as the importance of using and diffusing technologies with better environmental performances in several sectors, especially the energy one. More recently, the Johannesburg Declaration on Health and Sustainable Development (2002) stressed over the concept of sustainable development and was particularly aimed at triggering actions to access "[...] to reliable, affordable, economically viable, socially acceptable and environmentally sound energy services and resources, taking into account national specificities and circumstances" [126, p. 11]. Other international treaties with the attempt to promote stable growth while protecting the environment, such as the Maastricht Treaty (signed in 1992), the Amsterdam Treaty (signed in 1997), and the ratification of the well-known Kyoto Protocol in 1997, further set the basis for a change in the energy system.

Fig. 7 shows the leading countries in patenting alternative energy low-carbon technologies. It emerges that the U.S., Europe, and Japan represent the most innovative countries. Differently, India, China, and Brazil are not among the top patenting countries despite they strongly rely on clean energy [127,128]. This may suggest that those countries mainly adopt technology transfer systems, such as the Clean Development Mechanism defined in the Kyoto Protocol, as well as take advantage of knowledge spillovers from developed countries rather than being directly engaged in innovative activities [129,130].

Fig. 8 shows the linkage between basic and applied research. The graph depicts that, before 1991, patent references are mostly directed to patent documents. Differently, later on, a higher propensity to cite scientific publications emerged. This is in accordance with some policy interventions taken in place in those years. For instance, since the early 1990s the U.S. Department of Energy fostered basic research in the energy field to enhance technological development [131]. Similarly, starting from the same years, the Framework Program for Research and Technological Development created by the European Union funded projects in

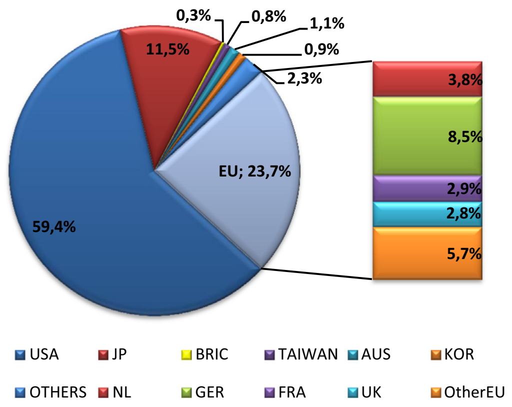

Fig. 7. "Alternative energy production" patent share by geographic area.

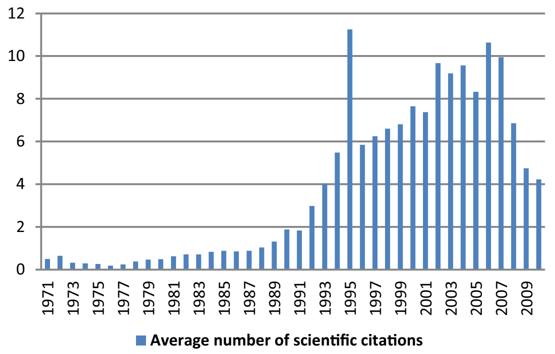

Fig. 8. "Alternative energy production" scientific citations analysis.

order to strengthen the link between science and technology in the energy field. More recently, the International Science Panel on Renewable Energies and the Energy Innovation Hubs have been established in order to integrate worldwide research centers that combine basic and applied research and provide analysis and strategic guidance for renewable energy R&D activities.

Following the same criteria used in the previous paragraph, we examined the top ten assignees by looking at the number of granted patents (see Fig. 9). Firstly, the chart shows that, although diverse governments have fostered eco-innovative actions for the development of alternative energy technologies, no national institution seems to have strongly affected the patenting activity in this class. Secondly, patents with the highest levels of technological impact are owned by companies that have put most of their innovative efforts at the beginning of the development phase, despite a greater number of technological solutions has been patented later on. For instance, it emerges the huge difference between the impact of technologies produced by Pioneer Hi-Bred International Inc. and Monsanto Technology LLC, and those produced by Hitachi Ltd. and Shell Oil Company. Explanations may depend on the fact that nowadays companies are exploiting established technologies instead of developing new ones (e.g., [132]). Finally, the figure also reveals that the University of California appears among the top ten organizations, hence confirming the fundamental role of research-based organizations (e.g., [133–136]). Figs. 10a and 10b present where and when the highly impacting alternative energy technologies have been developed, respectively. The former highlights that innovative efforts made in the U.S. figured out as the most relevant. The latter confirms that highly impacting patents were mainly filed in the initial stages of the technological development.

We extended the analysis of low-carbon energy technologies in the "Alternative energy production" class by considering their specific subclasses. Specifically, we divided them into two different categories by distinguishing the term "renewable" from the wider "alternative". Accordingly, we referred to renewable energy solutions as those innovations that rely on resources that can be totally replaced or are always naturally available and practically inexhaustible [137], as sunlight, wind, water, and geothermal heat. Differently, we considered non-renewable energy solutions as those innovative technologies that allow the production of energy without the undesirable consequences of the burning of fossil fuels, but still require physical and chemical processes. Tables 4a and 4b show the different subclasses belonging to renewable and non-renewable energy technologies, respectively, and the related eco-innovative activities both globally and within different geographic areas. Looking at Table 4a, it is worthy of note that renewable energy technologies only account for the 26.14% of all inventions and that the 18% of them is related to solar energy technologies. Furthermore, analyses depict that each country contributes in a similar way to the development of these innovations. Indeed, for each subclass, U.S., Europe, and Japan are the leading innovative countries, while a scant contribution is provided by BRIC, Taiwan, Australia, and South Korea. Table 4b points out the relevance of bio-fuel technologies (46.75% of the overall sample) in the "Alternative energy production" technology portfolio. Probably, this is due to the need to replace fossil fuels with solutions that do not suffer from the number of limitations linked to the production of energy by renewable sources, such as the variability of energy supply [138] and the high level of required investments [139], which still set the basis for new technological improvements (e.g., [132]). In addition, the distribution of innovative efforts across countries is similar to that presented in Table 4a except for "OPoUH", "Fuel cells", and "Geothermal energy" classes, where Japan is more innovative than Europe. This can be explained by comparing the geological conditions of the two regions. In fact, most active geothermal resources are usually found along major plate boundaries where earthquakes and volcanoes are concentrated, such as the area encircling the Pacific Ocean [140]. Thus, Japan is actually a better candidate for the use of geothermal energy solutions. Moreover, the high development level of fuel cells technologies can be associated with a government funded demonstration project dedicated to the installation of more than

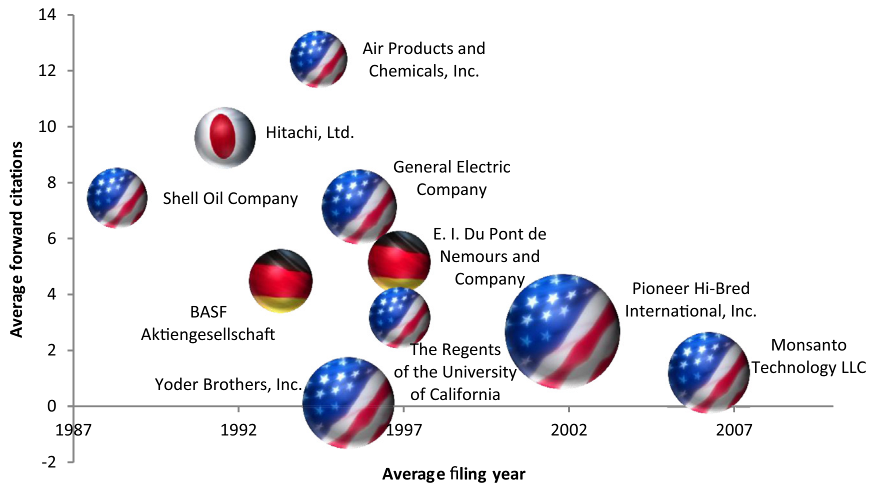

Fig. 9. Top ten organizations in the "Alternative energy production" class in terms of patent intensity (as represented by bubble size), period of the highest patenting activity (*x*-axis), and outcome quality (*y*-axis).

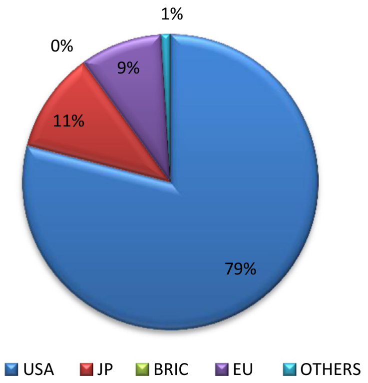

Fig. 10a. Geographical distribution of the highly impacting patents in the "Alternative energy production" class.

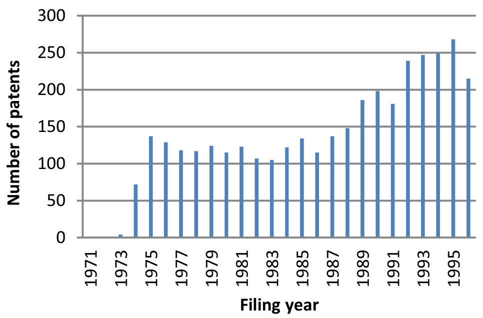

Fig. 10b. Development trend of the highly impacting "Alternative energy" patents.

5000 residential fuel cell systems to provide heat and power in homes, which involved multiple manufacturers (e.g., Panasonic, Toshiba, and Eneos). Nowadays, in fact, thousands of residential fuel cell systems are being sold in Japan [141].

Following our distinction between renewable and non-renewable innovations, Figs. 11a and 11b show how low-carbon energy technologies in the "Alternative energy production" class evolved. Fig. 11a describes the development trends of technologies for producing energy from renewable sources. In particular, it reveals that all of them present a U-shape trend, hence highlighting that, despite their environmental advantages, these technologies have not been used for a long time. In fact, their growing trend is visible during the oil shock, due to the need of new sources of energy. Then, a number of environmental programs, such as the Kyoto protocol, have fostered the use of less polluting electricity production technologies. In particular, while "Hydro energy" and "Wind energy" solutions initially received only marginal attention, in the last few years the interest toward their use seems increased. For instance, in 2005 the Global Wind Energy Council was launched to provide a credible and international representative forum for the entire wind energy sector. Differently, Fig. 11b depicts a steady growing development trend for all the different technological subclasses related to non-renewable alternative energy technologies (except for "pyrolysis or gasification of biomass", which probably reached its maturity stage in the early 1990s). This trend may be reasonable due to the fact that those solutions have been principally promoted by the environmental concerns came up in the late 1980s to replace oil-based energy sources.

4.3. Energy conservation

Especially due to the growing level of urbanization and industry proportion (e.g., [142,143]), reducing carbon emissions, as well as bridging the energy gap between energy production and consumption, let energy conservation practices receive an increasing attention in several countries [144–146]. Table 5 presents an overview of the "Energy conservation production" technological subclasses.

Fig. 12 presents the patenting application activity since 1971, as measured by patent count per year, both globally and per different geographical regions. It shows that, before the late 1980s, the interest toward energy conservation technologies is not comparable with the innovative efforts made between 1971 and 1986 in the "Alternative energy production" and "Nuclear energy" fields (see Figs. 1 and 6, respectively). In fact, only in the U.S., after the oil crisis, can be seen a slow growth in the development of energy conservation technologies, whereas a time of stagnation is depicted from 1976 till the end of 1980s. This could be justified by the fact that, differently from the other two technological classes, in this case innovative efforts are directed toward the reduction of energy consumption, rather than the exploitation of new energy sources. Thereby, the main exogenous shocks have probably not determined, at the global level, an analogous attention toward

Table 4a
Total patent share and percentage of patents owned by geographic area for "renewable" technologies.

Renewable technologies	Patent share	U.S.	JP	EU	BRIC	TAIWAN	AUS	KOR	OTHERS	Total by geographic area
Hydro energy	4.23	55.38	14.09	23.53	0.42	1.44	0.73	1.65	2.75	100
OTEC	0.09	82.93	2.44	13.41	0	0	0	0	1.22	100
Wind energy	2.23	62.16	4.72	26.51	0.70	2.28	0.84	0.89	1.89	100
Solar energy	18.26	63.68	14.49	15.04	0.23	1.92	0.95	1.60	2.08	100
Geothermal energy	1.33	72.70	11.04	8.26	0.35	2.35	1.74	0.87	2.70	100
Total	26.14									

Table 4b
Total patent share and percentage of patents owned by geographic area for "non-renewable" technologies.

Non-renewable technologies	Patent share	U.S.	JP	EU	BRIC	TAIWAN	AUS	KOR	OTHERS	Total by geographic area
Bio-fuels	46.75	57.23	7.57	29.74	0.36	0.30	1.64	0.50	2.66	100
IGCC	0.23	62.09	9.00	25.12	0.47	0	0	0	3.32	100
Fuel cells	9.61	55.27	26.06	14.51	0.24	0.49	0.38	2.03	1.01	100
Pyrolysis or gasification of biomass	2.37	60.28	6.57	29.28	0.37	0.28	0.61	0.23	2.38	100
Harnessing energy from manmade waste	11.13	65.77	10.25	20.84	0.22	0.54	0.40	0.76	1.22	100
OPoUH	0.58	52.38	24.00	19.05	0.38	0.19	0.19	1.14	2.67	100
Using waste heat	3.19	57.23	7.57	29.74	0.36	0.30	1.64	0.50	2.66	100
Total	73.86									

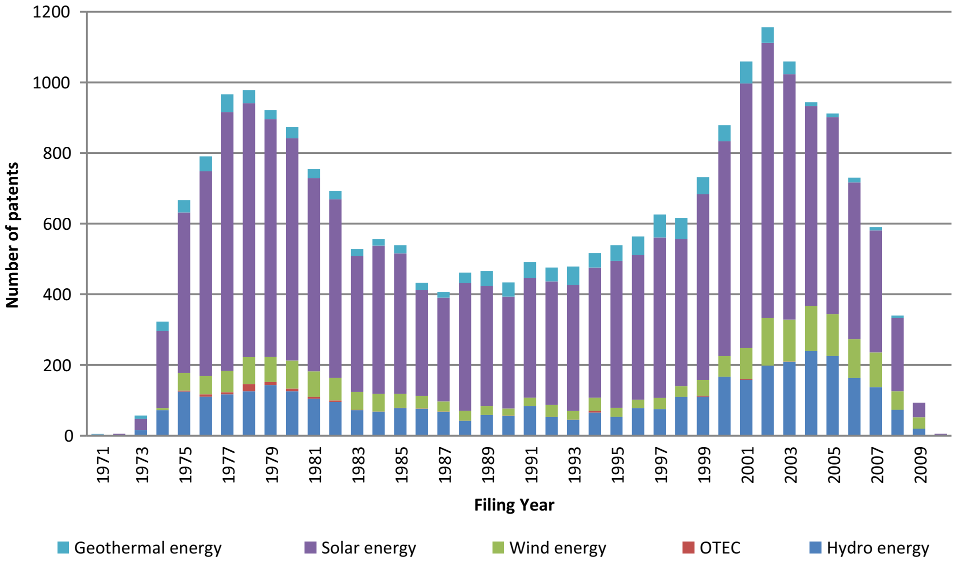

Fig. 11a. "Renewable" technologies' development trend.

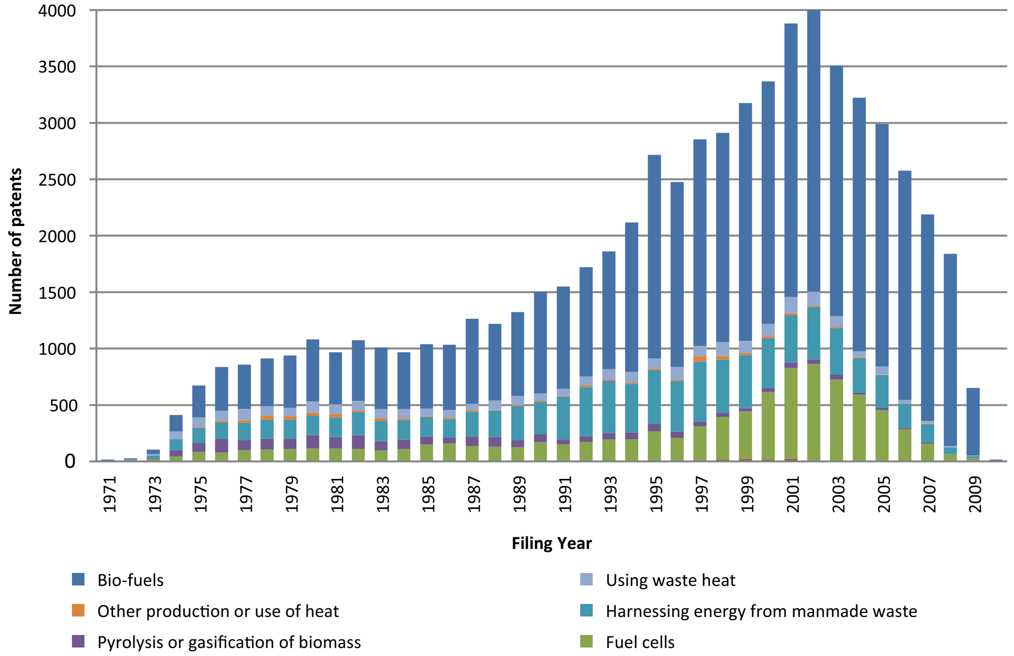

Fig. 11b. "Non-renewable" technologies' development trend.

conservation energy issues. Indeed, only in the U.S. there were some government initiatives focused on energy conservation, thus promoting spending on research, new laws, and the introduction of novel solutions [157].

By considering the years from 1985 to 2000, Fig. 12 shows that "Energy conservation" patenting activity is characterized by a sharp growth rate, even higher than that characterizing the "Alternative energy production" one. This is especially true for the U.S. and Japan. In fact, the number of patents granted in the "Alternative energy production" class in that period had an increase of 150%, while the number of patents granted in the "Energy conservation" class raised of 250%. This suggests that the relevance of energy conservation started under the banner of environmental protection and resources scarcity problems, as highlighted during several international conferences and in related documents, such as the Brundtland Report (e.g., [1]). Indeed, the growing trend can be related to policy initiatives taken place starting from late 1980s in response to those concerns. For example, in the U.S. a collaboration of manufacturers and energy efficiency advocates resulted in the 1987 National Appliance Energy Conservation Act, which set specific energy conservation standards for many household products [158]. A further energy efficiency legislation was the 1992 Energy Policy Act [159], which extended standards for other products, like motors, lamps, commercial heating, and cooling equipments. In addition, in Japan (from 1993 to 2008), after the Earth Summit held in 1992, a series of amendments were enacted so as to deal with global environmental issues and set energy conservation goals.[6] In particular, the New National Energy Strategy in 2006 and the Basic Energy Plan in 2007 specified that a clear tech-

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[6] http://www.asiaeec-col.eccj.or.jp/contents02.html.

Table 5
"Energy conservation production" subclasses.

Subclasses	Description
Storage of electrical energy	Electric energy storage is implemented by devices that storage chemical, kinetic, or potential energy, to convert it into electricity. Such storage may be useful cope with peaks in electricity demand by supplying electricity stored during periods of lower demand, hence balancing electricity supply and demand over small period [147]. The differences among the various types of technology mainly rely on the storage method. From an environmental perspective, electric energy storage may act as an important complementary asset for renewable energy technologies. In fact, as stated by the Center for Climate and Energy Solutions [147], they can smooth the variability in power flow from renewable generation so that it can be scheduled to provide specific amounts of power. In turn, this can decrease the cost of integrating renewable power with the electricity grid, while increases market penetration of renewable energy and leads to GHG emission reductions [148]
Power supply circuitry	A power supply is a device that supplies electric power to an electrical load. It may receive energy from different sources, such as electrical energy transmission systems, electric energy storage devices, and solar power. The major efforts are currently related to developing innovative power saving modes [149]
Measurement of electricity consumption	Measurement technologies refer to those devices that facilitate measurement tasks and provide an instructive inventory of electricity consumption, thus allowing energy saving interventions [150,151]
Storage of thermal energy	Similarly to the "Storage of electrical energy" subclass, the thermal energy storage can be defined as the temporary storage of thermal energy at high or low temperatures [152]. Thermal energy is usually stored by active solar collector together with heat and power plants, and then transferred to insulated reservoirs for later use. Hence, it makes renewable energy resources more viable. The advantages are the same of electrical energy storage [153]
Low energy lighting	Low energy lighting refers to all those solutions that aim at replacing incandescent lamps with more energy-efficient options [154], such as LED, OLED, and PLED
Thermal building insulation, in general	Thermal insulation is a significant factor for achieving the reduction of unwanted heat loss, in order to decrease the energy demands of heating and cooling systems. It is also of foremost importance for carbon emission reduction [142,155]
Recovering mechanical energy	"Recovering mechanical energy" subclass includes any technique or method for minimizing the input of energy to an overall system by the exchange of energy from one sub-system to another [156]

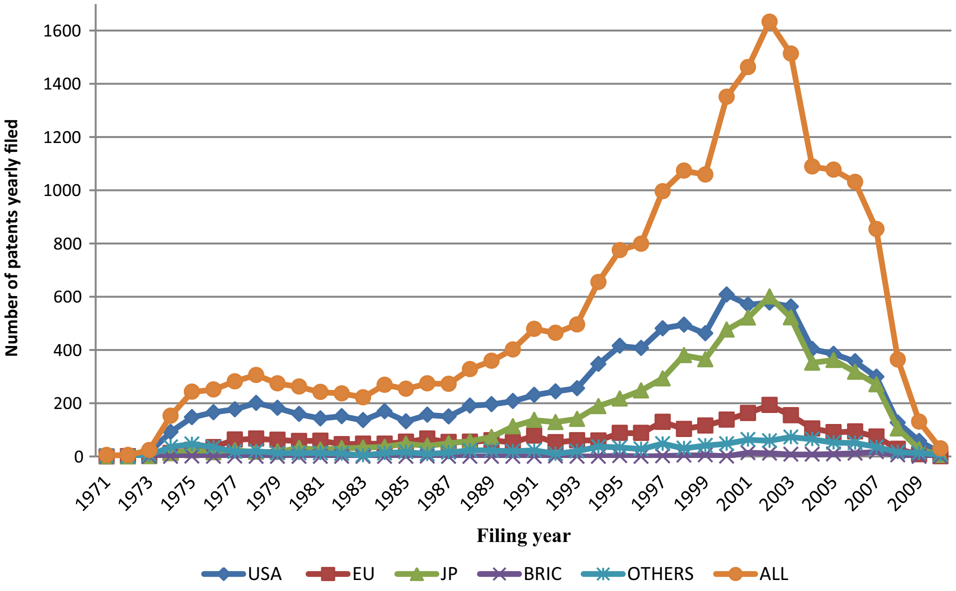

Fig. 12. Trend of "Energy conservation" patent applications.

nology strategy was mandatory, especially to identify a roadmap regarding long term technology development. In Fig. 13, another interesting finding emerges. Specifically, Europe does not seem to have significantly invested in energy conservation technologies. In fact, it is possible to notice that relative few efforts have been devoted in this area compared to the other technological domains previously discussed. Differently, patenting activities in the U.S. and Japan reveal a noteworthy attention toward energy conservation technologies, similar to that demonstrated for the production of renewable energy. Fig. 13 also reveals that other countries like South Korea and Taiwan have invested considerable resources for the development of these solutions, differently from what occurred for alternative energy technologies. Likely reasons lie in the fact that energy conservation technologies, such as low energy lighting lamps or new solutions for buildings' energy efficiency, result more marketable [160], hence reducing R&D investments' risks while assuring

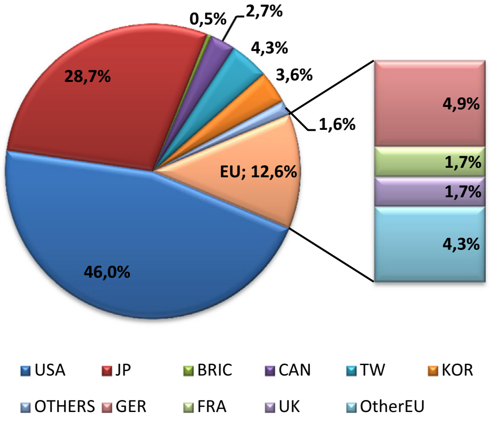

Fig. 13. "Energy conservation" patent share by geographic area.

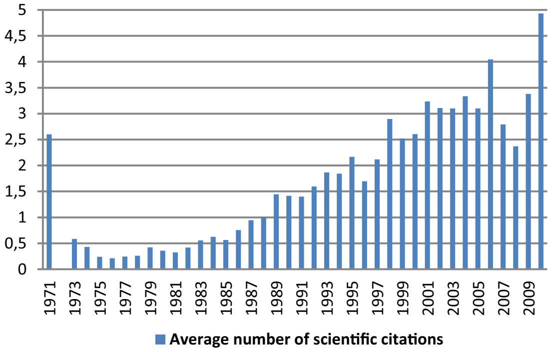

Fig. 14. “Energy conservation” scientific citations analysis.

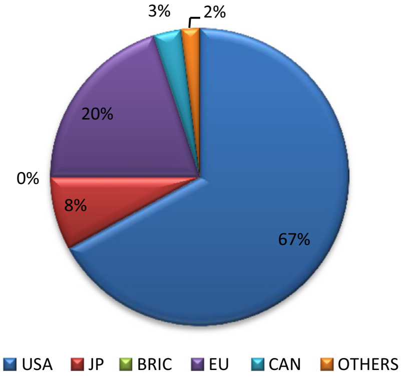

Fig. 16a. Geographical distribution of the highly impacting patents in the “Energy conservation” class.

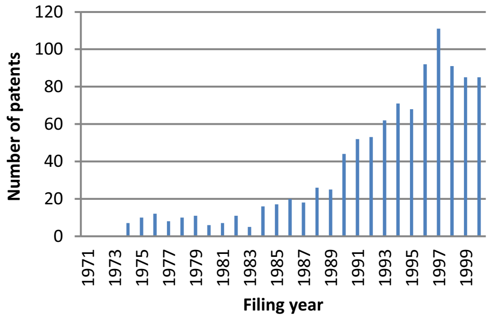

Fig. 16b. Development trend of the highly impacting “Energy conservation” patents.

good environmental performances. In addition, especially for Japan, energy conservation solutions are probably the best ways to cope with an ever increasing energy demand by relying only on the imports of fuel resources. In fact, it has been shown that between the years 2000 and 2010 self-produced resources in Japan were less than the 1% of those consumed [161], thus highlighting the relevant role played by energy saving practices. As revealed for the other two categories, also in this case inventors tend to refer to non-patent literature to develop “Energy conservation” technologies (see Fig. 14). Possible justifications can be offered by looking at the actions discussed in the previous paragraph, even though this behavior appears to be more recent in this technological class than in the “Alternative energy production” one.

Fig. 15, which shows the leading organizations in terms of number of patents owned, provides other important findings. First, no European organizations are in the top ten ranking. Second, Japanese firms present a significant patenting activity, especially in the recent years. However, their overall technological impact, as measured by forward citations, is lower than that characterizing U.S. firms. Finally, the U.S. Eastman Kodak Company, commonly known as Kodak, behaves differently from the other companies. In fact, it seems the only organization undermining the Japanese leadership in terms of both quantity and impact of technical solutions invented. Probably, it is the only firm that is trying to move toward new technological trajectories, thus developing the most cited patents. Fig. 16a shows the distribution of highly impacting innovations among the analyzed regions. It reveals that the U.S. companies hold the majority of patents with the highest technological impact, probably because of the Japan’s late entry in the patenting activity. In addition, Fig. 16b also reveals that the number of highly cited patents increased starting from the late 1980s, differently from what has emerged in the other two classes.

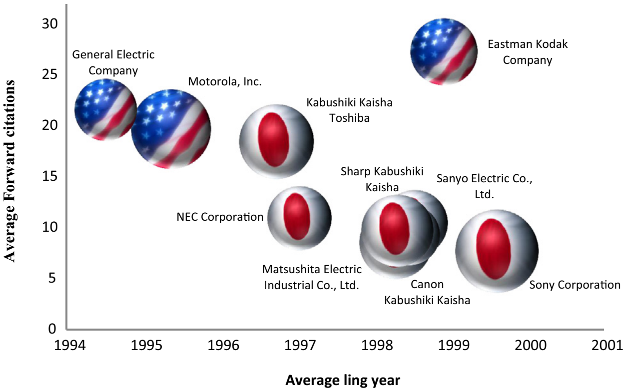

Fig. 15. Top ten organizations in the “Energy conservation” class in terms of patent intensity (as represented by bubble size), period of the highest patenting activity (*x*-axis), and outcome quality (*y*-axis).

Table 6 presents “Energy conservation” subclasses. It shows that, differently from the other two main classes, the U.S. does not always own the majority of patents in each category. Indeed, the number of patents in the “Low energy lighting” and “Measurement of electricity consumption” subclasses owned by Japan exceeds the number of patents granted by the U.S. This may be due to the fact that in the last energy plan the Japanese government actively promoted the use of LED lighting lamps to replace the traditional style incandescent bulbs and technologies for measuring energy consumption [162]. Finally, Fig. 17 shows temporal trends in patenting activity for each subclass. It highlights that only “Low energy lighting” and “Storage of electrical energy” had an increasing trend. This trend is also corroborated by the extensive academic literature that is posing its attention on new electrical energy storage solutions [148,152,163]. On the contrary, the other categories provide a little contribution to the overall trend.

5. Discussion and Implications

This paper analyzes the development over time of low-carbon energy technologies, which are of foremost importance in the eco-innovation context. Specifically, we investigated related patenting activity trends both at the country and at the organizational level. To the best of our knowledge, this study is the first attempt to depict a comprehensive scenario of technological eco-innovations’ evolution in the energy field. Furthermore, this paper tries to explain development trends as a result of related country policies, historical events, and private sector initiatives that may have fostered the development of such technological innovative solutions.

Table 6
Total patent share and percentage of patents owned by geographic area for "Energy conservation" technologies.

	Patent share	U.S.	EU	JP	BRIC	CAN	TAIWAN	KOR	OTHERS	Total by geographic area
Storage of electrical energy	30.47	49.71	9.50	27.11	0.74	3.20	4.65	3.27	1.82	100
Power supply circuitry	2.08	61.33	11.78	16.00	0.44	1.33	6.22	1.56	1.33	100
Measurement of electricity consumption	1.74	35.88	11.61	47.49	0	1.58	0.53	1.58	1.32	100
Storage of thermal energy	4.20	62.84	21.17	10.47	0.44	1.43	1.21	0.88	1.54	100
Low energy lighting	40.01	30.57	10.20	44.03	0.37	1.30	6.21	5.94	1.39	100
Thermal building insulation, in general	20.45	66.65	20.15	4.76	0.34	5.39	0.71	0.39	1.62	100
Recovering mechanical energy	1.05	65.35	18.86	5.26	0.44	5.26	1.32	0.44	3.07	100
Total	100									

To this aim, a unique database of patented inventions successfully filed at the U.S.PTO. between 1971 and 2010 and belonging to the "Nuclear power generation", "Alternative energy production", and "Energy conservation" IPC technological classes has been created and analyzed. Several interesting findings concerning the dynamics and distribution of low-carbon energy technologies emerged.

First, global development trends show the key role played by geopolitical circumstances. In fact, the eco-innovative activity in the energy field increases with the highest grow rate during the petrol crisis period and in the early 1990s, as a result of the global warming awareness, except for few technological categories, as "Pyrolysis or gasification of biomass", "OTEC", and "Storage of thermal energy". This highlights that governments' strategies and energy programs set important frameworks and initiatives to foster and sustain low-carbon energy technologies' development [43]. The main example is represented by the substantial contribution in developing nuclear power solutions provided by the U.S. government and the French Commissariat à l'Énergie Atomique, which appear two of the most productive organizations patenting in the nuclear energy class. A further example is given by Japan, which developed a governmental plan fostering the use of LED lamps and became the leading country for low energy lighting. Nevertheless, as shown through the analysis of the leading innovative organizations, private companies own the majority of the developed low-carbon energy technical solutions. Thereby, this reveals that commercial activities have an important role in their development. This is in line with previous studies [164,165], which highlighted how economic motivations act as the key drivers of innovation processes, hence making profit organizations central actors. Furthermore, this is also the result of the strategic relevance assumed by climate change issues in business competition [166], which have in turn significantly influenced and oriented firms' innovation strategies. Second, data analyses depict a great discrepancy between subclasses in each main technological area. In fact, some of them represent less than 1% of the total amount of patents developed within a specific class. In particular, what is worthy to note is that, although certain subclasses include hot technologies upon which current debates are focusing, these do not necessarily present a high patent share, such as in the case of the "Alternative energy production" class. Indeed, patent analysis has demonstrated that wind, geothermal, and hydro technologies represent only the 8% of the total amount of granted patents despite they are widely recognized as effective and sustainable technologies to be used in the next future [167]. Nevertheless, the current wholesale rate is certainly far from the required level. By taking into account what occurred for the development of some low-carbon energy technologies, such as nuclear plants and solar cells, the eventual push to full commercialization through the use of

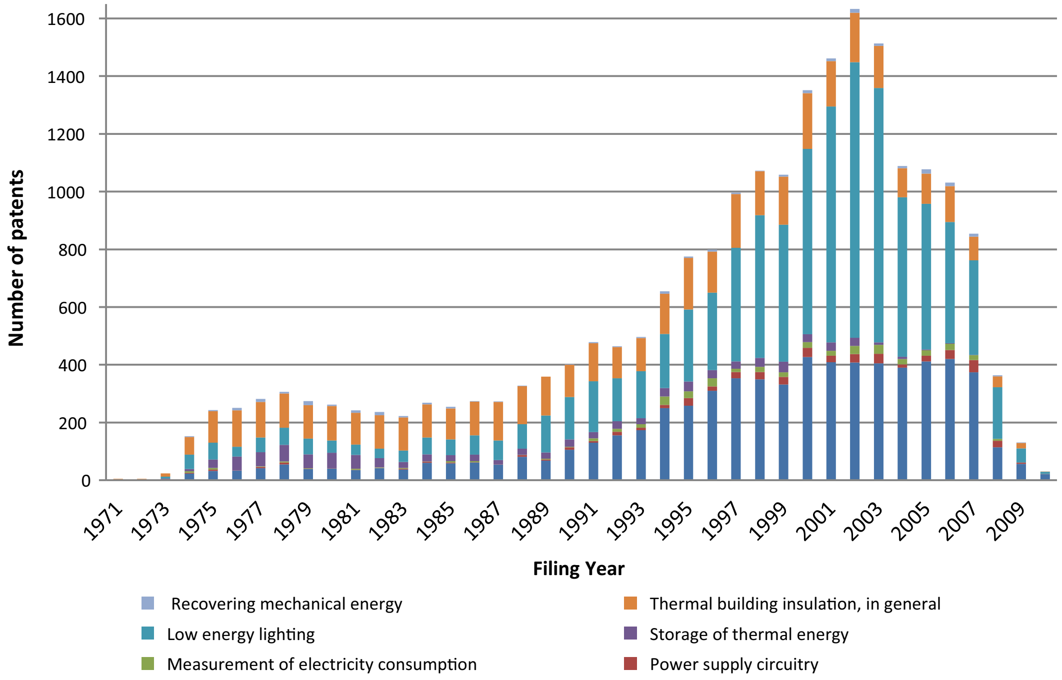

Fig. 17. "Energy conservation" technologies' development trend.

effective demand pull policies may significantly foster their spread and boost innovation. Accordingly, they allow the creation of new markets by protecting emerging technologies from the competition with established designs (e.g., [168]), hence again highlighting how commercial opportunities can enhance innovative efforts [164]. Third, our study sheds new light on the major inventing countries in the field under investigation. Specifically, innovation in low-carbon energy technologies is mostly generated in the U.S., which accounts for more than a half of the total innovations. The innovative performance of Japan is also particularly impressive, since in a number of subclasses, such as "Solar energy" and "Low energy lighting", it ranks equal to or better than Europe. Other countries, such as South Korea, Canada, Taiwan, and Australia, present significant contributions in the patenting activity only in some particular technological fields. For instance, Canada owns the 5% of all technologies in the thermal building insulation category and the 3% of the highly cited patents in the energy conservation class, while it does not contribute to the development of renewable energy technologies at all. Furthermore, South Korea and Taiwan primarily focus on energy conservation solutions. Looking at BRIC countries, despite their environmental awareness and the ever increasing use of low-carbon energy technologies, it seems that they are still far from intensive innovative activity [127,128]. Nevertheless, it should be noticed that our analysis looks at the trends of patents filed until 2010. During more recent years, BRIC investments in low-carbon energy solutions have significantly grown [169,170], thus suggesting an increasing tendency to patent which will likely be evident in next years. Another important result emerges from the analysis of scientific-based citations. Specifically, in recent years, the number of patents that are also based upon scientific literature has drastically grown. This indicates that the international initiative aimed at strengthening the role and the appliance of scientific knowledge to support sustainable development are becoming effective [171]. Thus, inventors are probably more deeply focusing on scientific research than in the past, hence making use of scientific knowledge to increase their understanding of environmental problems and creating suitable technological solutions [99]. Finally, we analyzed the innovative solutions with the highest levels of technological impact in the three different technological areas. Results show that for "Alternative energy production" and "Nuclear power generation" classes their development principally occurred in the earliest stage of related evolution processes. Likely reasons lie in the fact that knowledge about using wind, water, sun, or nuclear power dates back to some decades before the 1970s, but it was never fully exploited due to the widespread use of coal and petroleum. Nevertheless, since the early 1970s, resource scarcity problems and environmental concerns attracted funds and shifted global attention toward new forms of energy generation. As a consequence, new business opportunities have emerged, thus pushing organizations toward the development of highly impacting solutions to successfully compete in these new markets. On the contrary, highly cited patents in the "Energy conservation" class were developed in recent years. This could be explained by considering that energy efficiency needs emerged as a new concept under the banner of resource scarcity issues. It should be noticed that these results may be also related to the measure chosen for computing the technological impact, as described by forward citations. Indeed, early filed patents have less likelihood to be cited, hence being not fully recognized and appreciated by our proxy.

In terms of managerial and policy implications, our suggestions are threefold. First, our study highlights that the development of low-carbon energy technologies entails both private and public efforts. Thus, we encourage corporate executives and policymakers to invest in strengthening their networks. In this way, technical, economic, and political knowledge can be better integrated in order to follow both business and social needs, as well as to address the complexity characterizing the development of technological eco-innovations in the energy field [70]. Second, our study shows that different types of low-carbon energy technologies have been developed in response to environmental and geopolitical concerns. As a result, managers and policymakers are engaged in the development of different types of technical solution, which are, however, very difficult to be fully studied, assessed, and regulated. Thereby, a centralized organism that looks over the intensity and dynamics of the application of low-carbon energy technologies and their interaction with the society is needed. Furthermore, clear national policies should be underpinned by international agreements in the attempt to take actions aimed at reducing countries' environmental impacts and keeping pace with the ever changing technologies that are developed. Third, since environmental problems, such as pollution and climate change, are global externalities, with consequences all over the world (irrespective of who generated them), the development and the diffusion of low-carbon energy technologies are global issues. Thereby, transferring appropriate solutions by taking into account specific local needs, as well as ensuring their effective implementation, can help to address global environmental problems and reach sustainability targets [130]. This is especially true for developing countries where the assimilation, adaptation, and maintaining of the imported technologies are essential conditions to support sustainable development [172].

6. Limitations, future research directions, and conclusion

This study has some limitations that should be acknowledged. First, as explained in Section 2.1, the innovation process is described by means of patents, which do not represent the whole innovative portfolio, are subjected to unobserved heterogeneity, are not always the most suitable appropriation mechanisms, and there can be some biases in cross-country comparisons due to differences in the appropriability regimes [29–31]. Second, we focused on a specific type of eco-innovations in the energy field, as low-carbon energy technologies, although other kinds of eco-innovation, such as organizational and business ones, can be recognized and investigated (e.g., [173]).

In addition to address these limitations, future research should place more emphasis on the commercialization process underlying low-carbon energy technical solutions. We highlighted the relevance of commercial activities to spread these technical solutions. Thereby, empirical studies on how firms' strategies, technological characteristics, and environmental circumstances interact in order to bring those technologies to the market are needed. Furthermore, the economic impacts of energy-related technological eco-innovations are still not fully measured. Here, further research should be conducted in order to map out their diffusion and related socio-technical changes, as well as to assess their main macro-economic impacts. Moreover, scholars might focus their attention on the policies that have more effectively influenced low-carbon energy technologies' development, thus providing more detailed insights to policymakers. In conclusion, we believe that this study has taken the literature one step further in the on-going debate on the evolution of technological eco-innovations in the energy field and hope that it may encourage further studies in this relevant area of research.

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References

[1] WCED. Our common future: report of the world commission on environment and development. Switzerland; 1987.
[2] Linton JD. Letter from Kyoto—a call for research in science, technology, and society. Technovation 2013;33:101–3.
[3] Larson AL. Sustainable innovation through an entrepreneurship lens. Bus Strategy Environ 2000;9:304–17.
[4] OECD. The future of eco-innovation: the role of business models in green transformation. OECD background paper. Copenhagen, Denmark; 2012.
[5] Rennings K. Redefining innovation — eco-innovation research and the contribution from ecological economics. Ecol Econ 2000;32:319–32.
[6] Sneddon C, Howarth RB, Norgaard RB. Sustainable development in a post-Brundtland world. Ecol Econ 2006;57:253–68.
[7] McJeon HC, Clarke L, Kyle P, Wise M, Hackbarth A, Bryant BP, et al. Technology interactions among low-carbon energy technologies: what can we learn from a large number of scenarios? Energy Econ 2011;33:619–31.
[8] Zaragoza G, Ruiz-Aguirre A, Guillén-Burrieza E. Efficiency in the use of solar thermal energy of small membrane desalination systems for decentralized water production. Appl Energy 2014;130:491–9.
[9] EC. Impact Assessment SEC (2009) 1297 accompanying the Communication on Investing in the Development of Low Carbon Technologies (SET-Plan), COM (2009) 519 final; 2006.
[10] Kotha S, Orne D. Generic manufacturing strategies: a conceptual synthesis. Strateg Manage J 1989;10:211–31.
[11] Shrivastava P. Environmental technologies and competitive advantage. Strateg Manag J 1995;16:183–200.
[12] UNEP. Lessons learned on mainstreaming pilot projects into larger projects, united nations environment programme division of technology, industry and economics international environmental technology centre; 2009.
[13] OECD. Environmental policy technological innovation and patents. France, Paris: OECD Publishing; 2008.
[14] Wonglimpiyarat J. Technological change of the energy innovation system: from oil-based to bio-based energy. Appl Energy 2010;87:749–55.
[15] Eckman RS, Stackhouse Jr PW. CEOS contributions to informing energy management and policy decision making using space-based Earth observations. Appl Energy 2012;90:206–10.
[16] IEA. International low-carbon energy technology platform; 2012. <http://www.iea.org/media/technologyplatform/faq_tech_platform.pdf>.
[17] Nuttall WJ, Manz DL. A new energy security paradigm for the twenty-first century. Technol Forecast Soc Chang 2008;75:1247–59.
[18] Harmon RR, Cowan KR. A multiple perspectives view of the market case for green energy. Technol Forecast Soc Chang 2009;76:204–13.
[19] Palma D, Coletta G. Renewables technological competitiveness and sustainable development in the new global economy. ENEA Technology Transfer Unit; 2011.
[20] Johnstone N, Haščič I, Popp D. Renewable energy policies and technological innovation: evidence based on patent counts. Environ Resour Econ 2010;45:133–55.
[21] Demirel P, Kesidou E. Stimulating different types of eco-innovation in the UK: government policies and firm motivations. Ecol Econ 2011;70:1546–57.
[22] Kesidou E, Demirel P. On the drivers of eco-innovations: empirical evidence from the UK. Res Policy 2012;41:862–70.
[23] Horbach J, Rammer C, Rennings K. Determinants of eco-innovations by type of environmental impact — the role of regulatory push/pull, technology push and market pull. Ecol Econ 2012;78:112–22.
[24] Hargadon A, Sutton RI. Technology brokering and innovation in a product development firm. Adm Sci Q 1997;42:716–49.
[25] Rogers M. The definition and measurement of innovation. Melbourne Institute of Applied Economic and Social Research; 1998.
[26] Dangelico RM, Garavelli AC, Petruzzelli AM. A system dynamics model to analyze technology districts' evolution in a knowledge-based perspective. Technovation 2010;30:142–53.
[27] Evangelista R, Sandven T, Sirilli G, Smith K. Measuring innovation in european industry. Int J Econ Bus 1998;5:311–33.
[28] Griliches Z. Patent statistics as economic indicators: a survey. J Econ Literature 1990;28:1667–707.
[29] OECD. OECD patent statistics manual. France, Paris: OECD Publishing; 2009.
[30] Levin RC, Klevorick AK, Nelson RR, Winter SG. Appropriating the returns from industrial research and development. Brookings Papers on Economic Activity; 1987. p. 783.
[31] Bessen J. The value of U.S. patents by owner and patent characteristics. Res Policy 2008;37:932–45.
[32] Archibugi D, Pianta M. Innovation surveys and patents as technology indicators: the state of the art. France, Paris: Innovation, Patents and Technological Strategies, OECD; 1996.
[33] Pavitt K. Patent statistics as indicators of innovative activities: possibilities and problems. Scientometrics 1985;7:77–99.
[34] Messeni Petruzzelli A, Rotolo D, Albino V. Determinants of patent citations in biotechnology: an analysis of patent influence across the industrial and organizational boundaries. Technol Forecast Soc Chang 2014. http://dx.doi.org/10.1016/j.techfore.2014.02.018.
[35] Dernis H, Guellec D, Bruno van Pottelsberghe de la P. Using patent counts for cross-country comparisons of technology output. STI Review No. 27; 2001.
[36] Dernis H, Khan M. Triadic patent families methodology. France, Paris: OECD Publishing; 2004.
[37] Comanor WS, Scherer FM. Patent statistics as a measure of technical change. J Polit Econ 1969;77:392.
[38] Hagedoorn J, Cloodt M. Measuring innovative performance: is there an advantage in using multiple indicators? Res Policy 2003;32:1365.
[39] Singh J. Distributed R&D, cross-regional knowledge integration and quality of innovative output. Res Policy 2008;37:77–96.
[40] Jaffe AB, Trajtenberg M. Geographic localization of knowledge spillovers as evidenced by patent citations. Quart J Econ 1993;108:577.
[41] Liu JS, Kuan C-H, Cha S-C, Chuang W-L, Gau GJ, Jeng J-Y. Photovoltaic technology development: a perspective from patent growth analysis. Sol Energy Mater Sol Cells 2011;95:3130–6.
[42] Meyer M. Tracing knowledge flows in innovation systems. Scientometrics 2002;54:193–212.
[43] Popp D. Induced innovation and energy prices. Am Econ Rev 2002;92:160–80.
[44] Popp D. Lessons from patents: using patents to measure technological change in environmental models. Ecol Econ 2005;54:209–26.
[45] Abraham BP, Moitra SD. Innovation assessment through patent analysis. Technovation 2001;21:245–52.
[46] Oltra V, Kemp R, De Vries FP. Patents as a measure for eco-innovation. Int J Environ Technol Manage 2010;13:130–48.
[47] Trajtenberg M. A penny for your quotes: patent citations and the value of innovations. RAND J Econ (RAND J Econ) 1990;21:172–87.
[48] Harhoff D, Narin F, Scherer FM, Vopel K. Citation frequency and the value of patented inventions. Rev Econ Stat 1999;81:511–5.
[49] Hall BH, Jaffe A, Trajtenberg M. Market value and patent citations. Rand J Econ 2005;36:16–38.
[50] Hall BH, Jaffe AB, Trajtenberg M. The NBER patent citations data file: lessons, insights and methodological tools. Cambridge, MA: National Bureau of Economic Research; 2001.
[51] Gambardella A, Harhoff D, Verspagen B. The value of European patents. Eur Manage Rev 2008;5:69–84.
[52] Ahuja G, Lampert CM. Entrepreneurship in the large corporation: a longitudinal study of how established firms create breakthrough inventions. Strateg Manag J 2001;22:521–43.
[53] Leu H-J, Wu C-C, Lin C-Y. Technology exploration and forecasting of biofuels and biohydrogen energy from patent analysis. Int J Hydrogen Energy 2012;37:15719–25.
[54] Phene A, Fladmoe-Lindquist K, Marsh L. Breakthrough innovations in the U.S. biotechnology industry: the effects of technological space and geographic origin. Strateg Manag J 2006;27:369–88.
[55] Park JY. The evolution of waste into a resource: examining innovation in technologies reusing coal combustion by-products using patent data. Res Policy 2014. http://dx.doi.org/10.1016/j.respol.2014.06.002.
[56] EC. EUROPE 2020. A strategy for smart. Sustainable and inclusive growth, COM(2010) 2020 final. Belgium, Brussels; 2010.
[57] OECD. Oslo manual. France, Paris: OECD Publishing; 2005.
[58] OECD. Towards green growth. France, Paris: OECD Publishing; 2011.
[59] Hargroves K, Smith MH, Smith MH. The natural advantage of nations: business opportunities, innovation and governance in the 21st century. Earthscan LLC; 2013.
[60] Schiederig T, Tietze F, Herstatt C. Green innovation in technology and innovation management – an exploratory literature review. R&D Manage 2012;42:180–92.
[61] Fussler C, James P. Driving eco-innovation: a breakthrough discipline for innovation and sustainability. Pitman Publishing; 1996.
[62] Andersen MM. Eco-innovation-towards a taxonomy and theory. In: 25th DRUID celebration conference. Denmark, Copenhagen; 2008.
[63] Arundel A, Kemp R. Measuring eco-innovation. UNU Merit, Working Paper Series; 2008.
[64] Newell RG. Literature review of recent trends and future prospects for innovation in climate change mitigation; 2009.
[65] EC/EACI. Boosting green business. Executive agency for competitiveness and innovation and European commission. Luxembourg; 2011.
[66] Stern N. The economics of climate change. Am Econ Rev 2008;98:1–37.
[67] EC. Stimulating technologies for sustainable development: an environmental technologies action plan for the european union, IP/04/117. Brussels; 2004.
[68] OECD. Innovation and the environment. France, Paris: OECD Publishing; 2002.
[69] Machiba T. Eco-innovation for enabling resource efficiency and green growth: development of an analytical framework and preliminary analysis of industry and policy practices. IEEP 2010;7:357–70.
[70] Messeni Petruzzelli A, Dangelico RM, Rotolo D, Albino V. Organizational factors and technological features in the development of green innovations: evidence from patent analysis. Innovat: Manage, Policy Practice 2011;13:291–310.

[71] Sun Y, Lu Y, Wang T, Ma H, He G. Pattern of patent-based environmental technology innovation in China. Technol Forecast Soc Chang 2008;75:1032–42.
[72] Pilkington A, Dyerson R, Tissier O. The electric vehicle: patent data as indicators of technological development. World Patent Inf 2002;24:5–12.
[73] Brunnermeier SB, Cohen MA. Determinants of environmental innovation in US manufacturing industries. J Environ Econ Manage 2003;45:278–93.
[74] Hoggett R. Technology scale and supply chains in a secure, affordable and low carbon energy transition. Appl Energy 2014;123:296–306.
[75] Pilkington A. Technology portfolio alignment as an indicator of commercialisation: an investigation of fuel cell patenting. Technovation 2004;24:761–71.
[76] Oltra V, Saint Jean M. Sectoral systems of environmental innovation: an application to the French automotive industry. Technol Forecast Soc Chang 2009;76:567–83.
[77] UN. United nations conference on environment and development, Agenda 21, Chapter 34. Rio de Janeiro; 1992.
[78] Mani S. Is India becoming more innovative since 1991? Some disquieting features. Econ Polit Weekly 2009;44:41–51.
[79] Guruprasad K, Kanagavel P, Srikanth K, Radhika K, Sonal S. Analysis of US patents granted to indian inventors. J Intellect Prop Rights 2003;8:205–12.
[80] Huang M-H, Chang H-W, Chen D-Z. The trend of concentration in scientific research and technological innovation: a reduction of the predominant role of the U.S. in world research & technology. J Informetrics 2012;6:457–68.
[81] NREL. Clean energy innovation: sources of technical and commercial breakthroughs. Technical report NREL/TP-6A20-50624; 2011.
[82] Acs ZJ, Anselin L, Varga A. Patents and innovation counts as measures of regional production of new knowledge. Res Policy 2002;31:1069–85.
[83] Narin F, Hamilton KS, Olivastro D. The increasing linkage between U.S. technology and public science. Res Policy 1997;26:317–30.
[84] Meyer M. Does science push technology? Patents citing scientific literature. Res Policy 2000;29:409–34.
[85] Sharif MN. Measurement of technology for national development. Technol Forecast Soc Chang 1986;29:119–72.
[86] Deyle H-G, Grupp H. Commuters and the regional assignment of innovative activities: a methodological patent study of German districts. Res Policy 2005;34:221–34.
[87] Verspagen B, De Loo I. Technology spillovers between sectors. Technol Forecast Soc Chang 1999;60:215–35.
[88] USA Ibp. Global research nuclear reactors handbook, vol. 1. USA: International Business Publications; 2013.
[89] Lund PD. Fast market penetration of energy technologies in retrospect with application to clean energy futures. Appl Energy 2010;87:3575–83.
[90] Sovacool BK, Valentine SV. The national politics of nuclear power. Routledge: Economics, Security, and Governance; 2012.
[91] Nuttall WJ. Nuclear renaissance: technologies and policies for the future of nuclear power. Taylor & Francis; 2004.
[92] Public Law 109–58—AUG.8, Energy Policy Act of 2005; 2005. <http://www.gpo.gov/fdsys/pkg/PLAW-109publ58/pdf/PLAW-109publ58.pdf>.
[93] World Nuclear Association. Advanced nuclear power reactors. <http://vaec.gov.vn/userfiles/file/Advanced%20Nuclear%20Power%20Reactors%20t9_09.pdf>.
[94] OECD, IAEA. Uranium 2005: resources. France, Paris: Production and Demand, OECD Publishing; 2006.
[95] Jaffe AB. Real effects of academic research. Am Econ Rev 1989;79:957–70.
[96] Adams JD. Fundamental stocks of knowledge and productivity growth. J Polit Econ 1990;98:673–702.
[97] Brooks H. The relationship between science and technology. Res Policy 1994;23:477–86.
[98] Cockburn IM, Henderson RM. Absorptive capacity, coauthoring behavior, and the organization of research in drug discovery. J Ind Econ 1998;46:157–82.
[99] Fleming L, Sorenson O. Science as a map in technological search. Strateg Manag J 2004;25:909–28.
[100] Dasgupta P, David PA. Toward a new economics of science. Res Policy 1994;23:487–521.
[101] Cassiman B, Veugelers R, Zuniga P. In search of performance effects of (in)direct industry science links. Ind Corporate Change 2008;17:611–46.
[102] US Department of Energy. Basic research needs for advanced nuclear energy systems. Report of the basic energy sciences workshop on basic research needs for advanced nuclear energy systems; 2006 <http://li.mit.edu/Archive/Papers/06/ANES_rpt.pdf>.
[103] Li Y, Cao H, Wang S, Jin Y, Li D, Wang X, et al. Load shifting of nuclear power plants using cryogenic energy storage technology. Appl Energy 2014;113:1710–6.
[104] Griliches Z. Issues in assessing the contribution of research and development to productivity growth. Bell J Econ 1979;10:92–116.
[105] Mansfield E. Academic research and industrial innovation. Res Policy 1991;20:1–12.
[106] Rosenberg N, Nelson RR. American universities and technical advance in industry. Res Policy 1994;23:323–48.
[107] Cohen WM, Nelson RR, Walsh JP. Links and impacts: the influence of public research on industrial R&D. Manage Sci 2002;48:1–23.
[108] OECD. Innovation and growth. Rationale for an innovation strategy. France, Paris: OECD Publishing; 2007.
[109] I-NERI. Fiscal year 2011 Annual report. International Nuclear Energy Research Initiative; 2001.
[110] Demirbas A. Political, economic and environmental impacts of biofuels: a review. Appl Energy 2009;86(Supplement 1):S108–78.
[111] LFEE. An overview of coal based integrated gasification combined cycle (IGCC) technology. MIT LFEE 2005–002 WP; 2005.
[112] EPA. Technology characterization: fuel cells. Arlington, Virginia: Prepared by: Energy and Environmental Analysis; 2008.
[113] Basu P. Biomass gasification and pyrolysis: practical design and theory. Elsevier Science; 2010.
[114] Lee S, Shah YT. Biofuels and bioenergy: processes and technologies. Taylor & Francis; 2012.
[115] Wagner HJ, Mathur J. Introduction to hydro energy systems: basics, technology and operation. Springer; 2011.
[116] Nelson V. Wind energy: renewable energy and the environment. 2nd ed. Taylor & Francis; 2013.
[117] Ecoworld. How much solar energy hits earth?; 2011 <http://www.ecoworld.com/energy-fuels/how-much-solar-energy-hits-earth.html>.
[118] Desideri U, Zepparelli F, Morettini V, Garroni E. Comparative analysis of concentrating solar power and photovoltaic technologies: technical and environmental evaluations. Appl Energy 2013;102:765–84.
[119] Chow TT. A review on photovoltaic/thermal hybrid solar technology. Appl Energy 2010;87:365–79.
[120] Gupta HK, Roy S. Geothermal energy: an alternative resource for the 21st century. Elsevier Press; 2007.
[121] Langley BC. Heat pump technology. Prentice Hall; 2002.
[122] Capehart BL, Turner WC, Kennedy WJ. Guide to energy management. Fairmont Press; 2008.
[123] Bouadila S, Kooli S, Lazaar M, Skouri S, Farhat A. Performance of a new solar air heater with packed-bed latent storage energy for nocturnal use. Appl Energy 2013;110:267–75.
[124] Sellers R. Renewable energy markets: past and future trends, international energy agency; 2004. <http://www.enagri.info/gold/knowledge_base/reports_local/Biofuels_Sellers_Paper.pdf>.
[125] Jacobsson S, Johnson A. The diffusion of renewable energy technology: an analytical framework and key issues for research. Energy Policy 2000;28:625–40.
[126] UN. Report of the united nation conference on sustainable development, A/CONF.199/20. New York: United Nations publishing; 2002.
[127] Lewis J. Technology acquisition and innovation in the developing world: wind turbine development in China and India. Studies Comp Int Dev 2007;42:208–32.
[128] Levi MA, O'Neil EC, Segal SK. A energy innovation: driving technology competition and cooperation among the U.S. China, India, and Brazil. New York: Council on Foreign Relations; 2010.
[129] Schneider M, Holzer A, Hoffmann VH. Understanding the CDM's contribution to technology transfer. Energy Policy 2008;36:2930–8.
[130] van der Gaast W, Begg K, Flamos A. Promoting sustainable energy technology transfers to developing countries through the CDM. Appl Energy 2009;86:230–6.
[131] EIA. Federal energy subsidies. EIA service report, SR/EMEU/92-02, Distribution Category UC-98; 1998.
[132] Jafarian M, Arjomandi M, Nathan GJ. A hybrid solar chemical looping combustion system with a high solar share. Appl Energy 2014;126:69–77.
[133] Messeni Petruzzelli A. The impact of technological relatedness, prior ties, and geographical distance on university–industry collaborations: a joint-patent analysis. Technovation 2011;31:309–19.
[134] Fabrizio KR. Absorptive capacity and the search for innovation. Res Policy 2009;38:255–67.
[135] Audretsch DB, Lehmann EE, Warning S. University spillovers and new firm location. Res Policy 2005;34:1113–22.
[136] Saxenian A. Lessons from silicon valley. Technol Rev 1994;97:42–51.
[137] Gicquel R. Energy systems: a new approach to engineering thermodynamics. Taylor & Francis; 2012.
[138] Masini A, Menichetti E. Investment decisions in the renewable energy sector: an analysis of non-financial drivers. Technol Forecast Soc Chang 2013;80:510–24.
[139] Painuly JP. Barriers to renewable energy penetration; a framework for analysis. Renewable Energy 2001;24:73–89.
[140] Glassley WE. Geothermal energy: renewable energy and the environment. Taylor & Francis; 2011.
[141] IPHE. Hydrogen and fuel cell global commercialization & development update, international partnership for hydrogen and fuel cells in the economy; 2010 <http://www.iphe.net/docs/Resources/IPHE_FINAL_SON_press_quality.pdf>.
[142] Wang Z, Yin F, Zhang Y, Zhang X. An empirical research on the influencing factors of regional CO2 emissions: evidence from Beijing city, China. Appl Energy 2012;100:277–84.
[143] Yazawa K, Koh YR, Shakouri A. Optimization of thermoelectric topping combined steam turbine cycles for energy economy. Appl Energy 2013;109:1–9.
[144] Zhang L, Xia X, Zhang J. Improving energy efficiency of cyclone circuits in coal beneficiation plants by pump-storage systems. Appl Energy 2014;119:306–13.
[145] ES. Energy efficiency report. Italy, Milan: Energy & Strategy Group Publishing; 2012.
[146] Goe M, Gaustad G. Strengthening the case for recycling photovoltaics: an energy payback analysis. Appl Energy 2014;120:41–8.

[147] C2ES. Climate techbook, center for climate and energy solution. <http://www.c2es.org/climate-techbook>.

[148] N'Tsoukpoe KE, Schmidt T, Rammelberg HU, Watts BA, Ruck WKL. A systematic multi-step screening of numerous salt hydrates for low temperature thermochemical energy storage. Appl Energy 2014;124:1–16.

[149] Glisson TH. Introduction to circuit analysis and design. Springer; 2011.

[150] Xia X, Zhang J. Mathematical description for the measurement and verification of energy efficiency improvement. Appl Energy 2013;111: 247–56.

[151] Nørgård JS, Gula A, Almeida A. Division NATOSA. Development with sustainable use of electricity. Netherlands: Springer; 1998.

[152] White A, McTigue J, Markides C. Wave propagation and thermodynamic losses in packed-bed thermal reservoirs for energy storage. Appl Energy 2014;130:648–57.

[153] Paksoy HÖ, Division NATOPD. Thermal energy storage for sustainable energy consumption: fundamentals, case studies and design. Springer; 2007.

[154] Ltd W. The green office manual: a guide to responsible practice. Taylor & Francis; 2013.

[155] Mumovic D, Santamouris M. A handbook of sustainable building design and engineering: an integrated approach to energy, health and operational performance. Taylor & Francis; 2013.

[156] Nigg BM, MacIntosh BR, Mester J. Biomechanics and biology of movement. 1st ed. Human Kinetics; 2000.

[157] Wulfinghoff D. The modern history of energy conservation: an overview for information professionals. Energy Institute Press; 2001.

[158] Gillingham K, Newell R, Palmer K. Energy efficiency policies: a retrospective examination. Ann Rev Environ Resour 2006;31:161–92.

[159] Public Law 102-486-OCT.24. Energy Policy Act of 1992; 1992. <http://www.afdc.energy.gov/pdfs/2527.pdf>.

[160] López-Peña Á, Pérez-Arriaga I, Linares P. Renewables vs. energy efficiency: the cost of carbon emissions reduction in Spain. Energy Policy 2012;50: 659–68.

[161] EIA. Energy information administration. Japan: Country Analysis Brief; 2012 <http://www.eia.gov/cabs/Japan/pdf.pdf>.

[162] IEA. Phase out of incandescent lamp. France, Paris: Energy Efficiency Series; 2010.

[163] White AJ. Loss analysis of thermal reservoirs for electrical energy storage schemes. Appl Energy 2011;88:4150–9.

[164] Teece DJ. Profiting from technological innovation: implications for integration, collaboration, licensing and public policy. Res Policy 1986;15: 285–305.

[165] Henderson R. Underinvestment and incompetence as responses to radical innovation: evidence from the photolithographic alignment equipment industry. Rand J Econ 1993;24:248–70.

[166] Porter ME, Reinhardt F. A strategic approach to climate. Harvard Bus Rev 2007;85:22–6.

[167] ISPRE. Research and development on renewable energies: a global report on photovoltaic and wind energy. France, Paris: International Science Panel on Renewable Energies; 2009.

[168] PEW. Who's winning the clean energy race? Washington D.C.: The Pew Charitable Trusts; 2010.

[169] Nill J, Kemp R. Evolutionary approaches for sustainable innovation policies: from niche to paradigm? Res Policy 2009;38:668–80.

[170] Lema R, Berger A, Schmitz H. China's Impact on the Global Wind Power Industry. J Curr Chin Affairs 2013;42:37–69.

[171] UN. United nations conference on environment and development, Agenda 21, Chapter 35, Rio de Janeiro; 1992.

[172] UN. Report of the united nations conference on sustainable development, A/CONF.216/16. New York: United Nations publishing; 2012.

[173] Kemp R, Pearson P. Final report MEI project about measuring eco-innovation. Netherlands: Maastricht; 2008.