Master Thesis

Monitoring innovation progress of clean energy technologies

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Preface

The work presented henceforth concludes my Master thesis of the program Sustainable Development, Energy and Materials at Utrecht University. The research was executed during a five-month internship at Trinomics, an economic consultancy focused on the sectors of energy, environment and climate change. However, the results are an outcome of own elaboration, hence they do not necessarily represent the view of Trinomics.

Several people contributed to this Master thesis on an academic and on a personal level. First, I would like to express my gratitude to my university supervisor, Dr Robert Harmsen, who provided me constantly with insightful comments and guidance throughout the process of the thesis. Next, I would like to thank my internship supervisor Perla Torres, for her constant support and her continuous engagement with the topic, which was determinant for the completion of the thesis. Finally, I would like to express my gratitude to my loved ones and more specifically to my parents, who provided me constantly with support and encouragement throughout the years of my studies.

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Summary

The substantial intensification of climate change has given significant impetus to the development of clean energy technologies. The European Union is actively taking part in combating climate change, aiming in energy transition and in net-zero emissions by 2050. It has been acknowledged that innovation will play a key role in the accomplishment of a sustainable economic growth, while mitigating greenhouse gas emissions and energy consumption. Due to the significant importance of innovation, there has been a need for its quantification, however, it is a rather difficult task. There are three main categories of innovation indicators, namely input, throughput and output indicators. In this master thesis, the focus will be on the throughput indicators and more specifically on the patents and bibliometric indicators. Previous literature sources have already used these two types of indicators to measure innovation in the energy sector, yet to a limited extent. Therefore, the aim of this research is to gather the patent and bibliometric indicators used in previous literature, assess their merits and conclude which indicators are the most suitable to reflect adequately the innovation activity of clean energy technologies. To answer the research question "*Which are the most appropriate indicators to monitor the innovation progress of clean energy technologies under the prism of patents and bibliometrics?*", a conceptual framework is proposed which consists of a literature review for the collection of the indicators, a set of criteria and an assessment. The final set of patent and bibliometric indicators which concluded from the assessment were used to measure the progress of innovation of nine different clean energy technologies for the period 2007-2018. The results showed that even though some indicators might fulfil all the applied criteria, they provide skewed results, hence they should be avoided for innovation measurement. Regarding the evolution of innovation of the clean energy technologies, solar PV and wind energy technologies developed the most during the in-scope period, even though they have been well-established technologies for decades. Ocean energy and CCS/U are slowly developing, thus more R&D is required in these sectors. Finally, concerning the world leaders of innovation, China, Germany and the United States demonstrated the highest innovative activity, with regard to both patents and publications.

Keywords: innovation, clean energy technologies, patents, bibliometrics, indicators

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1 Introduction

1.1 Background

In the wake of the worldwide awareness regarding the environmental problems that our society faces, the development of clean energy technologies (CETs) has gained significant momentum. CETs include renewable energy sources (RES) as well as energy-saving technologies that contribute to the climate change mitigation, such as hydrogen and fuel cells (NCSEA, 2020). Europe has also been affected by global warming, which has direct economic effects and jeopardizes food, water and energy security (European Commission, 2018). The energy transition and the creation of a climate-neutral economy by 2050 are two main goals of the European Union (EU), and it is considered that innovation will play a significant role in facilitating the goal of net-zero emissions by 2050 (European Commission, 2018). Technological innovation is a key factor for sustained economic growth and improves productivity and competitiveness, since the deployment of new ideas and technologies results to more goods and services that can be produced by using the same input (European Central Bank, 2017). However, the quantification of innovation is a particularly challenging task. There is a complicated web of relationships in several stages between the research and innovation activities towards the commercialization of a product, which makes the measurement of innovation especially demanding (Archibugi & Planta, 1996).

The EU has acknowledged the importance of innovation in CETs and has developed a number of policies and funding mechanisms to support research, development and innovation (RD&I) in the field. Europe has committed to Mission Innovation (MI), which is a global initiative that works towards the achievement of clean energy innovation, in order to make clean energy affordable for everyone. The goals of MI are the strengthening of investments by the public sector in clean energy RD&I, the rise of private investments in energy innovation, the enhancement of collaboration among the country-members of MI, and the increase of awareness regarding the possibilities, the gaps and the new opportunities of energy innovation (Mission Innovation, 2016). Moreover, in order to achieve the energy transition and to increase energy security, sustainability and competitiveness, the EU has developed two strategic instruments, namely Energy Union and Strategic Energy Technology (SET) Plan. Energy Union is based on five pillars (European Commission, 2020):

i. energy security, solidarity and trust;
ii. a fully integrated European energy market;
iii. energy efficiency contributing to moderation of demand;
iv. decarbonising the economy;
v. research innovation and competitiveness.

The fifth pillar is focused on supporting innovation in low-carbon and clean energy sector by setting six RD&I priorities to drive the energy transition and improve competitiveness.

The SET Plan enhances and supports this fifth pillar, by focusing on ten actions, aligned to the RD&I priorities of Energy Union (European Commission, 2020), listed in Table 1.

Table 1 Energy Union's RD&I priorities and the SET Plan key actions for the realization of the energy transition.

RD&I priorities	SET Plan Key actions
1. Number one in renewables	1. Performant renewable technologies integrated into the system 2. Reduce the costs of technologies
2. Consumers in the energy system	3. New technologies & services for costumers 4. Resilience & security of the energy system
3. Efficient energy systems	5. New materials & technologies for buildings 6. Energy efficiency for industry
4. Sustainable transport	7. Competitive in the global battery sector & e-mobility 8. Renewable fuels and bioenergy
5. Carbon Capture Utilisation & Storage	9. Carbon Capture Storage/Use
6. Nuclear safety	10. Nuclear safety

Source: European Commission (2020)

From the SET Plan guidelines and the RD&I priorities of Energy Union, a disaggregation of the relevant CETs was conducted (see Chapter 2), whose progress of innovation was investigated in this research.

1.2 Problem description

1.2.1 The measurement of innovation

The measurement of innovation started from the decade of 1980s and is continuing until today at a developing pace (Bloch, 2007). The importance of quantifying innovation is significant, firstly because, on a theoretical level, the statistics of innovation can be used to examine the established theories and they can contribute to the expansion of knowledge. Secondly, public policies also benefit from the measurement of innovation, since the statistical indicators identify the strengths and the weaknesses of a certain technology. Finally, from the data of innovation, a geographical map of leader and laggard countries can be formed, which could assist future policies and investments (Carvalho et al., 2015).

In the literature, different categories of quantitative indicators are used to measure the progress of innovation. According to Borup & al. (2016), the first category includes the input indicators, which refer to human and other resources, such as research and development (R&D) personnel. Even though those types of indicators can provide useful insights about innovation outputs, they are difficult to use, mainly because the data availability is limited

and there are several data gaps (Haščič & Migotto, 2015). The second category, namely throughput indicators, comprises the intermediate products of the innovation process, such as patent applications, bibliometrics and citation statistics. These indicators are of significant interest, since patents provide detailed information about innovation procedures and facilitate the research per technological field, while bibliometrics focus on the diffusion of knowledge among institutions (e.g. universities, firms) and countries (Haščič & Migotto, 2015). An important advantage compared to the first category is that their data are easily accessible and at low costs (Fiorini et al., 2017). The last category includes the outputs indicators which encompasses the economic effects of innovative technologies, such as trade, exports and annual turnover. However, as Borup & al. (2016) stress, the economic effects of innovation are rather complicated to measure, since they can include learning effects that contribute indirectly to the financial returns. Moreover, the study argues that simultaneously with the innovation activities, other developments might occur in a country, such as changes in the energy mix or declination of access to fossil energy sources, hence the economic effects, in that case, are quite difficult to be distinguished.
Consequently, the throughput indicators (i.e. patents and bibliometrics) offer a good representation of innovation activity, while in terms of data availability, they can facilitate the quantification of innovation progress of CETs. For those reasons, this thesis research focused on these two types of indicators.

Literature gap on patent and bibliometric indicators

Several scientific studies have attempted to measure innovation by using patent and bibliometric indicators. More specifically, the study of Haščič & Migotto (2015) measured the innovation of environmental-related technologies by using patent statistics, such as counts of patent applications, patent citations and counts of co-inventions. The research of Hu & Mathews (2008), defines China's innovative capacity by using among others patent intensity, patent growth rate and patent citations. Noailly (2012) uses the data of patent applications in order to measure the technological innovation related to the energy efficiency of the buildings. The study of Lindman & Söderholm (2016) aims to investigate the impacts of public R&D support and feed-in tariff schemes on the innovation of wind energy, by taking patent application data as a proxy of wind energy innovation. However, these studies use only a very limited number of indicators related to patents, hence it is likely that they do not reflect in full the innovative activity. On top of that, it appears that several indicators, such as the number of patent applications, are preferred compared to others since they are used more frequently.

Similarly, bibliometric indicators have been used by several studies, yet to a limited extent. For instance, Albort-Morant et al. (2017) measured green innovation by using indicators such as the number of publications, the number of most cited papers and the number of empirical studies related to green innovation. Vidican et al. (2009) researched the technological innovation related to photovoltaics (PV) by using only the number of academic publications. However, the use of only one indicator might omit some aspects of knowledge diffusion.

In conclusion, the need for more in-depth research regarding the patent and bibliometric indicators arises, in order to evaluate the merits of the indicators and ultimately to determine which ones are optimum to measure the innovation progress of CETs. Additionally, by using these two categories of indicators simultaneously for the innovation measurement, interesting results might arise concerning in what extent they complement or strengthen each other, or whether they provide similar insights.

1.2.2 Research question

Based on the problem definition, the aim of this master thesis was to conduct an extensive research regarding the patent and bibliometric indicators, identify the most appropriate ones for measuring innovation in the clean energy sector and ultimately quantify innovation progress for the selected CETs. Consequently, the research question that emerges is:

Which are the most appropriate indicators to monitor the innovation progress of clean energy technologies under the prism of patents and bibliometrics?

The report has structured as follows in order to answer the research question; Chapter 2 discusses the scope of the study and the conceptual framework that was created for the needs of this study, which includes the literature review, the assessment criteria that were applied to the indicators and the assessment per se. Chapter 3 regards the data collection and the methodology that was followed in order to measure the progress innovation during the last decade for the selected CETs, by using the results of Chapter 2. In Chapter 4, the results of the innovation measurement are presented, while Chapter 5 discusses the limitations of the research, the contribution of the study to the scientific literature and recommendations for future research. Finally, Chapter 6 answers the research question and concludes the key messages of this research.

2 Theoretical Framework

2.1 Theory

2.1.1 Scope of the study

From the RD&I priorities of the Energy Union and the 10 actions of the SET Plan, the relevant CETs were disaggregated. The report of Fiorini et al. (2017) provides a detailed list of the technologies according to the six RD&I priorities categories. The present study did not include the priorities “Consumers in the energy system” and “Efficient energy systems”, firstly due to time constraints of the research and secondly due to the fact that the focus of this thesis was mainly on the technologies related to the energy sources. The selection of the CETs that are examined in this study is depicted in Table 2.

Table 2 The CETs that were researched in the thesis project, aligned with RD&I priorities and SET Plan key actions

RD&I priorities	SET Plan Key Actions	Clean Energy Technologies
No. 1 in Renewables	• Performant renewable technologies integrated in the system • Reduce technology costs	• Onshore and off-shore wind energy • Concentrated Solar Power • Solar photovoltaics • Ocean energy • Geothermal energy • Hydropower
Sustainable Transport	• Renewable fuels and bioenergy	• Bioenergy
Carbon Capture Utilisation and Storage	• Carbon Capture Utilisation and Storage	• Carbon Capture Utilisation and Storage (CCS/U)
Nuclear Safety	• Nuclear Safety	• Nuclear fission/fusion

Source: Fiorini et al. (2017)

Apart from assessing the patent and bibliometric indicators used in previous literature and identifying the most effective ones, the aim of this study is also to detect which countries globally are the leaders of innovation in the aforementioned CETs and simultaneously to report whether the EU is taking active part in the progress of innovation of the clean energy sector. The involvement of the EU-27 Member States in the development of the CETs can be used as an indication of whether the zero-emissions goals of the EU might be achieved by 2050.

Finally, the time frame of this research was from 2007 until the present[1] for two main reasons; first, the global financial crisis that occurred in 2007-2008, influenced heavily the

[1] Present is considered the most recent year with available data. For the case of patents the most recent year was 2018, while for bibliometrics was 2017.

energy developments, since it increased the price of the oil barrel which led to a rise of granted patents regarding renewable energy technologies (Bonnet et al., 2018). Therefore, it is significantly interesting to monitor how the research and the patent activity developed after that financial crisis. Secondly, during the last two decades, the political figures in a world level have recognised the urgency of climate change mitigation. This is portrayed by the several policies and accords that have been set in place, such as the Paris agreement in 2016 (UNFCCC, 2015). Also, in an EU level, many environmental policies have been established, such as the Renewable energy directive in 2009, to promote the renewable energy production in the EU (European Commission, 2020) and the EU Emissions Trading System (EU ETS), which targets the reduction of greenhouse gas emissions, introduced in 2005 (European Commission, 2015).

2.1.2 Patent and bibliometric indicators as measurement tools of innovation

Innovation is a term that has been discussed since 1934 by Schumpeter (Schumpeter, 1934), yet in this research, the definition of OECD (2018) is used, which states: "*An innovation is a new or improved product or process (or combination thereof) that differs significantly from the unit's previous products or processes and that has been made available to potential users (product) or brought into use by the unit (process)*" (OECD, 2018, p. 20). Innovation data and consequently their process is of significant importance for several actors such as managers of firms, academics, policy makers, as well as public and private organizations since they give valuable information regarding differences across countries and industries, innovation impacts and potential barriers (OECD, 2018). However, as Markatou (2013) stresses, innovation activities involve a wide range of nature, scope and products, hence its quantification can only be achieved indirectly through indicators. According to EEA (2003), "*An indicator is an observed value representative of a phenomenon of study. In general, indicators quantify information by aggregating different and multiple data*" (EEA, 2003, p.20).

Patent indicators

By conducting literature research, patent data seemed to be one of the most dominant methods for measuring innovation. According to OECD (2008), "*A patent is a right granted by a government to an inventor in exchange for the publication of the invention; it entitles the inventor to prevent any third party from using the invention in any way, for an agreed period*" (OECD, 2008, p.398). Some indicative studies that used patent data are the one of Crosby (2000) which calculates the amount of innovation in the economy of Australia, the study of Albino et al. (2014) that plotted the trends of low carbon energy technologies for a period of 40 years by using patent statistics, and the research of Wagner (2007) that verifies that environmental innovation can be computed from patent data.

The benefits of using patent statistics are multiple. Firstly, since a patent is by definition an entity that protects an invention, patent statistics are a proxy to track innovative performance (Fiorini et al., 2017). Secondly, a great part of patent data can be found online in low cost, hence information such as the technological context of an invention and the country of application is widely available to be used as knowledge diffusion indicator and to monitor cooperation between countries and firms (Fiorini et al., 2017). Finally, OECD (2009) points that due to the existence of long-term coverage patent data, the behavior and the development of the technologies as well as the links among the technical fields can be analyzed.

Yet, patent statistics should be elaborated cautiously. An important factor to consider is that not all inventions are patented due to the high costs of applications or due to the fact that some companies prefer to protect their inventions alternatively. An example is the use of secrecy or in other words trade secret[2] which has unlimited duration and has commercial value (Wajsman & García-Valero, 2017). Furthermore, the propensity of patent filings may differ across technical sectors, while there could be also differences in patent laws and practices among countries or patent offices. In addition, large-scale companies are in a favorable position in relation to the smaller ones, since usually they have the financial means to pay for the costs of the patent application. Also, the commercial value of the patents might be skewed, since many patents have no industrial use, hence low value, while a few have high industrial use and value (OECD, 2009). However, by using an appropriate methodology those drawbacks can be overcome.

Bibliometric indicators

The use of bibliometric indicators is another method to measure innovation that is often used in literature. More specifically, bibliometrics is a quantitative tool that measures the quality of technology and science as well as the innovation of a technology, a product, or an industry (Yeo et al., 2015). It usually involves data such as publication, title, author(s) and location (Borup & al., 2016). In this research, the main focus was on the scientific literature, hence the term "scientometrics" is the one that describes more appropriately this methodology (Hood & Wilson, 2001). Khan & Park (2012) use scientometrics in order to examine innovation progress in Asia, while Liu et al. (2015) identified how innovation systems evolved during a period of 37 years by using bibliometric indicators.

Literature indicates that bibliometric analysis facilitates the quantification of innovation. It is a powerful tool which allows the researchers to understand the past and predict the future, by exploring, analysing and organising past data and identify patterns (Daim et al., 2006). In addition, it is a relatively fair way to assess research institutions in terms of scientific outcomes (Kazakis et al., 2014). Moreover, scientific publications are a good indication of knowledge diffusion and they designate linkages between countries, industries and universities (Katz & Hicks, 1998). Yet, there are also some underlying limitations. Yeo et al. (2015) argue that not all the published scientific papers have the same quality and that a lot of scientific work remains unpublished. Moreover, a scientific paper will not necessarily result in an invention or a new product, since most of the research aims to the development of the knowledge and the technology.

[2] A trade secret needs to have commercial value, being secret and not accessible and actions should be taken in order to maintain the secret. Examples of information included in trade secrets are manufacturing processes, results of a marketing study, or information on customers and suppliers (Wajsman & García-Valero, 2017).

2.2 Conceptual framework

This section introduces the conceptual framework that was constructed, in order to achieve the goals of this research. More specifically, first the results of the literature review are presented, then the criteria that were selected to assess the indicators are discussed and finally the assessment of the indicators is described. An overview of the conceptual framework is presented in Figure 1.

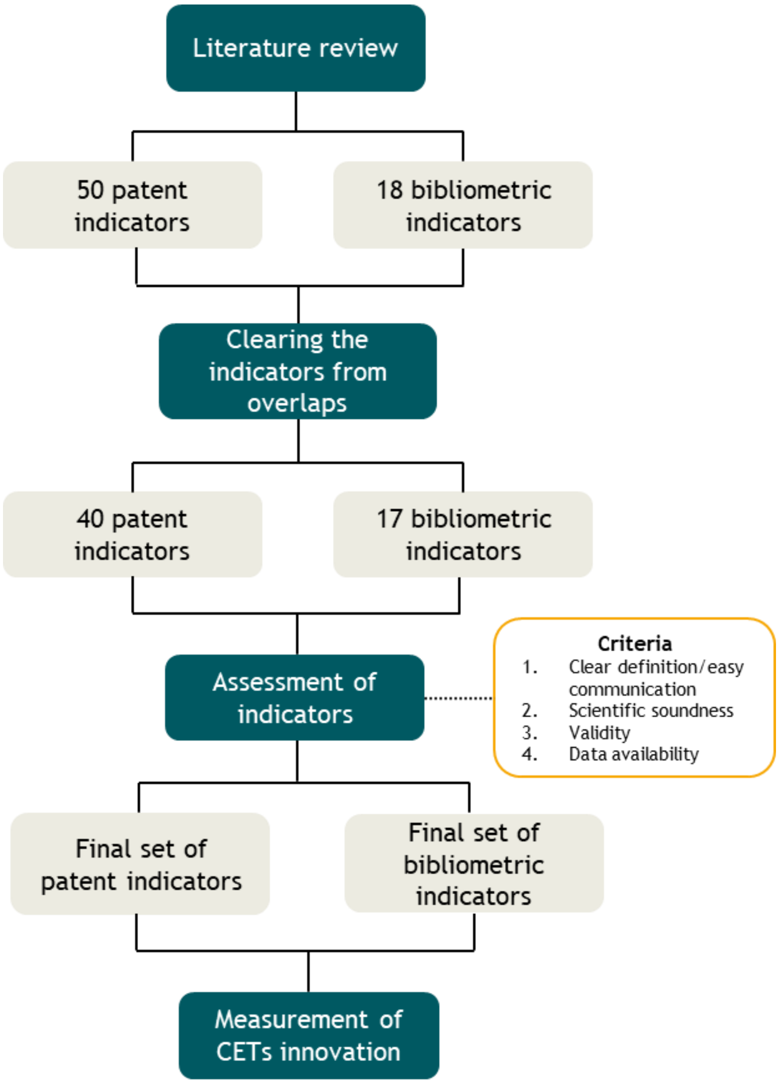

Figure 1 The conceptual framework of the research

2.2.1 Literature review

The primary aim of this study was to report which are the patent and bibliometric indicators that are used in previous literature. Therefore, an extensive literature review was conducted, in order to create a list of patent and bibliometric indicators, by using the search engines Google Scholar and Scopus. Only articles published in scientific journals were taken into account and the time frame of the literature search was from 1990 until the present, since before 1990 the innovation in the energy sector was limited (Bayer et al. 2013).

Therefore, the measurement of innovation before that period is expected to be insignificant.

First, an exploratory research was conducted to identify which indicators are mentioned in the literature, regardless of the technological field, by using general keywords, such as “patent indicators”, “bibliometric indicators”, “innovation measurement” and the combination of those keywords. Next, to focus more on the indicators used in the energy sector, more targeted keywords were used in combination with the aforementioned keywords, such as “energy”, “clean energy technologies”, “ocean energy”, “concentrated solar power”, as well as the names of rest of the CETs that are considered in this study. This research was conducted in April 2020.
In total, 50 patent indicators and 17 bibliometric indicators were gathered in this process. However, it was found that different articles use different names for the indicators to express the same concept, or the same name was used to express different indicators. In order to avoid the overlaps, the definitions of the indicators were compared and when they were identical, they were classified as one indicator (see Annex A). As a result, the indicators that were concluded regarding patents were 40, while for the bibliometrics were 16, which are presented in Table 3 and Table 4. The difference that occurs between the number of indicators in patents and bibliometrics is substantial, and it indicates the extensive use of patent indicators for the measurement of innovation in the literature.

Table 3 List of patent indicators found in literature after the clearing of overlaps

Patent indicators			
1.	Renewals of patents	23.	Patent intensity
2.	Number of claims	24.	Patent family
3.	Number of technical classes	25.	World patent shares
4.	Number of inventors in a patent	26.	Specialisation indicator
5.	Opposition	27.	Relative Patent Share (RPA)
6.	Granted patents	28.	Rate of assignment of patents (RAP)
7.	Patent scope	29.	Priority fillings
8.	Grant lag	30.	Transnational patents
9.	Backward citations	31.	Patent impact factor (PIF)
10.	Forward citations	32.	International Business Potential (IBP)
11.	Citations to non-patent literature (NPL)	33.	Relative growth rate (RGR)
12.	Breakthrough inventions	34.	Relative patent position (RPP)
13.	Generality index	35.	Patent production propensity (PPP)
14.	Originality index	36.	Lifespan of Patents
15.	Radicalness index	37.	Relative citation propensity
16.	Self-citations	38.	Marketability
17.	Patent age	39.	Citation velocity
18.	Number of patent applications	40.	Innovation index
19.	Counts of co-inventions		
20.	Technology Cycle Time (TCT)		
21.	Scientific linkages		
22.	Average citation frequency		

Table 4 List of bibliometric indicators found in literature after the clearing of overlaps

Bibliometric indicators	
1. Papers per capita	9. Co-citations
2. Growth index	10. Impact factor
3. Specialisation index (SI)	11. h-index
4. Average of relative citations (ARC)	12. Number of highly cited papers
5. Citations per paper	13. International collaboration
6. Collaborative papers	14. Average of Interdisciplinarity Index (AII)
7. Number of papers	15. Average of Interdisciplinarity Relative Index (AIRI)
8. Affinity index	16. Research Level

2.2.2 Criteria to assess the suitability of the indicators

In order to create a comprehensive and precise set of indicators that are suitable for the measurement of innovation in the sector of CETs, the need for an assessment methodology emerged. The methodology used in the study of Miremadi et al. (2018), which applied several criteria to identify the appropriate indicators among a long list, was considered as a basis. For the needs of the present study, five different literature sources were taken into account, each proposing a different set of criteria, regardless the sector of interest. The selected literature was found in Google Scholar by using the combination of the keywords "criteria", "selection of indicators", "assessment of indicators" and "energy sector". This research was also conducted in April 2020.

Table 5, provides a summary of those criteria and the respective literature source that suggests them. The sign ✓ was used to indicate which literature proposed the listed criteria. A detailed table with the criteria and their definitions is provided in Annex B.

Table 5 List of the considered criteria from five different sources

Criteria \ Literature	Miremadi et al. (2018)	Pwc (2017)	United Nations Statistical Division (2015)	Wolf et al. (2015)	Brown (2009)
Clear definition/ easy communication	✓	✓	✓	✓	✓
Available data	✓	✓	✓		
Relevance	✓		✓	✓	✓
Measurability	✓				
Validity		✓			✓
Performance-based		✓			✓
Widely accepted		✓			
Scientifically sound			✓	✓	✓
Effectiveness				✓	

Literature / Criteria	Miremadi et al. (2018)	Pwc (2017)	United Nations Statistical Division (2015)	Wolf et al. (2015)	Brown (2009)
Practicality				✓	
Relate where appropriate to other indicators					✓
Ability to be disaggregated over time					✓
Consistency over time					✓
Timeliness					✓
Linked to policy or emerging issues					✓
Compel interest and excite					✓

As it is shown in Table 5, some criteria are used in more than one sources, while others are proposed by only one source. To enhance the objectivity of this research, only the criteria that were used in three or more sources were selected; namely clear definition/easy communication, available data, relevance, measurability, validity and scientifically sound. It is noteworthy that the criteria "Relevance" and "Validity" by definition are expressing the same concept, i.e. the indicator should reflect the clean energy sector and more specifically they should be able to measure the progress of innovation, which is the aim of this research. Therefore, for the assessment of the indicators, these two criteria were combined and referred to as "Validity".

In conclusion, the criteria that were used in the research are defined as follows:

- ✓ **Clear definition/easy communication:** An indicator should be clearly defined and understandable in order to convey the message of (potentially) difficult concepts to the public as well as to the decision-makers (Pwc, 2017). In the specific research project, in which the complex concept of innovation is discussed, the use of clear indicators facilitates the process of its measurement.
- ✓ **Scientific soundness**: according to the United Nations Statistical Division (2015), the indicators should be based on concrete methodology and on existing definitions, classifications and standards. Also, their computation should have minimum uncertainty (Wolf et al., 2015). That criterion assures the high quality of the research process.
- ✓ **Validity:** The indicators must successfully reflect the desired sector of the research (Miremadi et al., 2018) and the phenomenon they represent (Pwc, 2017). In the case of this research, they should be relevant to the clean energy sector and they should provide insights for the progress of innovation of CETs.

- ✓ **Data availability:** There should be enough data and information to support the indicators (Miremadi et al., 2018).The selection of that criterion was based on the reasoning that even though an indicator might be clear, scientifically sound and reflects adequately the phenomenon that is researched, the lack of data creates inevitably an insurmountable barrier (Miremadi et al., 2018).

However, due to the fact that data collection is a time-consuming and challenging process, the criterion "Data availability" was applied only for the indicators that have met the first three criteria.

2.2.3 Assessment of patent and bibliometric indicators

For the set of patent and bibliometric indicators that resulted from the clearing (Table 3 and Table 4), the four criteria mentioned in section 2.2.2 were applied. The assessment is depicted in Table 6 and Table 8. When an indicator met a criterion, then the sign ✓ was used; when it did not, then no sign was used (i.e. gap). The reasoning behind the assessment of the indicators is explained in detail in Annex C.

Patent indicators

Table 6 provides an overview of the assessment of patent indicators. The eight highlighted indicators are those that fulfilled the three criteria simultaneously and to which the fourth criterion, namely data availability, was applied. By taking a closer look at the table, many indicators lack clear definition and validity; this implies that first, those indicators are not easily understandable from the public, hence communications problems might occur, and second, they are not suitable to reflect the innovation progress of CETs.

Table 6 Assessment of the patent indicators

Indicators / Criteria	Renewals of patents	Number of claims	Number of technical classes	Number of inventors in a patent	Opposition	Granted patents	Patent scope	Grant lag	Backward citations	Forward citations	Citations to non-patent literature (NPL)	Breakthrough inventions	Generality index	Originality index	Radicalness index
Clear definition/ easy communication	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓			✓
Scientific soundness	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Validity						✓									

Indicators / Criteria	Self-citations	Patent age	Number of patent applications	Counts of co-inventions	Technology Cycle Time (TCT)	Scientific linkages	Average citation frequency	Patent intensity	Patent family	World patent shares	Specialisation indicator	Relative Patent Share (RPA)	Rate of assignment of patents (RAP)	Priority fillings	Transnational patents
Clear definition/ easy communication	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓		✓	✓
Scientific soundness	✓	✓	✓	✓	✓			✓	✓	✓		✓	✓	✓	✓
Validity			✓		✓		✓	✓	✓	✓	✓	✓			

Indicators / Criteria	Patent impact factor (PIF)	International Business Potential (IBP)	Relative growth rate (RGR)	Relative patent position (RPP)	Patent production propensity (PPP)	Lifespan of Patents	Relative citation propensity	Marketability	Citation velocity	Innovation index
Clear definition/ easy communication				✓		✓				
Scientific soundness				✓		✓	✓			✓
Validity			✓		✓					

Source: Own elaboration

The highlighted indicators are the ones that fulfil the three criteria simultaneously

Consequently, the indicators that successfully met the three criteria along with their formulas are provided in Table 7.

Table 7 Patent indicators that met the criteria of clear definition, scientific soundness and validity, along with their calculation formulas

	Indicators	Formulas
Patents	Granted patents	$\sum_{ij} GP_{ij}$ per year, where GP is the granted patents, i is the country and j the technology.
	Number of patent applications	$\sum_{ij} P_{ij}$ per year, where P is the number of patent applications, i is the country and j the technology.
	Patent intensity	$\frac{\text{Average R\&D expenditure}}{\text{GP}}$ *per year*, where GP is the granted patents of a country
	Patent families	-
	World patent shares	$\text{WPS}_{\text{ij}} = 100 \times \left(\frac{\text{GP}_{\text{ij}}}{\sum_i \text{GP}_{\text{ij}}}\right)$ per year, where GP is the granted patents, i is the country and j the technology.
	Relative Patent Share (RPS)	$\text{RPS}_{\text{ij}} = 100 \times \tanh \ln \frac{\left[\frac{\text{GP}_{\text{ij}}}{\sum_{\text{i}} \text{GP}_{\text{ij}}}\right]}{\left[\frac{\sum_i \text{GP}_{\text{ij}}}{\sum_{\text{ij}} \text{GP}_{\text{ij}}}\right]}$ per year, where GP is the granted patents, i is the country and j the technology.

By observing the formulas of the indicators, it becomes clear that the main primary data that are required are the patent applications, the granted patents, the patent families and the R&D expenditures; the rest of the indicators can be calculated based on those data. However, the data regarding the R&D expenditures of the companies are often not reported, so their strategy remains protected (Fiorini et al., 2017). Therefore, there is a lack of accessible data, hence patent intensity does not fulfil the criterion of data availability and this indicator is excluded from the final set.

Regarding the data of patent applications, granted patents and patent families, the main and most concrete source is PATSTAT. Yet, the duration of the free access to those data is limited and advanced knowledge regarding the processing of this dataset is required. For that reason, a search for metadata was conducted; a reliable source of metadata was the Joint Research Centre (JRC), whose data were based on the PATSTAT database, 2019 autumn version. Yet, those data include the patent families, the high-value patent families, the granted patent families and the flow of inventions for 83 countries during the period 2007-2018[3]. It is worth to mention that other patent data sources were considered (e.g. OECD Statistics, 2020), yet their primary data were as well the patent families and not the patent applications; therefore, the selection of the JRC dataset for this research was based on the assumption that there are no data gaps and that the patent data are of high quality.

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[3] 2018 was the most recent year with available data.

In conclusion, due to the lack of the desired data and in order to fulfil the needs of the current study, the data of patent families and granted patent families were used, under the following considerations:

- ✓ **Using patent families instead of patent applications:** by definition, the former regards the set of patent applications which are filed in several countries and are protecting the same invention (Kapoor et al., 2012), while the latter regards the simple patent applications which are filed in a specific year in a country or worldwide (World Intellectual Property Organization, 2018). Several studies, such as the one of Fiorini et al. (2017), support that first by using patent families the double counting is avoided and second the "home country advantage[4]" is eliminated, making the comparisons between countries more objective. Therefore, it is an accurate measurement of patent filings and it was used instead of the patent applications.
- ✓ **Granted patent families instead of granted applications:** due to the fact that the data of patent applications were not available and since the grants are based on the patent applications, the indicator "granted patent families" was used instead of the granted applications.

In conclusion, the final set of indicators that fulfil the four criteria simultaneously and subsequently were used for the measurement of innovation progress of CETs is:

1. Patent families
2. Granted patent families
3. World Patent Share (WPS)
4. Relative Patent Share (RPA)

[4] Home country advantage effect is the tendency of patent applicants to file more applications in their home country patent office rather than in an international patent office (Criscuolo, 2006).

Bibliometric indicators

The four criteria discussed in section 2.2.2 were also applied to the 16 bibliometric indicators, as shown in Table 8. Only the four highlighted indicators met the criteria of clear definition, scientific soundness and validity. Those are the papers per capita, growth index, specialisation index (SI) and the number of papers. Once again, most of the indicators, do not meet the criterion of clear definition and validity.

Table 8 Assessment of the bibliometric indicators

Indicators / Criteria	Papers per capita	Growth index	Specialisation index (SI)	Average of relative citations (ARC)	Citations per paper	Collaborative papers	Number of papers	Affinity index	Co-citations	Impact factor	h-index	Number of highly cited papers	International collaboration	Average of Interdisciplinarity Index (AII)	Average of Interdisciplinarity Relative Index (AIRI)	Research Level
Clear definition/ easy communication	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓			
Scientific soundness	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Validity	✓	✓	✓				✓									✓

Source: Own elaboration

The highlighted indicators are the ones that fulfil the three criteria simultaneously.

Table 9 provides an overview of the four indicators that met the three criteria, along with their calculation formulas. All the indicators are calculated based on the number of papers and in the case of papers per capita, the population data of the countries are also required. Both data are available online from the Web of Science and the World Bank respectively. Therefore, regarding the data availability, all the four indicators meet that criterion, hence they compose the final set of bibliometric indicators for the measurement of innovation in the field of CETs.

Table 9 Bibliometric indicators that met the criteria of clear definition, scientific soundness and validity, along with their calculation formulas

Indicators		Formulas
Bibliometrics	Number of papers	N_{ij}, where N is the number of papers per year, i is the country and j the technology.
	Papers per capita	$\frac{N_{ij}}{Population_{i,x}}$, where N is the number of papers per year, i is the country, j the technology and $Population_{i,x}$ is the population of country i for year x.
	Growth index	$\frac{\frac{N_{ijy}}{N_{ijz}}}{\frac{\Sigma_i N_{ijy}}{\Sigma_i N_{ijz}}}$, where where N is the number of papers, i is the country, j the technology, y the period of time 2013-2017 and z the period 2008-2012.
	Specialisation index (SI)	$SI^5 = \frac{AI-1}{AI+1}$, where $AI^6 = \frac{\frac{N'_{ij}}{N'_{iT}}}{\frac{\Sigma_i N'_{ij}}{\Sigma_i N'_{iT}}}$, where N' is the number of papers for the period 2007-2017, i is the country, j the technology and T the total publications of all countries for all technologies (including non-energy related technologies) for the period 2007-2017.

[5] The formula is based on the study of Glänzel, W. (2000). Science in Scandinavia: A bibliometric approach. Scientometrics, 48(2), 121-150. https://doi.org/10.1023/A:1005640604267

[6] AI stands for Activity Index.

3 Methods

Chapter 3 discusses the methods that were used in this research. In the first section, the data collection for all the steps of the research is described in detail. Then, an overview of the main research methods that were implemented in this research is provided, in order to measure how innovation evolved the last decade, by using the patent and bibliometric indicators that were selected Chapter 2.

3.1 Data collection

The measurement of innovation of CETs by using the final set of patent and bibliometric indicators was the last step of this research. The required patent data for the period 2007-2018, i.e. number of patent families and granted patent families, were provided from the Joint Research Centre (JRC). The access to this data was enabled as a result of the cooperation between the JRC and Trinomics. The JRC data are based on the PATSTAT database, which is the official European Patent Office (EPO) database. However, it should be taken into account that the dataset has a 3.5 year time lag due to the fact that the application procedures are time-consuming and that EPO needs time to process the dataset (Fiorini et al., 2017). Since the last update was made from the JRC in December 2019, the last year with a full dataset is 2016.

Regarding the number of papers for the period 2007-2017[7], the data for the technologies of ocean energy, CCS/U, and nuclear energy (fission and fusion) were gathered from the Web of Science (WoS) by using keywords depending on the technology that was researched; for instance, for the CCS/U technology the keywords “Carbon Capture”, “Carbon Storage”, “Carbon Utilisation” and “Carbon Capture and Storage” were used. Only the papers filed as “Articles” were considered. For the rest of the technologies, the data were provided by Trinomics et al. (2019), which followed the same methodology. Finally, the data regarding the population of the countries for the in-scope period were gathered from the World Bank (2020) and Statista (2020).

3.2 Research Method

Methodological steps of patent data

After the conclusion of the four indicators discussed in Chapter 2, the patent data were collected from the JRC, as described in section 3.1. Due to the data limitations that were discussed in section 2.2.3, instead of patent applications and granted patent, the data of patent families and granted patent families were collected from the JRC, for each CET, during the period 2007-2018.

The first step was to summarise those the data for each technology per country and per year, as well as to find the number of patent families and granted patent families that each

[7] 2017 was the latest year with available pubication data.

country held for the whole in-scope period. As a result, the evolution of each CET was monitored for the whole in-scope period, and the top-10 countries were determined for each CET.

The computation of the other two indicators, namely World Patent Share (WPS) and Relative Patent Share (RPS) was conducted also based on the data of granted patent families. WPS was computed by using formula 1.

$$\mathbf{WPS_{ij}} = \mathbf{100} \times \left(\frac{\mathbf{GPF_{ij}}}{\sum_i \mathbf{GPF_{ij}}} \right) \qquad (1)$$

where GPF is the granted patent families, i is the country and j the technology. WPS indicates which countries dominate each CET.
On the other hand, the computation of the RPS was conducted by using formula 2.

$$\mathbf{RPS_{ij}} = \mathbf{100} \times \mathbf{tanh\,ln} \frac{\left[\frac{\mathbf{GPF_{ij}}}{\sum_i \mathbf{GPF_{ij}}}\right]}{\left[\frac{\sum_i \mathbf{GPF_{ij}}}{\sum_{ij} \mathbf{GPF_{ij}}}\right]} \qquad (2)$$

where the GPF is the granted patent families, i is the country and j the technology. The nominator expresses the WPS and the denominator equals the share of a country's granted patent families in all CETs divided with the world granted patent families in all CETs. RPS ranges from -100% to 100%; the positive value indicates that the country is performing well in the specific technology and the negative value means the opposite (Eichhammer & Walz, 2009). The calculation was repeated for all the countries that were included in the JRC dataset and for all the CETs. Specific attention was given to the EU-27 Member States, for which the specialisation per country and per CET was summarised. In addition, the average RPS number of the EU-27 for each technology was calculated.
The process of the data and the plotting of the graphs was conducted by using Excel.

Methodological steps of bibliometric data

After gathering the required data for the period 2007-2017 (see section 3.1), the calculation of the bibliometric indicators was conducted for each CET. The first task was to distinguish the countries that were included in each paper by using the following counting system; if a paper was written by e.g. three authors, two of whom were from the same country, then this country was counted one time. In that way, the double-counting of the countries was avoided. Then, it was identified how many papers each country produced per year as well as in the whole in-scope period. The results of this process were used to track the evolution of publications per CET during the in-scope period, as well as to determine the world players.

The indicator papers per capita for each CET was calculated by using the number of papers per country per year and the countries population data for the respective year. In order to simplify the results, the indicator was measured as number of papers per million inhabitants. Also, the average number of papers per million of inhabitants for each country as well as the respective average population was computed for the period 2007-2017 for each CET.

The next indicator that was computed was the growth index per CET. This indicator can be calculated at a world level and at a country level. The world growth index was calculated by dividing the world papers of a given technology for the period 2013-2017 with the world papers of that technology for the period 2008-2012[8]. In order to find the growth index per country, the same process was followed, except that now the number of papers that each country produced during the two periods were considered, and the result was divided with the world growth index. The countries that had zero papers in one of the two periods were excluded from the calculations. The values of growth index are generally higher than 1, where 1 indicates that the papers remained the same in the two sub-periods, 2 indicates that the papers doubled in the latter period, etc. During the elaboration of the results, it was noticed that the countries that had a low number of papers in the initial period were in a favourable position. For instance, Pakistan produced only one paper in the period 2008-2012 regarding wind energy technologies, while in the period 2013-2017 it produced 24 papers. Hence, the growth rate in that case was remarkable. On the contrary, the United States produced about 400 and 1100 papers for the respective periods, which even though in absolute numbers is much more significant, in terms of growth is less than Pakistan. Therefore, this indicator can be easily skewed and misleading conclusions regarding the innovative countries may result. In order to diminish the skewing of the results, a benchmark was introduced; the countries that produced in the whole in-scope period fewer papers than the average amount of papers that all countries produced, were omitted from the growth index results. Nevertheless, both findings, with and without the benchmark, are presented in Chapter 4, in order to illustrate the overall behaviour of this indicator.

The final bibliometric indicator that was computed was the specialisation index, which is based on the share of a technology's publications per country and the share of that technology's publications in the world, as described in section 2.2.3. The values of specialisation index range from -1 to 1, where 1 indicates an ultimate innovative activity compare to the world, and -1 indicates a lower than average innovative activity. When the values are close to 0, a balanced condition is implied between the country's and the world's share of publications in a given technology. From the results, two summary tables were created which included the EU-27 Member States' and the world players' specialisation index. Additionally, for the EU-27, the average number for each technology was calculated. The process of the data and the plotting of the graphs was also conducted by using Excel.

[8] The year 2007 was omitted in order to have two periods, each containing five years.

4 Results

In this chapter, the outcomes of the innovation measurement of CETs is presented, which are divided into two sections. First, the results of the patent data are summarised, which include the evolution of the CETs during the period 2007-2018, as measured by the number of patent families and granted patent families, the world players that led the innovative activity during the past decade and the specialisation of the EU-27 Member States and the world players in specific CETs. The second section comprises the evolution of CETs for the period 2007-2017, the world players that emerged as measured by the number of scientific papers and the key results of the indicators papers per capita, growth index and specialisation index.

4.1 Patents

4.1.1 Evolution over time

The initial aim of this research was to monitor the innovation performance of each CET. By using the JRC data for patent families and granted patent families, the evolution of each technology was plotted during the in-scope period 2007-2016[9]. Figure 2 depicts that the number of patent families of the solar PV technologies are significantly higher for the whole in-scope period, followed by wind energy, concentrated solar power and bioenergy technologies. The zoom-in in the rest of the technologies (Figure 3) shows that nuclear energy holds a significant share of patent families, recording almost 1200 patent families in 2012, while CCS/U, which is a rather new technology, demonstrated an upward trend during the majority of the years. Technologies related to geothermal energy showed the lowest innovation performance in terms of patent families, which could be attributed to the fact that it is a well-established energy source that has reached the pick of its technological potentials. Another interesting point is that most of the in-scope technologies had a considerable decrease in the number of patent families during the period 2012-2015. These low rates indicate low innovation activity in the sector of clean energy and could be attributed to the effects of the economic crisis that occurred in 2008.

[9] The years 2017 and 2018 were omitted from the graphs due to the lack of complete dataset (see section 3.1).

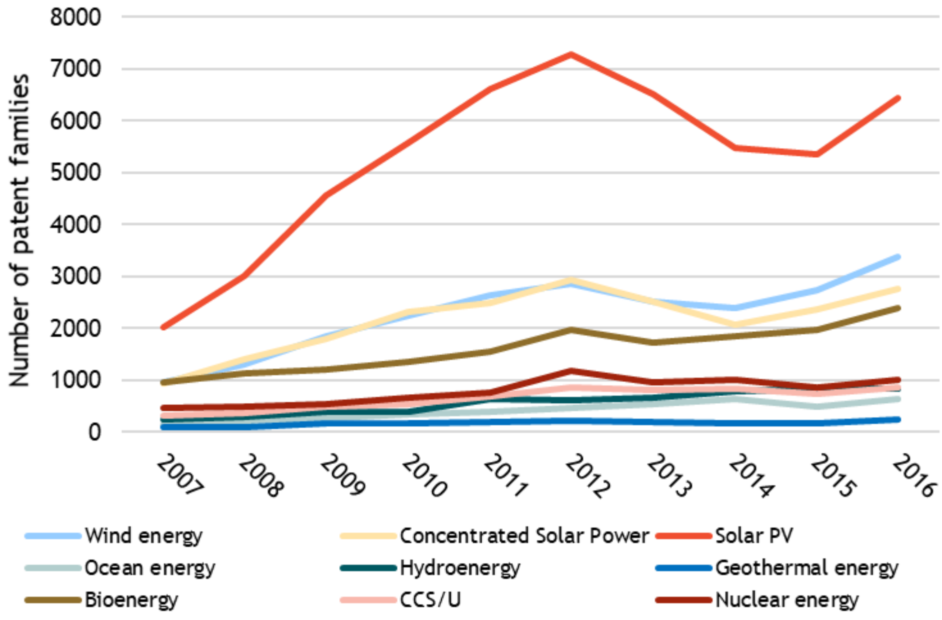

Figure 2 World patent families per CET during the period 2007-2016

Source: Own elaboration based on the data from the JRC.

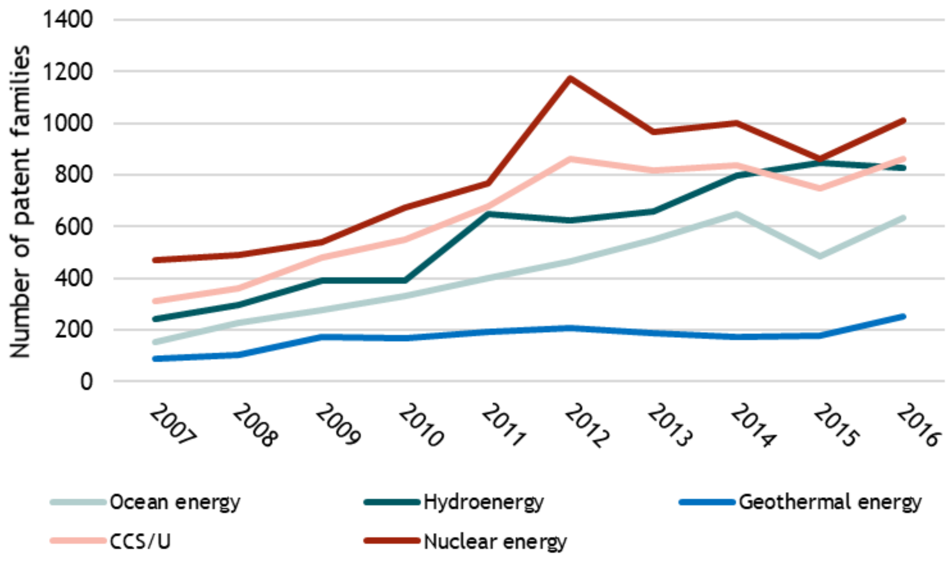

Figure 3 Zoom-in: world patent families of ocean energy, hydroenergy, geothermal energy, CCS/U and nuclear energy during the period 2007-2016

Source: Own elaboration based on the data from the JRC.

A comparable behaviour is recorded for all CETs regarding the world granted patent families (Figure 4); the main difference lies in the absolute numbers of granted patent families. Of all the patent families, the average share of grants for the whole in-scope period is 50%-60% per CET; consequently, only about half of the patent families fulfil the patentability criteria and will possibly reach the market in the long term. As a result, granted patent families can be considered as a more accurate representation of innovation performance.

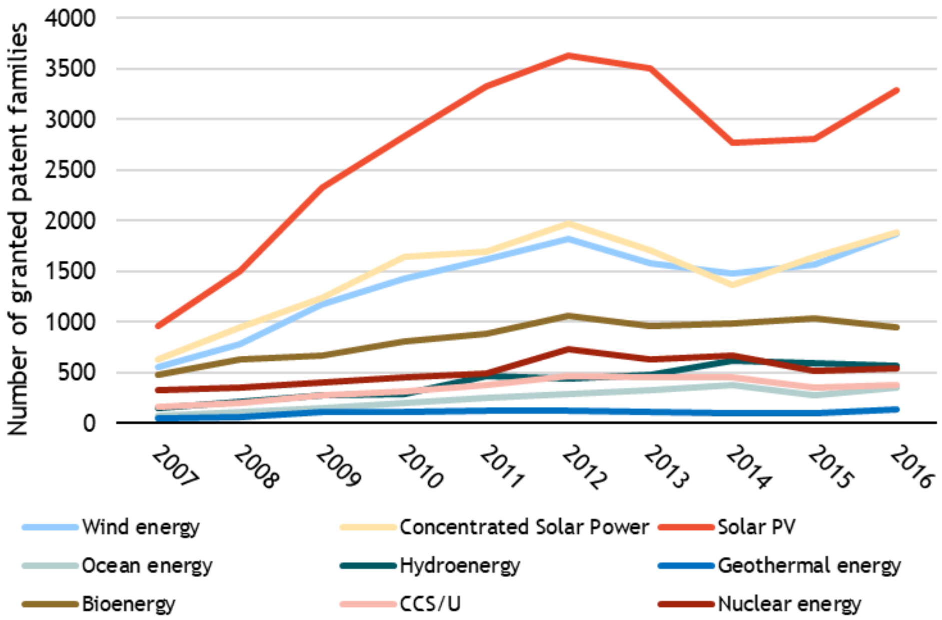

Figure 4 World granted patent families per CET during the period 2007-2016

Source: Own elaboration based on the data from the JRC.

4.1.2 World players & best performing countries

In Table 10, the countries that have reached the top-10 at least in one CET are presented, along with the numbers of the total patent families and the respective granted patent families in all CETs for the whole in-scope period. The ranking starts from the country with the highest number of patent families to the country with the lowest number of patent families. China is the world leader of innovation performance in terms of patent families, reaching more than 70000 for the whole in-scope period in all CETs. Next in line come Korea and Japan with more than 25000 and 19000 patent families respectively, while the top-5 ranking complete the United States and Germany.

However, it is important to notice the grant shares of the countries. Japan, the United States and Germany which are considered leaders of innovation with regard to the number of patent families have less than 40% share of grants. On the other hand, Taiwan and Spain recorded more than 60% of grant shares, while Russia has an exceptional 94% share of granted patent families, which makes it the most successful country in terms of grants. On the contrary, only 13% of Brazil's patent families got granted during the in-scope period, which makes it the country with the lowest grant share, followed by the United Kingdom and the Netherlands.

Table 10 Cumulative patent families and granted patent families during the period 2007-2018 of the countries that have reached at least in one CET the top-10

Countries	Total patent families in all CETs	Total granted patent families in all CETs	Grant Shares
China	73674	49190	67%
Japan	25503	9526	37%
Korea	19309	13216	68%
United States	10438	4121	39%
Germany	7874	2822	36%
Taiwan	4213	2876	68%
France	2284	994	44%
Denmark	1326	403	30%
Russia	1074	1011	94%
Spain	886	583	66%
Switzerland	627	200	32%
United Kingdom	611	150	25%
Italy	535	157	29%
Netherlands	318	85	27%
Brazil	313	41	13%
Canada	157	47	30%
Sweden	126	48	38%
Norway	65	31	48%
Poland	42	20	48%

Source: Own elaboration based on the data from the JRC.

The countries are ranked based on the number of total patent families, from the largest to the lowest value.

In Figure 5, the cumulative number of granted patent families of the world players for all CETs per year is depicted. It is clear that China dominates the patenting activity in the field of clean energy with an extraordinary increase of more than 700% in granted patent families in the decade 2007-2016. Contrarily, for the rest of the countries, after 2012 the number of granted patent families presents a downward trend. This behaviour could be attributed to the effect of the global economic crisis in 2008 as well as to the propensity of the countries to patent. For instance, Chinese companies, which are still in the developing phase and face a lot of market competition, are more inclined to patent in order to reach the foreign markets (Warner, 2015). On the other hand, the study of Wajsman & García-Valero (2017) suggests that EU-based companies[10] use more the trade secrets strategy to protect their inventions rather than patents.

[10] The companies reffered in this study do not belong necessarily to the energy sector.

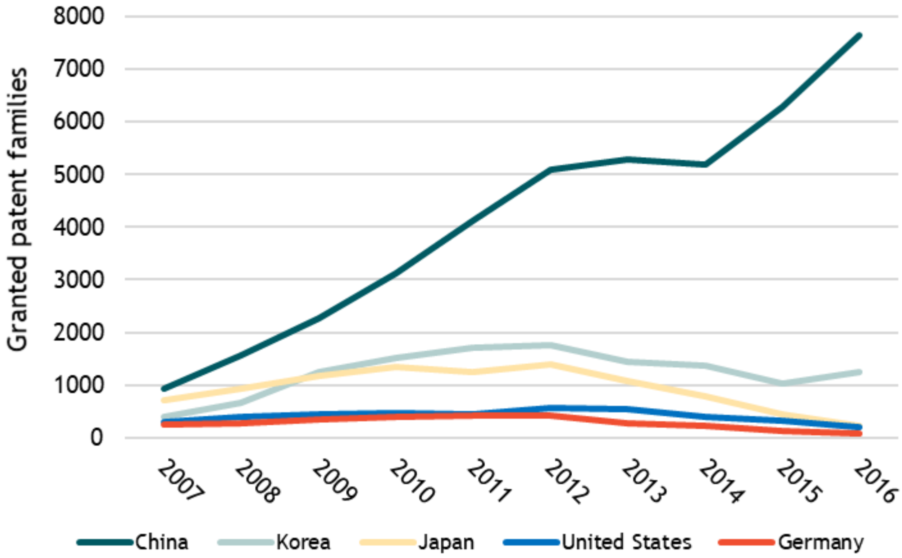

Figure 5 World players: number of granted patent families in all CET per year

Source: Own elaboration based on the data from the JRC.

4.1.3 Innovation as measured with World Patent Share (WPS)

By using the indicator World Patent Share (WPS) the main countries that held the most granted patent families in each CET are reported, during the whole in-scope period.

1. Wind energy

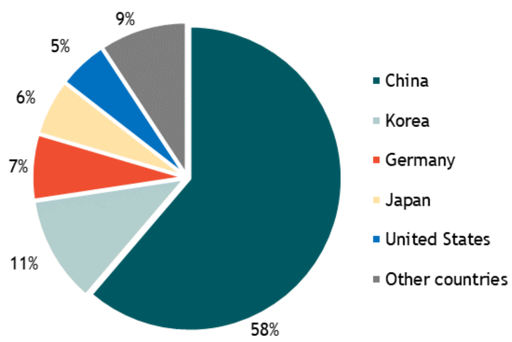

Figure 6 World Patent Share in wind energy for the period 2007-2018

Source: Own elaboration based on the data from the JRC.
"Other countries" include Denmark, Taiwan, Russia, Spain and France.

The country that dominated wind energy technologies is China, holding 58% of the WPS. Korea is the second country with the most shares, yet with a significantly lower percentage (i.e. 11%). Germany, Japan and the United States held also relatively small shares, while Denmark, Taiwan Russia, Spain and France accounted for 9% of the wind energy granted patent families.

2. Concentrated Solar Power

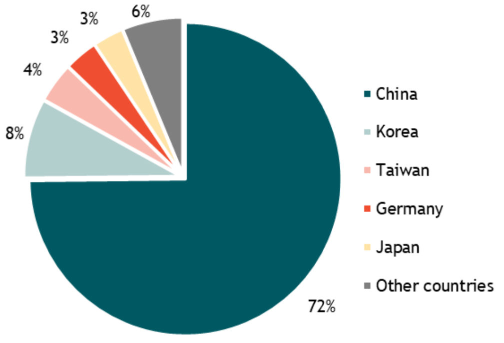

Figure 7 World Patent Share in concentrated solar power for the period 2007-2018

Source: Own elaboration based on the data from the JRC.
"Other countries" include the United States, Spain, Russia, France and Italy.

China is the ultimate innovator in concentrated solar power holding 72% of the granted patent families for the period 2007-2018, leaving only 28% to be split among 9 countries, as illustrated in Figure 7. China is a rapidly growing economy, with a continuing increase in energy demands, yet it needs to meet a 27.5% share of renewable energy by 2050. To reach that goal, the concentrated solar power is expected to play a key role, and China has already been focused on the R&D of that technology (Wang et al., 2017).

3. Solar PV

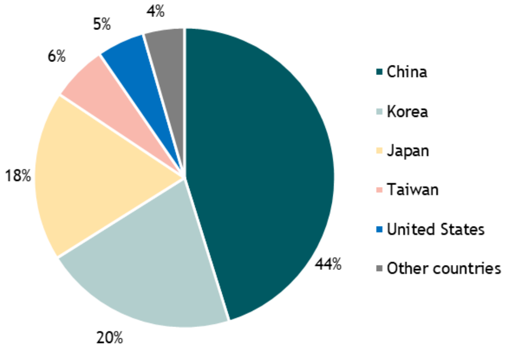

Figure 8 World Patent Share in solar PV for the period 2007-2018

Source: Own elaboration based on the data from the JRC.
"Other countries" include Germany, France, Russia, the Netherlands and Spain.

China, Korea and Japan prevail the solar PV technologies with 44%, 20% and 18% respectively in WPS. Taiwan also held 6% of the granted patent families, following by the United States with 5%. Germany, France, Russia, the Netherlands and Spain held only 4% of the granted patent families in solar PV. It is noteworthy, that the two top countries, i.e. China and Korea, used to be latecomers and were catching-up the developments of the more technologically advanced countries such as the United States (Wu & Mathews, 2012); yet, during the last decade, they are leading the technological developments of solar PV, leaving little room to the other countries to pioneer.

4. Ocean energy

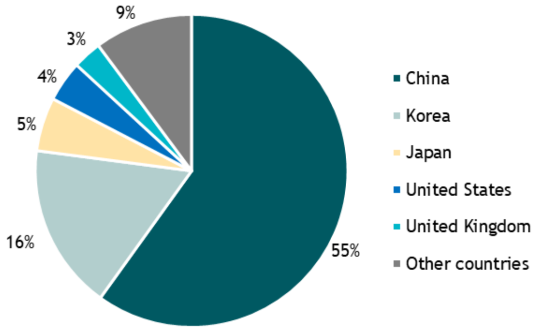

Figure 9 World Patent Share in ocean energy for the period 2007-2018

Source: Own elaboration based on the data from the JRC.
"Other countries" include Russia, Taiwan, Germany, France and Spain.

The granted patent families regarding ocean energy were mainly held by China with a 55% share of WPS, following by Korea with 16%. Japan, the United States and the United Kingdom accounted for only 5%, 4% and 3% of the WPS. European countries are performing poorly in this energy field since only three EU-27 countries take part in the 9% share of the granted patent families.

5. Hydroenergy

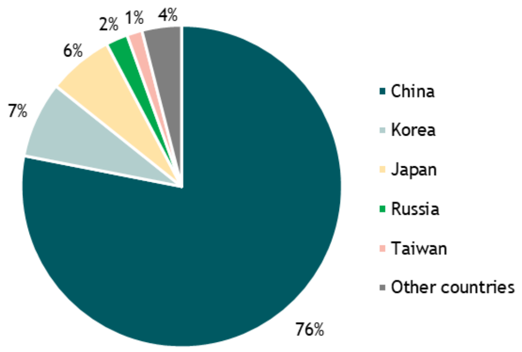

Figure 10 World Patent Share in hydroenergy for the period 2007-2018

Source: Own elaboration based on the data from the JRC.
"Other countries" include Germany, the United States, France, Czech Republic and Poland.

Hydroenergy is also a domain that China thrives, holding 76% of the WPS; this result is not surprising since China has the most abundant resources of hydroenergy globally (Zhang et al., 2017), therefore the R&D is expected to be higher there than in other places in the world. The WPS of the other countries is significantly lower than China's; as an indication, Korea is the second country in the rank, yet it held only 7% of the granted patent families.

6. Geothermal energy

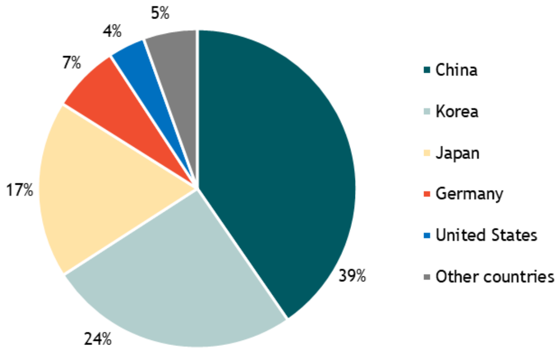

Figure 11 World Patent Share in geothermal energy for the period 2007-2018

Source: Own elaboration based on the data from the JRC.
"Other countries" include Switzerland, Russia, Poland, France and the Netherlands.

The WPS of geothermal energy is spread more evenly among the countries; Even though China is still the leader with a 39% share of the granted patent families, Korea and Japan held significant share as well, namely 24% and 17% respectively. Germany and the United States account for 7% and 4% respectively, while 5% of the WPS are held by Switzerland, Russia, Poland, France and the Netherlands.

7. Bioenergy

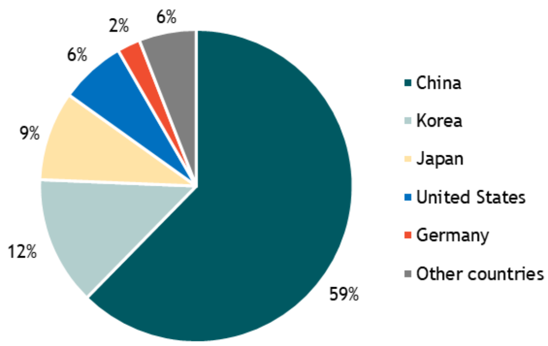

Figure 12 World Patent Share in geothermal energy for the period 2007-2018

Source: Own elaboration based on the data from the JRC.
"Other countries" include Russia, France, Czech Republic, Taiwan and the Netherlands.

Bioenergy is dominated by the world players identified in the previous section, namely China, Korea, Japan, the United States and Germany. Again, China is the innovation leader holding 59% of the WPS, while Korea held 12% and Japan 9%.

8. CCS/U

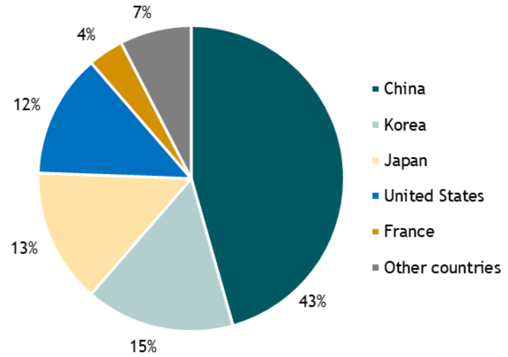

Figure 13 World Patent Share in geothermal energy for the period 2007-2018

Source: Own elaboration based on the data from the JRC.
"Other countries" include Germany, Switzerland, Russia, Taiwan and the Netherlands.

China, Korea and Japan held the majority of the CCS/U shares regarding granted patent families, however, the United States contributed also significantly, accounting for 12% of the WPS. The United States has a strong focus on the development of the CCS/U technologies since 2000, with increasing investments and intensive R&D (Qiu & Yang, 2018), which justifies the considerable share.

9. Nuclear energy

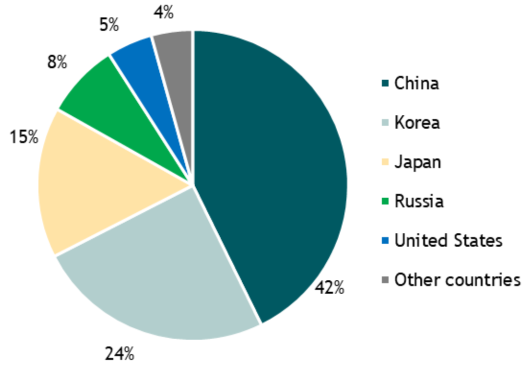

Figure 14 World Patent Share in geothermal energy for the period 2007-2018

Source: Own elaboration based on the data from the JRC.
"Other countries" include France, Germany, Taiwan, Czech Republic and Canada.

The majority of nuclear energy's granted patent families were as well held from the world players China, Korea and Japan, while Russia accounts for the substantial 8% of the WPS. The United States held 5% of the WPS while France, Germany, Taiwan, Czech Republic and Canada compose 4% of the WPS.

4.1.4 Innovation as measured with Relative Patent Share (RPS)

By using the indicator Relative Patent Share (RPS), the specialisation per country in each CET was concluded. For the purpose of the research, the focus remains on the EU-27 Member States and the world players, as identified in section 4.1.2. A detailed table with all the countries considered from the JRC and their respective RPS can be found in Annex D.
In general, if a country has a positive RPS in a specific technology, then it is considered specialised in that technology compared to the others. If the RPS is negative, then the opposite is true. Values close or equal to zero indicate that the country does not have any particular specialisation in the specific technology, which usually happens with countries

that have high a number of patents (Eichhammer & Walz, 2009). On the contrary, countries that have few granted patent families in the whole in-scope period, have values close to 100% or -100%.

Table 11 presents an overview of the RPS values per CET for the world players, as calculated for the period 2007-2018. China is specialised in the concentrated solar power and hydroenergy technologies. Korea has an equal specialisation in geothermal and nuclear energy, while there seems to be a lower focus on hydroenergy, concentrated solar power and wind. Japan is specialised in the same technologies as Korea, except for the ocean energy. Finally, the United States thrives in the CCS/U sector compared to all the other world players, while Germany is the most specialised country in the wind and geothermal energy among its peers.

Table 12 provides the RPS values of the EU-27 countries, as an indication for their specialisation performance. The country that presents the highest rate of wind energy specialisation is Denmark with 92%, following by Luxemburg and Spain with 64% and 61% respectively. Most EU-27 countries are specialised in the concentrated solar power technologies, while the opposite is true for solar PV technologies. This implies that non-EU countries held the majority of the granted patent families in this sector, such as Japan and China. Southern European countries dominate the ocean energy specialisation, such as Greece and Italy, while central European countries such as Slovakia and Slovenia are specialised in hydropower. France has developed a specialisation in nuclear energy technologies, as well as to the fairly new CCS/U technologies along with the Netherlands and Luxemburg. However, it is important to mention that a positive or a negative result of a country does not necessarily indicate that it has high numbers of granted patent families per se; it just suggests that compared to the other technologies, the country has more granted patent families in the specific technology, hence it is considered specialised. For instance, Luxemburg is specialised in wind energy, as mentioned above, yet its contribution to the global innovation activity can be deemed rather marginal.

Another interesting point is the overall specialisation of the EU-27 Member States, measured as an average of the RPS of all countries. EU-27 is slightly specialised in wind energy, concentrated solar power, ocean energy and bioenergy, while it has no specialisation in solar PV, CCS/U and nuclear energy. A rather neutral specialisation is indicated in hydroenergy and geothermal energy technologies.

Table 11 Relative Patent Share (RPS) for the world players during the period 2007-2018

World players	Wind energy	Concentrated Solar Power	Solar PV	Ocean energy	Hydroenergy	Geothermal energy	Bioenergy	CCS/U	Nuclear energy
China	6%	26%	-22%	0%	30%	-34%	6%	-25%	-26%
Korea	-30%	-56%	31%	6%	-60%	46%	-17%	0%	46%
Japan	-56%	-85%	48%	-63%	-48%	45%	-21%	22%	36%
United States	7%	-64%	8%	-17%	-92%	-25%	31%	75%	2%
Germany	63%	4%	-28%	-42%	-77%	62%	-33%	-35%	-87%

Source: Own elaboration based on the data from the JRC.

♦ Green colour indicates specialised countries ♦ Red colour indicates non-specialised countries ♦ Yellow colour indicates an equilibrium

Table 12 Relative Patent Share (RPS) for the EU-27 countries during the period 2007-2018

EU-27 countries	Wind energy	Concentrated Solar Power	Solar PV	Ocean energy	Hydroenergy	Geothermal energy	Bioenergy	CCS/U	Nuclear energy
Austria	-24%	47%	-42%	-57%	48%	38%	15%	68%	-100%
Belgium	34%	-2%	13%	22%	-99%	-43%	-13%	-34%	-91%
Bulgaria	29%	50%	-86%	0%	90%	0%	0%	0%	53%
Croatia	-94%	-98%	-82%	0%	97%	0%	0%	0%	96%
Cyprus	-16%	79%	-90%	25%	0%	0%	0%	0%	79%
Czech Republic	-97%	32%	-93%	-99%	69%	-99%	89%	-46%	25%
Denmark	92%	-99%	-100%	-61%	-97%	-99%	-18%	-66%	0%
Estonia	57%	77%	-97%	43%	0%	38%	-88%	0%	0%
Finland	44%	-69%	-61%	90%	-57%	3%	72%	5%	0%
France	-26%	-40%	-17%	31%	-36%	-51%	8%	82%	66%
Greece	-70%	82%	-45%	46%	31%	0%	0%	0%	0%

EU-27 countries	Wind energy	Concentrated Solar Power	Solar PV	Ocean energy	Hydroenergy	Geothermal energy	Bioenergy	CCS/U	Nuclear energy
Germany	63%	4%	-28%	-42%	-77%	62%	-33%	-35%	-87%
Hungary	48%	38%	-77%	0%	-8%	86%	55%	-86%	0%
Ireland	-46%	-67%	-38%	99%	-7%	0%	-37%	-93%	0%
Italy	-9%	44%	-24%	61%	-52%	32%	-4%	25%	-93%
Latvia	54%	49%	-42%	0%	0%	0%	20%	-98%	-94%
Lithuania	49%	44%	-54%	0%	79%	0%	-48%	0%	0%
Luxembourg	64%	-51%	-57%	-42%	0%	0%	-3%	93%	-95%
Malta	39%	-91%	0%	10%	-42%	0%	95%	0%	0%
Netherlands	51%	-35%	-32%	27%	-82%	36%	39%	64%	0%
Poland	27%	-6%	-72%	-8%	51%	85%	60%	42%	-76%
Portugal	-12%	35%	-88%	99%	-21%	0%	-49%	-91%	0%
Romania	3%	72%	-90%	-31%	40%	0%	27%	-70%	-78%
Slovakia	-58%	74%	-83%	0%	69%	-12%	15%	-99%	-2%
Slovenia	-81%	80%	-96%	-63%	94%	0%	0%	0%	-64%
Spain	61%	60%	-86%	30%	-75%	-47%	-44%	-40%	-90%
Sweden	31%	-52%	-85%	95%	-74%	80%	57%	-27%	31%
EU-27 Average	8%	9%	-61%	10%	-2%	4%	8%	-15%	-19%

Source: Own elaboration based on the data from the JRC.

Green colour indicates specialised countries ♦ Red colour indicates non-specialised countries ♦ Yellow colour indicates an equilibrium

4.2 Bibliometrics

4.2.1 Evolution over time

By using bibliometric indicators, the evolution of the scientific literature during the period 2007-2017 was identified, regarding the field of CETs. As Figure 15 illustrates, the most researched technological field was solar PV, which had a continuing upward trend until 2017. Wind and bioenergy technologies were researched considerably during the last decade, reaching more than 1500 and 900 articles respectively in their best year. The zoom-in in Figure 16 allows a more detailed view of the rest of the technologies. The research regarding the concentrated solar power technologies surpassed the research of hydroenergy and geothermal energy, which yet have an increasing number of papers during the whole in-scope period. Literature concerning CCS/U has developed, especially after 2012, when more than 100 papers were produced each year. Ocean energy has shown significant steps of development mainly after 2014, while the research of nuclear energy, both for fission and fusion technologies, remained low during the whole in-scope period.

An important observation is that the behaviour of the world publications differs from the respective of the world patent families (Figure 2; section 4.1.1). In the case of publications, a continuous increase is observed during the whole in-scope period, while a steep decrease in patent families was recorded for the period 2012-2015. This indicates that the production of scientific papers was not affected noticeably by the economic crisis in 2008.

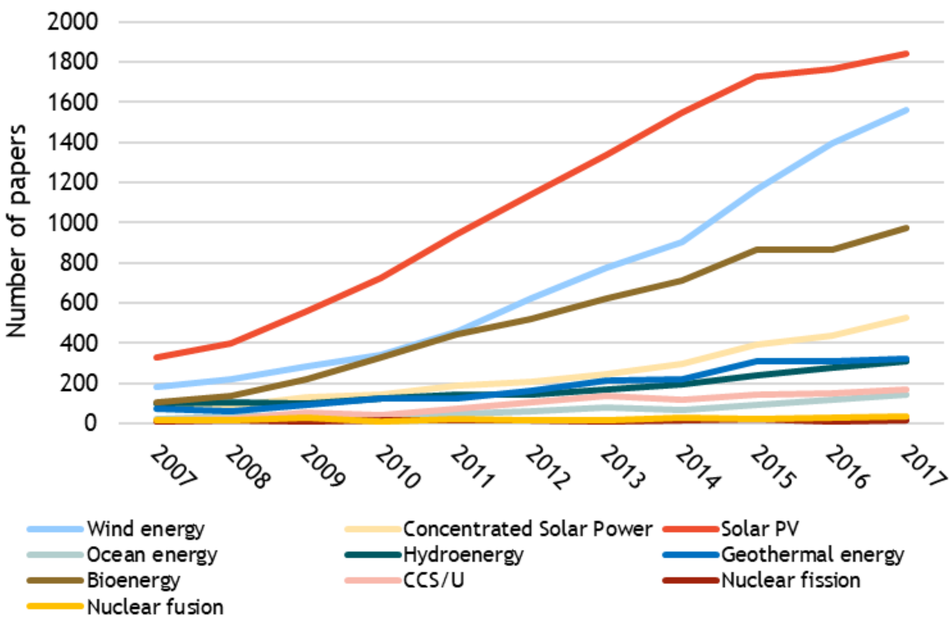

Figure 15 World publications per CET for the period 2007-2017

Source: Own elaboration based on the data from WoS.

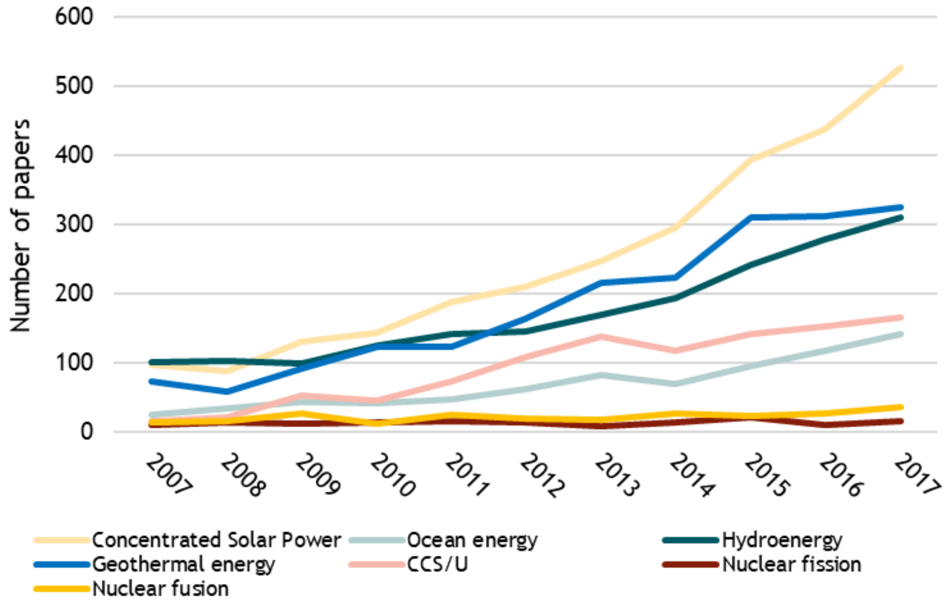

Figure 16 Zoom-in: world publications of concentrated solar power, ocean energy, hydroenergy, geothermal energy, CCS/U and nuclear energy (fission and fusion) for the period 2007-2017

Source: Own elaboration based on the data from WoS.

4.2.2 World players & best performing countries

The designation of the world players in the production of scientific papers was conducted by determining which countries performed best in each CET, i.e. which top-10 countries produced the most papers for the whole in-scope period per CET. The countries that had the most papers in most CETs are presented in Figure 17. The United States thrived in terms of scientific publications with more than 7500 articles and a strong preference in wind energy, solar PV and bioenergy. China comes second with approximately 5500 articles, almost half of which comes from the research of solar PV. The United Kingdom, Germany and Spain which complete the world players ranking, focused also mainly on those three technologies.

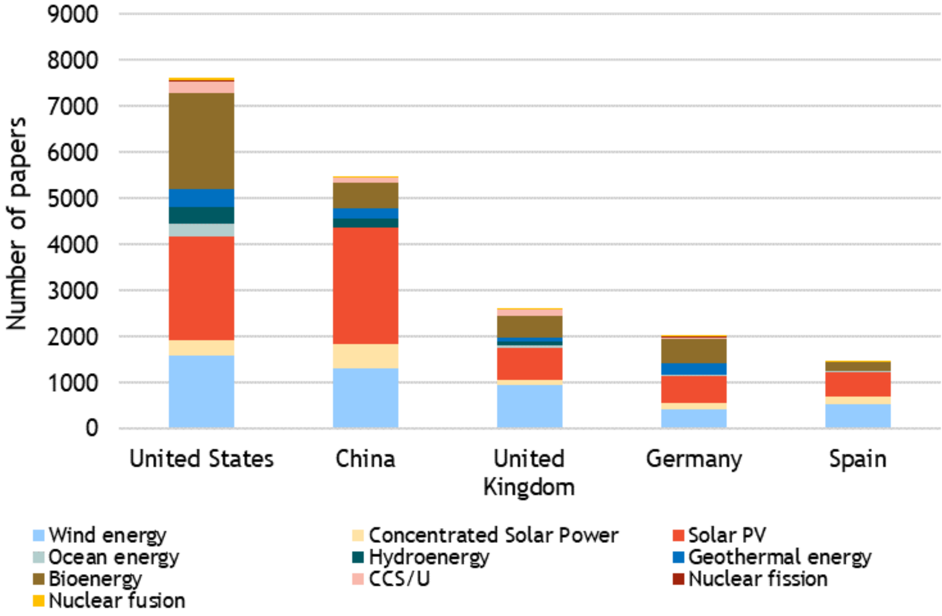

Figure 17 World players: number of papers per CET for the period 2007-2017

Source: Own elaboration based on the data from WoS.

4.2.3 Innovation as measured with Papers/Capita

The indicator papers per capita was found in Chapter 2 that meet the applied criteria, hence it was used as another measurement of innovation performance on a country level. Table 13 provides an overview of the best five performing countries in each CET. Denmark, Malta and Norway had an exceptional performance compared to their size regarding the wind energy technologies, while Iceland outstood in the research regarding geothermal energy. However, it is noticeable that none of the world players appears on that list. Since papers are weighted by the population of each country, this indicator mainly focuses on the scientific activity of each country compared to their size. Therefore, as presented in Table 13, countries with a small population are in favour and they are perceived as highly innovative. The results of wind energy are an apparent example; even though in the section 4.2.2 it was found that the United States and China have the highest number of papers in this sector, they have a quite large population, which leads to an overall small papers per capita value. On the contrary, countries such as Denmark and Malta, which produce many wind energy-related papers compared to their size, came on top of the list.

Table 13 Papers per million inhabitants: top-5 countries per CET

CET	Top 5 countries	Population	Papers/million inhabitants
Wind energy	Denmark	5,602,078	8.31
	Malta	428,029	5.59
	Norway	5,007,632	3.55
	Ireland	4,609,988	2.34
	Iceland	324,187	2.19
Concentrated Solar Power	Switzerland	8,005,669	0.65
	Australia	22,735,120	0.40
	Sweden	9,553,583	0.40
	Greece	10,973,976	0.38
	Spain	46,387,233	0.34
Solar PV	Cyprus	1,129,350	3.92
	Singapore	5,237,441	2.80
	Switzerland	8,005,669	2.48
	Taiwan	23,292,727	2.24
	Korea	50,137,000	2.00
Ocean energy	Ireland	4,609,988	0.48
	Norway	5,007,632	0.40
	Sweden	9,553,583	0.26
	Malta	428,029	0.19
	Portugal	10,468,825	0.19
Hydroenergy	Iceland	324,187	1.97
	Switzerland	8,005,669	0.72
	Malta	428,029	0.61
	Canada	34,699,962	0.55
	Croatia	4,251,388	0.47
Geothermal energy	Iceland	324,187	13.60
	New Zealand	4,451,236	1.04
	Switzerland	8,005,669	0.87
	Denmark	5,602,078	0.50
	Luxembourg	533,664	0.47
Bioenergy	Finland	5,408,192	4.31
	Sweden	9,553,583	3.01
	Denmark	5,602,078	2.27
	Norway	5,007,632	2.18
	Estonia	1,325,002	1.85
CCS/U	Norway	5,007,632	0.30
	Iceland	324,187	0.28
	Australia	22,735,120	0.18
	United Kingdom	63,695,305	0.17
	Singapore	5,237,441	0.17
Nuclear fission	Finland	5,408,192	0.08
	Sweden	9,553,583	0.08
	Belgium	11,047,472	0.06
	Slovenia	2,050,417	0.04
	Croatia	4,251,388	0.04
Nuclear fusion	Iceland	324,187	0.27
	Sweden	9,553,583	0.10
	Israel	7,926,273	0.08
	Portugal	10,468,825	0.07
	Czech Republic	10,486,827	0.06

Source: Own elaboration based on the data from WoS, World bank & Statista.

The population of each country was calculated as an average of the population during the period 2007-2017.

4.2.4 Innovation as measured with Growth Index

The growth index is another indicator used for the measurement of innovation performance in terms of scientific literature production. Figure 18 indicates that papers related to wind energy tripled during the in-scope period, while scientific research concerning concentrated solar power, hydroenergy and geothermal energy increased 2.5 times. It is noteworthy that articles for both ocean energy and CCS/U rose more than two units, indicating a significant development in scientific knowledge. Finally, the number of nuclear-related articles remained relatively stable during the two sub-periods, suggesting that the scientific community deviated from the research of nuclear energy and turned to other alternative technologies.

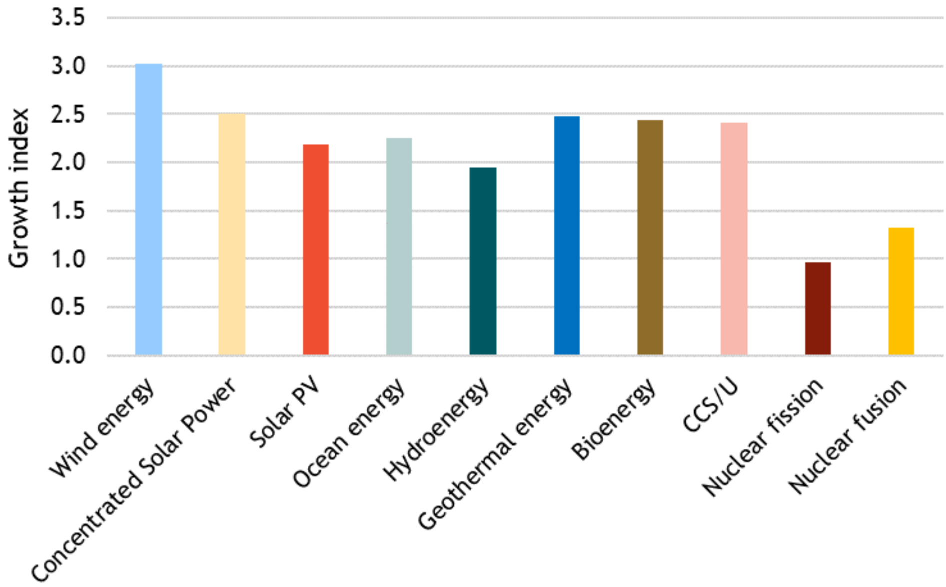

Figure 18 World growth index per CET for the period 2007-2017

Source: Own elaboration based on the data from WoS.

As discussed in section 3.2, the calculation of the growth index including all the countries that produced papers in the period 2007-2017 produced skewed results, favouring the countries with a low number of papers. For that reason, the benchmark of the average number of papers that all countries produced during the whole in-scope period was used, hence the countries with fewer papers than the average number were excluded from the process. Both results are illustrated in Table 14 and Table 15. The first noticeable difference is that the top-5 countries in each CET differ between the two cases; in Table 14 the majority of the countries are less innovative with small research impact and overall not especially developed in the clean energy sector (e.g. Pakistan, Nigeria, Malaysia). On the other hand, the results of Table 15 are more intuitive; the world players are present in the top-5 of most technologies, while countries with developed research activity are also included (e.g. France, Russia). Another difference lies in the values of the growth index; the values of Table 14 are much higher than the values of Table 15, which is justified considering their low research performance in the initial period. Finally, another interesting point concerning the outcomes of Table 15 is that the technologies regarding ocean energy, geothermal energy, CCS/U and nuclear fission had the most significant overall growth compared to the other technologies. Yet, geothermal energy and nuclear fission are well-established technologies, while ocean energy and CCS/U are fairly new with limited market potentials at the moment. Therefore, this indicator suggests that there has been intense research also in the established technologies and that more potentials in an economic and a technological level might emerge in the future even for renewable technologies that have been developed for decades.

Table 14 Growth index: top-5 countries per CET considering all the countries that produced papers in the period 2008-2017

CET	Top 5 countries	Growth index
Wind energy	Pakistan	7.95
	Malta	5.63
	Lithuania	5.63
	Qatar	3.97
	Malaysia	3.64
Concentrated Solar Power	Egypt	4.40
	Malaysia	2.20
	Iran	2.16
	Australia	2.10
	Spain	1.86
Solar PV	Nigeria	7.79
	Qatar	6.26
	Kuwait	5.73
	Portugal	4.05
	Senegal	3.21
Ocean energy	Italy	4.01
	India	2.52
	Spain	2.45
	China	2.38
	Saudi Arabia	2.23
Hydroenergy	Malaysia	9.76
	Laos	2.57
	Russia	2.31
	Norway	2.05
	Uruguay	2.05
Geothermal energy	Russia	5.66
	Belgium	4.85
	Indonesia	4.45
	Iran	3.37
	South Africa	3.23
Bioenergy	Colombia	5.75
	Indonesia	4.52
	Saudi Arabia	4.10
	Malaysia	4.00
	Pakistan	2.74
CCS/U	Singapore	3.73
	France	3.53
	China	3.25
	Iran	2.90
	India	2.77
Nuclear fission	China	3.09
	Spain	2.06
	Poland	2.06
	Uzbekistan	2.06
	France	1.80
Nuclear fusion	Canada	3.01
	Italy	2.26
	China	2.26
	Romania	2.26
	Poland	1.75

Source: Own elaboration based on the data from WoS.

Table 15 Growth index: top-5 countries per CET considering only the countries with a number of papers that is above the average in the period 2008-2017

CET	Top 5 countries	Growth index
Wind energy	Iran	2.38
	China	2.32
	Norway	1.45
	Italy	1.43
	India	1.38
Concentrated Solar Power	Spain	1.86
	United Kingdom	1.37
	China	1.18
	India	1.08
	Germany	0.99
Solar PV	Turkey	3.11
	India	2.11
	Switzerland	1.77
	China	1.30
	Canada	1.20
Ocean energy	Italy	4.01
	India	2.52
	Spain	2.45
	China	2.38
	Korea	1.91
Hydroenergy	Russia	2.31
	Norway	2.05
	Iran	1.98
	United Kingdom	1.74
	Italy	1.66
Geothermal energy	Iran	3.37
	Switzerland	2.71
	China	1.96
	Saudi Arabia	1.79
	Italy	1.60
Bioenergy	Italy	1.91
	Brazil	1.88
	Spain	1.77
	France	1.64
	Denmark	1.39
CCS/U	France	3.53
	China	3.25
	India	2.77
	Korea	2.35
	Canada	1.74
Nuclear fission	China	3.09
	Spain	2.06
	Poland	2.06
	France	1.80
	United States	1.51
Nuclear fusion	Italy	2.26
	China	2.26
	Poland	1.75
	Russia	1.72
	Spain	1.63

Source: Own elaboration based on the data from WoS.

4.2.5 Innovation as measured with Specialisation Index

Specialisation index is the final indicator that was used to assess the innovative performance of each country, under the prism of scientific publications.
As presented in Table 16 all the world players have the ultimate specialisation in wind energy, reaching 0.99. The United States has relatively balanced publications compared to the world, with an exception of solar PV which has lower activity than the rest of the world. China is less specialised in nuclear energy technologies, while Germany lacks in specialisation in hydroenergy and CCS/U. On the other hand, Spain showed the highest innovative activity among its peers in nuclear fusion while the United Kingdom performed best in CCS/U technologies.

Table 17 illustrates the specialisation index among the EU-27 countries. Wind energy is a strong research field among several European countries, resulting in a high average number, i.e. 0.65. Another interesting observation is that European countries are performing poorly in the concentrated solar power sector since only six out of the 27 Member States produced scientific papers during the in-scope period. The majority of the countries have also negative specialisation index for solar PV technologies; only Cyprus and Greece have positive values. In addition, ocean energy is not yet developed substantially within Europe, since many countries did not produce any paper during the in-scope period, while the average specialisation index is next to neutral. The research regarding CCS/U also did not flourish in the last decade, since most of the countries had lower innovative activity than the world average. On the contrary, hydroenergy, geothermal energy and bioenergy are the technologies in which the EU-27 Member States were more innovative in terms of scientific papers, while nuclear energy is a field in which only some of the EU-27 countries produced publications, during the period 2007-2017.

Table 16 Specialisation index for the world players during the period 2007-2017

World players	Wind energy	Concentrated Solar Power	Solar PV	Ocean energy	Hydroenergy	Geothermal energy	Bioenergy	CCS/U	Nuclear fission	Nuclear fusion
United States	0.99	-0.36	-0.18	0.14	-0.15	-0.14	0.16	-0.05	-0.09	0.00
China	0.99	0.14	0.16	-0.07	-0.17	-0.06	-0.22	-0.18	-0.45	-0.35
Germany	0.98	-0.15	-0.20	-0.17	-0.36	0.27	0.18	-0.45	0.26	0.30
United Kingdom	0.99	-0.16	-0.18	0.07	-0.20	-0.25	0.07	0.20	-0.39	0.01
Spain	0.98	0.26	0.14	0.16	-0.04	-0.15	-0.03	-0.34	0.19	0.36

Source: Own elaboration based on the data from WoS.

♦ *Green colour indicates specialised countries* ♦ *Red colour indicates non-specialised countries* ♦ *Yellow colour indicates an equilibrium*

Table 17 Specialisation index for the EU-27 countries during the period 2007-2017

EU-27 countries	Wind energy	Concentrated Solar Power	Solar PV	Ocean energy	Hydroenergy	Geothermal energy	Bioenergy	CCS/U	Nuclear fission	Nuclear fusion
Austria	0.74		0.04	-0.41	0.17	-0.14	0.53	-0.04	0.18	0.14
Belgium	0.91		-0.22	-0.55	-0.04	-0.24	0.19	-0.47	0.56	-0.04
Bulgaria	0.19		-0.70		-0.32	-0.19	-0.19	-0.30		0.39
Croatia	0.72		-0.24		0.73	0.62	-0.06		0.68	
Cyprus	-0.01		0.71		0.01	0.32	-0.23	0.48		
Czechia										
Denmark	0.98		-0.15	0.12	0.14	0.38	0.69	-0.28		
Estonia	0.10		0.08							
Finland	0.82		-0.28	-0.22	-0.15	-0.16		-0.36	0.54	0.01
France	0.96	-0.02	-0.07	0.04	0.14	-0.10	-0.11	-0.41	0.22	0.12
Greece	0.94	0.38	0.28	-0.47	0.51	0.59	0.40	-0.21	0.30	0.06
Germany	0.98	-0.15	-0.20	-0.17	-0.04	0.52	0.49	-0.45	0.26	0.30
Hungary	0.37		-0.78		-0.03	0.37	0.11		0.20	-0.04
Ireland	0.92		-0.20	0.73	0.14	0.03	0.86	-0.14		
Italy	0.97	0.07	-0.07	-0.22	0.17	0.59	0.54	-0.36	-0.50	0.43

EU-27 countries	Wind energy	Concentrated Solar Power	Solar PV	Ocean energy	Hydroenergy	Geothermal energy	Bioenergy	CCS/U	Nuclear fission	Nuclear fusion
Latvia	-0.01				0.71					
Lithuania	0.64		-0.24		0.51	0.28	0.86			
Luxembourg	-0.16		0.00				0.84			
Malta	0.63		-0.35	0.77						
Netherlands	0.96		-0.27	-0.17	0.10	0.39	0.80	0.09	-0.27	-0.49
Poland	0.91		-0.32	-0.44	0.44	0.39	0.16	-0.71	0.42	0.42
Portugal	0.94		-0.27	0.56	0.73	0.31	0.40	-0.27	-0.10	0.60
Romania	0.82		0.12	-0.01	0.62		-0.16	-0.16	0.12	0.59
Slovakia			-0.26		0.30		0.32			0.25
Slovenia	-0.01		-0.32		0.44	0.37	0.18			
Spain	0.98	0.26	0.14	0.16	0.30	0.25	0.41	-0.34	0.19	0.36
Sweden	0.94	-0.04	-0.04	0.37	0.65	0.18		-0.18	0.54	0.43
EU-27 Average	**0.65**	**0.08**	**-0.14**	**0.01**	**0.27**	**0.24**	**0.33**	**-0.24**	**0.22**	**0.22**

Source: Own elaboration based on the data from WoS.

The gaps in the table indicate that the country did not produce papers in the specific technology.

♦ Green colour indicates specialised countries ♦ Red colour indicates non-specialised countries ♦ Yellow colour indicates an equilibrium

5 Discussion

5.1 Contribution to literature

The present research had a twofold aim; first, it introduced a conceptual framework, in order to assess the existing patent and bibliometric indicators that were used in previous literature. The proposed framework consisted of three main steps, namely literature review which led to the collection of an extensive list of indicators, determination of the criteria that were required to select the most appropriate indicators, and assessment of the indicators. The suggested conceptual framework could be used in other researches as a methodology to assess any kind of indicators in the innovation context.

The second goal of this research was to measure innovation and to provide insights regarding the innovation performance of each CET, as well as to identify the world leaders that were steering the developments of the clean energy sector in the last decade. Regarding the evolution of the CETs during the period 2007-2018, the plots of the world patent families and the world publications depicted some similarities and some differences. In both cases, solar PV is the sector that stood out, with a much higher development than the rest of the technologies. Wind energy and bioenergy were also intensively developed in terms of patent intensity, as well as in terms of scientific literature production, even though they are considered as well-established forms of renewable energy. Ocean energy and CCS/U, which are both fairly new technologies, showed an upward trend both in terms of patent families and scientific papers. On the other hand, nuclear energy is the sector that developed differently under the prism of patents and publications; the scientific articles both for nuclear fission and fusion are the lowest among all the considered CETs, while regarding the patent activity, nuclear energy surpasses some conventional renewable technologies, such as geothermal and hydroenergy.

Concerning the world leaders of innovation, the results of the granted patent families and the publications showed that China, the United States and Germany are the countries that led the pre-commercialisation innovation activity. Korea and Japan performed also exceptionally under the prism of patent families, while Spain and the United Kingdom inserted the top-5 of scientific publications. It is worth to mention that two out of the seven world leader countries are members of the EU-27, which is an encouraging result. To dive more in-depth in the EU-27 innovation performance, the specialisation of each country per CET was analysed both in the context of patents and publications. The results showed a positive specialisation in bioenergy and wind energy technologies, while a negative specialisation was identified for solar PV and CCS/U technologies. The findings also suggest that European countries have specialised scientific knowledge in hydroenergy and geothermal energy, yet a close to neutrality behaviour was reported for these technologies when it comes to patent families. The opposite phenomenon was found for the concentrated solar power and ocean energy technologies. The outcomes regarding the strong and weak fields of the EU-27 Member States in the clean energy sector can be used as inputs for the EU to focus more on the research of those fields, in order to succeed in the energy transition and to meet the zero-emissions targets.

Finally, during the analysis of the results in Chapter 4, it was clear that some indicators, even though they met the criteria in the assessment phase, could not reflect the innovation performance of the countries objectively. More specifically, the indicator “papers per capita” sets the countries with a small population in a favourable position compared to the countries that might have produced many papers but they have a large population. In addition, the indicator “growth index” as discussed in section 4.2.4, gives an advantage to the countries that have very few papers in the initial period of measurement and that grow their scientific impact in the following period, even if the absolute number of papers is insignificant. Therefore, this research suggests the avoidance of those indicators for the innovation measurement, since the results are highly skewed.

Overall, the use of patent and bibliometric indicators are reflecting innovative activity in different phases of pre-commercialisation; the publications are describing the research and the experiments that are conducted during the stage of development of a technology, while patents represent inventions which are ready to enter the market. However, the majority of the results are showing the same patterns. The development trends of the CETs was similar both in the case of patents and publications, while a comparable specialisation was found by using the indicators “Relative Patent Share” and the “Specialisation index”. In the case of the world players of innovation, the results were complementary since not all countries are equally focused on the growth of the number of publications and the number of patents.

5.2 Limitations of the research

In this section, the limitations that were faced during the creation of the conceptual framework as well as during the research method phase, are addressed.
An important limitation of the conceptual framework is that the assessment of the indicators is a rather subjective process. The intension of the present study was to conclude in the most objective way the best indicators to measure innovation progress of CETs, and therefore criteria from five different literature sources were used for the assessment. Nevertheless, it is possible that the final results of the assessment might comprise the subjective view of the researcher. For instance, one of the criteria that the indicators should fulfilled was the clear definition/easy communication, which means that the indicator should be easily understandable. However, the level of comprehension differs among researchers, policy-makers, or the public, since it depends on the previous knowledge of the topic and on the context that one has on the subject.

The limitation of the research method, as discussed in section 2.2.3, was the lack of data regarding patent applications and granted patent applications. Due to the absence of knowledge of processing the PATSTAT database, there was a need of collecting those data through other sources. However, the gathering of accessible and high-value data for patent applications and granted patents was not possible, therefore the data for patent families and granted patent families were used instead. Yet, since patent families and patent applications are by definition highly correlated, the results regarding the CETs and the world players are not expected to be significantly different.

5.3 Recommendations for future research

The innovation performance that was measured in the current research could be used as an basis for further research regarding the phase of development of the CETs. The most well-known methodology of assessing the maturity of a technology is the Technology Readiness Level (TRL). This taxonomy has nine levels, starting from the early research phase where basic principles are observed, to the last level which includes technologies that are certified and commercialised in a large-scale (National Academies of Sciences, Engineering, and Medicine, 2016). However, the assignment of a TRL level to the CETs has been materialised in a limited extent. In order to fill this gap, an interesting approach would be to link the results of the patent and bibliometric analysis to the level of maturity of each technology. As mentioned in section 5.1, publications reflect the research that is conducted from the time a technology is being first developed, to the point where it can be fully applicable and demonstrative. Patents on the other hand, express the stage of development before a technology enters the market. If the information of these two different phases of development are combined, then they could be translated into levels of maturity. Nevertheless, in this research, the disaggregation of the technologies was conducted in a high level. Yet, for the assignment of TRL levels, a further disaggregation in to sub-technologies might be needed since each CET consists of many sub-components, which might have different levels of maturity.

6 Conclusions

The aim of the present study was to evaluate the patent and bibliometric indicators that have been used in the literature from the 1990s until the present, in order to measure innovation progress. Overall, this research confirmed the point of Archibugi & Planta (1996), who noticed that the quantification of innovation is a quite challenging task.
The results of this analysis were used as a tool to quantify the evolution of innovation in the technologies of the clean energy sector. To answer the research question "*Which are the most appropriate indicators to monitor the innovation progress of clean energy technologies under the prism of patents and bibliometrics?*", a conceptual framework was constructed which included three steps; the creation of an extensive list of indicators by conducting a literature review, the selection of the appropriate criteria that the indicators should met and the assessment of the indicators. From this procedure, the most appropriate indicators to measure innovation progress of CETs that were concluded for the dimension of patents were:

- Patent families;
- Granted patent families;
- World Patent Share (WPS);
- Relative Patent Share (RPA).

For the dimension of bibliometrics, four indicators were resulted, namely

- Number of papers;
- Papers per capita;
- Growth index;
- Specialization index (SI).

However, the use of those indicators for the measurement of innovation, showed that some of them produce highly skewed results. As discussed in section 4.2.3 and 4.2.4, the indicators "papers per capita" and "growth index" favor on the one hand, the countries with smaller populations, and on the other, the countries that at the beginning of the in-scope period produced very few papers. For that reason, they should be excluded from the list of the appropriate bibliometric indicators.

As far as the evolution of CETs is concerned, for some technologies such as ocean energy and CCS/U technologies, the scientific knowledge and the patenting activity was limited during the last decade. This indicates that more R&D should be invested in that direction. On the other hand, the research suggests that well-established technologies such as wind energy and solar PV technologies which have been researched for decades, led the innovative activity in terms of patents and publications.

Finally, regarding the EU innovation performance, it was concluded that even though the results of the EU-27 Member States are encouraging, more effort and investments should be made in the R&D of CETs for two reasons; first, the EU should catch-up the extremely innovative countries, such as China and Korea, in order to be competitive in the market. Secondly, an increase in innovation performance would play a crucial role to achieve the targets of energy transition and net-zero emissions that the EU has set by 2050.

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Annex A

Literature review

Extensive list of indicators

This section provides the extensive list of the patent and bibliometric indicators that were gathered during the literature review. For each indicator, the definition and the description are provided and for the indicators that was available, their respective limitations.

Table 18 Extensive list of patent indicators along with their respective definition, description and limitations

Article	Indicator	Definition	Description & Rationale	Limitations
OECD (2009)	Renewals of patents	The maintenance fees that the patent holder should pay periodically, in order to keep the patent on force.	During the period that the patent is on force, patent holders need to pay renewal fees usually every year, which increase over time. If the patent holder is not willing to pay the fee, then the invention is released in the public domain. The rationale of using this indicator is based on economic criteria, since the patent is renewed only if the profits from the patents exceed the costs of renewal.	-Not renewing a patent might be explained by change in company's strategy - Technologies have different rates of obsolescence, so the results are not objective -Exogenous factors might affect the decisions of renew a patent
	Number of claims	Each individual patent includes a bundle of inventive components, each reflected in a claim.	It is used as a proxy for the legal scope of the patents which is an important determinant for its economic value since it designates the legal dimensions of protection.	Some applicants inflate the number of claims, so the link between the claims and the scope becomes less reliable and the value of the indicator is degraded.
	Number of technical classes	The number of International Patent Classification (IPC) classes attributed	It is used as a proxy for the scope and subsequently the value of the patent.	Limited evidence has been found in literature that support the correlation between technical

Article	Indicator	Definition	Description & Rationale	Limitations
		to a patent application.		classes and the value of a patent.
	Number of inventors in a patent	The number of inventors that are listed in the patent application.	It is argued that the more inventors involved in a patent, the more resources were attributed to the research, hence the technical value could be higher.	It is a rough measure that considers all the inventors as equals. There is a need for additional information such as details on their career and their involvement on the invention.
	Opposition	The number of granted patents that have faced opposition from third parties.	Due to the fact that opposing to a patent is a costly procedure, it is implied that only the patents that have economic value will face opposition. The patents that survive the opposition have potentials of high profitability.	The share of the opposed patents is small (i.e. 5% in EPO) and the mutual settlements are hard to be detected.
	Granted patents	The number of patents that have been granted.	If a patent is granted, then the patent fulfils the patentability criteria, namely novelty, inventive step and industrial applicability. Those patents have higher economic and technological value than those that have not been granted.	A very large share are granted (i.e. approximately 60%), so the indicator does not provide many insights about the market value of a patent.
	Patent family size	The set of patents filed in several countries which are related to each other by one or several common priority filings.	The family size indicates the economic value of a patent; considering that the validation of a patent in several countries is a costly procedure, only the inventions that are expected to produce high profits will apply for patent protection. Also, a patent that is protected	

Article	Indicator	Definition	Description & Rationale	Limitations
			internationally, will have larger market coverage hence greater profit potentials.	
OECD (2015)	Patent scope	The field of interest of the patent.	The scope of a patent is related to the technological and economic value. The wider a scope is, the more substitutes are included in the same product class, hence the patent is more valuable. The scope of a patent can be measured by using the sub-classes of the IPC.	
	Grant lag	Grant lag period is the time between the date of filing an application and the date of the grant.	Applicants that consider that their inventions have high value, try to accelerate the grant procedure by well-documenting their applications and by following closely the actions of the patent office. Hence, there is a correlation between the value of a patent and the length of grant lag period.	
	Backward citations	Backward citations are the references that include prior scientific work, sources of knowledge or other patents, that an invention is based on.	They are used to assess whether an invention is patentable and define whether the claims stated in the application are legit.	Large number of backward citation might indicate that the invention is in an incremental phase. - Patent offices have different citation practices and disclosure rules, so data produced from alternative data sources might not be comparable.

Article	Indicator	Definition	Description & Rationale	Limitations
	Forward citations	The number of citations a specific patent receives.	It is an indication of the technological importance of a patent to the deployment of the subsequent inventions and reflects the economic value of the invention.	Forward citations appear after a period of 5 or 7 years after the publication date, so the timeliness of the indicator is decreased[11].
	Citations to non-patent literature (NPL)	NPL includes scientific and conference papers, databases and other relevant literature that are used as references in the patent application.	They reflect the correlation between the patent and the scientific knowledge and the links between the technological and scientific development.	- The patent offices might influence the references included in the patent application due to differences in examination procedures - It is difficult to establish causation between the citing patent and the cited article.
	Breakthrough inventions	The top 1% cited patents, that is the most highly cited patents.	Those inventions are related to entrepreneurial strategies and to further technological development. They are high impact innovations which are used as a basis for future technological developments Alternative definition:	Since they are based on citations, there is a time lag of 5 years in order to identify the most cited patents in a particular technological field.
	Generality index	Generality index measures the width of the applicability of an invention across different technological fields[12].	The index is based on forward citations and IPC technology classes. A high value of generality index indicates a wide applicability of the invention (meaning that a given patent is cited for inventions that are in other technical classes), hence high market value	- If the number of patents that the index is based on is small, then the measurement is biased. -Equal treatment for technologies that are related but exist in different IPC classes and for very distant technology domains,

[11] OECD (2009). OECD Patent Statistics Manual 2009
[12] Marku, E. (2018). Measuring Innovation Quality: A Patent Analysis. IOSR Journal of Business and Management (IOSR-JBM). DOI: 10.9790/487X-2008055158

Article	Indicator	Definition	Description & Rationale	Limitations
			and usefulness for other inventions.	hence overestimation or underestimation of the generality of patents.
	Originality index	Originality index measures the width of technological knowledge synthesized in an invention[12].	The index is based on backward citations and IPC technology classes. The rationale behind this index relies on the claim that inventions based on a wide range of knowledge sources, hence on patents that belong to different technological sectors, have original results.	Same limitations with the generality index.
	Radicalness index	Radicalness index refers to the extend at which an invention is different from other inventions on the same field[13].	If an invention is considered radical, then it is expected to have high value for the society and for the market.	It does not take into account the patents filled during the same period of time in the same sector, hence if it is "unique" for the given time period.
Fischer & Leidinger (2014)	Self-citations	The citations a patent receives from documents that belongs to the same assignee.	If a patentee has many self-citations, his patents gain more strength and become more competitive.	- Only citations received in the 5-year time-frame from the filling date are taken into account. -Self-citations are not included in PATSTAT database, so the data are difficult to be obtained.
	Patent age	The time passed from the date that the patent was granted.	The older a patent is, the higher degree of market penetration the underlying technology reaches.	The underlying technology of older patents is more likely to be obsolete.
Lanjouw & Schankerman (2004)	USPC	United States Patent Classification is a system that	When working with patents of different technologies, it is a useful tool to categorise	

[13] Shane, S. (2001). Technological opportunities and new firm creation. Management science, 47(2), 205-220. https://doi.org/10.1287/mnsc.47.2.205.9837

Article	Indicator	Definition	Description & Rationale	Limitations
		organises the U.S patents documents in specific technological groups considering the common subject matter[14].	them according to an official classification system.	
World Intellectual Property Organization. (2018)	Number of patent applications	The number of applications that have been filed in a specific year or period of time, worldwide or in a specific country.	The number of patent applications are a clear indication whether a country in inclined to innovation by providing absolute numbers. A major advantage is that the data can be easily obtained.	
Haščič & Migotto (2015)	Counts of co-inventions	The number of inventions that they have inventors from multiple countries.	Useful to track the collaboration among the counties in the clean energy technologies.	
Hu & Mathews (2008)	Technology Cycle Time (TCT)	It measures how fast a technology is turning over, in terms of years, by using the median age of the patents cited on a patent document.	TCT measures the progress of technological innovation, by using patent citations as an indication of the age of the innovations in which the new innovation is based on. A small amount of cycles (e.g. 3-5 years) implies fast substitutions, hence fast progress of innovation and vice versa.	
	Scientific linkages	The count of the patent references that include scientific papers.	A high number of scientific linkages indicates that the technology of the patent is based on scientific knowledge.	
	Average citation frequency	Average citation frequency counts	It measures how often these patents were used	

[14] USPTO (2017). Patent classification. Retrieved from https://www.uspto.gov/patents-application-process/patent-search/classification-standards-and-development

Article	Indicator	Definition	Description & Rationale	Limitations
		how many times the patents of a sector, in force the last 5 years, are cited in the USPTO during the current year.	as basis for newest patents.	
	Patent intensity	It refers to the average R&D expenditure per granted patent (from the USPTO)		
Hu, Skea, & Hannon (2016)	Triadic patent families	Triadic patent families include a set of patents that are filled from the same applicant and for the same invention at the USPTO, EPO and JPO[15].	By using triadic families, first the "home advantage effect"[16] is decreased and secondly they indicate the objective value of the patents.	The consideration of only OECD triadic patent family might omit important inventions from catching-up countries that might not afford the expenses of the triadic family.
	PCT patent applications	Patent applications filed under the Patent Cooperation Treaty (PCT).	The PCT is signed by 145 Contracting States, so by applying in PCT, the inventor ensures that his patent will be protected in a larger number of regions (if granted). Also, international patent applications have specific, yet demanding procedures which require a significant amount of time and money. Therefore, only the patents with high potential commercial value are expected to be filled internationally, hence this indicator is	

[15] United States Patent and Trademark Office (USPTO), European Patent Office (EPO) and Japan Patent Office (JPO).
[16] Applicants reside in the same region as the patent office, have higher contribution to the patent publication.

Article	Indicator	Definition	Description & Rationale	Limitations
			associated with product innovation[17].	
Kapoor et al. (2012)	International Patent Classification (IPC)	IPC is a classification system which divides the technologies in sections and sub-divisions[18].	IPC provides a clear distinction of the technological fields that an invention belongs to.	An invention might be used for different commercial purpose that it was originally intended to. In that case, the IPC does not provide accurate information about the invention, since it only defines the technology that it is used and not the commercial use of the invention.
	Patent family	Patent family is a group of patents that protect the same invention and they are filed in several countries. The concept of patent family is frequently associated with the concept of invention[19].	Filling a patent in several patent offices in different countries is a cost-intensive procedure. Hence, it is deemed that these patents have high market value. Also, by using this indicator, the double-counting of patents is avoided when doing cross-countries comparisons[20].	The time lag between the application and the grant of a patent might reach 44 months (for the USPTO). Thus, the complete statistics of the patent families will have a delay of approximately 3 years.
Eichhammer & Walz (2009)	World patent shares	The indicator expresses the fraction of the patents that a country holds for a specific technology to the world patents of that technology.	This indicator can be used as a tool for easy comparison between countries and different technologies.	
	Specialisation indicator	When a country has a better performance in a	The specialisation indicators are dimensionless, and	

[17] Bayer, P., Dolan, L., & Urpelainen, J. (2013). Global patterns of renewable energy innovation, 1990–2009. Energy for Sustainable Development, 17(3), 288-295.
[18] WIPO (2020). Guide to the International Patent Classification. Retrieved from https://www.wipo.int/edocs/pubdocs/en/wipo_guide_ipc_2020.pdf
[19] Fiorini, A., Georgakaki, A., Pasimeni, F., & Tzimas, E. (2017). Monitoring R&I in Low-Carbon Energy Technologies.
[20] Shubbak, M. H. (2019). Advances in solar photovoltaics: Technology review and patent trends. Renewable and Sustainable Energy Reviews, 115, 109383. https://doi.org/10.1016/j.rser.2019.109383

Article	Indicator	Definition	Description & Rationale	Limitations
		specific technology compared to other countries or to other field of technologies.	usually measured in a -100 to +100 or in a -1 to +1 scale. That facilitates comparison of the activities between the countries.	
	Relative Patent Share (RPA)	The patent share of a country for a given technology compared to patent shares of the country in all technological fields.	This indicator provides a clear representation of how well a specific technology performs in terms of innovation in a given country, compared to the other fields.	
Marinova (2008)	Rate of assignment of patents (RAP)	The number of patents assigned to the residents of a country divided by the number of patents.	RAP provides an indication of how close a patent is to be commercialised.	
Shubbak (2019)	Priority fillings	It indicates the place and the time when the first patent filing took place.	This indicator provides information about the time and place where an invention first occurred and it gives a more representative image about the patenting activities of the countries.	
	Transnational patents	This indicator includes the patents filed at the European Patent Office (EPO) as well as the patents filed internationally under the Patent Cooperation Treaty (PCT).	This indicator verifies the economic and technological value of the patent, while it is a method to avoid double counting of patents that are included in the same patent family.	
	Patent impact factor (PIF)	PIS is equal to the number of citations received at family level per	PIF indicates the most influential patents by taking into account the forward citations of the patents.	

Article	Indicator	Definition	Description & Rationale	Limitations
		priority patent life time (age).		
	International Business Potential (IBP)	It is the percentage of the number of patent families that contains at least one transnational patent application per total number of the country's priority filings.	IBP can be used as a proxy for the business potential of patent applications in an international level.	
	Revealed Technology Advantage index (RTAI)	RTAI is expressed as the proportion of the patent applications held by a country in a particular technological sector over the patents of that country in all sectors, divided with the proportion of the world patents in a particular technological sector over the world patents in all technological sectors.	RTA reflects the technological specialization of a country regarding its patenting activities. A RTA greater than 1 means that a country is specialised in a specific technological field compared to other countries, and vice versa.	
Wu (2014)	Relative growth rate (RGR)	RGR is expressed as the average growth rate of granted patents for a specific technological field divided with the average growth rate of the cumulative granted patents for all technological fields	RGR indicates whether a technology is attractive to the industry. A high value of RGR implies a high value of growth rate, hence a high level of R&D.	

Article	Indicator	Definition	Description & Rationale	Limitations
		for the total in-scope period.		
	Relative patent position (RPP)	RPR is expressed as the number of patents held by a country for a specific technological sector divided with the number of patents held by the most active competitor in the specific technological sector.	The largest competitor country acts as a benchmark to compare the R&D intensity of other countries.	
Jang et al. (2013)	Patent share (PS)	PS is expressed as the total number of granted patents of a technological sector a country holds divided with the world granted patents in the specific technological sector.	Patent share indicates the innovative capability of a country which is an important factor for the competitiveness of a country and its market position.	
	Patent production propensity (PPP)	The ratio of a country's production output of a specific technology in a given year (e.g. 2006) to the cumulative patent stock in that technology between a specific period of time (e.g. 1996-2006).	By using this indicator, the benefits of cumulative innovative capacity in a given technology can be measured, compared to the total production of all the technologies.	
	Revealed technological advantage (RTA)	RTA is expressed as the share of a country's global patenting activity in a particular	This indicator is useful to measure the competence of a given country in a specific technological field.	

Article	Indicator	Definition	Description & Rationale	Limitations
		relative to the share of the country's global patenting activity in all technological sectors.		
Qiu & Yang (2018)	Lifespan of Patents	The period of time when the patentee pays an annual fee in order to maintain the patent in force.	*Same rationale with renewal fees*	
Wu & Mathews (2012)	Relative citation propensity	This indicator is expressed as the deviation of a country's x citations to another country y in a given year per total citations made by country x in a given year to the citations made to country y in the given year excluding the citations from country x per total citations in the given year excluding the citations from country x.	This indicator compares the behaviours of patent citing among different countries.	
Kacham et al. (2012)	Marketability	Marketability is expressed as the average number of patent applications in several countries as a result of the particular patent applications or patent family size.	This indicator measures the commercial value of patents.	

Article	Indicator	Definition	Description & Rationale	Limitations
	Citation velocity	This indicator is expressed as the counts of patent citations divided with the years passed from the publication date of the patent.	This indicator signifies the technological significance of a patent.	
Míguez et al. (2020)	Innovation index	Innovation index is expressed as the number of patents citing a patent x minus the number of patents cited by patent x divided with the subtraction of the present year with the publication year of patent x.	By using this indicator, "a comparison between the number of times a patent is cited and how many patents are cited within a given patent" can be conducted.	

Table 19 Extensive list of bibliometric indicators along with their respective definition, description and limitations

Article	Indicator	Definition	Description & Rationale	Limitations
Archambault et al. (2009)	Papers per capita	The number of scientific papers at a country level, divided by the population of the given country.	The rationale for the use of this indicator is to compare the scientific output with the size of a country and to make comparisons between countries.	
	Growth	The number of papers produced in a certain period of time (e.g. 2002-2007) divided by the number of papers produced in a previous period of time (e.g. 1996-2001).	By comparing the growth in country and global level, comparisons among the countries can be done to conclude which countries present the biggest increase in scientific knowledge in terms of innovation.	
	Specialisation index (SI)	The research intensity of a country compared	If a country scores higher than 1, then the country is specialised in the given topic compared to	

Article	Indicator	Definition	Description & Rationale	Limitations
		to the rest of the world.	the rest of the world, while a value lower than 1 indicates the opposite.	
	Average of relative citations (ARC)	It measures the scientific impact of papers produced in a country, based on the citations received from other papers from their publication until a specific year.	This indicator shows whether a paper has high citation impact.	
Katz & Hicks (1998)	Citations per paper	The number of citations a paper receives during a citation window[21].	This indicator measures the impact of a given paper to the production of the scientific knowledge. The most citations it receives, the greater the impact it has in the research community.	The diffusion of knowledge does not occur at the same rate in all the scientific fields. Consequently, the number of citations might not be an objective indicator, in terms of cross-fields comparisons.
	Collaborative papers	Scientific papers that have been written by multiple co-authors from the same or different institutions.	The collaboration can be identified in domestic and international level. This indicator shows the interaction between institutions and countries in order to produce scientific knowledge.	
Okubo (1997)	Number of papers	The counts of papers (books, journals, newspapers, reviews, reports, articles) that reflect the scientific output.	This indicator is used as an approximation of the quantity of work produced by scientific institutions (laboratory, schools, R&D team) and by countries.	This indicator does not account the quality of the mentioned papers, neither distinguish the contribution of each co-author, in case there is more than one.

[21] Citation window is a time frame in which a paper receives citations. The duration can vary but usually in the 5th year, a paper has received approximately 50% of their citations (Katz & Hicks, 1998).

Article	Indicator	Definition	Description & Rationale	Limitations
	Number of co-signers (co-authors)	The numbers of papers that are written from more than one writers.	It indicates the national or international cooperation.	-some authors might work and live in different countries; yet usually, the place of work is used as address. -some authors might have more than 1 affiliations with different institutes in different countries.
	Affinity index	The indicator is expressed as the grade of scientific exchanges between two countries during a specific period of time over the international cooperation of between those countries during that specific period of time.	The affinity index indicates the links among countries and the power of those linkages	The affinity index can only be applied in cases of cooperative links between the countries, occurring in both directions.
	Co-citations	The number of times two papers are cited by the same article simultaneously.	Co-citations might create clusters which have related research subjects. From those clusters, the evolution of the fields can be described.	This indicators is biased towards scientific literature and might omit the technical literature, because they describe only a part of the assembling of knowledge.
Mao et al. (2015)	Impact factor	It is expressed as the number of citations a journal acquires divided with the articles that the journal has published the previous two years per number of articles published also the last two years.	By measuring the citations a journal receives, the quality of the article and its significance in a specific field can be identified.	

Article	Indicator	Definition	Description & Rationale	Limitations
	h-index	A researcher has index h if h of his/her N papers received at least h citations per paper and the N-h papers have received less than h citations per paper.	This indicator considers both the quality and quantity of the outcome that a scientist produces, so it provides an objective overview of the impact of his/her work.	
Robitaille et al. (2015)	Number of highly cited papers	The papers that are in the top 1% or 5% most cited papers.	This indicator shows which papers are the most influential in the scientific community.	
	International collaboration	The authors of the paper should be affiliated with institutions that are located in different countries.	It indicates the scientific collaboration among countries.	
	Average of Interdisciplinarity Index (AII)	The Interdisciplinarity Index is the share of references that a paper has which belongs to different fields than its own. For any set of papers, the Average of Interdisciplinarity Index is the average of the individual Interdisciplinarity Index.	This indicator indicates how many different disciplines take part in a part, hence how interdisciplinary is the paper.	
	Average of Interdisciplinarity Relative Index (AIRI)	The Interdisciplinarity Relative Index is the normalised Interdisciplinarity Index by the average interdisciplinarity index (AII) of all	*Same rationale as with the Average of Interdisciplinarity Index (AII).*	

Article	Indicator	Definition	Description & Rationale	Limitations
		papers from the same disciplinary field. So, For any set of papers, the Average of Interdisciplinarity Relative Index is the average of the individual Interdisciplinarity Relative Index.		
	Research Level	It is based on the type of research each journal publishes; a) clinical observation or applied technology, b) clinical mix or engineering-technological mix, c) clinical investigation or applied research and d) basic research.	It indicates how progressed a research is.	

Overlaps of the indicators

In this section, the definitions of the indicators that gathered during the literature review, and have similar names or express similar concepts are compared, in order to conclude a list of unique indicators.

i. Patents

Renewals & Lifespan of Patents

- **Renewals:** The maintenance fees that the patent holder should pay periodically, in order to keep the patent on force (OECD, 2009).
- **Lifespan of Patents**: The period of time when the patentee pays an annual fee in order to maintain the patent in force (Qiu & Yang, 2018).

These two indicators regard both the maintenance fees of the patents, yet they are not expressing the same concept. Renewals represent the maintenance fees that needs to be paid, while the lifespan of patents counts the period of time that those fees are being paid. Therefore, for the assessment they were treated separately.

Different Classification systems

- **Number of technical classes**: The number of International Patent Classification (IPC) classes attributed to a patent application (OECD, 2009).
- **USPC**: United States Patent Classification is a system that organises the U.S patents documents in specific technological groups considering the common subject matter (Lanjouw & Schankerman, 2004).
- **PCT patent applications***:* Patent applications filed under the Patent Cooperation Treaty (PCT) (Hu, Skea, & Hannon, 2016).
- **International Patent Classification (IPC***):* IPC is a classification system which divides the technologies in sections and sub-divisions (Kapoor et al., 2012).

The International Patent Classification (IPC), which is under the administration of World Intellectual Property Organization (WIPO), contains 8 technology sections and 70.000 subdivisions and provides an internationally uniform classification (WIPO, 2020). However, many countries that produce a large number of patent per year, have their own patent classification system. The most prominent ones are the United States Patent Classification (USPC) system (which includes only the U.S patent documents and categorize them to the respective technological field), the European Patent Office (EPO), the China National Intellectual Property Administration (CNIPA), the Japan Patent Office (JPO) and the Korean Intellectual Property Office (KIPO). In 2013, the U.S and Europe jointed their forces and created a common classification system, namely Cooperative Patent Classification (CPC) system. This initiative intended to have a similar structure to IPC, yet to be a more detailed classification system (CPC, 2020).
Finally, the Patent Cooperation Treaty (PCT), which is under the administration of the International Bureau (IB) of the World Intellectual Property Organisation (WIPO), enables a patentee to seek protection in a large number of countries (i.e. to the 145 that have signed the treaty), by filling an international patent application.

For the assessment phase of the indicators, all the different categories of classifications systems (e.g. IPC, USPC) were treated as one under the name "Number of technical classes", since the differences underlie only in the country of force.

Patent families & Triadic patent families & Patent family size & Priority fillings

- **Triadic patent families:** Triadic patent families include a set of patents that are filled from the same applicant and for the same invention at the USPTO, EPO and JPO (Hu, Skea, & Hannon, 2016).
- **Patent family:** Patent family is a group of patents that protect the same invention and they are filed in several countries. The concept of patent family is frequently associated with the concept of invention (Fiorini et al., 2017)
- **Patent family size:** The set of patents filed in several countries which are related to each other by one or several common priority filings (OECD, 2009).

- **Priority filling:** The place and the time when the first patent filing took place. (Shubbak, 2019).

The definition of patent family size is the same with the definition of patent family, so they were treated as one. The definition of priority filling is not a replication of the definition of patent families, therefore it was treated as a separate indicator. Finally, the patent families is a big category, which can incorporate different types of families, such as triadic patent families and trilateral patent families (OECD, 2009). Hence, for the assessment, the general category (i.e. patent family) was considered.

World patent shares & Patent share (PS)

- **World patent shares:** The fraction of the patents that a country holds for a specific technology to the world patents of that technology. (Eichhammer & Walz, 2009).
- **Patent share (PS):** The total number of granted patents of a technological sector a country holds divided with the world granted patents in the specific technological sector (Jang et al., 2013).

These 2 indicators express the same concept, therefore only the "World patent shares" was considered for the assessment of the indicators.

Revealed Technological Advantage & Revealed Technology Advantage index & Relative Patent Share

- **Revealed technological advantage (RTA):** The region's share of global patenting in a specific technological field, divided by its share of global patenting in all technological fields (Jang et al., 2013). It is based on the formula:

  $$RTA_{ij} = \frac{PS_{ij}}{PS_i}$$

  where PSi is the number of granted patents of all technological fields and PS_{ij} is the patent share calculated as $PS_{ij} = \frac{GP_{ij}}{\sum_i GP_{ij}}$ where GP_{ij} are the granted patents of i country and j technology of a specific year and $\sum_i GP_{ij}$ are the total cumulative granted patents of i country and j technology over a specific period of time. According to Jang et al. (2013), a RTA value greater than one indicates that the country is specialised in the technology under investigation, while a value smaller that one indicates the opposite.

- **Revealed Technology Advantage index (RTAI):** The share of patent applications of a country in a particular technological field over the total patents of the country in all technological fields divided with the share of world patents in the specific field over the world patents of all technological fields (Shubbak, 2019). The indicator is based on the following formula:

$$RTAI = \frac{\frac{P_{ij}}{P_{iT}}}{\frac{P_{Nj}}{P_{NT}}}$$

Where P is the patent applications, i is the country, j is a specific technological field, N is the number of all countries and T all the technological fields. Again, this indicator expresses how specialised is a country in a specific technology by using positive and negative values for the RTAI.

- **Relative Patent Share (RPA)**: The patent share of a country for a given technology compared to patent shares of the country in all technological fields (Eichhammer & Walz, 2017). The indicator is given from the formula:

$$RPA_{ij} = 100 \times \tanh ln \frac{\left[\frac{GP_{ij}}{\sum_i GP_{ij}}\right]}{\left[\frac{\sum_j GP_{ij}}{\sum_{ij} GP_{ij}}\right]}$$

  where i is the country and j is the technology and GP_{ij} are the granted patents. This indicator expresses how specialised is a country in a specific technology compared to the other technological fields.

Since all the aforementioned indicators express the specialisation of a country to a specific technology, only the indicator Relative Patent Share (RPA) was included in the list of indicators and was subsequently assessed.

ii. Bibliometrics

Collaborative papers & Number of co-signers (co-authors)

- **Number of co-signers (co-authors):** The numbers of papers that are written from more than one writers (Okubo, 1997).
- **Collaborative papers:** Scientific papers that have been written by multiple co-authors from the same or different institutions (Katz & Hicks, 1998).

These two articles, use different names in the indicators for expressing the same concept, i.e. papers that are written from more than one authors. Therefore, for the assessment, the term “collaborative papers” was used.

Annex B

Criteria of the assessment

Table 20 provides a detailed list of the criteria that were proposed in the five sources that were selected, along with the respective definition of each one. Since different names are often used to describe the same concept, a colouring system has been applied in order to distinguish which sources are using the same criteria. The criteria that are expressing the same concept are highlighted with the same colour.

Table 20 Criteria retrieved from five sources and their respective definitions

Literature	Criterion	Definition
Miremadi et al. (2018)	Understanding	Indicators should be quite simple and understandable, therefore if the definition of an indicator is difficult to comprehend or it has multiple sub-components it will be rejected.
	Availability	There should be enough data and information to support the indicators, in order to have a complete overview. If there is a lack of data for a particular indicator, it should be omitted.
	Relevance	The indicators should reflect the desired sector of the research. In the specific case of CET, the indicator should be relevant to the energy sector.
	Measurability	In this research, only numerical indicators will be included (e.g. counts, percentages), so the results are more tangible and useful for comparisons between countries and technologies.
Pwc (2017)	Validity	The indicators must successfully reflect the phenomenon they represent. Hence, a change in the indicators should illustrate the change in the respective phenomenon.
	Accessible data	It is important to assure that there are enough data when deciding to use a specific indicator.
	Performance-based	These indicators provide information for the changes and progress that might occur. [22]
	Easily communicable	The indicators should be understandable even for the audience that is not specialised to the topic. Also, it is important that complex data are being communicated in an simplified manner, so the public is adequately informed.

[22] On contrary, practice-based indicators focus on whether certain practices are being well-adopted and adhered.

Literature	Criterion	Definition
	Clearly defined and standardised	If an indicator is well defined and standardised, then comparisons among countries and time are possible.
	Widely accepted	If the indicators are widely accepted by the audience/ policy-makers, the chances are higher that a change might occur.
United Nations Statistical Division (2015)	Relevant	Linked to the target and applicable at the appropriate level (i.e. the indicator should be applicable to all countries if the goal is the global monitoring, the indicator should be related to the national priorities if the goal is the national monitoring)
	Methodologically sound	The indicators should be based on concrete methodology (e.g. data sources, method of computation) and on existing definitions, classifications and standards.
	Measurable	Sources of data should be available in order to build the indicators.
	Easy to communicate and access	The indicator should be clear and easy to communicate to the public, policy-makers and all relevant stakeholders. Also, the access should be easy for all the aforementioned stakeholders.
Wolf et al. (2015)	Robustness	The indicators should be scientifically sound and their computation should have the minimum uncertainty.
	Relevance	The indicators should assist the measurement of progress of a specific goal, increase the awareness regarding an important issue and support the decision-making.
	Effectiveness	The indicators should be relevant to the technical and functional performance.
	Clear and easy to measure	The measurement procedures should be standardised and within acceptable effort limits.
	Practicality	The indicators should be applicable with low costs and sufficient duration.
Brown (2009)	Valid and meaningful	The indicator should mirror sufficiently the phenomenon that is measured and should be user-friendly.
	Sensitive and specific to the underlying phenomenon	The indicator should be able to reflect the variations which result from changes in the measured phenomenon.
	Grounded in research	The indicator should reflect the factors that influence the results.

Literature	Criterion	Definition
	Statistically sound	The indicator should be methodologically sound and be relevant to the purpose of the measurement.
	Intelligible and easily interpreted	The indicators should be easy to be interpreted and they should reflect intuitively what they are measuring.
	Relate where appropriate to other indicators	An indicator might need to be interpreted together with other indicators in order to reflect in total the phenomenon.
	Allow international comparison	The indicators should be able to be consistent with international indicators, in order to allow comparisons.
	Ability to be disaggregated over time	The indicators should be able to be disaggregated into sub-groups, areas or populations.
	Consistency over time	The indicators should reflect the changes of a phenomenon over time.
	Timeliness	The collection and the reporting of data should incorporate minimal time lag, so the results are up to date.
	Linked to policy or emerging issues	The indicators should reflect important problems and be able to monitor them.
	Compel interest and excite	The indicator should be compelling and exciting for the audience.

The criteria with the same colour in the list are expressing the same concept.

Annex C

Justification of the assessment of the indicators

This section presents in more detail the reasoning behind the assessment of the indicators.

Patent indicators

Table 21 Justification for the assessment of the patent indicators

Indicators	Clear definition/ easy communication	Scientific soundness	Validity
Renewals of patents	The definition is clear and straightforward.	It is based on existing definitions and previous studies have use it as well,	The criterion of validity is not met because this indicator is used mostly as a proxy of the market value of the invention, rather than for the progression of the invention.
Number of claims	The definition is clear and straightforward.	It is based on existing definitions and previous studies have use it as well, so it is scientifically sound.	The criterion of validity is not met because the claims represent the scope of the patent, which indicates the economic value and the market value of a patent, hence no connection to the innovation progress of patents.
Number of technical classes	The definition is clear and straightforward.	It is based on existing definitions and previous studies have use it as well, so it is scientifically sound.	The criterion of validity is not met because this indicator is used as an approximation of the scope, therefore it represents the value of the patent.
Number of inventors in a patent	The definition is clear and straightforward.	Several studies have used this indicators so it can be considered as scientifically sound.	The criterion of validity is not met because it estimates the technical and economic value of the patent by using the costs for the research of the invention. Hence, the progress of innovation is not reflected from that indicator.

Indicators	Clear definition/ easy communication	Scientific soundness	Validity
Opposition	The definition is clear and straightforward.	Several studies have used this indicators so it can be considered as scientifically sound.	The criterion of validity is not met because the number of patents that have been opposed is not connected to the innovation progress of the CET. It is once again an economic and technical value measurement.
Granted patents	The definition is clear and straightforward.	Several studies have used this indicators so it can be considered as scientifically sound.	Regarding the validity, by monitoring the patents that have been granted per year and per country, useful conclusions can be drawn regarding how much a specific technology has shown. If there is an increase, that means that in the specific technology has many new inventions that fulfil the patentability criteria and have industrial applications. If there is a decrease, then it can be concluded that the technology is becoming obsolete.
Patent scope	The definition is not very clear and explicit.	It is based on concrete methodology hence it is scientifically sound.	The criterion of validity is not met because the scope of the patent in a given technological field does not provide information about the progress of that technology. It reflects the economic and technical value of the patent.
Grant lag	The definition is clear and straightforward.	It is based on concrete methodology hence it is scientifically sound.	The criterion of validity is not met because the grant lag is an indication of the value of the patent.
Backward citations	The definition is clear and straightforward.	It is based on concrete methodology hence it is scientifically sound.	The criterion of validity is not met because this indicator is used to assure the patentability and the legitimacy of the patents. It is not linked to the progress of innovation.
Forward citations	The definition is clear and straightforward.	It is based on concrete methodology hence it is scientifically sound.	The criterion of validity is not met because this indicator signifies the economic importance of the patent.

Indicators	Clear definition/ easy communication	Scientific soundness	Validity
Citations to non-patent literature (NPL)	The definition is clear and straightforward.	It is frequently used and it is based on the existing definitions, hence it is scientifically sound.	The criterion of validity is not met because it does not directly indicate the progress of innovation.
Breakthrough inventions	The definition is clear and straightforward.	It is based on previous definitions and the methodology is concrete, however there is a time lag of 5 years to classify the 1% most cited patents.	The criterion of validity is not met since they are based on patent citations, which for this research are consider as not an appropriate way of measuring innovation progress since they are (potentially) indirect indicators of innovation.
Generality index	The definition is not very clear; it needs additional information in order to be understandable.	It is based on concrete methodology hence it is scientifically sound.	The criterion of validity is not met since this indicator reflects mostly the usefulness of the patent to other patents and market value of the patent.
Originality index	The definition is not very clear; it needs additional information in order to be understandable.	It is based on concrete methodology hence it is scientifically sound.	The criterion of validity is not met since this indicator reflects mostly the usefulness of the patent to other patents and the market value of the patent.
Radicalness index	The definition is clear and straightforward.	It is based on concrete methodology and it is used in several studies, hence it is scientifically sound.	The criterion of validity is not met since it assesses the radicalness of the invention, therefore it is an indication of the market and society value of the patent and not of the progress of innovation.
Self-citations	The definition is clear and straightforward.	It is based on previous literature and definitions so it is scientifically sound.	The criterion of validity is not met since it does not provide any information about the progress of innovation. It is mostly relevant to the market value of the patent.
Patent age	The definition is clear and straightforward.	It is based on previous literature and definitions so it is scientifically sound.	The criterion of validity is not met since the age of the patent does not provide information about the progress of innovation; it can only indicate how obsolete a technology is.
Number of patent applications	The definition is clear and straightforward.	It is based on previous literature and definitions so it is scientifically sound.	The criterion of validity is met because the patent applications show during a specific period of time per

Indicators	Clear definition/ easy communication	Scientific soundness	Validity
			country which technologies are developing and which are falling behind; hence, it is a measurement of the progress of innovation and comparisons between countries and technologies can be made.
Counts of co-inventions	The definition is clear and straightforward.	It is based on previous literature and definitions so it is scientifically sound.	The criterion of validity is not met since the collaboration among countries and institutions does not directly measures the innovation.
Technology Cycle Time (TCT)	The definition is not very clear and it might not be easily understandable from an public with little knowledge on the field of patents and inventions	It is based on previous literature and definitions so it is scientifically sound.	The criterion of validity is met since it is an indicator that measures the evolution of technological progress, however it uses patents citations which are an indirect measurement of innovation progress.
Scientific linkages	The definition is clear and straightforward.	It is not based on previous literature and definitions so it is not scientifically sound.	The criterion of validity is not met since it indicates if a patent is based on scientific literature and the concerning technology is science-based, which has no link to the progress of innovation.
Average citation frequency	The definition is clear and straightforward.	The article is not referring to previous literature regarding the definition, so it is considered as not scientifically sound.	The criterion of validity is met since if a patent is referred a lot the last 5 years, that means that the technology is relevant and it is under intense development. Therefore, this indicator implies the progress of innovation in a specific technology.
Patent intensity	The definition is clear and straightforward.	It is based on previous literature and definitions so it is scientifically sound.	The criterion of validity is met since the evolution of R&D expenditures per technology can show which technology is fairly new and needs further developments, which has reached a peak ad which is considered obsolete, considering that new technological ideas need further investigation, hence heavy investments in research.

Indicators	Clear definition/ easy communication	Scientific soundness	Validity
Patent families	The definition is clear and straightforward.	It is based on previous literature and definitions so it is scientifically sound.	By considering that a patent family represents an invention in several countries, the track of the patent families per countries and technologies provides information about the progress of innovation and from the results comparison between countries can be made. Therefore, the criterion of validity is met.
World patent shares	The definition is clear and straightforward.	It is based on concrete methodology so it is scientifically sound.	The criterion of validity is met since the world shares of patents indicate how each country progressed in terms of innovation per technology during a given period of time, and it is very useful to make comparisons between countries for the same technologies.
Specialisation indicator	The definition is not clear (e.g. how the performance is measured).	The article does not provide sources to base the methodology and the definition of this indicator, so it is considered as not scientifically sound.	The criterion of validity is met since we can track how specialised is a country in a given technology. That means that during a period of time a country might innovate a lot so becomes a specialist in a specific technology. Hence, the progress of innovation is reflected in this indicator.
Relative Patent Share (RPA)	The definition is clear and straightforward.	It is based on concrete methodology so it is scientifically sound.	The criterion of validity is met since this indicator measures the progress of innovation in a specific technology compared to the other technological fields. Also, it enhances cross country comparisons in order to identify in which technologies the countries are more innovative.
Rate of assignment of patents (RAP)	The definition and reasoning of this indicator is not clear; the link between the patents assigned to residents of country and the stage	It is based on concrete methodology so it is scientifically sound.	The criterion of validity is not met because this indicator reflects mostly the market impact of an invention.

Indicators	Clear definition/ easy communication	Scientific soundness	Validity
	of commercialisation is not well explained.		
Priority fillings	The definition is clear and straightforward.	It is based on previous literature and definitions so it is scientifically sound.	The criterion of validity is not met because it provides a better overview about where and when a patent application was filled but it does not provide information about the progress of innovation.
Transnational patents	The definition is clear and straightforward.	It is based on concrete methodology so it is scientifically sound.	The criterion of validity is not met since the patent office in which a patent was applied does not provide information about its progress of innovation; it is mostly relevant for business and market purposes.
Patent impact factor (PIF)	The definition is not understandable for the public and the article does not provide much information about it.	It is not based on concrete methodology so it is not scientifically sound.	The criterion of validity is not met since it expresses which patent is the most influential, so it is irrelevant to the progress of innovation.
International Business Potential (IBP)	The definition is not understandable for the public and the article does not provide much information about it.	It does not provide previous sources that use this indicator so it is not scientifically sound.	The criterion of validity is not met since it expresses the business potential of patent applications in an international level.
Relative growth rate (RGR)	The definition is not clear and easily understandable.	The indicator is not based on previous literature, so it is not scientifically sound.	The criterion of validity is met since the growth rate is included in the indicator, which is directly linked to the innovation progress of each technology.
Relative patent position (RPP)	Even though the definition is straightforward, the article does not explain in detail the how some components are defined or calculated, therefore it has a high level of ambiguity.	The indicator is based on previous literature, so it is scientifically sound.	The criterion of validity is met since this indicator monitors whether a country increases or decreases its innovative activities in a specific technology compared to a leader country. Therefore the progress of innovation is reflected.

Indicators	Clear definition/ easy communication	Scientific soundness	Validity
Patent production propensity (PPP)	The definition is not clear and the message it attempts to convey is quite complex	It is not based on previous literature, so it is not scientifically sound.	The criterion of validity is met since it compares the production of a given technology to the cumulative patent stock of that technology, so it indicates what percentage of the patent reaches the commercial production. That is an indication of progress.
Lifespan of Patents	The definition is clear and easily understandable.	It is based on previous literature, so it is scientifically sound.	The criterion of validity is not met because the lifespan of patents is irrelevant to their progress of innovation. It mainly reflects the economic potential of the patents
Relative citation propensity	The definition is very complex and difficult to be understandable from the public.	The indicator is based on previous literature, so it is scientifically sound.	The criterion of validity is not met because it compares behaviours of patent citing among different countries and does not reflect the innovation progress of clean energy technologies.
Marketability	The definition is quite complex and difficult to be understandable from the public.	The article does not mention previous studies to back up the indicator, so it is not scientifically sound.	The criterion of validity is not met because it does not reflect the innovation progress of clean energy technologies. It is linked to the commercial value of the patent.
Citation velocity	The definition is quite complex and difficult to be understandable from the public.	The article does not mention previous studies to back up the indicator, so it is not scientifically sound.	The criterion of validity is not met because it does not reflect the innovation progress of clean energy technologies; it rather measures how important is a patent to a technology.
Innovation index	The definition is quite complex and difficult to be understandable from the public.	The indicator is based on previous literature, so it is scientifically sound.	The criterion of validity is not met because the patents citations do reflect the innovation progress of CET.

Bibliometric indicators

Table 22 Justification for the assessment of the bibliometric indicators

Indicators	Clear definition/ easy communication	Scientific soundness	Validity
Papers per capita	The definition is clear and easily understandable.	The indicator is based on concrete methodology so it is scientifically sound.	It is valid for the current research because by measuring the number of papers produced per capita in the defined period of time, the performance of each country can be identified in terms of scientific output of the clean energy technologies. Hence, it can be identified how well or bad each country is doing compared to its size and identify the changes in time.
Growth index	The definition is clear and easily understandable.	The indicator is based on concrete methodology so it is scientifically sound.	It is valid for the current research because it indicates if a country has increased or decreased the research, in terms of scientific output, regarding CET, compared to a previous period. So, it is an indicator that measures progress in innovation. However, for this study, the considered period will be in total 10 years, so the results might not be as useful as if the period was larger.
Specialisation index (SI)	It is clearly defined how this indicator is computed by looking at the formula and it is clear what it represents.	The indicator is based on concrete methodology and previous sources so it is scientifically sound.	The criterion of validity is met because it can measure if the specialisation for a specific technology of each country changed during the defined period of time, so if it progressed in terms of innovation.
Average of relative citations (ARC)	The definition is quite complex and does not convey the message in an easy and understandable manner.	The indicator is based on concrete methodology and previous sources so it is scientifically sound.	The criterion of validity is not met because the citation impact that each publication has does not provide information about the innovation progress of each CET.
Citations per paper	The definition is clear and straightforward.	The indicator is based on concrete methodology and previous sources so it is scientifically sound.	The criterion of validity is not met because the number of citations that each publication receives does not

Indicators	Clear definition/ easy communication	Scientific soundness	Validity
			provide information about the innovation progress of each CET.
Collaborative papers	The definition is clear and straightforward.	The indicator is based on concrete methodology and previous sources so it is scientifically sound.	The criterion of validity is not met because the collaboration among institutions and countries does not provide direct information about the innovation progress of each CET, which is the desired indication of this research.
Number of papers	The definition is clear and straightforward.	The indicator is based on concrete methodology and previous sources so it is scientifically sound.	The criterion of validity is met because by measuring the number of papers in a specific period of time, the increase or decrease of scientific output can be identified, hence it can be shown whether a country has invested more or less in the research and innovation of a specific technology.
Affinity index	The definition is quite complex and does not convey the message in an easy and understandable manner.	The indicator is based on concrete methodology and previous sources so it is scientifically sound.	The criterion of validity is not met because the collaboration among countries does not indicate directly the progress of innovation.
Co-citations	The definition is clear and straightforward.	The indicator is based on concrete methodology and previous sources so it is scientifically sound.	The criterion of validity is not met because the co-citations are mostly used to identify which technological fields and institutions are involved in the research, which is not directly relevant to the innovation progress.
Impact factor	The definition is very complex and does not convey the message in an easy and understandable manner.	The indicator is based on concrete methodology and previous sources so it is scientifically sound.	The criterion of validity is not met because the this indicator is measuring the quality of the article, which not relevant to the measurement of innovation.
h-index	The definition is very complex and does not convey the message in an easy and understandable manner.	The indicator is based on concrete methodology and previous sources so it is scientifically sound.	The criterion of validity is not met because this indicator measures the quality and quantity of the work of the author, which are not relevant for the progress of innovation in CET.

Indicators	Clear definition/ easy communication	Scientific soundness	Validity
Number of highly cited papers	The definition is clear and straightforward.	The indicator is based on concrete methodology and previous sources so it is scientifically sound.	The criterion of validity is not met because this indicator identifies which are the most influential papers in the scientific community, which does not directly indicate the progress of innovation.
International collaboration	The definition is clear and straightforward.	The indicator is based on concrete methodology and previous sources so it is scientifically sound.	The criterion of validity is not met because the international collaboration does not give a direct measurement of innovation and the progress of it during the defined period of time, even though it is interesting to identify which institutions and countries are collaborating.
Average of Interdisciplinarity Index (AII)	The definition is very complex and does not convey the message in an easy and understandable manner.	The indicator is based on concrete methodology and previous sources so it is scientifically sound.	The criterion of validity is not met because the involvement of different technological fields to the research does not indicate progress of innovation.
Average of Interdisciplinarity Relative Index (AIRI)	The definition is very complex and does not convey the message in an easy and understandable manner.	The indicator is based on concrete methodology and previous sources so it is scientifically sound.	The criterion of validity is not met for the same reason as for the AII; the involvement of different technological fields to the research does not indicate progress of innovation.
Research Level	The definition is not very clear and explicitly detailed.	The indicator is based on concrete methodology and previous sources so it is scientifically sound.	The criterion of validity is met since the level of research of which an article presents, indicates the level of progress that the specific technology is.

Annex D

Relative Patent Share

Table 23 provides an overview of the Relative Patent Share values per CET for all the countries that were considered from the JRC.

Table 23 Relative Patent Share (RPS) for all the countries considered from the JRC.

JRC Countries	Wind energy	Concentrated Solar Power	Solar PV	Ocean energy	Hydroenergy	Geothermal energy	Bioenergy	CCS/U	Nuclear energy
United Arab Emirates	20%	-99%	-96.7%				94.5%	80.6%	
Argentina	-11%	62%		89.73%			75.4%	-92.2%	-34.3%
Austria	-24%	47%	-42.4%	-56.63%	48.0%	37.6%	15.5%	68.2%	-99.9%
Australia	-72%	26%	-21.0%	87.64%	-45.4%	19.8%	30.0%	75.0%	
Belgium	34%	-2%	12.9%	21.73%	-99.1%	-43.0%	-13.0%	-34.4%	-90.7%
Bulgaria	29%	50%	-85.7%		90.3%				52.8%
Bermuda	73%						93.5%		
Brunei			79.9%						
Brazil	-41%	-58%	-99.0%	-14.52%	26.4%		95.0%	-21.6%	
Belize	94%								
Canada	-43%	-67%	-36.6%	30.97%	-72.8%	32.4%	69.1%	88.5%	40.8%
Switzerland	-43%	18%	-38.7%	-19.69%	-82.3%	94.0%	12.8%	92.2%	-96.5%
Chile		48%							
China	6%	26%	-21.6%	-0.26%	30.5%	-33.9%	6.0%	-24.8%	-26.0%
Colombia	83%						88.4%		
Costa Rica		93%							
Cuba									

JRC Countries	Wind energy	Concentrated Solar Power	Solar PV	Ocean energy	Hydroenergy	Geothermal energy	Bioenergy	CCS/U	Nuclear energy
Cyprus	-16%	79%	-89.6%	25.46%					79.5%
Czech Republic	-97%	32%	-92.8%	-99.00%	68.9%	-99.1%	89.0%	-46.0%	24.7%
Germany	63%	4%	-28.2%	-41.95%	-77.4%	62.3%	-33.1%	-34.8%	-87.0%
Denmark	92%	-99%	-99.5%	-60.94%	-97.3%	-99.3%	-18.0%	-66.1%	
Dominican Republic									
Ecuador									
Estonia	57%	77%	-97.3%	43.34%		38.5%	-88.0%		
Greece	-70%	82%	-45.2%	45.81%	30.9%				
Spain	61%	60%	-86.4%	29.85%	-74.5%	-47.1%	-43.8%	-39.5%	-90.1%
Finland	44%	-69%	-60.9%	90.02%	-57.4%	2.8%	72.3%	5.3%	
France	-26%	-40%	-17.0%	31.37%	-36.4%	-51.0%	8.1%	81.9%	65.7%
Georgia	19%				99.1%				
Hong Kong	-83%	-6%	58.5%	20.58%			-73.2%	-8.0%	
Croatia	-94%	-98%	-81.8%		97.0%				95.8%
Hungary	48%	38%	-76.5%		-8.3%	85.7%	55.3%	-85.9%	
Indonesia									
Ireland	-46%	-67%	-38.5%	99.14%	-7.3%		-37.1%	-93.1%	
Israel	-94%	68%	21.5%	3.21%	-99.4%		-28.0%	-94.2%	
India	-66%	-65%	-60.1%	75.19%	-74.4%		78.4%	95.3%	-90.8%
Iran									
Island	56%						95.5%		
Italy	-9%	44%	-23.5%	60.95%	-52.4%	32.4%	-3.6%	24.5%	-93.0%
Jordan									
Japan	-56%	-85%	47.7%	-63.00%	-47.8%	44.8%	-20.5%	22.0%	35.7%
Korea	-30%	-56%	31.1%	6.05%	-60.1%	46.3%	-16.8%	-0.2%	46.4%

JRC Countries	Wind energy	Concentrated Solar Power	Solar PV	Ocean energy	Hydroenergy	Geothermal energy	Bioenergy	CCS/U	Nuclear energy
Kazakhstan									
Liberia									
Lithuania	49%	44%	-54.4%		78.7%		-47.5%		
Luxembourg	64%	-51%	-57.5%	-42.08%			-3.2%	93.1%	-95.5%
Latvia	54%	49%	-42.3%				19.8%	-97.9%	-94.5%
Morocco	45%	62%	-86.4%	94.67%	-99.9%		-63.8%		
Moldova	72%	-2%	-76.3%	90.99%	-24.2%		-65.6%	-46.0%	
Macao	94%								
Malta	39%	-91%		9.82%	-42.3%		94.9%		
Mexico	-59%	76%	-88.0%	-50.94%			65.3%	29.3%	-85.6%
Malaysia	-41%	-76%	-15.6%	-89.57%	-98.8%		88.8%	72.5%	
Netherlands	51%	-35%	-31.5%	26.60%	-82.3%	35.8%	38.8%	64.3%	
Norway	31%	-91%	-86.7%	97.37%	58.3%	62.1%	-29.2%	86.6%	-96.4%
New Zealand	-89%	-96%	-94.5%			-48.2%	97.2%	-52.2%	
Philippines			-56.5%						
Poland	27%	-6%	-72.4%	-8.04%	51.2%	84.6%	60.1%	41.9%	-76.3%
Puerto Rico									
Portugal	-12%	35%	-88.1%	98.73%	-21.0%		-49.1%	-90.7%	
Romania	3%	72%	-90.0%	-30.93%	39.5%		27.4%	-69.5%	-77.7%
Russia	19%	-57%	-79.9%	36.43%	28.8%	-10.2%	13.2%	-21.9%	91.9%
Saudi Arabia	-51%	19%	-39.2%	43.84%		-64.6%	-73.7%	97.1%	-75.3%
Seychelles									
Sweden	31%	-52%	-85.2%	94.79%	-73.8%	80.5%	56.7%	-27.2%	31.5%
Singapore	-44%	-90%	46.0%	80.44%	-48.7%	-92.7%	25.9%	-4.9%	
Slovenia	-81%	80%	-95.5%	-62.79%	93.6%				-64.2%

JRC Countries	Wind energy	Concentrated Solar Power	Solar PV	Ocean energy	Hydroenergy	Geothermal energy	Bioenergy	CCS/U	Nuclear energy
Slovakia	-58%	74%	-82.8%		68.6%	-12.2%	14.8%	-99.3%	-1.9%
Syria	94%								
Thailand	-81%		-5.4%	45.59%			88.1%	89.7%	
Tunisia	-34%						97.3%		
Turkey	-40%	85%	-98.3%	-94.12%	79.0%		-83.7%		
Taiwan	-49%	15%	50.6%	-39.29%	-67.7%	-98.0%	-86.4%	-76.2%	-98.0%
Ukraine	72%	14%	-67.7%	-64.22%	42.7%		-59.3%	-66.1%	-61.2%
United Kingdom	35%	-78%	-52.1%	97.12%	-24.7%	38.3%	7.7%	24.6%	-82.3%
United States	7%	-64%	8.3%	-17.36%	-91.9%	-24.5%	31.4%	75.2%	1.7%
Uruguay									
British Virgin Islands	74%		-61.8%		32.6%		27.5%	-22.4%	
U.S. Virgin Islands	94%								
Vietnam	94%								
Vanuatu	94%								
Samoa	90%		-42.9%						
South Africa	-30%		-98.1%	82.47%	-73.2%	98.6%	74.7%	-31.0%	-70.6%

Source: Own elaboration based on the data from JRC.