



## Digitalisation in wind and solar power technologies

H.L. Kangas<sup>a</sup>, K. Ollikka<sup>b,\*</sup>, J. Ahola<sup>c</sup>, Y. Kim<sup>a</sup>

<sup>a</sup> Finnish Environment Institute (SYKE), Latokartanonkaari 11, 00790, Finland

<sup>b</sup> VATT Institute for Economic Research, PL 1279, 00101, Helsinki, Finland

<sup>c</sup> LUT University, PL 20, 53851, Lappeenranta, Finland

### ARTICLE INFO

#### Keywords:

Smart energy  
Renewable energy  
Digitalisation  
Technology convergence  
Patent

### ABSTRACT

Smart energy transition includes a widespread deployment of clean energy technologies and intelligent energy management with information and communication technologies (ICTs). In this paper, the smart energy transition is studied from the viewpoint of the technology convergence of renewable energy sources (RESs) and ICTs. Two important, fast-growing and weather-dependent renewable energy generation technologies: wind power and solar PV (photovoltaic) are studied. This paper provides technology convergence analyses of RES and ICT inventions based on international patent data. Digitalisation is changing the whole of society, and according to the results, this transition can also be seen in the studied renewable energy generation technologies. The digitalisation of RES production covers technologies that control, manage and optimise electricity production in different intelligent ways. Differences between wind power and solar PV technologies are found: in the case of wind power, the development from virtually no ICT solutions to partial technology convergence with the ICT sector is straightforward. However, in the case of solar PV, the development of basic technologies has been even faster than the development of the solar PV ICT solutions, which may indicate the immature nature of solar PV technologies during the studied years. The digitalisation of the renewable energy sector poses challenges for RES companies in following and predicting ICT development and opportunities for innovations and collaborations with ICT companies. This conclusion can also be expanded to society and policy levels because focusing on only a narrow field when planning innovation policy instruments can negatively impact the country's competitiveness.

### 1. Introduction

Renewable energy production capacity is expected to double during the years 2019–2024, led by solar and wind power investments [1]. As the share of weather-dependent renewable electricity generation increases, smart energy inventions are needed to enable the transition [2]. Park and Heo [3, p. 2] defined smart energy transition as a 'series of activities or transitions to increase the efficiency, safety, and eco-friendliness of an energy system by ICT convergence along the energy life cycle of production, transmission, and consumption', where the initialism *ICT* stands for 'information and communication technology'.

Technological transition and inventions often lead to the fusion or convergence of technologies. Technology convergence is the blurring of boundaries between at least two areas of technology, and it increases the connectedness of the areas, which can be seen in patenting behaviour [4]. Technology convergence is an important way of developing innovations, especially in the era of digitalisation [5–8].

The aim of this paper is to deepen the understanding of the smart

energy transition. A technology convergence analysis based on patent data for the renewable energy sources (RESs) and ICT is carried out. Thus, the implications of digitalisation for RESs are analysed. Solar photovoltaic (PV) and wind power are used as case studies of RES technologies. These technologies were chosen because their capacity and importance in the energy markets is increasing rapidly [1]. In addition, these technologies have undergone major developments in recent decades and have patent classifications that are suitable for technology convergence analysis. Moreover, enough accumulated patent data are available for the technology convergence analysis.

Digital technologies and ICT have influenced almost all technologies [9]. ICT convergence occurs when ICT inventions are embedded into products and services from other industries [3]. The ICT convergence of different sectors has become the subject of a handful of studies utilising patent data. In particular, the convergence of broadcasting, entertainment and ICT [10], biotechnology and ICT [7,11,12], and nutraceuticals and functional foods and ICT [4] have been studied. However, the convergence of renewable energy technologies and ICTs has not been studied with patent data.

\* Corresponding author.

E-mail addresses: [hanna-liisa.kangas@syke.fi](mailto:hanna-liisa.kangas@syke.fi) (H.L. Kangas), [kimmo.ollikka@vatt.fi](mailto:kimmo.ollikka@vatt.fi) (K. Ollikka).

<https://doi.org/10.1016/j.rser.2021.111356>

Received 7 October 2020; Received in revised form 11 May 2021; Accepted 10 June 2021

Available online 3 July 2021

1364-0321/© 2021 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

### List of abbreviations

BOP	Balance of plant
CCMT	Climate change mitigation technology
CPC	Cooperative Patent Classification
ICT	Information and communication technology
IPC	International Patent Classification
MPPT	Maximum power point tracking
OECD	Organisation for Economic Co-operation and Development
PATSTAT	Worldwide Patent Statistical Database
PPA	Power purchase agreement
PV	Photovoltaic
RES	Renewable energy source

In the research framework, the metric defining technology convergence is the co-classification of solar PV and wind power patents with ICT patents. *Co-classification* means that the patents of two formerly separate fields are increasingly classified as belonging to both technology fields. Thus, a macro-perspective on the technology convergence by using aggregate numbers and shares of RES and ICT patent co-classifications is applied in this paper. The research framework is mainly based on quantitative analysis, although to demonstrate the smart energy transition in RES production, examples of the most prominent patents co-classified as wind power or solar PV technologies and ICT are provided.

The research questions are as follows:

- 1 Are there signs of the technology convergence of renewable energy (wind power and solar PV) technologies and ICTs?
- 2 If so, are there differences in the technology convergence between the wind power and solar PV technologies?
- 3 How can the developments in the technology sub-fields and inventor countries of the studied technologies explain the dynamics of any technology convergence?

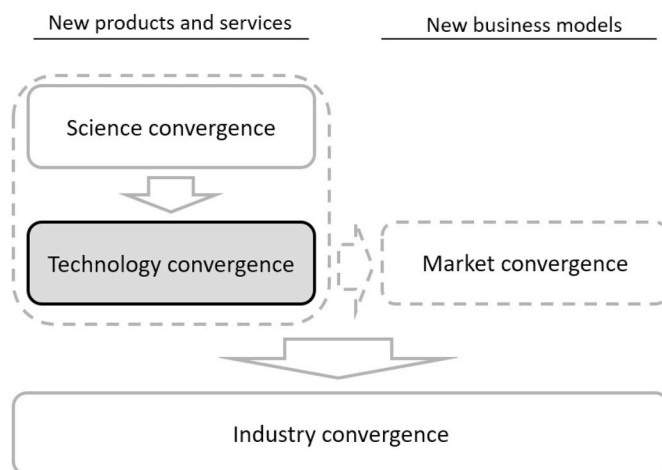
The remainder of the paper is organised as follows. Section 2 covers the literature on technology convergence and patent data. Section 3 presents the used materials and methods, and Section 4 presents the results. In Section 5 the results are discussed, and in Section 6, conclusions are offered.

## 2. Technology convergence and patent data

### 2.1. Technology convergence

Industries have always undergone evolution and radical changes. Within the last decades, a powerful phenomenon has been identified: the technology convergence of industries [4]. Due to the novelty of the field, the literature on it is still quite limited; a general definition of the term *convergence* is still missing in the related literature, and multiple definitions exist [13].

In this paper, the Curran and Leker's [4] much-cited definition of *convergence* is used. Thus, convergence is defined as the blurring of boundaries between at least two thus far separate areas of science, technology, markets or industries. Through convergence, a new segment



**Fig. 1.** Science, technology, market and industry convergence (based on Curran and Leker [4]). Technology convergence has been marked in grey since it is the focus of this paper.

is created as a merger of the parts of the old areas. This process is shown as an increase in the connections between the areas, such as an increase in patenting behaviour. Moreover, they distinguish four levels of convergence: science, technology, market and industry convergence (see Fig. 1).

*Science convergence* is the convergence of different scientific disciplines or areas, which is shown in cross-disciplinary citations and, eventually, in research collaboration. After science convergence has started, the *technology convergence* of the central technologies of different application areas should follow, which can induce *market convergence* or the convergence of markets in different technology fields. *Industry convergence* emerges when scientific fields, technologies and/or markets have converged, thus leading to the merging of companies. It is important to note that convergence does not necessarily lead to new industries or markets [14]. Thus, convergence can occur as a new area of collaboration. Additionally, most of the operations of different areas can remain unaltered and separate [4]. In this paper, the focus is on technology convergence. Athreye and Keeble [15, p. 228] defined *technology convergence* as a process where 'two hitherto different industrial sectors come to share a common knowledge and technological base'.

The technological interfaces of different sectors are among the most important sources of cross-industry innovations [16]. Technology convergence opens the possibility for new business models, growth possibilities, markets and customers for companies. However, if the companies are not prepared for the convergence, it can entail some threats because the companies face new competitors that have significant knowledge of the converged industry sector. Therefore, there is a demand to anticipate convergence, which allows the firms to already form new alliances and adopt new technologies at the early stages of convergence [4,13].

### 2.2. Patent data and indicators of convergence

Patents give ample information of technical knowledge and technology dynamics [8,12]. Developments in technology are often secured by scientists and companies by patenting prior to their availability to the general public; therefore, patents offer a method for looking into the

future. Additionally, patents hold accumulated information for a field. Patents usually describe the technologies in detail and are mainly intended for specialists in the field. However, patents and their relations to other patents can give important information on technology trends [4].

Sung and Kim [5] stated that patent data are particularly suited for understanding technology convergence. Patents entail information that is useful for convergence studies (e.g. information on technology fields, applicants and citations) [4]. Patents are usually a first step towards new technologies; therefore, increasing cross-sectoral patenting and patent citations indicates technology convergence. Thus, technology convergence has primarily been studied utilising patent data [12,17]. The most often used method to study technology convergence with patent data is co-classification analysis, but co-citation analysis and a combination of co-classification and co-citation have also been used [7,17].

All patents are arranged in different technology classes by the examiners of patent offices, according to their technical features [18]. The same patent can be classified into multiple technology fields (i.e. it can be co-classified; see Fig. 2). If the co-classification of formerly separate technology fields increases, it can be an indicator of technology convergence [13]. This assumption is used as the basis of this study.

### 3. Materials and methods

The Worldwide Patent Statistical Database (PATSTAT) is used for the data collection [19]. Detailed information about the RES technologies and ICTs used in the study is given in Appendix A (Table A1). Patent data is used from 1980 to 2011, where the invention year is based on the ‘earliest filing year’ in PATSTAT [19]. The last year is 2011 because it was the last year that complete patent information was given when the analysis was carried out.<sup>1</sup> The unit of observation is invention or patent family. One invention may have many patent applications in different patent offices. These patents create a family of patents related to one particular invention. The data set contains all patent applications, including patent applications that have not been granted.

In defining renewable energy technologies, the so-called Y02 tags (the classification codes of the climate change mitigation technologies CCMTs) of the Cooperative Patent Classification (CPC) are used. In particular, the CPC classification Y02E on the reduction of greenhouse gas emissions related to energy generation, transmission or distribution [21] is utilised. The selected renewable energy technologies are wind power (Y02E 10/70) and solar PV (Y02E 10/50). Both technologies have subcategories. Wind power’s subcategories are *conversion*, *wind turbines* and *wind energy*. The solar PV subcategories are *maximum power point tracking (MPPT)*, *conversion*, *concentrators*, *materials* and *PV energy*. The subcategories of wind energy and PV energy include the patents that do not fall under the other subcategories.

The Organisation for Economic Co-operation and Development’s

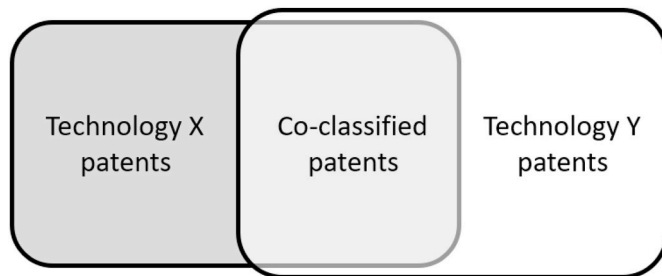


Fig. 2. A definition of co-classification between technology fields X and Y.

<sup>1</sup> Full global patent data statistics have a ‘publication lag’ of multiple years due to the slow nature of the patenting-, publishing- and statistics-related processes [20].

(OECD’s) [22] classification of International Patent Classification (IPC) codes related to ICTs [23] are used.<sup>2</sup> Semiconductor devices (IPC class H01L) are excluded from the set of ICT inventions due to the importance of semiconductors in both solar PV technologies and ICTs. However, only those semiconductor inventions that were not included in some other ICT classification were excluded. In doing so, the aim is to separate the use of common input from the convergence of two distinct technology classes. For instance, in commercially available PV modules, the active energy conversion part is based on semiconductor materials. The rest of the modules’ structural parts are mainly meant to provide encapsulation against weather conditions, collect electric current from solar cells and guarantee robust installation and electrical safety. Over 95% of solar PV patents are also categorised as *semiconductor patents*, and they would thus be observed as ICT inventions if semiconductor devices were to be included in the analysis. However, the aim is to detect how PV technologies are converging with so-called smart technologies.

Our data set contains a total of 66 027 solar PV inventions and 31 521 wind power inventions. Moreover, there are over seven million ICT inventions. From all the ICT inventions, a total of 6122 inventions are co-classified as *solar PV technologies* and 1519 as *wind power technologies*.

Co-classification is used as an indicator for convergence. The co-classified inventions are classified under both ICT and RES technologies. Formally, *co-classification* is defined as follows. Let  $\#Inv(A)_t$  denote the number of inventions in technology field  $A$  that have the first patent application filed in year  $t$ , and  $\#Inv(A, B)_t$  is the number of inventions which have been characterised in both technology fields  $A$  and  $B$  with the first patent filing in year  $t$ . Hence, inventions included in  $\#Inv(A, B)_t$  are also in the set of inventions that are counted in  $\#Inv(A)_t$ . Then, the metric for co-classification between technology fields  $A$  and  $B$  in year  $t$  is the share of co-classified inventions in all the inventions of field  $A$ :

$$CC(B \text{ in } A)_t = \frac{\#Inv(A, B)_t}{\#Inv(A)_t} \quad (1)$$

For example, the co-classified solar PV ICT inventions share of all solar PV inventions between 1980 and 2011 was

$$CC(ICT \text{ in } PV)_{1980-2011} = \frac{\sum_{t=1980}^{2011} \#Inv(PV, ICT)_t}{\sum_{t=1980}^{2011} \#Inv(PV)_t} = \frac{6122}{66027} \approx 9.3\% \quad (2)$$

and the solar PV ICT inventions share of all ICT inventions between 1980 and 2011 was

$$CC(PV \text{ in } ICT)_{1980-2011} = \frac{\sum_{t=1980}^{2011} \#Inv(PV, ICT)_t}{\sum_{t=1980}^{2011} \#Inv(ICT)_t} = \frac{6122}{7107037} \approx 0.09\% \quad (3)$$

The co-classification shares of wind power ICT inventions are, respectively,

<sup>2</sup> The ICT taxonomy used in this paper is from 2003, and there are also other, later-introduced taxonomies for ICT patents which provide an updated and more detailed classification of ICT patents [24]. Compared with the 2003 taxonomy, the taxonomy proposed in 2017, for instance, excludes some of the patent classes that mainly pertain to other technological domains (e.g. typewriters and printing mechanisms) and introduces other new ICT patent classes that have been overlooked before or did not even exist in 2003 (e.g. technologies related to home automation or the internet of things [24]). These changes are not relevant for the purposes of this paper as the technology development of solar PV and wind power technologies was already very strong in 2003 and the changes are not expected to be related to co-classified solar PV or wind-ICT inventions. Hence, the use of some other ICT patent definition would not then change the main results. Moreover, the ICT classification used for the analysis of this paper is simple but still sufficiently descriptive. The more detailed description of ICT classes could provide interesting insights into the integration dynamics of RES and ICT domains. However, this detailed analysis is out of the scope of this paper, and that analysis is left for the future research.

$$CC(CT \text{ in } Wind)_{1980-2011} = \frac{\sum_{t=1980}^{2011} \#Inv(Wind, ICT)_t}{\sum_{t=1980}^{2011} \#Inv(Wind)_t} = \frac{1519}{31521} \approx 4.8 \% \quad (4)$$

and

$$CC(Wind \text{ in } ICT)_{1980-2011} = \frac{\sum_{t=1980}^{2011} \#Inv(Wind, ICT)_t}{\sum_{t=1980}^{2011} \#Inv(ICT)_t} = \frac{1519}{7107037} \approx 0.02 \% \quad (5)$$

These figures show the overall co-classification shares for the entire study period. However, the dynamics, and in particular, the annual development of the co-classification shares since 2000, are interesting and they are examined in the next section.

The analysis relies on patent data. A semantic analysis such as that performed by Leker, Preschitschek et al. [13] is not performed due to the large set of data. They analysed the semantic similarity of 326 US patents on phytosterols, whereas the data set of this paper includes almost 100 000 solar PV and wind power inventions, and over seven million ICT inventions worldwide. Moreover, the data set covers a wide range of different technologies in both the energy and ICT sectors, and thus it is not possible to use any narrow set of keywords or search terms such as those used by Golembiewski, Sick et al. [25] in their study of convergence between the agricultural and energy sectors. In addition, in this study, the focus is on patent classifications and the analysis of patent citations is left for further research.

However, some examples of co-classified technology inventions are given. By these examples, insights into typical inventions related to different sub-fields of wind power and solar PV technologies and ICTs are provided. The example invention search was conducted with the Google Patent Advanced [26] search engine using the technology category codes presented in Appendix A. To find the prominent patents for each category, the patents from the search were sorted according to their 'relevance', and the one of the top 5 patents receiving the most citations was chosen as an example. The Google Patent search algorithm considers a topic and then creates a distance matrix of subtopics from the main topic, and the closer the subtopic is to the main topic, the higher it is in the search results [27].

## 4. Results

### 4.1. Overview

Based on the patent data analysis for the years 1980–2011 (described in Section 3), the total number of wind power and solar PV inventions increased rapidly during the studied time frame (see Fig. 3), especially after the year 1996. The number of solar PV innovations increased especially fast, reaching over 10 000 annual inventions by 2011. Even though the growth of wind power inventions was rapid, the number of wind power inventions was a bit less than half of the number of solar PV inventions in 2011.

The number of wind power-ICT inventions was very low until the year 2005, after which it started to increase (see Fig. 3). The share of ICT of all wind power inventions has increased from close to zero to approximately seven percent during the studied time frame (see Fig. 4). The number of solar PV-ICT inventions increased during the studied time frame, especially during the years 2007–2011 (see Fig. 3). However, the share of ICT inventions of all solar PV inventions has fluctuated over time (see Fig. 4). There were peaks in the solar PV-ICT's share around the years 1984 (where it was 17%) and 1996 (where it was also 17%). After the year 1996, the number solar PV-ICT inventions has increased, although not as rapidly as the total number of solar PV inventions; therefore, the share ICT decreased until the year 2011 (where it was 7%). The share of wind power and solar PV ICT inventions of all ICT inventions was very low (under 0.25%) due to the large total number of ICT inventions (see Fig. 4). However, the growth of the shares was very fast, especially after the year 2005.

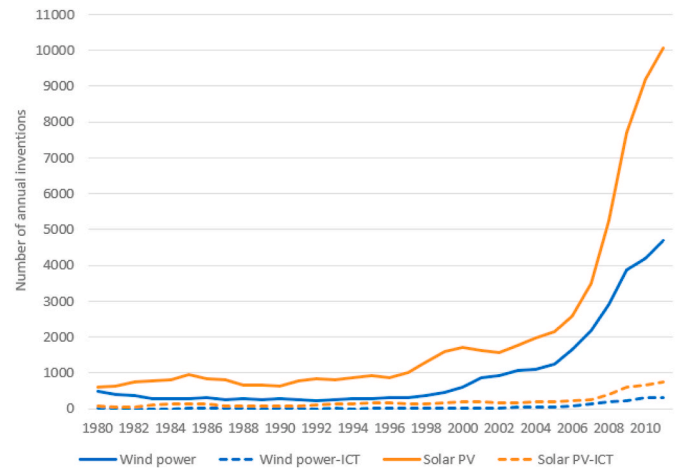


Fig. 3. The number of annual wind power, solar PV, wind power-ICT and solar PV-ICT inventions.

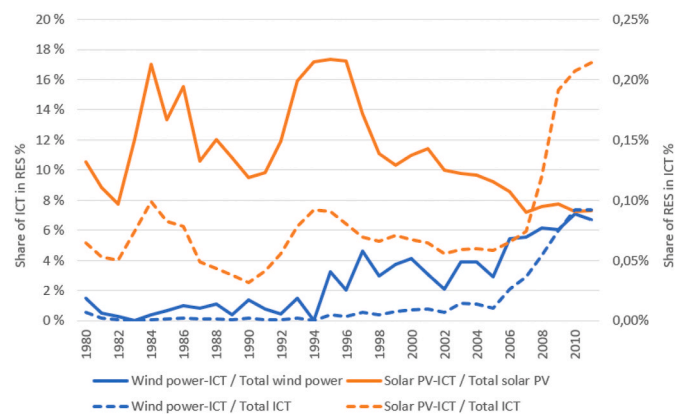


Fig. 4. The ICT inventions share of RES inventions (solid lines) and RES inventions share of ICT inventions (dashed lines).

When compared with the total numbers of inventions or to the total ICT invention development, it is clear that the development in wind power and solar PV technologies and their ICT solutions has been especially rapid after the year 2005 (see Fig. 5). Also, when compared to the overall development of CCMTs and their ICT solutions, it is visible that wind power and solar PV technology inventions and their ICT solutions have increased especially rapidly. The relative growth of wind power-ICT inventions has been faster than the growth of all wind power inventions. With solar PV, the opposite has occurred, and the total number of solar PV inventions has increased more rapidly than the number of solar PV-ICT inventions.

### 4.2. Wind power

A wind turbine is a complex of many rotating subsystems. The use of ICT in modern wind power plants has become the norm and offers numerous benefits in addressing the challenges of wind power integration. In recent decades, the wind industry has seen many ICT-based improvements in technology, such as variable-speed generators [28, 29]. Fixed rotor speed systems led the wind turbine market until the end of the last millennium. Currently, most of the installed wind turbines utilise variable speed, and ICT methods are used to control, optimise and monitor the power flow.

ICT can support the efficient scheduling of wind power generation and energy dispatch and can be used in automation, protection and even in reactive power and synthetic inertia control applications. The use of

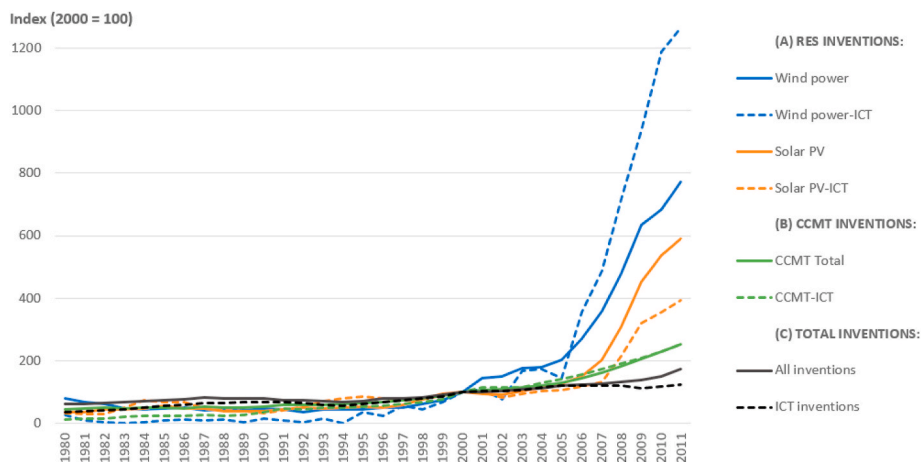


Fig. 5. RES, CCMT and ICT inventions and all inventions in 1980–2011, indexed so that the year 2000 = 100.

appropriate communication systems is critical in allowing for seamless information exchange between different applications in wind power plants. Real-time data exchange consists of the monitoring and control of data, such as wind speed, wind direction, pitch angle, beacon status, frequency, switch position and control operations data. In addition, voltage regulation and reactive power control are essential in order to meet the voltage constraints and stability of wind power plants [30]. The control, monitoring and optimisation of wind power conversion are based on programmable ICT methods that are embedded in the different sub-systems of wind power plants. For example, functionalities such as synchronisation to grid, adjustment of generation rotation speed or torque, control of reactive power or the handling of exceptional situations are embedded as software algorithms in the converter connecting the wind power plant to the grid.

In 2020 the wind power industry installed 93 GW of new capacity, which was the highest yearly addition ever [31]. For the next five years the growth of annually installed global capacity is expected to be around four percent [31]. Onshore wind still represents more than 90% of installed capacity, but the fraction of offshore capacity is expected to increase in the coming years [31]. The global wind industry is currently highly consolidated. The turbine market is mainly divided into European and Chinese manufacturers [32]. Wind energy projects typically consist of two major elements: turbines and balance of plant (BOP). The complete turbine systems, including towers and blades, are provided by the turbine manufacturer. The BOP includes for example civil works and electrical connections from turbines to substations. It is provided by variety of companies, such as legal consultants and builders, which are typically local and have knowledge of local conditions [32].

The wind power technology sub-fields are *wind turbines* (which cover the inventions related to wind turbine technologies), *wind conversion* (which covers the inventions related to power conversion in wind power technologies) and *wind energy* (which covers all of the wind power inventions that do not fall under turbines or conversion technologies). Based on the patent analysis, wind turbines have dominated the wind power sub-field inventions during the whole studied time frame (see Fig. 6). The share of wind conversion technologies increased, and the share of wind energy inventions decreased during the years 1980–2011.

Differences were observed in the ICT shares between the wind power sub-fields (see Fig. 7). In relative terms, ICT inventions are most prominent in the sub-field of wind conversion, and ICT has been important for conversion technologies during the whole studied time frame. Moreover, conversion technology inventions increased faster than other inventions (see Fig. 6). The share of conversion technologies of all wind power technologies was approximately one percent in 1980, and it increased to approximately nine percent in 2011. The share of turbine inventions of all wind power inventions has stayed at a level of

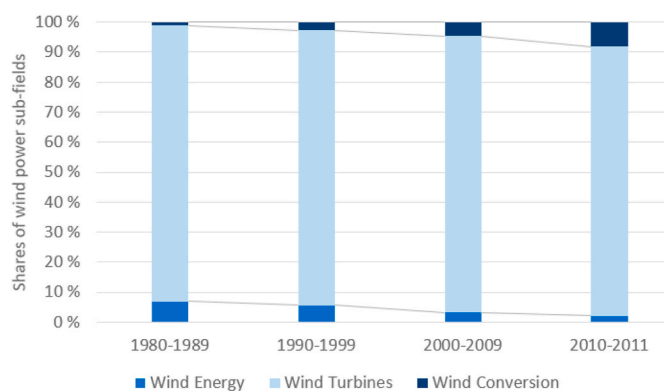


Fig. 6. The shares of wind power technology sub-fields of all wind power inventions.

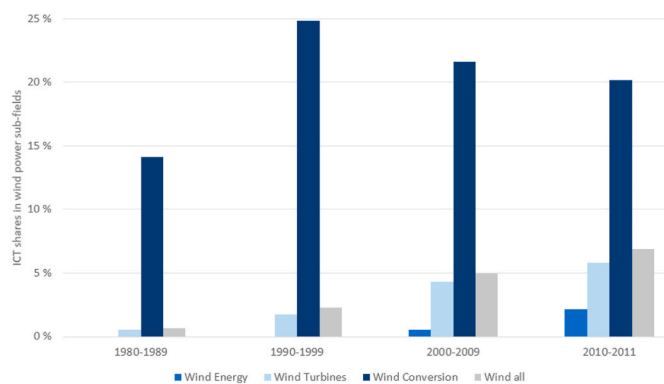


Fig. 7. The ICT shares of wind power technology sub-fields' inventions.

approximately 90% during the years 1980–2011 (see Fig. 6). At the same time, the share of ICT inventions increased from approximately one to six percent in the wind turbine sub-field (see Fig. 7). In the wind energy sub-field, the ICT shares were very low during the whole studied time frame (see Fig. 7). Therefore, the ICT share of wind power has increased during 1980–2011 due to both the increased share of conversion technologies of all wind power inventions and due to the increased ICT shares of wind turbine technologies.

Wind power inventions have increased heavily since the year 2000, and the six main inventor countries are Korea, Germany, the United States, Denmark, China and Japan (see Fig. 8).<sup>3</sup> The shares of ICT in wind power inventions differed between the countries during 1980–2011. When compared with the global average of five percent, the ICT shares were high in Denmark, the US, Germany and Japan (16, 10, 9 and 9%, respectively). *The increase in the global share of wind power ICT is thus mostly explained by inventions made in the US, Germany, Denmark and Japan.* In Korea and China, however, the shares of co-classified wind power-ICT inventions have been more modest at approximately two percent in both countries. In addition, the number of wind power inventions decreased in China after the year 2007, decreasing China's relative importance in wind power inventions.

The ICT sub-fields are *telecommunications, consumer electronics, computers and office machinery, and other ICT* (Table 1). Table 2 presents some examples of wind power-ICT inventions that represent the wind power and ICT sub-field combinations with the most co-classified inventions. The example inventions represent forecasting, measuring, monitoring, controlling and management ICT systems, devices and methods. Their main functions are to increase the efficiency of wind power production and detect and prevent failures. One interesting example of wind-ICT inventions is the method for controlling the feed of reactive power in a wind power generation system and thus improving grid stability.

#### 4.3. Solar PV

The solar PV system does not have complex machinery or rotating parts, works silently and needs little maintenance, and this kind of simplicity of a solar PV system provides limited opportunity to control the performance once it is installed. However, there is potential in single-axis tracking technology for solar PV, meaning that the solar panels rotate in a smart way, according to sunlight [34]. Solar PV generation yield is mainly determined by the irradiation, weather conditions, module performance, installation and operation of MPPTs.

An MPPT algorithm is an important ICT application in solar PV systems since it enables the extraction of maximum power from the PV modules [35]. It is a software algorithm implemented in solar PV inverters or plants. It continuously controls the direct current for the solar module, module string or plant in order to generate the maximum electrical power during the varying irradiation conditions and temperatures [29,36]. There are numerous published MPPT methods available, and they are practically all based on the measurement of PV voltage and

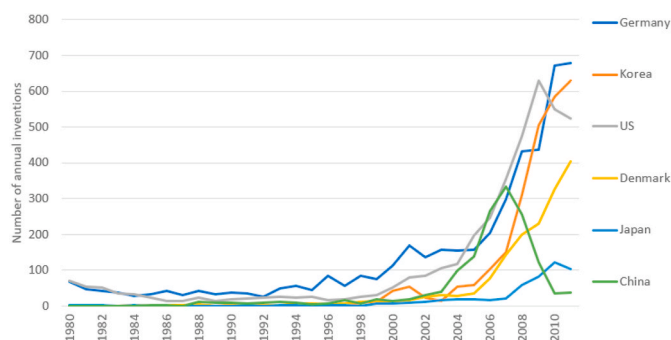


Fig. 8. The wind power inventions of the top 6 inventor countries.

<sup>3</sup> The increase has also been rapid in Japan, although this cannot be fully seen in PATSTAT data. Information on the inventor's country of residence is largely lacking in the priority documents of PATSTAT, from where the information on the inventor country was retrieved. This is especially the case for Japan [33].

Table 1

The wind power technology and ICT sub-fields of the co-classified inventions (1980–2011).

Technology sub-fields: ICT/wind power	Energy	Turbines	Conversion
Telecommunications	3	151	26
Consumer electronics	0	22	1
Computers and office machinery	2	415	303
Other ICT	7	856	107

current [37,38]. Another application of ICT methods in solar PV is the operation and maintenance of power plants, such as system or component performance monitoring and fault detection [39].

Solar PV has already been the largest annually installed power generation technology globally for several years. Yearly installed PV capacity has grown from roughly 30 GW in 2011 to 112 GW in 2019 [40]. The costs of solar PV systems have decreased rapidly. In 2014 the least-cost power purchase agreement (PPA) was €80/MWh while in 2020 the new PPA world record was achieved with a price around €11/MWh [40]. The main drivers in this remarkable achievement have been the declining cost of the system components, competition and the availability of low interest rate capital [40]. During recent years the PV wafer, solar cell and module industry has become highly consolidated. Large Chinese manufacturers dominate global markets with shares of more than 70% [40]. Technology-wise the market is dominated by crystalline silicon cells [41]. Renewable and local energy sources can also be used as complementary hybrid systems (for example solar PV and hydro power hybrid), and these can potentially improve the technical and economic aspects of RES power production [42]. In addition to solar PV power production, solar energy systems can be utilised in heating and cooling [43].

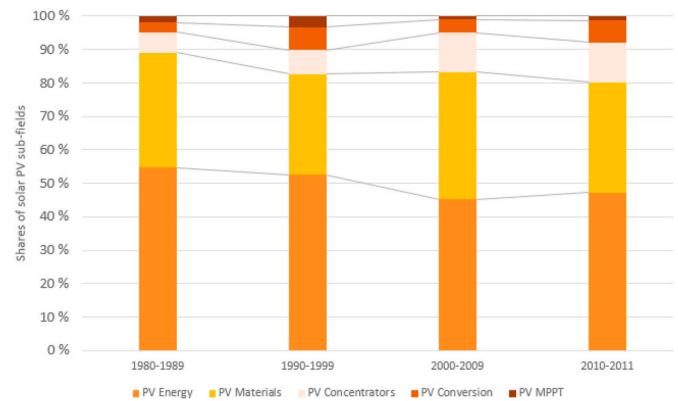
There are five technology sub-fields under the solar PV inventions: *PV MPPT, PV conversion* (power-conversion electric or electronic aspects), *PV concentrators, PV materials* (covering different organic and inorganic materials) and *PV energy* (which covers solar PV technologies that do not fall under the other sub-fields). The most prominent solar PV sub-fields have been PV energy and PV materials during the whole studied time frame (see Fig. 9).

In absolute numbers, most of the solar PV-ICT inventions fall under the energy sub-field. However, in relative terms, the MPPT and conversion technology sub-fields have the highest ICT shares (see Fig. 10). During and around the peak years for solar PV-ICT shares (1984 and 1996), the number of MPPT and conversion technologies' inventions was also peaking. After 2002, the number of MPPT technology inventions started to increase again, but since the number of inventions in other technology sub-fields (especially the materials and concentrators sub-fields) grew even faster, the share of MPPT technologies of all solar PV technologies has remained very low (1–2%) after the year 1996. Additionally, the share of ICT of all MPPT inventions has decreased from the 99% level during the years 1980–1989 to the 74% level during the years 2010–2011 (see Fig. 10). The same phenomenon can be seen to a lesser extent with the PV energy (and materials) sub-field: during 1980–1989 the share of ICT was 11 (9) percent of all PV energy (materials) inventions, and it dropped to the 5 (4) percent level for the years 2010–2011 (see Fig. 10). In summary, *the peaks in solar PV-ICT shares can be explained by developments in MPPT and conversion technologies, which have high interconnections with ICTs. The decrease in the solar PV-ICT shares after the year 1996 can be explained by multiple factors: the rapid development in materials and concentrators technologies (which are not highly interconnected with ICTs) and a decrease in the importance of ICT in the innovations made in MPPT, conversion and materials technologies.*

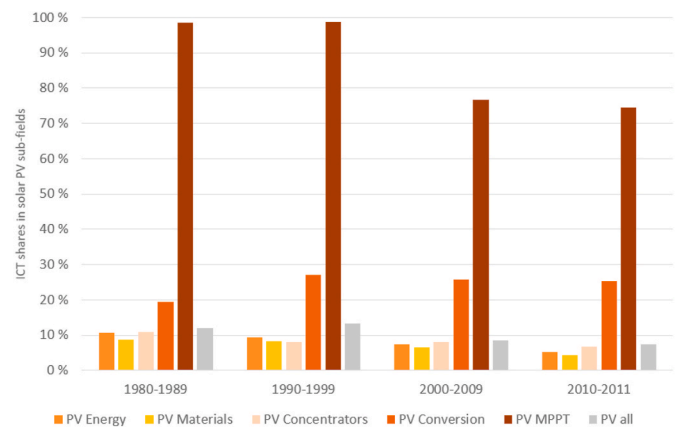
Based on the analysis, *one important factor underlying the decreasing share of ICT in solar PV since the mid-1990s stands out. That is, the increased number of solar PV inventions in two Asian countries, namely, Korea and China.* The focus of innovation policies in these countries has been to decrease the costs of solar PV power production [44,45], which has

**Table 2**  
Examples of wind power-ICT inventions; source: Google Patents Search [26].

Name and year of the patent	Wind power technology sub-field	ICT technology sub-field	A short description of the invention
Optical air data systems and methods (2008)	Turbines	Other ICT	Systems and methods to sense, e.g. air speed, air temperature and air pressure
Forecasting an energy output of a wind farm (2003)	Turbines	Other ICT	Methods and apparatus for forecasting the energy output of a wind farm
Turbulence sensor and blade condition sensor system (2009)	Turbines	Other ICT	A sensor system to detect accumulated matter, such as dirt and ice, on wind turbine components
Field control for wind-driven generators (1980)	Turbines	Computers and office machinery	A device for prevailing wind speed and pivoting the blades in order to achieve maximum aerodynamic efficiency
Method and apparatus for controlling the feed of reactive power in a wind power generation system (2009)	Turbines	Computers and office machinery	A method and apparatus for controlling wind power generation; the system is connected to a grid and is devised to feed reactive power to the grid in order to improve grid stability
Atmospheric measurement system (2010)	Turbines	Telecommunications	A method for measuring atmospheric wind conditions in order to predict an upper bound on the power-generating capability of each wind turbine of a wind farm
Power extractor detecting a power change (2003)	Conversion	Computers and office machinery	A power extractor that allows the power source to provide an optimal amount of power transfer that is greater than it would be without impedance matching
Pitch control battery backup methods and system (2005)	Conversion	Computers and office machinery	A back-up battery system and method for pitch control in a wind turbine energy system
System and method for monitoring and managing energy performance (2001)	Conversion	Other ICT	A system and method for monitoring real-time facility operations and energy information, used for real-time energy performance management and operations



**Fig. 9.** The shares of the solar PV technology sub-fields of all solar PV inventions.



**Fig. 10.** The ICT co-classification shares of the solar PV technology sub-fields' inventions.

pushed forward the developments in the basic solar PV technologies faster than the solar PV-ICT technologies.

When looking at the top seven inventor countries (see Fig. 11), the most remarkable development from 2000 to 2011 was the increase of solar PV inventions made by Korean inventors. During the 1990s, the inventors of less than two percent of solar PV inventions came from Korea, whereas in 2011, the share of solar PV inventions that had a Korean inventor was nearly 20%. The share of ICT in Korean solar PV inventions was four percent during 1980–2011, which is low when compared to the global share of nine percent. Moreover, Korean inventors made less MPPT and conversion technology inventions compared with the global average (1% versus 2% for MPPT and 3 versus 5% for conversion). In addition, the shares of ICT of both MPPT and conversion technologies were far less for Korean inventors compared with the global average (57% versus 84% for MPPT and 19% versus 28% for conversion).

Another important country case is China. First, the share of ICT in solar PV inventions was seven percent for Chinese inventors (9% globally) during the years 1980–2011. Second, for the sub-fields that are most important from an ICT perspective, the share of ICT in the inventions created by Chinese inventors was lower than globally (65% for MPPT and 17% for conversion; globally the shares were 84 and 28%, respectively). The share of solar PV inventions by Chinese inventors grew from zero percent in 1980 to about seven percent in 2007 and dropped after that.

Table 4 presents some examples solar PV-ICT inventions representing the solar PV and ICT sub-field combinations with the most co-classified inventions (see Table 3). The example inventions are

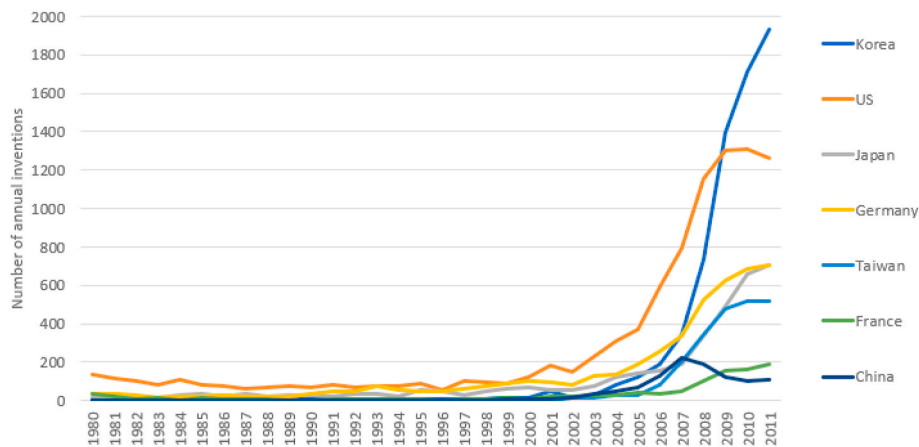


Fig. 11. The solar PV inventions of the top 7 inventor countries.

Table 3

The solar-PV technology and ICT sub-fields of the co-classified inventions (1980–2011).

Technology sub-fields: ICT/solar PV	Energy	Concentrators	Materials	Conversion	MPPT
Telecommunications	349	99	298	106	17
Consumer electronics	159	19	123	18	1
Computers and office machinery	1230	178	746	743	1019
Other ICT	881	351	486	247	60

tracking, controlling, regulating and smart material systems, devices and methods to increase the efficiency, lessen the volatility and decrease the errors of solar-PV production.

## 5. Discussion

Technology convergence between renewable energy production technologies (wind power and solar PV) and ICT technologies was found in this paper. The co-classifications of RES technologies and ICTs were used as indicators of technology convergence; analysing co-classification is the most common method of monitoring technology convergence in the related academic literature [12,17]. A growing number of co-classified RES-ICT inventions using wind power and solar PV was found, and the growth was faster in these RES technologies than in climate change mitigation technologies in average. However, the two studied RES technologies differ vastly in their development.

Wind power production requires a complex system with rotating parts; therefore, it offers multiple ways to optimise production with smart ICT solutions [28]. Based on the results, the wind power sector shows indications of a transition from being almost completely separate from the ICT sector to some convergence with it in all the studied aspects. From the almost non-existing co-classification with the ICT sector in the 1980s, wind power inventions have experienced a rapid increase in ICT solutions, especially after the year 1990, in both relative and absolute terms. The co-classification of wind power inventions has increased in two ways: the importance of the wind power sub-technology with most interlinkages with ICT – that is, conversion – has increased and the ICT interlinkages of the wind power sub-technology with most inventions – that is, turbines – have increased gradually over time. The most relevant inventor countries driving the technology convergence of wind power with ICT were the US, Germany and Denmark.

Solar PV systems, in turn, may offer more limited opportunities for electricity production optimisation with ICTs. However, there are some opportunities for smart energy applications, such as MPPT, plant performance monitoring and failure diagnosis. The results show that the convergence development of solar PV with the ICT sector is not as straightforward as with wind power. In absolute terms, the number of

solar PV-ICT inventions has increased especially rapidly after the year 2007. However, the relative impact of ICT in solar PV inventions decreased during the last studied years. This result is driven by rapid development in solar PV materials and other basic technologies which have no (or little) interactions with smart ICT solutions. At the same time, the price of solar PV systems decreased and the investments in solar PV increased very rapidly globally [40]. One factor behind these developments was the increase of Asian – especially Korean and Chinese – inventors and producers in the solar PV sector, who focused on decreasing the cost of the solar PV technologies [44,45]. Therefore, although smart solar PV technologies developed rapidly during the studied time frame, the development of the basic solar PV technologies was even faster.

Curran and Leker [4] and Geum, Kim et al. [12] found evidence of ICT convergence in nutraceuticals and functional foods and biotechnology. The results of this paper are mostly in line with these earlier studies: digitalisation has advanced rapidly, which has implications for other technology fields. However, in the case of solar PV technologies, the rapid development of the basic inventions has been even faster than the growth of the ICT solutions in the sector, which deviates the findings of this paper from the earlier experiences reported in the literature.

## 6. Conclusions

In this paper, the smart energy transition was studied from the viewpoint of the technology convergence of the renewable energy and ICT sectors. The analysis was based on international patent data from the years 1980–2011. The indicator for convergence was co-classification (i.e. cases where patents have been classified under both RES and ICT). Two important and fast-growing renewable energy technologies, namely wind power and solar PV, were analysed. The aim was to determine whether technology convergence occurs between the studied renewable energy technologies and ICTs and whether differences occur between the wind power and solar PV technologies in this regard. In addition, the sub-fields of the renewable energy technologies and ICTs, as well as the inventor countries, were looked at in order to find explanations for the results. Digitalisation and ICT solutions are changing the whole of society, and according to the results of this paper,



**Table 4**  
Examples of solar PV-ICT inventions; source: Google Patents Search 2020 [26].

Name and year of the patent	Solar PV technology sub-field	ICT technology sub-field	A short description of the invention
Control circuit for a DC-to-DC switching converter (2005)	Energy	Computers and office machinery	A control circuit to maximise solar PV system production by controlling the DC-to-DC switching converter
Photovoltaic source switching regulator with maximum power transfer efficiency without voltage change (1990)	Energy	Computers and office machinery	A regulator to improve the conversion efficiency when converting from solar energy to electrical energy
Solar photovoltaic module safety shutdown system (2010)	Energy	Computers and office machinery	A system that shuts solar PV modules off automatically if there is no light or in the case of damage or natural disasters
Maximum power point tracking method, photovoltaic system controller and photovoltaic system (2010)	MPPT	Computers and office machinery	An MPPT method and a PV system controller that can extract the maximum power out of a PV system
Smart photovoltaic module (2004)	MPPT	Computers and office machinery	A PV module tracking the point of maximum individual power of each PV panel and connecting to other panels that thus increases the efficiency of production
Cloud tracking (2010)	Energy	Other ICT	A cloud tracking system reducing the variability of PV plants by predicting and anticipating cloud cover
Solar string power point optimisation (2009)	Conversion	Computers and office machinery	An apparatus and method that control the power produced by a string (i.e. a series) of solar cells, thus enabling the string to generate its maximum power
Systems and methods for depositing patterned materials for solar panel production (2010)	Materials	Computers and office machinery	Systems and methods for the smart and auto-correcting production of solar panel materials in order to decrease production errors and increase the quality of the panels
III-V photonic integration on silicon (2006)	Materials	Other ICT	A method for integrating electronic devices (e.g. a laser, drive electronics, memory, processing circuits or a wavelength converter) on silicon

smart transition can also be seen in the studied renewable energy technologies.

Differences between the wind power and the solar PV technologies were found. In the case of wind power, the development from virtually no ICT solutions to partial convergence with the ICT sector is straightforward and clearly seen in the results. The ICT convergence of wind

power technologies was driven by the US, Germany and Denmark. In solar PV, the development in basic technologies was even faster than the development of the solar PV-ICT solutions. This difference can indicate the immature nature of solar PV technologies during the studied years. Additionally, the rise of Korean and Chinese inventors, focusing on cost reductions of the basic technologies, impacted on ICT technology-convergence development during the studied time frame. These trends can continue after the studied years since the basic material technologies are likely to have considerable improvement potential left in both energy conversion efficiency and cost efficiency.

Based on the results, the development of technology convergence is not always linear and straightforward within a technology field. The development of the novel technologies that bring different technology fields together can be shadowed by even more rapid developments in basic technologies if they are not mature.

The found RES-ICT technology convergence covers technologies that control, manage and optimise electricity production in different intelligent ways. The inventions presented in this study differ from each other in the 'deepness' of their convergence. Some of the smart energy inventions have diffused ICTs into renewable energy technologies. However, some of them show holistic integration of ICT into important parts of generation control, for example, the method for controlling the feed of reactive power in a wind power generation system in order to improve grid stability. In practice, a wind power plant or a PV plant includes multiple smart energy technologies, and some are more integrated into the actual power production than others.

The years studied in this paper only represent the beginning of the energy transition towards cleaner energy production. Thus far, in most wind power and solar PV inventions, the purpose of including ICT has been to improve the generation performance of power generation. It is already clear that the installation of wind power and solar PV has continued to increase rapidly after 2011. Since the production of wind power and solar PV power is weather dependent, their increasing shares in electricity production pose a growing need for smart ICT solutions in order to improve grid stability, for example. Therefore, it is likely that only the very beginning of the smart energy transition has been seen so far.

According to the results, the renewable energy and ICT sectors are becoming increasingly interlinked, which is valuable information since convergence is important for technology transitions. This convergence poses challenges for the RES companies in terms of following and predicting ICT development and identifying opportunities for innovations and collaborations with ICT companies. In addition, ICT companies should follow renewable energy development and develop technologies and services for the energy sector. The convergence literature has indicated that companies following and anticipating the technology convergence trends and acting accordingly have competitive advantages over the companies lagging behind. This conclusion can also be expanded to society and policy levels because focusing on only a narrow field when planning innovation policy instruments can slow down convergence, which can have an impact on a country's competitiveness in technology markets.

In this paper, only renewable electricity production technologies were studied, whereas many important smart energy opportunities exist in the smart grid and consumption-side management technologies. Due to the data constraints, the patent data could only be studied until the year 2011; therefore, the number of smart grid and consumption-side management technology inventions was still too small to carry out a similar study for those fields. After a couple of years, when sufficient data are available, it would be fruitful to study the technology convergence in these more novel fields. Additionally, the co-citations or other quality indicators of the inventions were not considered, which could also be a possible future line of study.

## Funding

This work was supported by the Strategic Research Council of the Academy of Finland (grant number 293405).

## Credit author statement

Hanna-Liisa Kangas, Conceptualization, Methodology, Writing – Original Draft, Writing – Review & Editing, Visualization, Supervision, Project administration. Kimmo Ollikka, Conceptualization, Methodology, Software, Formal analysis. Jero Ahola, Conceptualization, Validation. Kim Yukyong, Data Curation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

We are very grateful to the three anonymous reviewers for their valuable comments on the manuscript. We thank the participants of the 3rd AIEE Symposium in Milan, Italy, in December 2018 for their valuable comments for the preliminary results of this paper.

## Appendix A. A list of patent symbols for the studied technologies

PATSTAT contains bibliographical data related to more than 90 million patent documents from leading developed and developing countries. There is patent information regarding applications, publications, applicants and inventors, citations, patent families, technological classifications and legal status. A patent can be classified using the International Patent Classification (IPC) system, the Cooperative Patent Classification (CPC) system or national patent classification systems. To collect a dataset of inventions in renewable energy technologies, we adapted the CPC system's section Y on climate change mitigation technologies (CCMTs). For information and communications technologies (ICTs), we used the Organisation for Economic Co-operation and Development's (OECD's) (2008) ICT definition in order to identify ICT patents based on the IPC codes. The ICT sector is divided into four subfields: (1) telecommunications, (2) consumer electronics, (3) computers and office machinery and (4) other ICTs. However, we excluded one IPC subclass from the ICT data set (semiconductor devices, H01L).

**Table A1**

A list of IPC or CPC symbols for the studied technologies.<sup>1</sup>

Technology	Sub-category	IPC or CPC codes
Solar PV*Y02E 10/5	PV energy	Y02E 10/50
		Y02E 10/52
	PV with concentrators	Y02E 10/54
		Y02E 10/541 CuInSe2
	Material technologies	Y02E 10/542 Dye sensitized solar cells (DSSC)
		Y02E 10/543 Solar cells from group II-VI materials
		Y02E 10/544 Solar cells from Group III-V materials
		Y02E 10/545 Microcrystalline Si PV (micro-Si)
		Y02E 10/546 Polycrystalline Si PV (mc-Si)
		Y02E 10/547 Monocrystalline Si PV (sc-Si)
		Y02E 10/548 Amorphous Si PV (a-Si)
	Power conversion electric or electronic aspects	Y02E 10/549 Organic PV cells (OPV)
		Y02E 10/56
Y02E 10/563 Grid-connected applications		
Y02E 10/566 Power management inside the plant, e.g. battery charging/discharging, economical operation, hybridization with other energy sources		
Maximum power point tracking [MPPT] systems	Y02E 10/58	
Wind power*Y02E 10/7	Wind energy	Y02E 10/70
	Wind turbines	Y02E 10/72 Wind turbines with rotation axis in wind direction
		Y02E 10/74 Wind turbines with rotation axis perpendicular to the wind direction
	Power conversion electric or electronic aspects	Y02E 10/76
ICT**	Telecommunications	G01S, G08C, G09C, H01P, H01Q,
		H01S 3/(025 043 063,067,085,0933,0941 103 133,18,19,25), H01S 5, H03B, H03C, H03D, H03H, H03 M, H04B, H04J, H04K, H04L, H04 M, H04Q
		G11B, H03F, H03G, H03J, H04H, H04 N, H04R, H04S
	Consumer electronics	B07C, B41J, B41K, G02F, G03G, G05F, G06, G07, G09G, G10L, G11C, H03K, H03L
		G01B, G01C, G01D, G01F, G01G, G01H, G01J, G01K, G01L, G01 M, G01 N, G01P, G01R, G01V, G01W, G02B6, G05B, G08G, G09B, H01B11,
	Computer, office machinery	H01J (11/,13/,15/,17/,19/,21/,23/,25/,27/,29/,31/,33/,40/,41/,43/,45/)
	Other ICT	

Note: \*CPC, \*\*IPC and the OECD.

<sup>1</sup> See the IPC: <https://www.wipo.int/classifications/ipc/en/or> or CPC: <https://www.epo.org/searching-for-patents/helpful-resources/first-time-here/classification/cpc.html>.

## References

- [1] Renewables IEA. Market analysis and forecast from 2019 to 2024. 2019. 2019.
- [2] Ahmed F, Naeem M, Iqbal M. ICT and renewable energy: a way forward to the next generation telecom base stations. *Telecommun Syst* 2017;64:43–56.
- [3] Park C, Heo W. Review of the changing electricity industry value chain in the ICT convergence era. *J Clean Prod* 2020;258:120743.
- [4] Curran C, Leker J. Patent indicators for monitoring convergence – examples from NFF and ICT. *Tech Forecast Soc Chang - TECHNOL FORECAST SOC CHANG* 2011; 78:256–73.
- [5] Sung K, Kim T, Kong H-k. Microscopic approach to evaluating technological convergence using patent citation analysis. In: Kim T-h, Ma J, Fang W-c, Park B,

- Kang B-H, Ślęzak D, editors. U- and E-service, science and technology. Berlin, Heidelberg: Springer Berlin Heidelberg; 2010. p. 188–94.
- [6] Feng S, An H, Li H, Qi Y, Wang Z, Guan Q, et al. The technology convergence of electric vehicles: exploring promising and potential technology convergence relationships and topics. *J Clean Prod* 2020;120992.
- [7] Kim J, Lee S. Forecasting and identifying multi-technology convergence based on patent data: the case of IT and BT industries in 2020. *Scientometrics* 2017;111:47–65.
- [8] San Kim T, Sohn SY. Machine-learning-based deep semantic analysis approach for forecasting new technology convergence. *Technol Forecast Soc Change* 2020;157:120095.
- [9] Song CH, Elvers D, Leker J. Anticipation of converging technology areas — a refined approach for the identification of attractive fields of innovation. *Tech Forecast Soc Chang SV* 2017;116:98–115.
- [10] Borés C, Saurina C, Torres R. Technological convergence: a strategic perspective. *Technovation* 2003;23:1–13.
- [11] Kim J, Lee S. A methodology to evaluate industry convergence using the patent information : technology relationship analysis. *J Kor Inst Indus Eng* 2013;39:212–21.
- [12] Geum Y, Kim C, Lee S, Kim M-S. Technological convergence of IT and BT: evidence from patent analysis. *ETRI J* 2012;34:439–49.
- [13] Leker J, Preschitschek N, Niemann H, Moehrl M. Anticipating industry convergence: semantic analyses vs IPC co-classification analyses of patents. *Foresight - J Fut Stud Strat Think Pol* 2013;15:446–64.
- [14] Gambardella A, Torrisi S. Does technological convergence imply convergence in markets? Evidence from the electronics industry. *Res Pol* 1998;27:445–63.
- [15] Athreye S, Keeble D. Technological convergence, globalisation and ownership in the UK computer industry. *Technovation* 2000;20:227–45.
- [16] Karvonen M, Kässi T. Patent citations as a tool for analysing the early stages of convergence. *Technol Forecast Soc Change* 2013;80:1094–107.
- [17] Choi YJ, Jeong S, Kim K. A study on diffusion pattern of technology convergence: patent analysis for Korea. *Sustainability* 2015;7.
- [18] Kim M-S, Kim C. On a patent analysis method for technological convergence. *Procedia - Soc Behav Sci* 2012;40:657–63.
- [19] Epo. PATSTAT 2016 Autumn edition. 2016.
- [20] Hašćić I, Migotto M. Measuring environmental innovation using patent data. 2015.
- [21] Cpc. CPC scheme and definitions. 2020.
- [22] Oecd. OECD information technology outlook 20082008.
- [23] Wipo. International patent classification (IPC). The World Intellectual Property Organization (WIPO); 2020.
- [24] Inaba T, Squicciarini M. ICT: a new taxonomy based on the international patent classification. In: OECD science, technology and industry working papers. Paris: OECD Publishing; 2017.
- [25] Golembiewski B, Sick N, Bröring S. Patterns of convergence within the emerging bioeconomy — the case of the agricultural and energy sector. *Int J Innovat Technol Manag* 2015;12. 1550012.
- [26] Google. Google patent advanced. 2020.
- [27] Kinsta. Google's patents and SEO ranking factors: connecting the dots. 2020.
- [28] Cao W, Xie Y, Tan Z. Wind turbine generator technologies chapter 7. *Intech*; 2012. p. 177–204.
- [29] Dreidy M, Mokhlis H, Mekhilef S. Inertia response and frequency control techniques for renewable energy sources: a review. *Renew Sustain Energy Rev* 2017;69:144–55.
- [30] Alizadeh SM, Ozansoy C. The role of communications and standardization in wind power applications – a review. *Renew Sustain Energy Rev* 2016;54:944–58.
- [31] Gwec. Global wind report 2021. 2021.
- [32] Lacal-Arántegui R. Globalization in the wind energy industry: contribution and economic impact of European companies. *Renew Energy* 2019;134:612–28.
- [33] De Rassenfosse G, Dernis H, Guellec D, Picci L, van Pottelsberghe B. The worldwide count of priority patents: a new indicator of inventive activity. *Res Pol* 2012;42.
- [34] Afanasyeva S, Bogdanov D, Breyer C. Relevance of PV with single-axis tracking for energy scenarios. *Sol Energy* 2018;173:173–91.
- [35] Parvaneh MH, Khorasani PG. A new hybrid method based on fuzzy logic for maximum power point tracking of photovoltaic systems. *Energy Rep* 2020;6:1619–32.
- [36] Lupangu C, Bansal R. A review of technical issues on the development of solar photovoltaic systems. *Renew Sustain Energy Rev* 2017;73:950–65.
- [37] Jordehi AR. Maximum power point tracking in photovoltaic (PV) systems: a review of different approaches. *Renew Sustain Energy Rev* 2016;65:1127–38.
- [38] Koutroulis E, Blaabjerg F. Overview of maximum power point tracking techniques for photovoltaic energy production systems. *Elec Power Compon Syst* 2015;43:1329–51.
- [39] Triki-Lahiani A, Bennani-Ben Abdelghani A, Slama-Belkhdja I. Fault detection and monitoring systems for photovoltaic installations: a review. *Renew Sustain Energy Rev* 2018;82:2680–92.
- [40] Trends IEA. In photovoltaic applications 2020. 2020.
- [41] Allen TG, Bullock J, Yang X, Javey A, De Wolf S. Passivating contacts for crystalline silicon solar cells. *Nat Energy* 2019;4:914–28.
- [42] Hoseinzadeh S, Ghasemi MH, Heyns S. Application of hybrid systems in solution of low power generation at hot seasons for micro hydro systems. *Renew Energy* 2020;160:323–32.
- [43] Hoseinzadeh S, Azadi R. Simulation and optimization of a solar-assisted heating and cooling system for a house in Northern of Iran. *J Renew Sustain Energy* 2017;9:045101.
- [44] Carvalho M, Dechezleprêtre A, Glachant M. Understanding the dynamics of global value chains for solar photovoltaic technologies. WIPO Economic Research Working Papers No. 40. World Intellectual Property Organization; 2017.
- [45] Ha Y-H, Byrne J, Lee H-S, Lee Y-J, Kim D-H. Assessing the impact of R&D policy on PV market development: the case of South Korea. *WIREs Energy Environ* 2020;9:e366.