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Comparative patent analysis for the identification of global research trends for the case of battery storage, hydrogen and bioenergy

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ABSTRACT

Patent documents provide knowledge about which countries are investing in certain technologies and make it possible to identify potential innovation trends. The aim of this article is to analyze trends in patenting that might result in innovations for three energy technologies: thermochemical conversion of biomass (Bioenergy), lithium-ion battery storage, and hydrogen production by alkaline water electrolysis. Based on different patent indicators, the most active countries are compared to provide insights into the global market position of a country, particularly Germany which is used as a reference here. In line with this, a freely available patent analysis software tool was developed directly using the European Patent Office database through their Open Patent Services. The results for named technologies show that patenting activity of Germany is considered lower in comparison to countries such as Japan, China, and the US. Whereas the position of Germany for batteries and hydrogen is comparable, bioenergy shows different results regarding the identified countries and the number of patents found. However, a broader context beyond patenting is suggested for consideration to make robust statements about particular technology trends. The presented tool and methodology in this study can serve as a blueprint for explorative assessments in any technological domain.

Introduction

Science, policy and lawmakers across the globe are stressing that the energy system must be transformed from a fossil-based to a renewable energy-based one to limit temperature rises below 2°C. This global energy transformation is based on ongoing “energy transitions” in many countries (IRENA, 2019). One particular ambitious example is the German energy transition, which represents an attempt in which German politicians agreed to phase out both nuclear power by 2022 and fossil fuel by 2038. Furthermore, the federal government wants also to increase the share of renewables in gross final energy consumption to 60% in 2050 (Umweltbundesamt, 2019), (Umweltbundesamt, 2020). The German case is cited as one of the most ambitious energy transitions worldwide (Strunz, 2014) and serves as a blueprint for the global and multiple national energy transitions (Valdes et al., 2019), (Meckling, 2019). However, changes to the energy system, including technical adjustments and the successful implementation of new energy technologies, are necessary to facilitate a sustainable and future-oriented energy transition (Sohre, 2014). A key to master this ambitious goal is to spur innovations related to renewable electricity generation, distribution and storage, and the heating, industry and transport sectors. At the same time, the international competitiveness of a country as e.g. Germany as an industrial nation, should be increased or at least not be jeopardized (Federal Ministry for Economic Affairs and Energy, 2019). Understanding the innovation processes of technologies is thus an essential factor for research itself and an issue for public policies for a magnitude of reasons named by Mueller et al. (Mueller et al., 2015). First, there is enormous economic potential for improved and innovative technologies. Second, policy-makers seek for technology leadership by their countries for which they need information about their national

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performance with respect to technology innovation. Such information provides orientation knowledge for decision-makers to intervene in the market, e.g., with possible technology push or market pull subsidies. Furthermore, utilities and energy system researchers are interested in getting insights, which energy technologies could dominate their field of application in the future (Mueller et al., 2015).

Novel ideas related to new energy technologies are likely patented before they are scientifically published to request exclusive rights for their commercial exploitation (Mueller et al., 2015), (Chanchetti et al., 2016). Patent documents provide a strong source for e.g., which countries, institutes, and companies are investing in different technologies and to what extent. Information contained in patent applications enables in-depth assessments of national policies and allow the analysis of technological life cycles (Chanchetti et al., 2016). Patents can strongly influence decisions regarding investment in academic and non-profit funding of economically favorable technologies in order to assure market leadership and economic growth (Trippe, 2015).

It is considered in this work that national research and development (R&D) efforts, technology trends and market changes through the development of new energy technologies in frame of the energy transition are reflected by the number of patents registered in the respective country. In our work, we analyze current patenting trends on a national level for selected countries and technologies considered as relevant for the energy transition. A focus is put on Germany, which represents a prominent example for an ongoing energy transition and is used here as a reference. Additionally, it is contrasted to other countries highly active in considered technology domains. The analyzed technology fields are lithium-based battery systems, thermochemical conversion of biomass into fuel, electricity and heat and hydrogen production by alkaline water electrolysis (AWE) for mobility applications. All named technologies are explicitly named in the German Integrated National Energy and Climate Plan, (Umweltbundesamt, 2020), (Federal Ministry for Economic Affairs and Energy, 2019) and in the European Green Deal (The European Green Deal, 2019). The latter especially highlights the relevance of a European battery industry, clean hydrogen supply and other clean fuel alternatives for different transport modes for Europe to become a resource-efficient, carbon-free, and competitive economy. In line with this, these technology are also objects of investigation within the Helmholtz Initiative Energy System 2050 (Helmholtz Association, 2019), which has the goal to explore the integration of technological key elements into the energy system and to elaborate technological solutions to be taken up by politics and industry. The presented approach may serve as a blueprint for other technologies from different sectors like communication, transport or robotics and is not limited to the technologies named here.

The work is carried out using patents as a quantitative indicator to explore potential innovation implications by considering different technology life cycles and determining the R & D activity for named technologies in the face of the ongoing global energy transition. For the interpretation of the results, a literature review on patent analysis, innovation and national research policies of selected countries active in research and manufacturing is carried out to contextualize and interpret our findings. A new patent analysis tool combined with a crawler, which is freely available on request, has been developed to do so. Then, recommendations are provided out of a methodological and technological perspective to support future research.

Literature review

First of all, a comprehensive review of the general usage of patents as an indicator and their value for innovation is given. After this, a specific review of literature and recent studies related to the use of patents as indicators to monitor trends and ongoing developments in the domain of energy technologies is provided. Finally, it is outlined how this approach differs and complements other findings contributing to the discussion on patent analysis and the transformation of the energy system.

Patent systems

From a societal perspective, it is argued that firms might underinvest in R&D because of their inability to get sufficient returns from their investments (Arrow, 1962). This is why governments want to stimulate investments in R&D by a patent system (Granstrand, 2006). Through patent systems, governments create temporary monopolies as incentive to innovate by granting exclusive and prohibition rights to the patent owner. This exclusiveness and prohibition right is highlighted in the EPO patent definition:

"Legal title that gives inventors the right, for a limited period (usually 20 years), to prevent others from making, using or selling their invention without their permission in the countries for which the patent has been granted." (EPO, 2019)

Patents represent intellectual property rights for the protection of an invention within individual jurisdictions. Mere ideas and discoveries are not valid subjects for patenting (Trippe, 2015). The submission of a patent is related to the so-called date of priority filing. It is the date in which an assignee is able to claim a priority for his patent application. The submission of a patent in one nation, e.g. Germany, does not assure protection in another country as patents are a claim of sought in individual jurisdictions. Thus, it is allowed to claim for further priorities in all of the 173 member countries of the Paris Convention for the protection of intellectual property, which facilitates the filings in different jurisdictions. Subsequent applications are based on the same invention and have to be filed within a twelve-month period starting from the filing date of the first application. These claims refer to the same priority date and can be considered to be kindred (they cover the same technical content) (Kastner, 2011), (European Patent Office, 2017)[1]. These connected claims of one invention in different countries are called patent family relations and are, as mentioned before, valid in all countries of Paris Convention (Trippe, 2015).

It is possible to submit a patent to any national patent office (Offenburger, 2014) or the European Patent Office (EPO). The latter offers the possibility to submit a patent through a European Patent Attorney in various European countries. This is also possible on a global scale through a patent submission to the World Intellectual Property Organization (WIPO) under the Patent Cooperation Treaty (PCT) (WIPO, 2017), (Offenburger, 2014). PCT submissions have then to be verified by national patent entities. The main advantage of this process is to assure the possibility of submitting patents in different PCT member states within 30 months (Trippe, 2015), (Offenburger, 2014).

Maximum coverage time of a patent is 20 years for almost all jurisdictions. Patents constitute an economic value and are related to registration, examination, yearly patent and attorney fees, which can vary considerably among countries. The cost for a national patent with durance of seven years without internal handling expenses in a European country is around 10.000 €, a European patent is worth around 50.000 € and a global PCT based patent is related to cost around 100.000 € (Appel et al., 2015). These values do not consider the costs associated to develop and write a patent within a company or research unit. It is obvious that large patent families are related to high economic expectations. They may thus be considered as potentially more important in relation to small patent families due to the monetary efforts undertaken to protect a certain set of knowledge. The size of these patent families is an indicator of how companies are interested in protecting their inventions in different markets due to higher economic potential from these. For example, triadic patents have at least one EPO patent

[1] For example an applicant with residence in Germany filed a first application for a patent in Germany. Then the same applicant filed a subsequent application in the US within the time frame of twelve months. Now the applicant claims the first filing in Germany for right of priority and his invention will be protected in the US from the priority- date of the first filing onwards (adopted from (European Patent Office, 2017))

number, one United States Patent and Trademark Office (USPTO) patent number, and one Japan Patent Office (JPO) patent number (Chanchetti et al., 2016).

Patents as an indicator: potentials and limitations

The number of patents is considered a standardized and objective source representing a good proxy to measure innovation activities. They allow deriving technology trends, as well as the current level of technological innovation (Lee and Lee, 2013) in different countries and for different fields of application. There is an indisputable connection between R&D efforts and patents (Greif, 1997). Successful R&D efforts may lead to potential innovations, which might be reflected in the number of patents. They can be seen as suitable indicators to e.g. describe R&D activities, technological and economic structures and developments, innovation strength of an industry and international relations related to economy, society and technology (Appel et al., 2015), (Greif, 1997), (Frietsch et al., 2010). All these indicators provide the most information if they are analyzed over time in order to analyze trends or identify product life cycle stages of technologies. Furthermore, the international scope, as well as the value of a patent, can be described by the size of patent families (Chanchetti et al., 2016), (Ernst, 2003).

Despite these advantages, there are also considerable limitations on the informative value of patents. Not all R&D efforts result in inventions, which vice versa themselves are not all translated into patents (it has to be new, real invention, etc.). Only a certain amount of R & D efforts result in innovations, which then have to prove themselves in markets, which is discussed in detail in the following section. Furthermore, patent application depends on several factors such as the degree of market forces in a field of application, cost of patent applications, or keeping inventions secret (Greif, 1997). Companies may use strategic patenting to disguise their technology strategy as a signal for markets or for marketing reasons. It is reported that this represents an increasing trend towards multinational cooperation since the 1990ies (Frietsch et al., 2010). Such forms of patenting can lead to confusing patent data, which does not describe real technology development trends.

In general, the applied patent research methodology is highly dependent on the study goal, available time and money as well as topic (Appel et al., 2015). It is possible to distinguish between quantitative and qualitative patent research generally. The qualitative patent research includes the evaluation of patents by reading single patents and to, e.g., determine their value, which is not considered as recommendable[2] due to the vast amount of available patent documents. Quantitative methods are carried out by the use of bibliometric approaches and indicators. This represents merely the statistical analysis of bibliometric data and a measure to derive information about specific situations and developments regarding patents (Kastner, 2011), (Offenburger, 2014). Here quantitative research is applied as these approaches allow to unveil e.g., certain technology development trends, to identify market leaders, or to search for key markets for specific technology solutions (e.g., based on the patenting activity of other companies). Such statistical analyzes can be based on the available number of patents related to a certain IPC (International Patent Classification) class, one inventor or a certain time period, number of forward citations etc. (Kastner, 2011).

There are worldwide over 100 patent databases available - each with different data and suitable for different purposes. Most of these sources are freely available and provide access to patents and bibliographic data (Kastner, 2011). The most popular ones will be briefly introduced here. The WIPO provides a global database named Patentscope (WIPO, 2017), Espacenet is a database provided by the EPO (EPO, 2017) and the German patent office DPMA (Deutsches Patent- und Markenamt) provides Depatisnet (Deutsches Patent- und Markenamt, 2015). All three provide patent collections from a multitude of countries.

There are differences between the databases regarding data coverage, search functionality, result list of records, bibliographic view and patent data export. The search modes in the three databases are similarly based on command line searching and search fields. Searches can be conducted either by the use of keywords or technological classifications or the combination of both to identify patents of certain technology fields (Mueller et al., 2015). Patentscope owns a large number of patent collections with full-text searching capability, whereas the available patent collections (amount of patents collected from a certain country) and patent records (e.g. Espacenet only allows to export up to 500 patent records) are very limited with respect to full-text search. A good in-depth comparison of differences between Patentscope, Espacenet and Depatisnet is given in Jürgens et al. (2015) (Jürgens and Herrero-Solana, 2015). A brief overview of these three different patent data sources is given in Table 1.

Innovation and patent activity

For the analysis of innovation trends, it is important to understand the limitations of patent analysis and, therefore the difference between the invention and the innovation. An invention is not yet an innovation. An invention can be rather seen as an act of intellectual creativity and without importance for any economic analysis (Schumpeter, 1939), whereas an innovation implies an application and adoption of the invention. Some scholars even add a successful implementation from an economic perspective as a criterion for an invention to become an innovation (Heunks, 1998). The pure act of inventions comprises new ideas, including prototype construction or concrete concept development in the pre-market phase. We can only speak of innovation in the economic sense if its usefulness is recognized and a product, production process or business model is introduced or changed accordingly. Different innovations require different intellectual property rights such as trade secrets, trademarks, copyrights or patents to become protected from imitation. Only technical inventions and, therefore, technical innovations can be protected by patents. Table 2 gives an overview of the innovation types introduced by the OECD Oslo Manual (OECD, 2005).

Patents are solely an indicator for inventions in the first place and non-exhaustive since often only a small fraction of inventions are patented alongside a development process, illustrated in Fig. 1 (Basberg, 1987).

However, patents are very important since they bring a broad range of benefits; they prevent competitors from improving their own market position by prohibiting copying the development or results without paying. This can even force competitors to circumvent patents by developing alternative solutions (Hung and Hsu, 2007). Patents are often seen as evidence of innovative strength (Narin et al., 1987). To assess the importance of patents in different industries, “patent propensity” is an established indicator. An overview of the corresponding literature is given in Table 3 (Scherer, 1983)–(Mäkinen, 2007). Despite its limitations, patent analysis is often applied to assess technological

Table 1
Brief overview of Patentscope, Espacenet, and Depatisnet based on (Jürgens and Herrero-Solana, 2015)

Name	Patent records	Available patent collections (countries)	Source
German patent office - Depatisnet	~ 90 m.	101	(Deutsches Patent- und Markenamt, 2015)
European patent office - Espacenet	~ 90 m	101	(EPO, 2017)
World intellectual property organization - Patentscope	~ 37 m	39	(WIPO, 2017)

[2] It has to be mentioned that companies developing technologies have to conduct such detailed analyzes

Table 2
Innovation typology adopted from the OECD Oslo manual 3rd Edition and their patentability (OECD, 2005)

Type of innovation	Patentable
Product innovation / goods	Yes
Product innovation / services	No
Process innovation (new or significantly improved methods of production)	Yes
Marketing innovation (new methods of marketing)	No
Organizational innovation (new forms of organizations or business practices)	No

newness and innovation (Kleinknecht et al., 2002).

Review of patent based assessments for energy technologies

A literature review is carried out to provide an overview of studies that conduct a patent analysis of one or several alternative and renewable energy technologies to highlight and contrast the contribution of this study against other findings. The review includes studies from 2010 to 2020. The reviewed studies cover a wide range of energy technologies from renewables as photovoltaics (Shubbak, 2019) or wind turbines (Lindman and Söderholm, 2016) up to enabling technologies as hydrogen storage materials (Chanchetti et al., 2016). The following major differences can be used to categorize most studies: i) included technologies and related granularity of the assessment (e.g, entire concepts or specific materials), ii) used tools and data sources, iii) included regions and countries, iv) and of course, the used indicators. However, they mostly aim to analyze technological progress, innovation dynamics or to identify a specific technology scope. A summary of the analyzed literature can be found in table 4 and is discussed in detail in the following.

Abbas et al. (Abbas et al., 2020) analyzes in detail a set of different thermal energy storage technologies (TES) and identifies major depository countries. Here Japan (69%) followed by China (9%), have the most published patents. Lindman et al. (OECD, 2020) conducted comprehensive research on the Wind power sector of western European countries (Lindman and Söderholm, 2016) using the OECD database and sorted by inventor country of residence. Results show that R&D support and feed-in tariffs have positively influenced patent applications (with a high share of German patents). Lanzi et al. (Lanzi et al., 2011) analyzes in their work the patenting trends over time and across countries related to efficiency improving technologies for fossil fuel-based electricity generation. Herein, Espacenet (European Patent Office, 2020) is used and patents are allocated by the inventor country of residence. OECD member states are sought to be the top innovators in the field, followed by China as a non-OECD country. Shubbak (Shubbak, 2019); reviewed in detail the most influential inventions in the field of PV and analyzed in parallel geographical, organizational, and technical trends over the past six decades. Japan has the most patent applications (49%), but China has the highest growth rate here. Chanchetti et al. (Chanchetti et al., 2016) took a detailed look at different hydrogen storage materials and concluded that USA, Japan, China and the European Union (EU) are the main patenting territories.

The study of Albino et al. (Albino et al., 2014) takes a more general stance by focusing on different energy technologies with potential lower environmental impacts than the relevant alternatives. Technologies included here are nuclear power, alternative energy production technologies (PV, fuel cells, wind power, waste heat etc.) and energy conservation (storage of electrical energy, power supply security, low energy lighting). The database used is the USPTO. The withdrawn data were then flanked by deriving information from relevant ministries of corresponding countries (e.g., US Department of Energy, Ministry of economy, trade and industry (METI) or the European Commission, OECD, and IEA). Patent allocation is based on the inventor and applicant country of residence. Results provide a picture of major developments of considered low-carbon technologies and how environmental programs, private sector initiatives, and historical events have impacted their development.

Different from other studies, we refer to CPC-classifications and use the EPO bulk database. Most importantly, we developed a customized analysis tool that is freely available on request, and that can be adopted for individual purposes. The precondition to do so is to apply for a developer access to the EPO raw bulk database. Furthermore, we do not pre-define countries (despite our reference to Germany here); rather, they are identified by the used analysis tool. The article on hand includes different technology granularities, e.g., technology-specific analyzes for the alkaline electrolysis and biomass pyrolysis and gasification and a broader analysis of lithium-Ion batteries, and uses a comprehensive set of combined indicators. These indicators are finally combined into one portfolio analysis. Additionally, a look at the technology life cycle curve (TLC) related to each assessed technology is taken to derive major trends for each considered technology. Only Chanchetti et al. (Chanchetti et al., 2016) uses a similar approach regarding the TLC.

Selection and introduction of three emerging technology domains

With the reviewed literature, the German energy transition and the German Integrated National Energy and Climate Plan (Umweltbundesamt, 2020), (Federal Ministry for Economic Affairs and Energy, 2019), as well as the European Green Deal (The European Green Deal, 2019) in mind, three highly relevant use cases were selected and analyzed for the

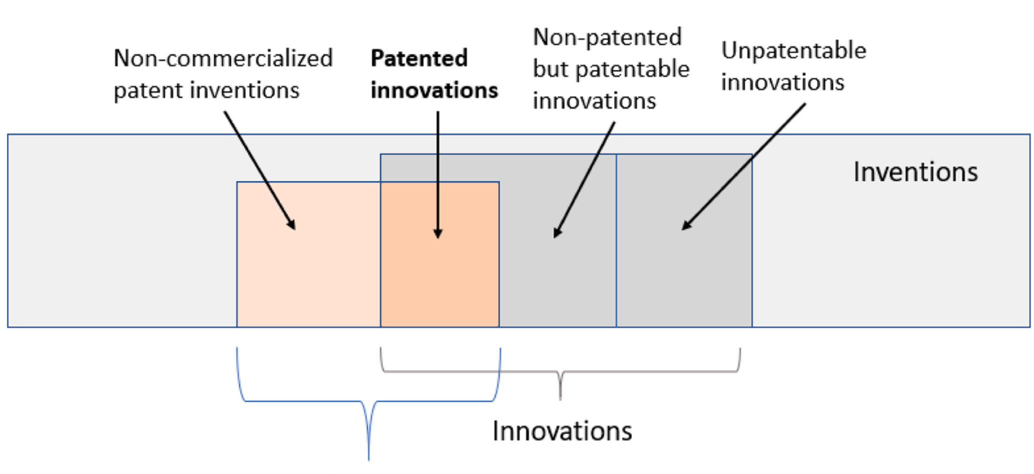

Fig. 1. The share of patented innovations adopted from Basberg 1998 (Basberg, 1987)

Table 3
Different indicators and their concepts for patent propensity

Indicators for patent propensity	Description	Source
$\frac{\textit{Patents}}{\$\ \textit{of R\&D expenditure}}$ "propensity to patent is measured here in terms of the number of patents industrial corporations obtain per million dollars of company financed research and development (R&D)"	This patent propensity can be used to investigate differences in patent yield for different technologies, firms, markets and industries. (-) Complex to interpret due to dependency of efficiency of R&D (+) Can be calculated for a large number of countries that provide public statistics on R&D expenditures	Scherer (1983) (Scherer, 1983)
$\frac{\textit{Patented innovations}}{\textit{All patentable innovations}}$ "the percentage of patentable inventions that are patented"	Mansfield extends the literature on patent propensity by investigating to which extend firms and industries make use of the patent system in the first place. Patentable refers to the legal requirements, of an innovation (+) valuable for research on conditions and differences why firms or industries choose to patent (-) not obvious which kind of inventions meet the criteria to be potentially patentable	Mansfield (1986) (Mansfield, 1986)
$\frac{\textit{Innovations with at least one patent}}{\textit{All Innovations}}$ "percentage of innovations for which a patent application is filed"	To investigate a firm or industries innovation activities patent applications became an established indicator in technology and innovation literature. Arundel and Kabla define the so called patent application propensity rate, which they also refer to as patent propensity rate. (+) Patent applications indicate innovation activities and the intention to commercialize an invention by a firm, or in an industry independent if the patent is finally granted or not (-) Not all patent applications are granted, the results overestimate the true patent propensity rate.	Arundel and Kabla (1998) (Arundel and Kabla, 1998)

Energy System 2050 Initiative of the Helmholtz Association (Helmholtz Association, 2019). The scope and depth of the assessment is described in the following descriptions for each of the three technologies, which also serve as the initial basis defining the technological domains for the patent analysis in this study.

Lithium-Ion batteries

The growing market share of intermittent renewable energy sources leads to the increasing demand for appropriate balancing options. Especially li-Ion batteries are considered as such an option able to mitigate short- to mid-term fluctuations of energy provision in the electricity grid (Versteeg et al., 2017), (Baumann et al., 2019). In addition, li-Ion batteries are considered highly relevant as a technology not only in stationary applications covering a wide field of services but also for the electrification of transport and portable devices. It is expected that the li-Ion battery market will significantly grow from 184 GWh in 2018 to 2.623 GWh in 2030 (for mobility, stationary and portable applications) (World Economic Forum, 2019). In general, there are several chemistries available including e.g. lithium-iron-phosphate (LFP), lithium-manganese oxide (LMO), nickel-cobalt-aluminium-oxide (NCA) and nickel-cobalt-manganese-oxide (NCM) (Baumann et al., 2016). Each of these chemistries share the comparable operation principles, cell production processes and require a battery management system. Also, cells primarily produced for mobility applications are applied for stationary solutions as in the case of the Tesla power wall (Tesla, 2015). Therefore the focus is put in a very general way on lithium-ion batteries including all the named chemistries mentioned before as well as cell types (cylindrical, pouch and prismatic). It has to be noted that a stationary battery storage system requires - apart from battery cells - electronics, infrastructure, and auxiliaries (Baumann et al., 2016), which are not subject of this analysis.

Hydrogen

Hydrogen as well is a suitable option to buffer intermittent renewable energy sources. It can even be stored for several months to mitigate seasonal differences in intermittent power generation, e.g. in salt caverns. Furthermore, hydrogen enables the use of electricity – in the best case from renewable energy sources – in other sectors by direct use, e.g. hydrogen mobility by fuel cells or steel production (direct reduction processes), or after several process steps as methane, liquid fuels or chemical products (Wulf and Kaltschmitt, 2018). These processes are often connected to the keywords sector coupling or Power-to-X. The backbone of all these processes is the hydrogen production from renewable energy sources. The most promising option is water electrolysis (Wulf et al., 2018). Three different types of electrolyzers are under consideration for such applications, i.e. alkaline water electrolysis (AWE), proton exchange membrane (PEM) electrolysis and high-temperature electrolysis. Each type has its own advantages and disadvantages and is on different levels of technology development. In this study, the focus is on AWE, which is commercially available since several decades. However, the rather new developments in the field of Power-to-X also brought new momentum in the development of AWE (Wulf and Kaltschmitt, 2018).

Bioenergy

Biomass is an important resource to compensate fluctuating availability of wind and solar power. It is also a promising renewable alternative to obtain liquid fuels for the transport sector (Faba et al., 2015). In this paper, the use case bioenergy focuses on the thermochemical conversion of lignocellulosic residues, i.e. residual cereal straw and residual forest wood, into fuels, electricity, and heat. The considered process chain includes decentral biomass pre-treatment (chipping, drying, pyrolysis), transport of the intermediate product biosyncrude (mixture of pyrolysis oil and coke, also referred to as "slurry") to central production sites, production of raw synthesis gas by gasification of the biosyncrude, gas cleaning of the raw synthesis gas, and synthesis to a liquid transportation fuel (e.g. gasoline via DME synthesis) (cf. (Dahmen et al., 2017)). Pyrolysis gas is assumed to be burned for covering the internal heat demand as well as gaseous synthesis products in a

Table 4
Overview of selected literature with a focus on patent analyzes in the field of energy technologies using standard country codes (ISO, 2020), souces are sorted by their publication year.

Source	Aim of the study	Considered Technology	Considered regions	Used software/tool	Used indicators
Lanzi et al. 2011 (Lanzi et al., 2011)	Analyze the patenting dynamics in efficiency-improving electricity generation technologies regarding innovation activity	Efficiency improving technologies for fossil fuel electricity generation (coal gasification, fluidized bed etc.)	FI, CH, GR, DK, DE, BR, IN, PL, US, JP, SE, AT, RU	Espacenet (European Patent Office, 2020)	Patent counts for duplicates, singulars and claimed priorities
Albino et al. 2014 (Albino et al., 2014)	Analyze the evolution of a specific type of econ-innovations that, namely low carbon technologies related to different regions	Nuclear power and alternatives for energy production. (summary of PV; etc.) and Energy conservation."	US, EU, JP, BRIC, Others,	USPTO Tool (ISO, 2020)	Forward citation, number of patents, total share of patents
Lindman 2016 (OECD, 2020)	Analyze the impacts of public R&D support and feed-in tariff schemes on innovation in the wind energy sector	Wind energy and green economy	DK; DE, ES, SE	OECD patent database (OECD, 2020)	Total patent count, public research expenses
Chanchetti et al. 2016 (Chanchetti et al., 2016)	Evaluation of the technological life cycle stage as well as class prominence and the role of different countries in hydrogen storage materials patenting	Various hydrogen storage materials (Activated Carbon, Amides, Fullerene, Graphene etc.)	JP, US, CH, KR, EU, Other countries	VantagePoint (ISO, 2020)	Number of patent families, total patent families, number of patent applications per year, technology life cycle assessment
Abbas et al. (2019) (Abbas et al., 2020)	Analyze the evolution of domestic and industrial applications of TES related to different countries	Different types of TES (sensible, latent, cold, process integration etc.)	JP, CN, EPO, WIPO, US, DE, EN, IN, CA, FR,	IncoPat, including 12 sources for patents (Lindman and Söderholm, 2016)	Published patents
Shubbak 2019 (Shubbak, 2019)	Development of the PV technological system; analyzed along with a review of the most influential inventions	Different photovoltaic technologies	World, JP, CN, KR, US, DE, TW, FR	Patstat (EPO, 2020)	Number of priority patents, international business potential indicator

combined heat and power (CHP) plant, excess electricity is fed into the grid (Trippe, 2013), (Haase and Rösch, 2018), (Haase and Rösch, 2019). Ongoing research focuses on feed-in of hydrogen produced from renewable electricity in order to increase the yield of synthesis gas and fuel, respectively. In this paper, the combination of the first two biomass conversion steps of the described process chain, i.e. pyrolysis and gasification, are subject of the analysis.

Methodology

The aim of this study is to analyze trends in patenting that might result in innovations on an international level for three energy transition technologies in selected countries. These trends are compared with the situation in Germany, which serves as a reference in this study. Bibliometric research is carried out by collecting data from the EPO to do so (EPO, 2017). Different patent indicators are used for the assessment based on this bibliometric data. Further details on the used methods are given in the following.

Research methodology

An overview of the research methodologyis given in Fig. 2. The first step is the formulation of a Boolean search query using relevant keywords and cooperative patent classification (CPC)[3] classes using a developer access for the EPO database Open Patent Service (OPS). The search interface is a python-based crawler (see corresponding section 0). Relevant data (e.g. residence country of the inventors, patent family size and priority date) are collected from the EPO OPS database and provided in a Microsoft Excel sheet, which can be analyzed with an automated template. In a second step, the template analyzes the five most active countries in the considered technology field. These countries form the base for further assessment and are compared to Germany. It is worth to be mentioned that depending on the technology, different countries might be selected based on their patenting activity in the field. After this, a bibliometric analysis is carried out for the selected countries and the corresponding technologies. This analysis gives information on the patenting activity, intensity, and strategy of corresponding countries. Furthermore, an analysis of the current state of technology development is provided.

Simple patent families[4], which are available in the bulk data set[5] of the EPO worldwide bibliographic database (DOCDB), are used in the analysis. These simple patent families contain a collection of related patent applications with the same technical content and are indicated with a common patent family ID (European Patent Office, 2017). In general, information about the inventor and applicant is provided in patents, which makes it possible to allocate them to a country. First, the date of the priority filing is identified. This is followed by identifying the inventors' country of residence as recommended by (eurostat, 2017) and applied in (Gregori et al., 2020). It is worth mentioning that there are several ways of attributing a patent to a geographical region e.g., by taking the applicant's country of origin, which is discussed in detail in section 6.1. There is often more than one inventor indicated on a patent through, e.g., international cooperation. In such a case, one can attribute the patent to a country in three ways:

I) full attribution of a patent to each named country for every inventor,
II) attribution only to the country of residence of the first-named inventor or
III) each of the n inventors is assigned a fraction of 1/n of the patent.

Here the latter is applied following the OECD Manual for Patent Statistics (eurostat, 2009) to avoid double counting and to credit each country accordingly with a correct proportion.

[3] The CPC represents an extension of the IPC and is divided into nine sections (A-H and Y). It is jointly managed by the US Patent and Trademark Office and the EPO (EPO, 2019)

[4] The technical content covered by these patents are considered identical and have all priorities in common with all other members. For more information check the corresponding EPO information (European Patent Office, 2017)

[5] Bulk data sets are bulk extractions from the EPO-internal patent databases that are available to external users for further processing (EPO, 2019).

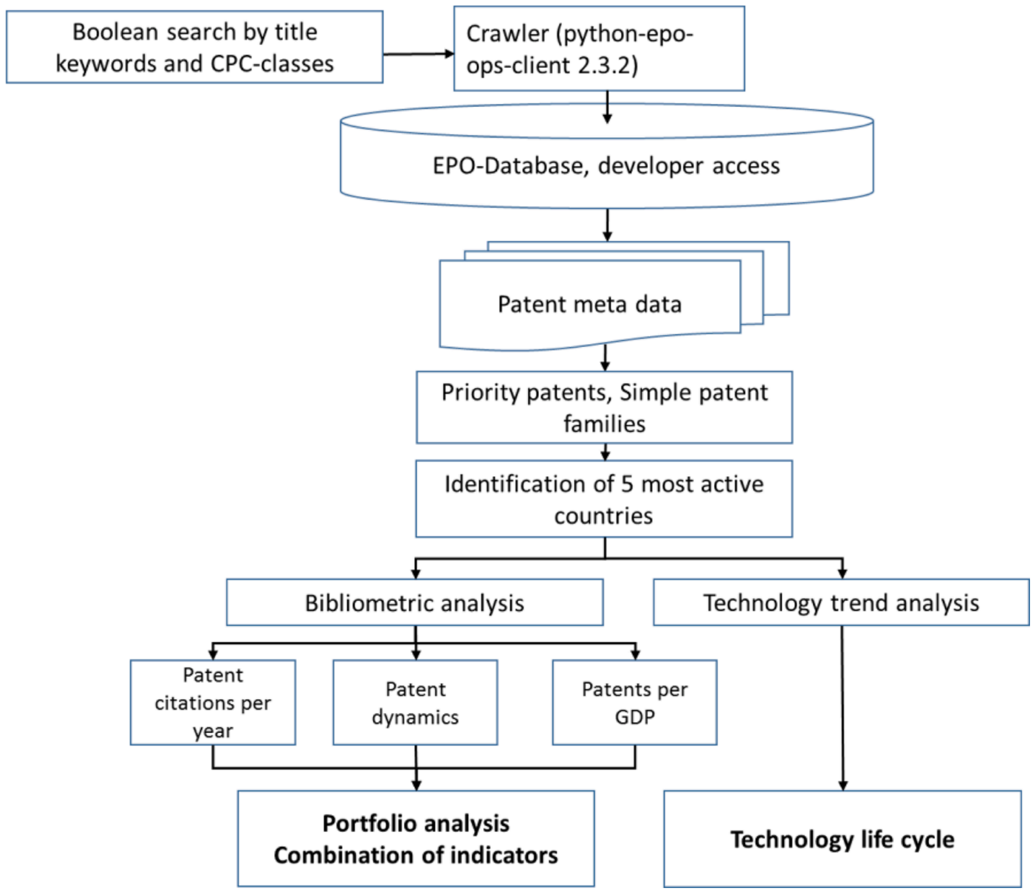

Fig. 2. Overview of the research methodology

As reported in the literature (eurostat, 2009) and in accordance to our experience, raw data from the EPO is not formatted in the same way in all cases (e.g. there is only a certain region but no country named or there is no inventor name given). A three-stage allocation is used to mitigate these inconsistencies in case of missing inventor data: In case of an error, simply the applicants (referring to the company that owns the patent) country of origin is taken instead of the inventor residence country in a second step. If neither inventor nor applicant data is available, the priority claim is taken for allocation in step three. Patents that do not provide any of this information are ignored in the analysis.

Patents that have the same family ID with a publication date later than the priority claim date are handled as doublings (e.g. members of the patent family) and are considered separately in the analysis. These patents are allocated to the country, or in other words, the inventor that holds the claims on the priority patent. There are also patents that are only published in one country. These are labelled as national patents in the evaluation.

Two kinds of analyzes are provided by the evaluation template: a quantitative analysis based on bibliometric data and a qualitative analysis, which requires a certain degree of interpretation (technology trend analysis). The quantitative-based indicators are then combined in the form of a portfolio analysis to gather a quick overview of countries activities in the area. All indicators are described in the following sections 3.2 and 3.3.

Patent collection

There are several strategies available to conduct patent research. Mostly keyword or classification-based searches are applied (Clarke, 2018), e.g. by inventors, applications, titles, abstracts, country, international patent classification (IPC), etc. A pure keyword-based search inhibits the risk of potentially excluding patents through a too narrow combination of keywords related to a certain area. Or vice versa to include wrong patents by a too loose formulation. Another associated problem to this kind of research are differences in the wording used in patent applications within different jurisdictions (Kastner, 2011) (Clarke, 2018). Changing a keyword or logical operator may lead to completely different results.

A purely IPC based search allows only a certain resolution regarding technology classification (e.g. batteries to H01M[6]). It is worth to mention that patents are categorized within the IPC into different units. Each patent is classified in up to 70.000 subcategories. Categorization is normally organized by choosing a main group, a subclass, a group and finally, a subgroup. There are in total eight sections defined (WIPO, 2017), (Greif, 1997).

The combination of both search strategies – IPC and keyword-based search - can circumvent these challenges. The recently introduced CPC between the United States Patent and Trademark Office (USPTO) and EPO as well as South Korea (Kim and Bae, 2017) allows an even more refined search manner of technologies in a certain area e.g., related to transmission or distribution, transport, etc. (Mueller et al., 2015). The search combination of this work consists of the CPC main classes and subclasses, and keywords for the technology.

The search was carried out iteratively by starting with certain search terms and by analyzing in detail the resulting collection of patents (by screening randomly the abstracts and titles). This process was repeated several times until a high number of patents had been achieved, which

[6] As an example: the classification H01M refers to "*PROCESSES OR MEANS, e.g. BATTERIES, FOR THE DIRECT CONVERSION OF CHEMICAL ENERGY INTO ELECTRICAL ENERGY*" (WIPO, 2017).

fit into the search conducted. It is worth mentioning that this is a highly time-consuming procedure that should be carried out with care. The results for each technology are based on the search terms constituted out of the technology keywords and CPC-main and subclasses, as shown in Table 5. Additionally, the total number of patents found is indicated. It can be observed that there is a high difference between the three types of technologies. Reasons for this difference are two factors; i) the scope[7] of each use case and ii) different development stages of each technology.

Patent crawler EPO OPS Tool and MS Excel template

A customized software tool was developed for the patent analysis to gather results from the EPO OPS database. The different steps of the query procedure are illustrated in Fig. 3 and referenced in the following description. The OPS is a web service, which provides access to EPO's data via a standardized XML interface by using the RESTful architecture (EPO, 2019) (4). The developed software allows an automated use of the EPO database search API via the python client library python-epo-ops-client 2.3.2 (Song, 2018) (3, 5). For better usability, a graphical user interface was designed to facilitate search request handling (1). An overview of the interface is provided in the supplementary materials (SI). The resulting client-server solution is based on Angular6 and Node.js and allows parallel use of the limited EPO account login by job queueing (2). Therefore, the patent search term requests are processed asynchronously on the server side. In the end, the query results are prepared and provided on the server as excel reports (see Fig. 3). These automatically generated excel reports serve as raw input data for the later described excel template, where the patent analysis itself is conducted (6, 7).

The EPO OPS Tool (EOT) forwards the EPO database query and automatizes its response. Additionally, it handles the splitting of the query by time periods if the original response exceeds the EPO limits (> 2000 hits). Therefore, all EPO database search term rules also apply for the EOT. This allows logical operators, full keyword and classification based searches (EPO, 2019). A free EPO-OPS access login can be requested directly from the EPO. In general, only one access is given for each institution, which is part of the fair use policy. It has to be considered that the data download limit for the free account is 4 GB per week (EPO, 2019). A higher download volume requires an annual, paid subscription. The EOT provides an overview of the used data volume, which is sufficient by far if only metadata is required for patent analysis instead of related technical drawings.

The Excel template for the patent evaluation allows to upload the raw data provided by the crawler and to easily customize the results as well as statistical analysis in the template. In total, five different result matrixes are used for the assessment within the template. Other data, such as the total number of patents and GDP/PPP are based on EPO (EPO, 2017) and the World Bank (The World Bank, 2019) and can also be updated anytime. The current version of EOT-code is also freely available[8]. Additionally, the xls-vba template used for patent analysis is also provided for free use and further development. Both template and crawler can be used with citing this article. An overview of the template is provided in the SI.

Framework and theoretical perspectives

A mixed approach is applied to exploit established quantitative and qualitative concepts of patent analysis and indicators. We first assess the Technology-Life-Cycle for each of our selected technology domains, because the information value of patent indicators is the highest if their dynamic development over time is considered (Ernst, 1999). Here a time horizon between 1995, which is marked by the the first UN Climate Change Conference in Berlin till today, cutting off the data in 2018. This should cover the relevant period since the energy transition received a stronger focus in politics and industry leveraging the momentum of technological development of new energy technologies. This global picture is complemented by a national perspective for the most active OECD countries, analyzing their positioning among the previously introduced technology domains for li-ion-batteries, hydrogen (AWE) and bioenergy technologies, based on their national patent portfolios.

Technology-Life-Cycle analysis

The concept of the technology life cycle (TLC) allows determining a technology life cycle stage and thus to estimate future R&D trends (Altuntas et al., 2015). It is based on the assumption that technological change follows a specific scheme in which different development stages can be identified (Ernst, 1997). This classical s-shaped curve can be supplemented by the so-called hype phase (Chanchetti et al., 2016). The latter is based on an overly positive reaction to the introduction of new technologies in an early development stage. This hype phase is followed by commercial adoption failing to meet performance expectations (Dedehayir and Steinert, 2016), leading to a temporarily reduced activity in the area. There are several approaches available to determine the life stages of a technology through the use of patents (Campbell, 1983), (Ernst, 1997). An illustrative TLC, including a hype level, is depicted in Fig. 4, which expresses the theoretical development of patenting activity. This activity can be measured by the number of patent applications over time. It is possible to distinguish four idealized phases within a TLC based as follows ((Chanchetti et al., 2016), (Ernst, 1997)):

I) an emerging phase of new technology; initially with stable patent activity followed by an abruptly increasing activity (representing the end of the development phase);
II) a consolidation phase with decreasing growth of patent activity due to a new focus on first experiences with the new technology;
III) a market penetration phase with strong growth of patent activities as new companies start to filing patents in the area;
IV) a maturity phase where the peak can be seen as a breakthrough when technology reaches maturity.

It has to be mentioned that patent applications may also follow the stages of hype cycles, more precisely the expectation phase (between stage I and II). This might indicate a market reserve characteristic than real technology development (Strunz, 2014) rather.

It is assumed that the number of patents mirrors to a certain degree the changes in technological development. Such a TLC curve can be plotted by patent applications over time. The identification of a certain technology stage related to Fig. 4. gives insights into a technology R&D "level" and enables the analyst to derive information about potential trends in the area (Ernst, 1997)[9]. Within this work, the TLC for the considered technologies is built upon the total number of patents published per year and is interpreted in a qualitative way (by visual interpretation using a 4th-degree polynomial trend). As the real development of the number of patents does not always follow the ideal curve depicted in Fig. 4, the identification of life cycle states is prone to uncertainties.

[7] Lithium-ion batteries are widely applied including a manifold of chemistries, in the hydrogen case, a focus is put on one certain electrolyzer technology, the AWE. Also in the case of bioenergy a more restricted research is conducted

[8] Link to the crawler including the blank analysis template http://itas-vm-1.itas.kit.edu:4000/

[9] It is recommended to invest into a certain technology if it is in a growth phase from a decision maker perspective, e.g. regarding a company strategy. In contrary it is not recommended to invest into a certain field in an initiation and saturation stage (Altuntas et al., 2015).

Table 5
Considered technologies and their corresponding keywords, CPC and IPC (Umweltbundesamt, 2020), (WIPO, 2017) and (Müller et al., 2014)

Technology field	Technology keyword	CPC main and subclasses	Groups & subgroups	Boolean search terms	Total Patent number
Stationary battery storage	Li-ion battery	H01M Y02E Y02T	10/052 60/122 10/7011	ti=(Lithium Ion battery) or ti=(Li-Ion Battery) or ti=(Lithium-Ion Battery) or (lithium Ion cell) or (lithium-Ion cell) and (cpc = H01M10/052 or cpc = Y02E60/122 or cpc = Y02T10/7011)	5822
Hydrogen	Alkaline water electrolysis	C25B Y02E	60/366 1/04 and other	cl=C25B1 or cl=C25B9 or cl=C25B11 or C25B13 or C25B15 or cl=Y02E60/366 and ti=electroly* and ti=alkaline pd within "19950101 20181231"	204
Bioenergy	Pyrolysis and gasification	C10J Y02E	2300/0926 50	“ta=Pyroly* and ta=Gasif* and CPC=(Y02E50 or C10J2300/0926) pd within "19950101 20181231“	841

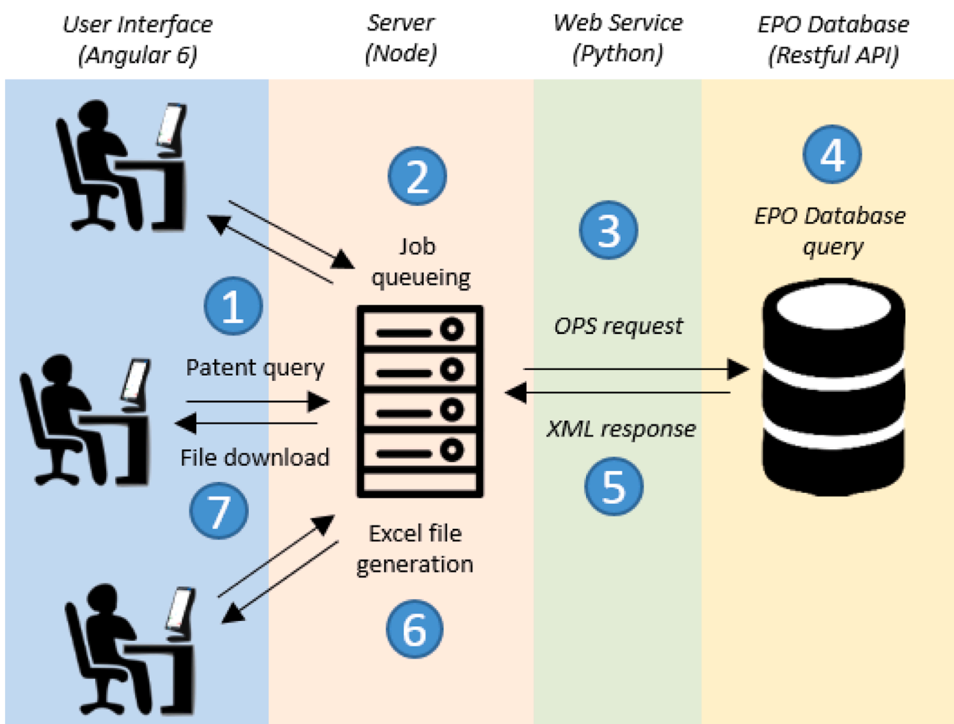

Fig. 3. Structure of the EPO patent crawler

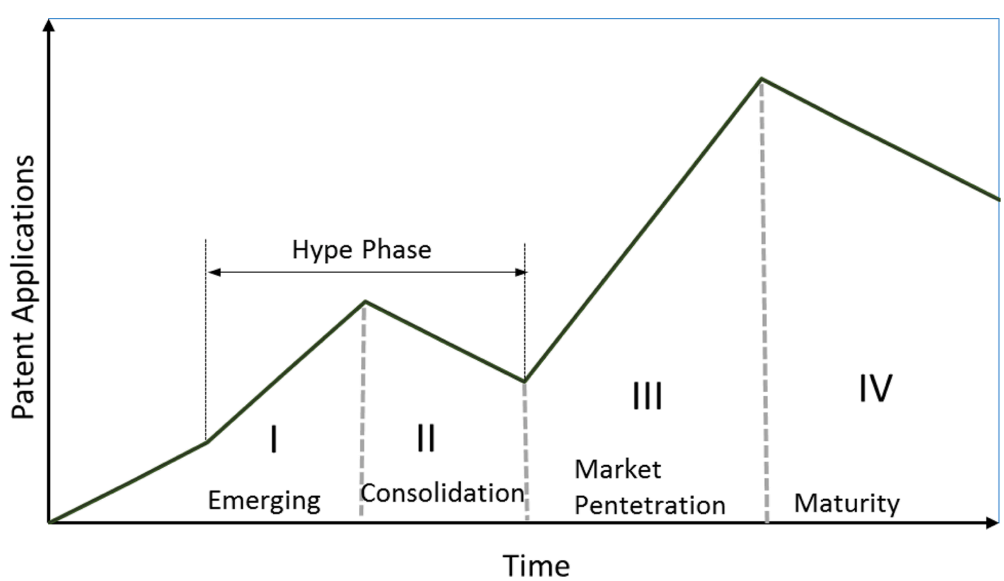

Fig. 4. Number of patent applications for different stages of the technological life cycle based on (Chanchetti et al., 2016) and (Ernst, 1997).

Patent portfolio analysis

The R&D focus of a country can be analyzed by its *patent activity* in a certain technology field and time span (total number of patents over time). The amount of patents also often reflects, to a certain degree the global market position of a country (e.g. through a relation of total turnover and patent activity). In theory, the indicator also captures a countries competitive position in R&D (comparable to the market share stemming from the marketing domain) (Ernst, 2003). Significant changes in technology patent shares can be understood as a change in national R&D strategies. The temporal development of the patent activity can be interpreted as changing levels of R&D activities over time and allows drawing a trend of future technological and commercial interest (Ernst, 2003)[10]. It also makes it possible to compare different country's R&D activities in the same area and to identify weak and strong areas in national innovation systems (eurostat 2009). Additionally using technological potential analysis can increase the informative value provided by patents. Such a technology potential analysis is based on *patent growth* resulting from positive or negative patent application growth rates (Lee and Lee, 2013), (Blundell et al., 1999). The *patent growth* indicator is based on the assumption that present rapid growth of patent applications indicates increasing R&D expenditures and a corresponding high future growth potential of the technology. The opposite comes true in case of low or decreasing patents (Lee and Lee, 2013), (Ernst, 2003). Here the arithmetic mean over three years is used to evaluate the technology potential. The third indicator is concerned about the changing national emphasis of R&D related to different countries and technology areas. The "*national technology share*" is an indicator that describes the relation of national patent applications in a certain technology in relation to the total national portfolio of patent applications. It allows to gather information about the technology scope of a country, e.g. a high share of the patents may indicate a strong research emphasis in the corresponding technology area. It has to be considered that a country's patenting activity is dependent on its specific level of development as well as its economic growth. It is thus useful to reflect the national patenting activity with regard to R&D spending, population size, or the GDP. Such indicators are often referred to as patent intensity (World Intellectual Property Organization 2017). Here, the patenting activity is related to the GDP (in terms of purchasing power parity (PPP)). It represents changes in the nominal output or income of an economy considering the combination of several forces (price inflation, exchange rates, and real growth) (The World Bank May 06, 2019). The international scope is described by the size of the patent family that allows deriving the economic value of a patent as described in section 2.1. A large patent family indicates a certain economic value[11] and international scope of patent.

Here, the difference between the types of patents is given by separating priority patents (first patent in a country that has a patent family), family members that are based on a priority patent and national patents that are only registered in one country. The number of patents per country (patent activity per country) and the share of priority patents, family members and simple patents (residential/national patents) per inventor home country is presented for each case study. Furthermore, comparing national patents with priority patents and their corresponding family members allows deriving different innovation efforts of a country related to market-specific inventions versus those that might have a more international application (Lanzi et al., 2011). An overview of all indicators used in this work is given in Table 6. All these indicators use patent data, which are converted into numerical indicators of potential interest (Ernst, 2003).

The final comparison of patenting efforts and technology orientation in this work is carried out by a portfolio analysis. The aim is to determine the role of Germany in comparison to other countries, their related patenting and the importance of the technology within their own R&D portfolio. Several approaches to use patent data for portfolio analyzes are available (Ernst, 2003), (Ernst, 1998). This work builds upon the approach described in Ernst (2003) (Ernst, 2003) by the use of a typical four field portfolio matrix, as depicted in Fig. 5, which has been adapted slightly for our purposes (not on a company, but on a national level). The time period 2013-2018 is analyzed to understand recent technology trends better. An advantage of portfolios is the possibility to structure and visualize complex problems (e.g., combination of named patenting indicators) while focusing on the most important factors (Ernst, 2003).

The x-axis represents the patent intensity (patenting activity in a certain technology field per GDP (ppp)). This allows to identify a country's specialization and if there is a lot of effort put into patenting of a certain technology. The y-axis describes the patent growth rate of patents of recent years in relation to preceding years (patent growth) (see Table 6). Bubbles size represents the relative R&D emphasis of a country related to a single technology (national technology share).

Results and Discussion

First we provide a general analysis of country specific data to provide an overview and first insights for each technological domain.The following results for the TLC and patent portfoliosare structured in the same way for all three technology domains, representing use cases for the patent analysis tool. The TLC for each is analyzed in a first step to better understand the current development status of each technology.

Table 6
Used patent indicators for R&D assessment in different countries (inspired by (Lee and Lee, 2013), (Ernst, 2003), (Ernst, 1997), (World Intellectual Property Organization 2017))

Patent indicator	Definition	Meaning	Comment
Patent activity	Sum of patents for technology in a country over a period of time	Proxy for national R&D expenditures in a technology in a global context	Based on applicants country of residence
International scope	Size of patent family	Economic quality of a country's total patent activity and international orientation	Patents with the same family ID/ simple patent families in the EPO
Technology life cycle	Sum of yearly patents and shape of approximated TLC (4^{th}-degree polynomial regression)	Level of technology development within TLC, estimation of further development	Based on the total number of yearly published patents
National technology share (NTS)	Number of patents of a technology in relation to all national patents	Relevance of national R&D activities of a certain technology field in the national context	$NTS = \frac{P_i}{P_a}$
Patent growth (Pg)	Patent growth rate in % of a technology for a defined time period (considering all types of patents)	Growth potential of the technology	$Pg = \frac{P_{i,t}}{P_{i,\ t-1}}$
Patent intensity (Pint)	Number of patents of a technology of a country in relation to its GDP (PPP)	R&D efforts of a country with regard to its economic potential	$Pint = \frac{P_{i,t}}{GDP_{PPP}}$

Specific patents=Pi; Total national patents=PA

[10] There are empirical studies that show a positive lagged relationship between patent growth and changes in markets (Ernst, 2003), (Ernst, 1997).

[11] Several patent applications in different jurisdictions are related to cost for registration, examination, etc. An inventor might thus face high costs in case of patenting in several countries in order to protect his patent. Thus, patenting in several countries indicates that inventors expect a higher revenue from their patent (Lanzi et al., 2011).

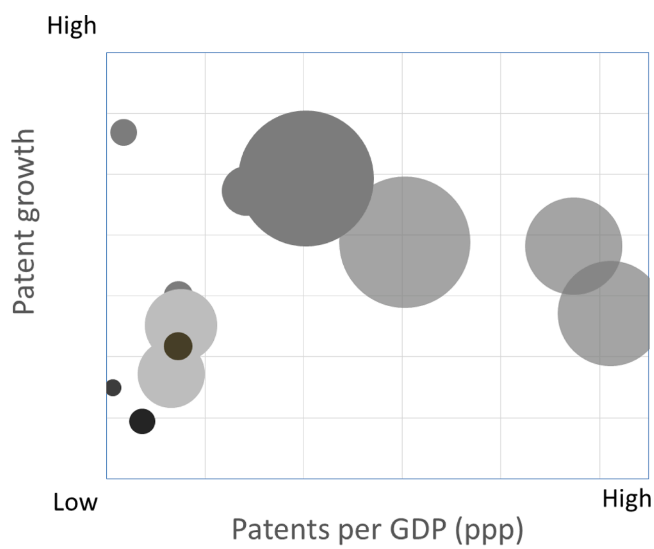

Fig. 5. Scheme of the conducted portfolio analyzes based on Ernst 1998 (Ernst, 1998)

After this, relevant single patent indicators are provided to determine the countries technology scope (e.g. national or international orientation) followed by the patent portfolio analysis. Based on this we aim to derive potential implications relating to the innovation potential of each technology.

A comparison of patent activity for the three considered technologies is given in Fig. 6. Here the five most active countries besides Germany are identified for the period 1995-2018, remaining countries are labeled as Rest of the World (RoW). It can be seen that in the case of AWE and Li-Ion batteries Japan (JP) is the most active country in the last twenty years. Several other countries amongst them Germany (DE) are also highly active in the field of electrochemical technologies. The Bioenergy use case is different as China (CN) is the most active country, followed by the United States (US), Japan and Germany. Other countries patenting in the thermochemical conversion of biomass are Australia (AU) and Great Britain (GB). The RoW share on patenting is also provided in Fig. 6 and shows that there is considerable activity besides the analyzed countries.

It has to be considered that a country's patenting potential is dependent – among other factors – on its economic growth, population size as well as development status in general. The results on hand should thus be related to these more general statistic data in order to gather a better understanding of country's patent intensity (World Intellectual Property Organization 2017) and to estimate the importance of each nation's R&D activities in the three fields of technology relative to the importance in other countries. The number of total patents related in the identified countries is given in Fig. 7. Patent intensity, (P/GDP (PPP)) is described by the total annual average number of published patents (TP) in the periods 2013-2015 and 2016-2018. The choice of two periods allows gathering a better picture of overall developments. It can be observed that Germany has a very high patent intensity, followed by Japan, Korea, France, and Australia.

At the same time, the results show that there are different developments observable in the magnitude of new patent applications between these two time periods. For most of the analyzed countries, only a small increase in both, patent activity and patent intensity is identified. However, for China a high increase of 35% for patent intensity and 42% for total patents is shown in Fig. 7. For Japan and Australia, a negative and stagnating trend can be observed for patent intensity (-3%, in JP, 0% in AU).

Domain and use case 1: Li-Ion battery storage

Patenting in the field of Li-Ion batteries has been continuously growing on a global level since 1995 (cf. Fig 8). After an emerging phase (I), a consolidation phase (II) took place around 2001 to 2010 (see Fig. 8, small graph with corresponding time frame). Both innovation phases are strongly characterized by national patenting efforts where already an increasing share of priority patents and a corresponding size of families can be noted. The maximum patenting activity takes place in 2016. Here the share of priority and family patents increased significantly. This increasing share indicates a technology transfer from an inventor country into other receiving countries, which will be analyzed in detail later on. The entire timespan represents a strong market penetration phase (III), where Li-Ion batteries became one of the most used technologies for portable devices like mobile phones or notebooks and electric transportation recently. Nowadays, it seems that Li-Ion technologies enter into a saturation phase (IV), wherein patent applications are decreasing slightly. The results for 2018 are object to changes as patent publications at EPO can take up to 18 months. Thus, there is a high possibility that there are some patents missing in our analysis for these years as indicated in Fig. 8.

An overview of total patent applications for Li-Ion batteries per country for the same period is given in Fig. 9 a, whilst Fig. 9 b provides an overview of the types of patents. As explained before, fractional counting is applied to give each country a "share" of a patent in the case of multiple nationalities of applicants and to avoid double counting. Japan dominates in terms of patent applications until today, where it also pioneered research in 1990 through its "New Sunshine Program", which was initialized by the Agency of Industrial Science and Technology and MITI (Ishikawa, 1999). It was finally Sony that managed to improve the work of John B. Goodenough, who proved the suitability of $LiCoO_2$ as positive active material (Stadler, 2014). The combination of this electrode with a carbon-based negative electrode made it possible to produce first rechargeable Li-Ion cells for mass markets. China and South Korea have been increasing their activities steadily since 2005 with a sharp increase since 2010 in the case of China. There is a clear dominance of Eastern Asia in the entire field in relation to western countries, which is in line with the results from Mueller et al. (2015). US activities in the field remain steady whilst France and Germany temporarily increased their activities in 2010-2014. Most patents in Germany are based on Bosch, which decided to stop its activities in the field of cell manufacturing (Cremer, 2018) in 2018 leading to a decrease of national German patent activities. It can also be recognized that the share of national patents is the highest for most countries, followed by family members and finally priority patents. This constellation is not surprising as most inventors tend to patent first in their home country (Lanzi et al., 2011). However, this is not always the case; the US, for example, has almost as much national patents as priority patents. Furthermore, the amount of patent family members (253 Patents) is the highest among all patents here. There seems to be a high interest in protecting US inventions in different markets (see Fig. 9 b) due to a very strong international focus. This development can also be observed in China's case, where a high international focus can be identified. Fig. 9 b provides an overview of the value of the patents of inventions stemming from a certain country. In general, the results shown in Fig. 9 correspond to the finding recently published in (Gregori et al., 2020), though with different numbers for e.g. South Korea. This can be explained by different search methods and terms, which will be discussed later on.

It is important to highlight that actual market positions are not directly reflected in the analysis, which is also in line with (Gregori et al., 2020). The global cell production capacity in 2018 was about 292 GWh. From this capacity, about 51% were provided by China, 1% by the EU, 15% by NAFTA, 9% by Japan and 24% by south Korea (installed cell production by supplier origin) (Bernhardt et al., 2019). Interestingly, Japan's patent dominance in the field of batteries has not been translated into market shares (Gregori et al., 2020).

In the following, a patent portfolio analyzes is conducted. Here all types of patents – national, priority, and family members - are included in the analysis depicted in Fig. 10. A detailed explanation of the portfolio

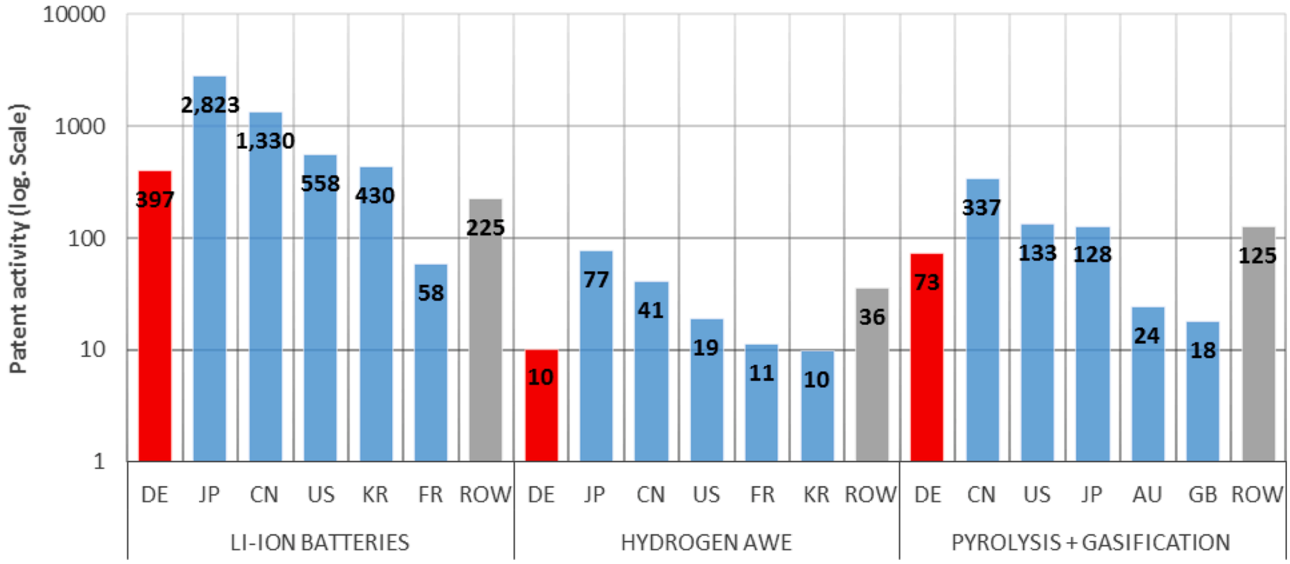

Fig. 6. Patent activity of the five most relevant countries and rest of the World (RoW in grey) related to the three use cases (Batteries, Hydrogen, Bioenergy) in comparison to the reference case Germany (in red) from 1995 to 2018, logarithmic scale (data from (European Patent Office, 2017), retrieved in 2019).

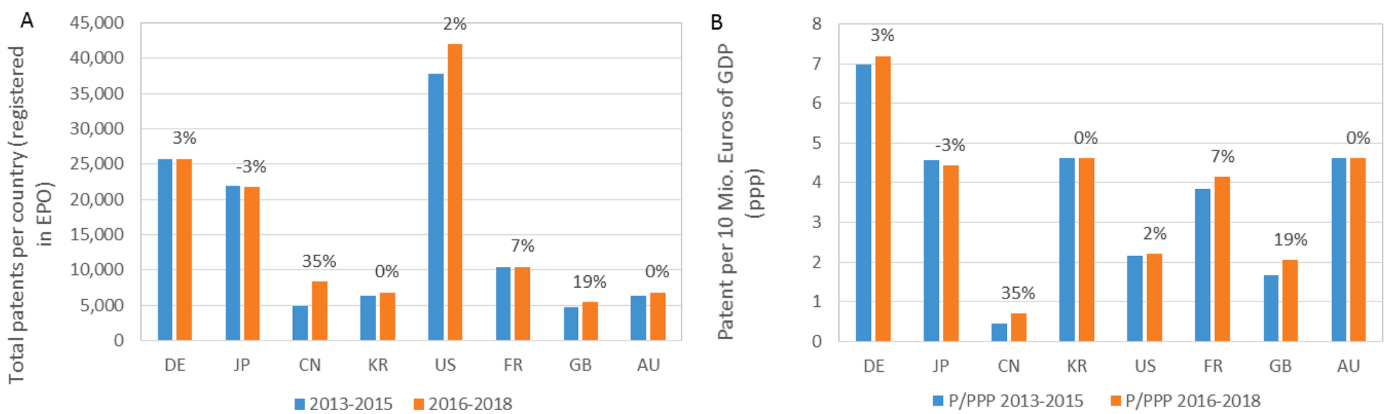

Fig. 7. A) Total number of patents per considered country (blue and orange bars), change in total number of patents (in %); and B) General patent intensity per considered country using the first-named applicant's country of residence and GDP (PPP) (current international $) considering EPO applications (based on (European Patent Office, 2017) and (The World Bank, 2019) in 2019) (blue and orange bars), change in patent intensity (in %),.

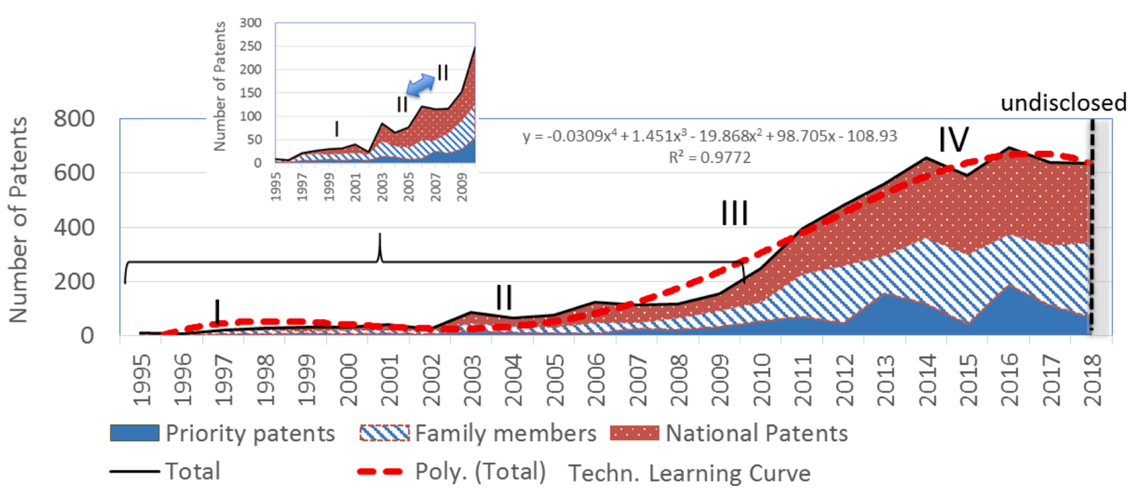

Fig. 8. TLC for Li-Ion batteries based on the published number of all patents (including RoW)

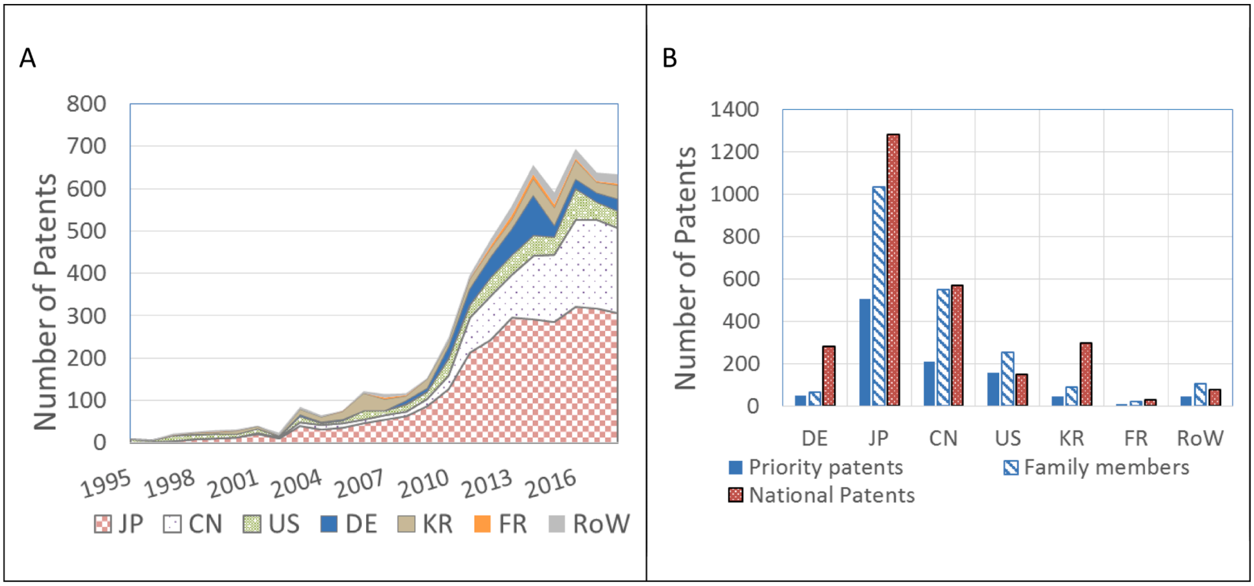

Fig. 9. a) Patent activity of different countries analyzed for Li-Ion batteries b) Share of priority patents, family members and simple patents (residential/national patents) per inventor home country for Li-Ion batteries (1995-2018).

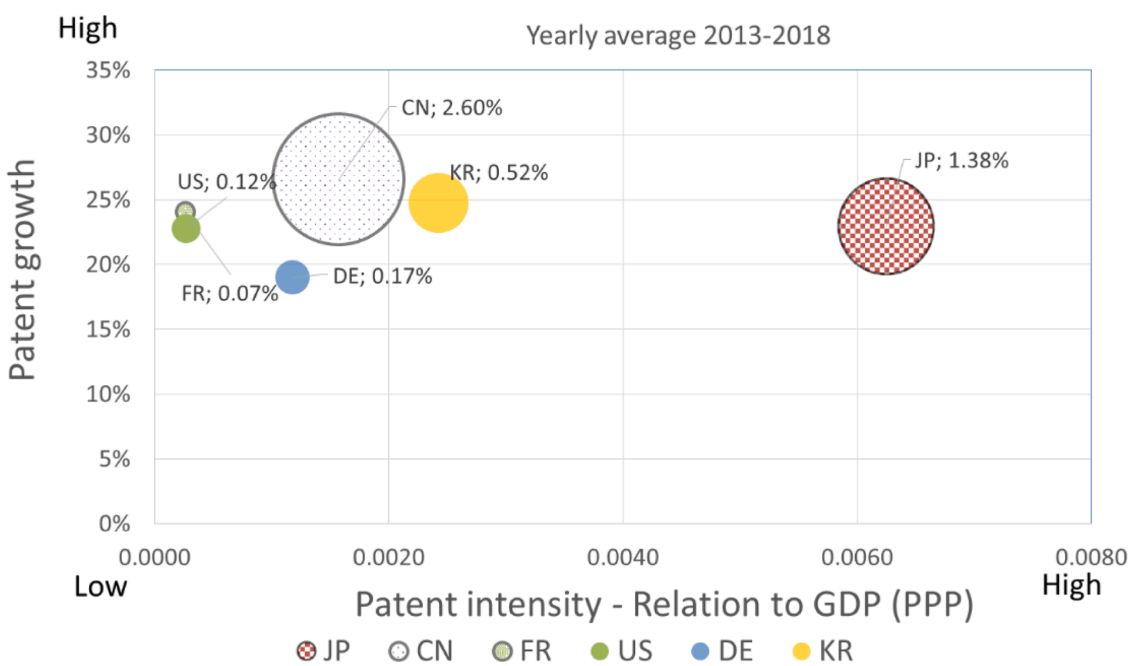

Fig. 10. Patent portfolio to determine R&D orientation and technology share of different countries for Li-Ion batteries. The percentages behind each country abbreviation refer to the technology's share in the national total patent activities (also depicted by the bubble size).

analysis is given in section 3.3. It can be seen that Japan and Korea have a high patent intensity (= patent activity in relation to their GDP (PPP) (x-axis)) as well as a high relevance of Li-Ion batteries in the total national patenting activity (bubble size), which indicates a strong specialization of both countries in this field. China is attributing a high effort into field in combination with a high patent growth (y-axis), which seems to correlate with its expected dominance on the battery market in the coming years. These three Asian countries are in a strong competition for the domination of the field. The US, Germany and France have reduced their patent efforts in the field and might face the danger to be left behind in terms of patenting if no actions are undertaken in the near future.

There are considerable activities in the field of Li-Ion battery manufacturing taking place in France, the US and Germany nowadays. In Germany VW announced their attempt to build up a cell factory in Lower Saxony (Manthey, 2019). The same comes true for the French-German consortium of PSA, Opel and Saft battery to build up new cell production capacities (Hampel, 2019). Tesla is the most prominent example of new cell production capacities (TESLA, 2017). Also CATL announced a factors in Erfurt. However, the latter two are companies of non-German origin. Europe, and in consequence, Germany still face significant market entry barriers in regards to technology and process knowhow (Bernhardt et al., 2019). The market is expected to be led by Asian companies, which is strongly reflected in the portfolio analysis. It is difficult to foresee how these developments might impact the patenting landscape in years to come, but it can be expected that this will lead to more patent applications in the mid-term. In addition, it would be very interesting for future research, to analyze how patenting is developing regarding emerging post-lithium technologies as e.g. Magnesium and Sodium-Ion batteries.

Domain and use case 2: Hydrogen production by alkaline water electrolysis (AWE)

Although it is not expected that all patents filed in 2018 have been added to the database, the number of patents in 2018 is still growing for alkaline water electrolyzers compared to the earlier years, Fig. 11. According to the theory about TLCs (section 3.2) this indicates that this type of electrolyzers is still in its market penetration phase (III) and a saturation of the market is not reached, yet. The market penetration has started around 2012, indicated by a sharp increase in worldwide patent activity. Before that ups and downs in patent activity can be observed with peaks in 1998, 2005 and 2010. Due to the small number of issued patents, however, it cannot be concluded if several hype cycles (phase I+II) took place or not. One has to be careful with predictions, a sharp increase in patent activity could also be part of another hype cycle. For example, Chen et al. (2011) (Chen et al., 2011) expected that hydrogen generation would reach maturity in 2012 based on the TLC curve. Another interesting aspect about the TLC is that since 2015 only the number of family member patents increases. The number of filed national and priority patents stays more or less constant.

The type of patents is closely related to a country's strategy regarding patenting (Fig. 12 b). Japan has filed over the last twenty-five years significantly more family member patens than national patents or priority patents. In China, South Korea and Germany, in contrast, national patents predominate. Japan is not only for Li-Ion batteries the country with the most filed patents but also for alkaline water electrolysis (Fig. 12 a). This technology also gained from the money put into technology development for renewable energies by the New Sunshine Programme. Over the last years, however, China developed a growing interest in patenting. In 2014, even more patents from China were filed than from Japan. These patents, however, are mainly national patents that only apply for China. Some countries not even see the need to patent their technology development. Hekkert et al. 2005 (Hekkert et al., 2005) have shown that there is a growing number of R&D projects regarding hydrogen storage in Germany, but the number of filed patents has not increased accordingly.

A good overview of the position of the most important countries towards each other gives the portfolio analysis for the years 2013 until 2018 (Fig. 13). The outstanding position of Japan is underlined with this analysis. Japan filed a high number of patents also with regard to their PPP and showed a high patent growth. Only Germany has a higher growth rate. However, this is only because Germany had not filed any patents in the five years before 2013. The importance of technology in the country is depicted by the bubble size. Compared to the overall number of filed patents in particular Germany and the US fall short, whereas China has a great interest in this technology. Compared to the Asian countries Japan, South Korea and China, in Germany this electrolyzer technology is much less described by patents than other technologies (cv. Fig. 13). Furthermore, compared to its PPP in Germany are much less patents filed than in these countries. However, Germany is very active in pilot projects regarding electrolytic hydrogen production (Faba et al., 2015). In contrast, a market overview of technology developers for water electrolyzers in 2017 (Smolinka, 2017) has shown that alkaline electrolyzers are not developed in Germany, but other technologies for water electrolysis.

Similar to the situation with Li-ion battery systems, the high patent activity does not reflect the share of Japanese companies in the global electrolyzer market. Two out of the three largest electrolyzer manufacturing companies (based on revenues) are situated in the US, i. e. Proton onsite 15.6 % share of revenue in electolzer market and Teledyne Energy Systems 8.1 %, and the third company in the top three is situated in China, i.e. PERIC with a share of 14.2 % (MarketWatch, 2020).

Domain and use case 3: Thermochemical conversion of biomass

Patenting in the field of pyrolysis and gasification of lignocellulose has been growing since 1995 (cf. Fig. 14). The course of the total number of patents shows several ups and downs (e.g. peak in 2007 and 2009, decreasing number of patents from 2009 until 2012). From 2012 until 2015 total patents are increasing again, from 2015 until 2017 a slight decrease in total patents can be observed. According to the theory about TLCs (section 3.2) one could interpret that after an emerging phase (I) a consolidation phase (II) took place from 2009 until 2012 and that the technology entered a market penetration phase (III) in 2012. One could also interpret that this technology entered into a saturation phase (IV) after 2015, wherein patent applications are decreasing. As there have been several ups and downs of the total patent curve over the years, caution is advised when interpreting the results though. With the revised version of the Renewable Energies Directive of the European Parliament and of the Council adopted in December 2018 (RED II for short), the EU introduces the political framework for the use of renewable energy sources in the transportation sector for the time period from 2021 to 2030 (MarketWatch, 2018). This framework includes a minimum share of renewable energy sources in transportation of 14 %, including a minimum share of 3.5 % from advanced biofuels, i.e. biofuels obtained from lignocellulosic biomass using e.g. pyrolysis and/or gasification, by 2030. At least for Europe, this should drive research and development as well as patenting towards commercialization. Additionally, in (MarketWatch, 2020) forecasts for the period 2020-2027 concerning global biomass markets are carried out as well as analysis of the latest industry

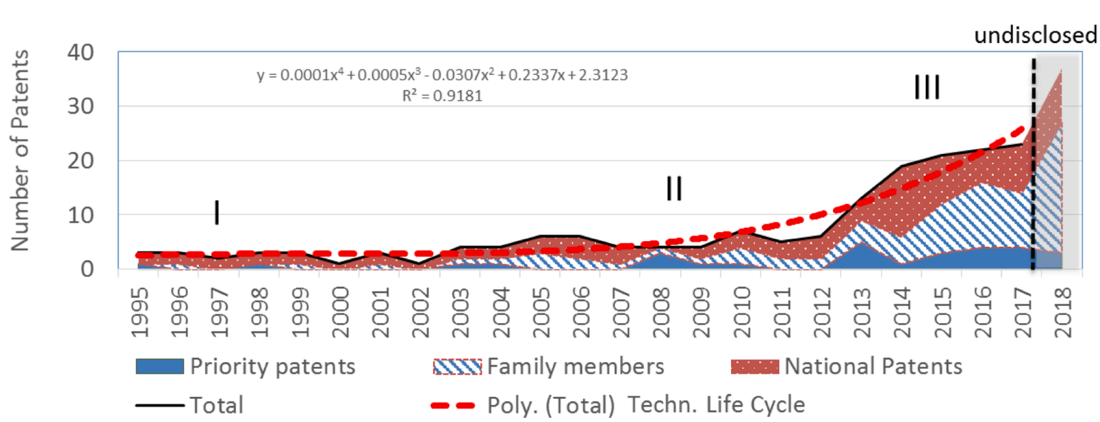

Fig. 11. TLC for alkaline water electrolyzers based on the published number of patents.

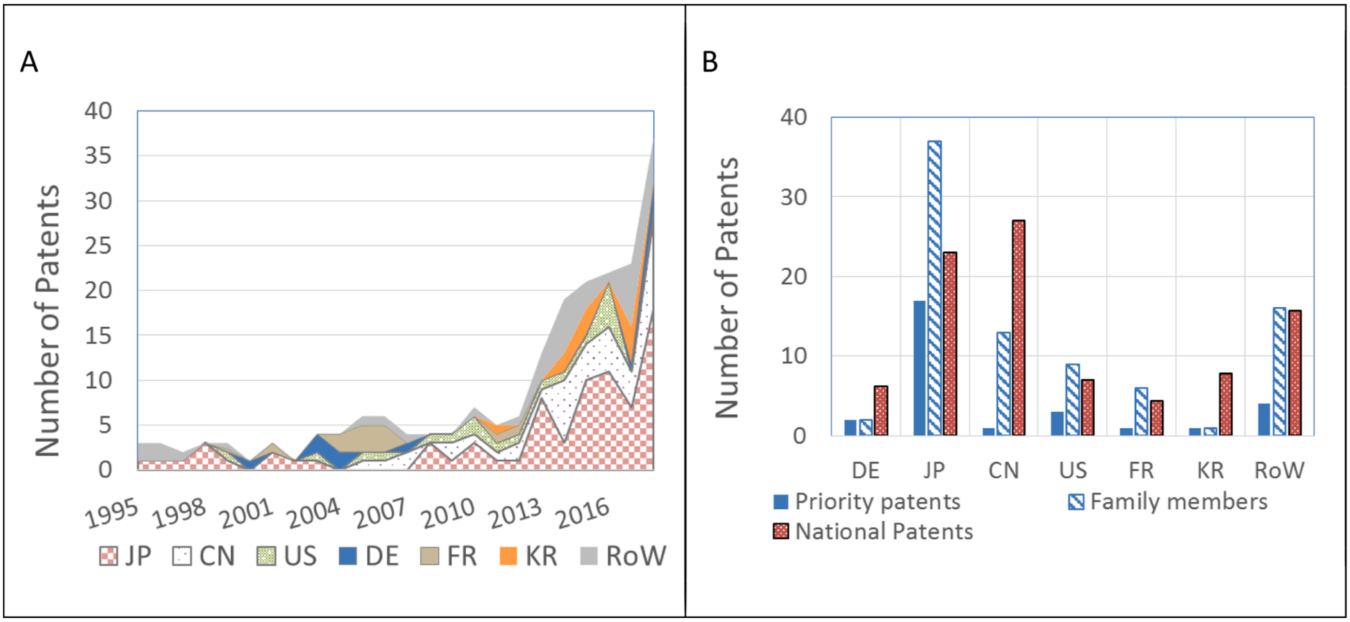

Fig. 12. a) Patent activity of different countries analyzed; b) Share of priority patents, family members and simple patents (residential/national patents) per inventor home country, both for alkaline water electrolyzers (1995-2018).

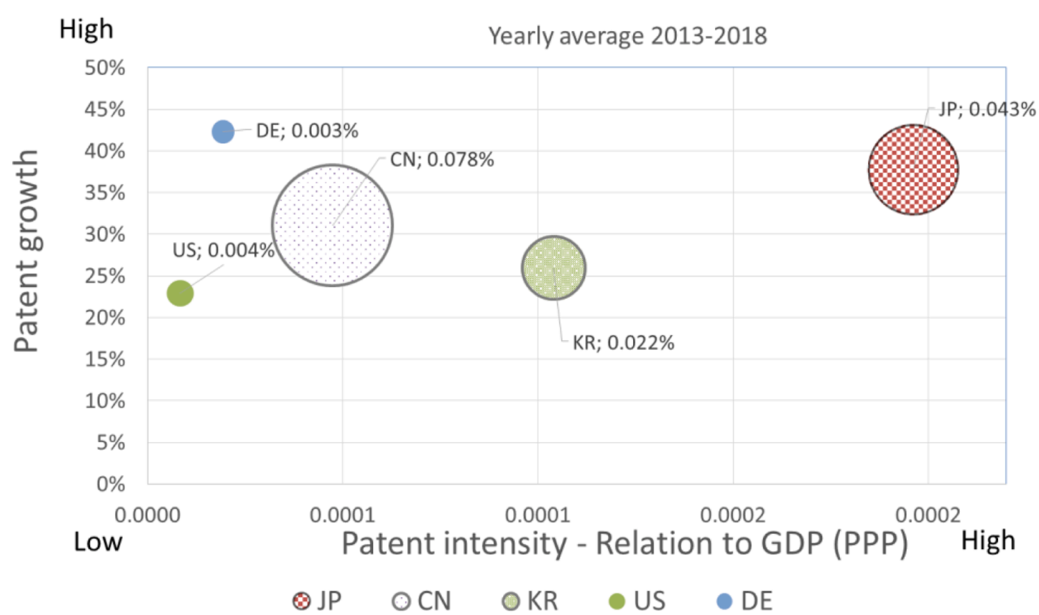

Fig. 13. Patent portfolio to determine R&D orientation and technology share of different countries for alkaline water electrolysis. The percentages behind each country's abbreviation refer to the technology's share in the national total patent activities (also depicted by the bubble size).

trends. Amongst the three biomass technology segments (combustion, anaerobic digestion, gasification), the gasification segment is anticipated to attain the fastest growth rate over the forecast period owing to the high operational efficiency of the process. It is therefore likely, that the technology is in phase III (market penetration) of the TLC rather than in phase IV (saturation). From 2001 on, an increasing share of family members can be observed. This indicates a technology transfer from an inventor country into other receiving countries, which will be analyzed in detail later on. In Köhler et al. (2014) (Köhler et al., 2014) patent search is carried out for second generation biofuels for aviation using the PATSTAT database (European Patents - EP and World Patents - WO). They state that beginning in 2001, the number of worldwide patents filed continuously increased. When comparing the periods 1995-1999 and 2004-2008, all countries with a relatively large number of patents (e.g. US, Japan, Germany, France) show a large increase between the two periods (cf. Köhler et al., 2014) (Köhler et al., 2014). Toivanen and Novotny (2017) (Toivanen and Novotny, 2017) state that annual patenting of lignocellulosic biofuels increased about eightfold between 2002 and 2015. They also state that this can be interpreted as significant and as an intensified technological and economic interest in this technology. In Madvar et al. (2019) (Dehghani Madvar et al., 2019), the technology trends of various biofuel technologies, amongst others bio-pyrolysis, are plotted until 2016. According to Madvar et al. (2019) (Dehghani Madvar et al., 2019), patent publications are declining from the year 2015 on. This is in line with our results for the thermochemical conversion of biomass (pyrolysis + gasification). For technology forecasting, Madvar et al. (2019) (Dehghani Madvar et al., 2019) carried out S-curve analysis (as logistic plots) and their results indicate, that

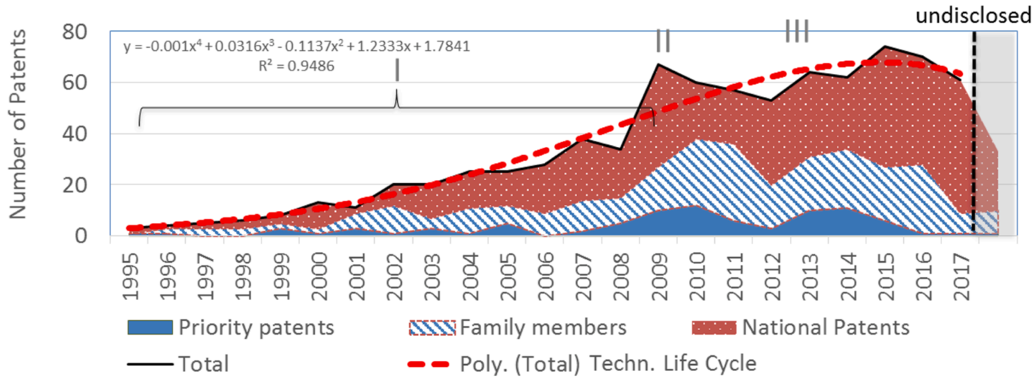

Fig. 14. TLC for pyrolysis + gasification of lignocellulose based on the published number of patents.

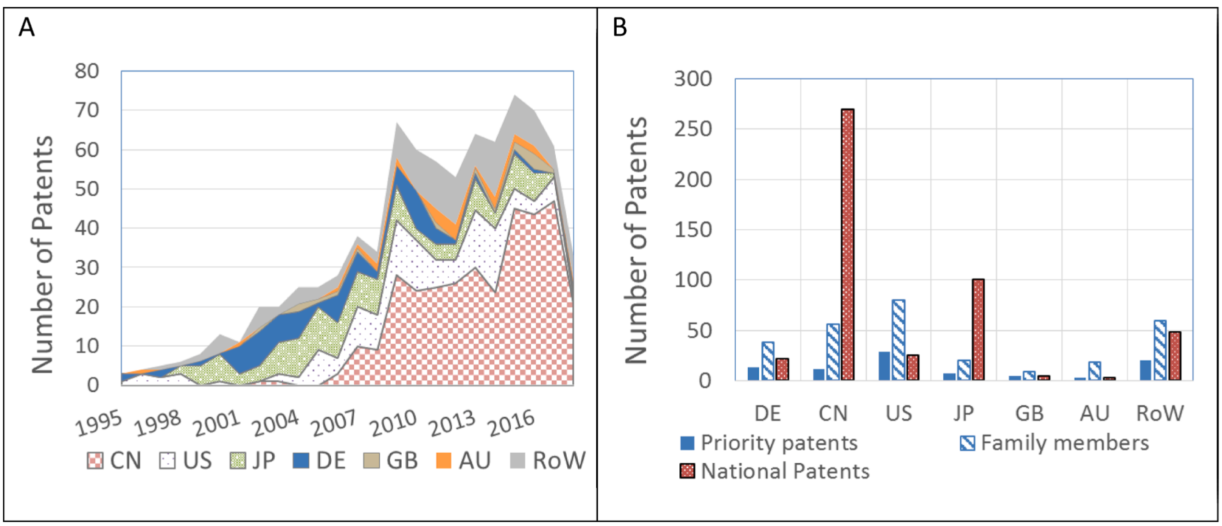

Fig. 15. a) Patent activity of different countries analyzed for pyrolysis + gasification b) Share of priority patents, family members and simple patents (residential/ national patents) per inventor home country for pyrolysis + gasification (1995-2018).

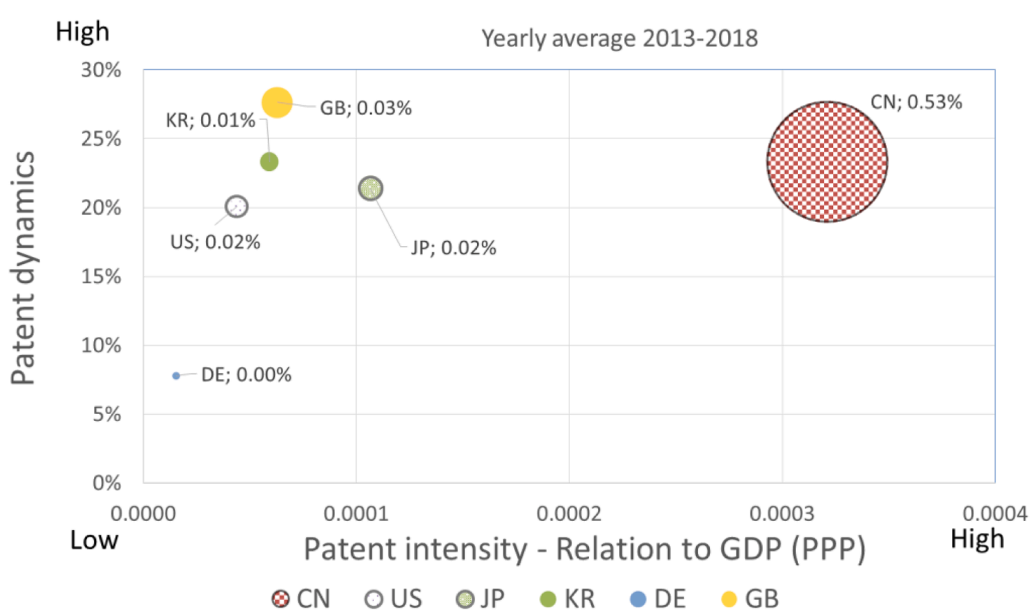

Fig. 16. Patent portfolio to determine R&D orientation and technology share of different countries for pyrolysis + gasification of biomass. The percentages behind each country abbreviation refer to the technology's share in the national total patent activities (also depicted by the bubble size).

bio-pyrolysis technologies are still in the growth stage.

An overview of total patent applications for pyrolysis + gasification per country is given in Fig. 15 a, whilst Fig. 15 b provides an overview of the types of patents for the years 1995-2018. China dominates from around 2010 on (Fig. 15a). Before 2007, Japan and Germany dominated. From 2004 on, US patent activity has increased steadily. After 2013, German patenting almost stopped (Fig. 15 a). It can also be recognized that for China and Japan, the share of simple patents is the highest, while for Germany, family members have the highest share (Fig. 15 b). There seems to be a high interest in protecting German inventions in different markets due to a strong international focus. The same applies to US patents. The comparison of the number of priority patents, family members, and national patents of different countries (Fig. 15 b) allows an estimation of the value of the patents of inventions stemming from a certain country: the high number of family members compared to the number of priority patents suggests a high value of German patents.

In Fig. 16, the results of the patent portfolio analyzes for the most recent years (2013 – 2018) are presented, including all types of patents. It can be seen that China has a big advantage regarding patent activity in relation to its GDP (PPP) (x-axis). China also shows the highest national technology share, i.e. R&D emphasis (bubble size) for biomass pyrolysis + gasification compared with the total national patent activity, while patent growth for 2013-2018 is highest in GB (y-axis). Since after 2013 German patenting almost stopped in this technology field (Fig. 15 a), the bubble for Germany can be found in the lower-left area of the diagram with a very small bubble size. Advanced biofuel technologies are currently in the pilot/demonstration stage of the innovation process. Köhler et al., 2014 (Köhler et al., 2014) argue that technological capability of a country can, therefore, be assessed through both pilot/demonstration process plants and patent data of a certain country. Likewise, Palage et al., 2019 (Palage et al., 2019) use patent counts as a proxy for innovation and accentuate on the context of pilot and demonstration plants for 2nd generation biofuels and technology innovations. Looking at the summary given in Köhler et al. (2014), there are no demonstration and pilot activities for 2nd generation biofuels in China. The highest number (21) is given for the US, followed by Brazil (six) and Germany (five). It has to be noted that this list includes not only process plants for thermochemical conversion of lignocellulosic biomass but also for the production of biofuels from vegetable oils produced from sources that do not directly compete with crops for high-quality land (e.g. Jatropha).

Major trends among the selected technology domains

The results show that there has been a strong growth for the three considered technologies on a global level. Especially the case of Li-Ion batteries has been growing strongly, which comes true for energy storage in general (Gregori et al., 2020). Interestingly, the three use cases have shown that national R&D foci vary and are highly dependent on the illustrated technology. This also comes true for the patenting strategy (e.g., national patenting vs. international patenting activities). Despite its role as blueprint for energy transitions in other countries, Germany patent activity is lower in comparison to other countries as Japan, China, South Korea, and the US. In more detail, patenting landscapes for batteries and hydrogen are comparable regarding the lagging position of Germany in relation to the other countries. Germany has gained some momentum in patent activity for the AWE. The situation for thermochemical conversion of biomass is slightly different, where Germany has a rather low patenting activity in combination with a low share of patents related to its, overall strong total patenting activity.

The technology life cycle perspective allows to qualitatively derive if a technology can already be considered as mature (e.g. as it entered a saturation phase) or as emerging (e.g. in a hype cycle phase). The latter can be seen as a phase where more patents are generated that might precipitate into an innovation. Our analysis suggests that Li-Ion battery systems are considered to be a mature technology, whereas the thermochemical conversion is potentially in a market penetration phase and AWE and potentially entering a market penetration phase. The effort for countries to catch up in areas where market penetration phase takes place is considered easier in relation to a mature technology where a set of established companies is already existing (as in the case of Li-Ion batteries) (Bernhardt et al., 2019). Our analysis indicates, that there already is an international competition in the three technological areas. Here, literature suggests market pull strategies to favor well-positioned countries (more correctly, its corresponding companies or research centers) situated in a different country as e.g., for Li-Ion batteries where Chinese or Korean manufacturers invest in Germany. Whilst other literature suggests technology push initiatives to also enable new companies (Mueller et al., 2015). The second perspective is particularly important when considering current developments in the EU to promote battery production in the case of Li-Ion batteries and AWE technologies. There is, in terms of patents, an absence of German companies in both areas and it is crucial to consider such demand-pull vs. technology push support activities that might merge into a potential “innovation”. A more detailed assessment about the implications of both strategies for similar relevant technologies for a clean energy transition as e.g. photovoltaics is provided in (Peters et al., 2012).

Critical reflection and avenues for future research

There are several restrictions associated with patent analysis, which have already been introduced briefly in section 2. In this section, major implications regarding our analysis and its limitations are discussed. It is worth mentioning that these limitations not only apply to this research but in general for any kind of assessment including patents.

Methodological challenges

The collected number of patents for each technology differs strongly. Over 5,822 patents could be found for the Li-Ion battery case. A large amount of data for this use case allows it to derive the TLC in a relatively robust way. In contrary, only 204 and 841 patents are available for the hydrogen production by alkaline water electrolysis and the thermochemical conversion of biomass, respectively, making it challenging to determine the actual status of both technologies related to a TLC. Furthermore, the number of collected patents highly depends on the formulation of adequate search terms, which has been addressed in section 3.4. This argument can be underpinned by the experiences collected in the frame of the patent analysis for the three use cases in this paper. The results have to be seen in the context of the named search combination in Table 5. Already minor changes as e.g. changing the title based keyword search into a title and abstract based keyword search can result in a delta of 2000 hits in e.g. the case of batteries. It is also worth mentioning that there are some differences observable for the case of Li-Ion batteries when compared to the recent results published in (Gregori et al., 2020), which stem from different search terms. Nevertheless, the trends of (Gregori et al., 2020) are close to those stated here in the corresponding portfolio graph. This high sensitivity to changing search terms is also observable for the alkaline water electrolysis and the thermochemical conversion of biomass. However, also with these different magnitudes of patents related to the three different use cases presented here, it can be said that patenting activities have been growing for all thre technologies.

It is important to mention that there are different ways of allocating a patent to a certain geographic region (e.g., by the applicants, country of priority filling, or the inventors residence). Some literature uses the inventors country of residence, e.g. (Lindman and Söderholm, 2016), (Lanzi et al., 2011), while others use the first applicants address (Abbas et al., 2020) or even both (Albino et al., 2014). It is even possible to carry out the patent count by priority office. This allows deriving of how attractive a countries patenting process is (in terms of rules, cost and size of the market). Using these different ways of allocation can lead to very different results (eurostat, 2009). In any case, the choice of which way of allocation should be selected depends on the analysis's aim. The OECD manual on statistics states in this regard, e.g., that. (eurostat, 2009);

> "if the aim is to measure the inventive performance of countries, then the criterion for calculating the indicator ought to be the *inventor*'s country of residence, whereas if the aim is to measure ownership of inventions, then applicant's country of residence is the most appropriate criterion."

However, Eurostat states that using the applicant's country of residence leads to an allocation problem for institutions with several sites in various regions. This stems from the circumstance that a patent application is usually filled in through a headquarter, which leads to the problem that these regions are then overestimated. Using the inventor's address of residence avoids this. Nevertheless, some underestimation of the regional potential of innovation is still possible, as not every inventor will register his address, but rather the address of the enterprise or institution where they are affiliated to (eurostat, 2017).

In this analysis, the approach recommended by Eurostat is applied, and the country of residence of applicants is selected only when no inventor related data was available. If neither the inventor data nor the applicant's data is available, the office of priority filling is selected. The software tool provided with this study offers the possibility to select these different ways of patent allocation.

Differences in patent value

The position of China is very strong for the considered technology use cases, why a closer look is taken on this particular country using most recent literature. Total Chinese patent applications have grown 38 fold since 2000 until 2015 (increasing its R&D expenditure by 132.5%). Applications by the US have doubled whilst Japanese patents decreased in the same time period (Fisch et al., 2017). This represents an impressive growth rate of Chinese patents but also may lead to the question of how valuable Chinese patents are in comparison to e.g. US or German patents. The work of Fisch et al. (2017) (Fisch et al., 2017) analyzed the citation lag to evaluate the value of Chinese patents. Such a citation lag represents the elapsed time between patent application and the first forward citation it receives. There is a big citation lag related to Chinese patents when compared to the patent value of other countries. Fisch et al. (2017) (Fisch et al., 2017) also point out that this comes, in particular, true for national patents (domestic patents filed out in China by Chinese). Liu et al. (2014) (Liu et al., 2014) underpin this argument by showing that the number of patent examiners has not been increased so much in relation to patent applications. The authors suggest that this results in an increase of examiners workload and might lead to the situation that the examination process is not as thorough as in other countries. However, it is also reported that Chinese patent value has been increasing recently (Fisch et al., 2017). These implications should be considered when comparing the different countries and interpreting the results. In any case, more research is required to give deeper insights into the value of corresponding patents.

Recommendations and avenues for future research

In this section, some principal methodological and "operative" recommendations are provided based on the challenges and used literature identified in frame of this assessment. These recommendations can help to facilitate the process of patent analysis for less experienced scholars. Naturally, some recommendations might be overlapping with each other in some cases.

- Beyond well defined and validated keywords, search strings need to be checked for robustness. It is crucial to also take a closer look at the titles and abstracts of the collected patents to see if these fit into the search. A good overview of how to conduct patent research is provided by (Clarke, 2018).
- It is crucial to adequately select how to geographically allocate patents (assignees vs. inventor vs. priority country). This is dependent on the aim of a particular assessment and should be reasoned accordingly. A good overview of different ways of patent allocation is provided in (eurostat, 2017), (eurostat, 2009).
- Own results should be, as far as possible, be sharply contrasted to other literature to i) validate own results and, ii) to be able to reflect own results critical by, e.g., referring to market developments as it was done here.
- The patent value (quality) should be addressed for country-specific comparisons due to differences in national patent systems as pointed out in (Fisch et al., 2017). Otherwise, one might get a wrong picture of the overall development.
- Patent activity also has to be seen in a wider context before drawing a conclusion about the development trends of a technology by e.g., contrasting is to historical events, environmental laws or private sector initiatives as described in (Albino et al., 2014).
- Future research has to include innovation indicators as patents obtained per unit of R&D or the propensity to patent R&D trends to estimate particular technology innovation potentials within a specific country. Some helpful literature has been presented in chapter 2 as e.g., (Scherer, 1983) and (Arundel and Kabla, 1998).

Conclusion

Our study offers an overview of current trends in patenting for three selected energy conversion technologies (lithium-based battery systems, thermochemical conversion of biomass as well as hydrogen production via alkaline water electrolysis) for the energy transition. Different patent indicators, with Germany as a reference country, are used to provide insights into the technological maturity and countries positioning. Patenting activity for all three technologies has been increasing considerably on a global level in the context of the global energy transformation. There are several ongoing "energy transitions" in many countries with distinct strategies, which are reflected to a certain degree in patenting activities. Germany, often named as a reference for an energy transition, showed in this assessment a lower patenting activity in relation to other countries like Japan, China or the US in the named areas. In line with literature, it has been shown that patenting activities have not been translated into market as e.g. in the case of Japan for Li-ion batteries and AWE, which might also come true for Germany. It is suggested that both, knowledge generation, more demonstration projects and investments related to the manufacturing are required to spur the development of named technologies, as it is currently happening in Germany to a certain extend. However, up to now, it appears that knowledge property (and manufacturing capacities) is left to non-European countries. This is also in line with the reviewed literature for e.g. thermal energy storage (Abbas et al., 2020) or in a more general way alternative generation technologies (Albino et al., 2014).

In any case, it is crucial to develop complementary low to zero carbon technologies to achieve a clean energy transition and not only look at certain technological paths. It is important to remain open to all solutions as they have each their distinct advantages and drawbacks. Li-ion batteries need to overcome some hurdles related to mobility (e.g. charging times, recycling etc.), where other power train solutions as fuel cells (Bernhardt et al., 2019) (with AWE being crucial for hydrogen supply) or internal combustion engines using biofuels to a certain degree avoid these problems. Another example is related to stationary energy storage, where Li-Ion batteries and AWE can provide complementary services coming from short-term to long-term seasonal storage services.

However, the methodology and software tool presented in this study can serve as a blueprint for further and finer grained assessments in different technology areas to gather a fast and comprehensive picture of corresponding global and national technology trends. This includes the identification of leading nations, its historical patenting activity, and strategy. Furthermore, the presented software tool (crawler and analysis tool) can be adopted for each technology assessment and is freely available[12]. The only pre-condition is an EPO developer access, which can be requested without any additional costs for free.

Author contributions

Manuel Baumann: Conceptualization, Methodology, Software, Writing - Original Draft, Investigation, Formal analysis **Tobias Domnik:** Software, Conceptualization, Methodology, Writing – Original, Draft, Formal analysis, Resources **Martina Haase:** Conceptualization, Methodology, Writing - Original Draft, Investigation, Formal analysis **Christina Wulf:** Conceptualization, Methodology, Writing - Original Draft, Investigation, Formal analysis **Philip Emmerich**: Writing - Original Draft, Conceptualization, Writing - Review & Editing **Christine Rösch:** Writing - Review & Editing, Methodology, Project administration, **Petra Zapp:** Project administration, Writing - Review & Editing, Methodology **Tobias Naegler**: Project administration, Writing - Review & Editing, Methodology **Marcel Weil:** Project administration, Writing - Review & Editing, Methodology

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Supplementary materials

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