Norwegian School of Economics
Bergen, Autumn 2024

Rethinking the Collapse in Green Innovation

An Exploratory Analysis of the Value of Innovations within Key Technologies for the Clean Energy Transition

Daniel Bømark and Thomas Bråten Stangjordet
Supervisor: Isabel Montero Hovdahl

Master thesis, Economics and Business Administration
Major: Business Analytics and Energy, Natural Resources and the Environment

NORWEGIAN SCHOOL OF ECONOMICS

Abstract

This thesis examines the collapse in green innovation by analyzing patent activity and value for LCE technologies from 1978 to 2020. Previous research has highlighted a sharp decline in patent activity for LCE technologies since 2010, often linked to reduced subsidies and referred to as the "collapse in green innovation". This thesis examines whether the value of LCE patents has also decreased alongside the decline in activity.

The analysis reveals a misalignment between patent activity and the value of innovations. While the "collapse in green innovation" is observed in patent activity, the value of these technologies remains stable. The results also indicate that public subsidies drive an increase in patent activity but have no clear impact on value. Assuming public subsidies for the energy transition are implemented to replace Fossil Fuels, the findings suggest that current subsidies may be suboptimally designed or implemented. Current subsidies seem to be more effective for emission-reduction technologies like CCUS rather than replacement technologies.

Keywords – Energy transition, green innovation, patent quality, public subsidies

Acknowledgements

This Master's thesis marks the end of our studies for our Master of Science in Economics and Business Administration at the Norwegian School of Economics. During our master's degree, we have gained a better understanding of the important role energy plays. Whether from fossil fuels or renewables, energy remains essential to nearly everything we do today. As the next generation entering the workforce, we believe that technological developments in renewable energy will be an important area in the years to come. This belief has driven our motivation for our thesis.

Our partnership has been a journey marked by intense discussions, late nights, and even a year of living together — remarkably, without a single tear shed. Throughout this experience, we have both grown professionally, pushing each other to new heights. By supporting each other when motivation faltered and genuinely celebrating each other's successes, we have built a strong and lasting friendship. It's been a rewarding journey, and for that, we are deeply grateful.

We would like to give a special thanks to our supervisor, Isabel Montero Hovdahl, for her insights into our research topic and for always being available to provide support. Her expertise in green innovation has shined through during our meetings and motivated us throughout the research process.

We also want to send our gratitude to friends, family, and especially our partners, Camilla Dyring Hansen and Emilie Sofie Apelqvist, for their support throughout our five years of studies.

Norwegian School of Economics

Bergen, December 2024

Daniel Bømark

Thomas Bråten Stangjordet

List of Abbreviations

CCUS Carbon Capture and Utilization Storage

CO2 Carbone Dioxide

CPC Cooperative Patent Classification

IEA International Energy Agency

IPC International Patent Classification

LCE Low Carbon Energy

NPL Citations Non-Patent Literature Citations

OECD Organization for Economic Cooperation and Development

R&D Research & Development

REGPAT Regional Patent

SDS Sustainable Development Scenario

PATSTAT Worldwide Patent Statistical Database

JPO Japan Patent Office

USPTO United States Patent and Trademark Office

US United States

Contents

List of Figures

List of Tables

1 Introduction

The Paris Agreement marks the start of a global commitment to reduce emissions. Global temperatures keep increasing, primarily driven by Greenhouse Gas (GHG) emissions from burning Fossil Fuels. To reduce emissions and reach climate goals, the dependency on Fossil Fuels needs to be reduced. The International Energy Agency (IEA) has identified innovation in Low Carbon Energy (LCE) technologies as an important factor in achieving the energy transition. It is being pointed out that technologies currently only in prototype or non-existent will contribute to almost 40 percent of future emission reductions (IEA, 2020).

Despite the need for innovation in LCE technologies, researchers such as Popp et al. (2020) point out a significant decline in patent activity beginning around 2010. This was measured through patent applications, a widely used indicator to measure innovation. Volumes of patents related to LCE Supply experienced rapid growth in the late 2000s. After the peak, these technologies declined rapidly and dropped to about half of their peak by 2015. This trend is often referred to as "the collapse in green innovation".

One of the most recent research on the collapse in green innovation is the paper by Acemoglu et al. (2023). It highlights how the slowdown in innovation happened at the same time as the United States (US) shale gas revolution. This new method of extracting shale gas has shown short-term benefits but may lead to a potential long-term issue for green innovation. The US shale gas revolution increased gas supply, replacing coal as the primary fuel source in the US electricity sector. The paper discusses that the availability of cheaper shale gas reduced the incentive to invest in LCE technologies, resulting in the "collapse of green innovation". To avoid ending in the "fossil-fuel trap" which shifts long-term innovation from renewables, Acemoglu et al. (2023) discusses subsidies as one key factor to reverse the effect of cheaper, but Fossil Fuel-related technology. Subsidies towards LCE technologies could create incentives for innovation towards these technologies. Although the collapse in green innovation is shown in patent application volumes, it does not necessarily mean a decline in the quality of the innovations. With this in mind, the motivation for this thesis is to analyze whether there has been a decrease in the quality of patents related to LCE technologies.

Earlier research has found that patent quality could drive innovation. The paper by Guellec (2007) discusses the importance of good patents for driving innovative incentives and technological development. It is important to look beyond patent activity to capture the innovation, like looking at the quality of each patent. Hall et al. (2004) highlights how lower patent quality contributes to market uncertainty and potentially slows down the pace of innovation. An issue discussed with lower patent quality is its impact on technological development that depends on prior technical advances, referred to as "cumulative invention". This paper also points out how increased patent application volumes could lead to a bad circle of increased low-quality patents. The increase in patent activity at an already overburdened patent office can lead to cursory examinations, further reducing the quality of patents.

To capture the quality of patent applications, Squicciarini et al. (2013) provides an overview of indicators to use in order to measure patent quality. These indicators capture the technological and economic value of the patent. This paper describes how each indicator reflects how valuable the patent is, rather than directly the quality of each patent. Building on Guellec (2007), higher value is understood to incentivize innovation and increase further technological developments.

Many papers have discussed innovation in LCE technologies by focusing on the volume of patent activity. However, few have analyzed the quality of these patents. This thesis aims to contribute to the discussion on innovation in LCE technologies by analyzing patent quality. In particular, we look into whether patent quality declined during the "collapse in green innovation", where we saw a rapid decline in patent activity.

This thesis is an analysis of patent quality in energy-related technologies during the period from 1978 to 2020. Our results are based on patent applications filed at the European Patent Office (EPO), captured in the OECD's REGPAT database. The structure of the database allows us to classify energy-related technologies, which is central to our analysis. Gentile (2024) discusses the intermittency problem by including technologies such as Solar, Wind, Enabling, and Fossil Fuel-related in her analysis. The paper argues that further development to Enabling technologies such as energy storage is important to the energy transition. Her analysis motivates the selection of energy-related technologies in this thesis, which includes LCE Supply, Enabling, and Fossil Fuels. By further classifying these into sub-technologies, we identify that the green collapse was mainly driven by Solar.

The key finding of the analysis is a misalignment between patent activity and value. The results reveal a relationship between rapid growth in patent activity that seems to affect the value negatively. This issue is supported by the findings of Hall et al. (2004) and Griliches (1990), who highlight a potential bad circle of increased patent activity with decreasing value over time. They point towards overburdened patent offices that raise the likelihood of granting low-quality patents. There is further discussed whether rapid growth in patent activity can be caused by increasing public subsidies. This is supported by Popp et al. (2020) and Johnstone et al. (2010) that highlights subsidies as a key driver for patent activity. Assuming subsidies for the energy transition are implemented to replace Fossil Fuels, Acemoglu et al. (2012, 2023) highlights the importance of their design to achieve this goal. According to this, increasing activity combined with decreasing value indicates that current subsidies are not implemented or designed optimally. Subsidies also seem to be more effective for emission-reduction innovations like CCUS rather than for replacement technologies. This indicates a need for continuous subsidies.

The thesis is structured as follows. Section 2 describes the theoretical background related to the analysis. Section 3 describes the selection of data and the methodology for classification and how values for each patent quality indicator are obtained. In section 4, we present the results from analyzing each quality indicator. In section 5, we discuss the results and connect them to the theoretical background. In section 6 we provide limitations, before finally concluding and comment on further research in section 7.

2 Theoretical Background

This section outlines the literature on the relationship between innovation and patent information. It begins by discussing the importance of technological innovation for economic development and defining innovation. Next, it examines challenges in measuring innovation and explores how patent information can serve as an indicator of innovation. Additionally, the concept of patent quality is introduced, including methods for measuring quality and how it reflects the value of the innovations.

2.1 Innovation's Effect on the Economy

Technological development has long been linked to economic growth, with multiple studies highlighting a positive connection between the two. Early works by Schumpeter (1911/2017) and Romer (1990) show how increased productivity and reduced production costs result from positive externalities. Similarly, the OECD (2015b) finds that innovation plays a role in driving productivity and economic growth. Their framework identifies various factors influencing economic growth, and while not all are directly associated with innovation, they note that innovation impacts all of them to some degree. The same study finds a positive relationship between innovation and green growth, pointing out innovation as a key driver in this area. Examples such as improving efficiency to reduce material usage, lowering the costs of LCE technologies, and improving the current LCE system are among the predicted outcomes of technological development. According to the IEA (2023), their scenario analysis suggests that most future emissions reductions will rely on technologies currently at the prototype stage. They highlight the role of LCE technologies, especially Enabling such as Batteries, Hydrogen, and CCUS. Despite research showing the positive effects of innovation, its definition remains inconsistent and varies across different perspectives.

2.2 Definition of Innovation

One of the earliest works on innovation was by the economist Joseph Schumpeter, who identified five types of innovation. He focused on how new products, processes, markets, supply sources, and industry structures drive development in the economy (Schumpeter, 1939). In many ways, this has been considered as the foundation for defining innovation (OECD, 1997). Later research has seen the need to narrow the definition to understand what to measure. This is supported by the analysis done by Baregheh et al. (2009), who collected 60 different definitions for innovation. Despite creating a generic definition, they argue that a definition of innovation depends on the focus of the research.

Another definition was made by the OECD. They developed a guide named the Oslo Manual, which serves as a benchmark for collecting and doing research on innovation. It narrows the definition by focusing on product and process innovation, defining innovation as "*a new or improved product or process (or combined therefor) that differs significantly from the unit's previous products or processes and that has been made available to potential users (product) or brought into use by the unit (process)".* As highlighted in the manual, innovation can not only be measured as an activity but also as an outcome. This understanding makes the Oslo Manual a valuable tool when working on innovation (OECD, 1997).

2.3 Measure Innovation

"When you cannot measure it when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind" (Lord Kelvin, cited in Ratcliffe (2016)). This quote highlights a challenge in understanding innovation; the difficulty of measuring it accurately. This issue has been the subject of various research, with one of the most central research being the article published by Griliches (1990). Although it was written three decades ago, the topic remains relevant today. In his work, Griliches highlighted the lack of good measures for understanding technological progress, or as mentioned earlier, the development of innovation.

In recent decades, significant efforts have been made to capture, categorize, and standardize measures related to innovation. The two most common approaches to analyzing innovation involve using either Research and Development (R&D) expenditures or patent data. R&D expenditures serve as an input to the innovation process and offer benefits such as being widely understood and providing clear financial metrics for comparison. As noted by Rogers (1998), it can act as a proxy for the level of innovative effort. Despite their advantages and the consensus that R&D is a driver of innovation, R&D expenditures have limitations as a measure of innovation. These include the lack of detailed data for analyzing specific technological sectors and focusing on inputs rather than the output of the innovation process (Griliches, 1990; Haščič & Migotto, 2015; Nagaoka et al., 2010; Rogers, 1998).

Patents offer an alternative approach to measuring innovation and are one of the most researched methods in this field. A patent is a legal document granting its holder exclusive rights to an invention for a specified period, in exchange for publicly disclosing the details of the invention (OECD, 1997). Studies have highlighted that the availability of patent data makes it a preferred output indicator for innovation (Griliches, 1990; Johnstone et al., 2010; Nagaoka et al., 2010). Tools developed by organizations such as the EPO and the OECD help structure patent data and make it easier to use in research. Patent applications include detailed information on inventors, applicants, technology classifications, and dates, making them useful for comparing innovations across technological sectors (Haščič & Migotto, 2015).

It is important to consider certain issues when working with patent data. The first issue is the highly skewed distribution of patent value; research has shown that the top 10 percent of the most valuable patents account for 80 percent of the total value of all patents (Scherer & Harhoff, 2000). This makes it challenging to differentiate the value of individual patents. Secondly, not all inventions are patented. This could be due to strategic decisions by companies that choose not to reveal their new technologies publicly, or due to documentation issues where applicants fail to meet the required standards. Patent data may underrepresent actual innovation activity, as some inventions are simply not patentable. Griliches (1990) argues that by focusing on a specific industry and using a large dataset, many of these issues can be controlled. Patent information remains one of the best measures to analyze innovation (Johnstone et al., 2010).

2.4 Measure Patent Quality

Guellec (2007) determines patent quality by evaluating both their technological and economic value, which should incentivize innovation and technological development. Squicciarini et al. (2013) introduces several indicators of patent quality that are based on Guellec (2007)'s definition. The study suggests that higher values for these indicators correlate with greater value. In addition, Hirschey and Richardson (2004) found that patent quality can be a useful tool for investors to estimate the future earnings of an investment. Higher patent quality can indicate a higher estimated economic value of the invention. This is particularly helpful for investments with limited financial history. Other research has instead focused on the negative effects of low-quality patents on innovative and economic development. For instance, Hall et al. (2004) found that lower quality patents contribute to market uncertainty, reducing innovation incentives. This uncertainty weakens both innovation and economic growth. Similarly, Hall and Harhoff (2012) points to that innovation is cumulative, which means today's breakthroughs are built on past discoveries.

Other studies explore the economic benefits of owning patents. For example, a report by the Ménière et al. (2021) found that companies holding patents generate significantly higher revenue compared to those without. Hall and Harhoff (2012) shows that patents can serve as valuable assets to secure financing, particularly through venture capital. These findings highlight the role patents play in driving innovation and business growth.

The definition of patent quality has traditionally started with its legal validity, which is based on the patent's satisfaction with the legal standards of a grant. As the literature on this topic expands, more professionals argue that legal validity alone is not enough to determine patent quality (Guerrini, 2013). As Guerrini (2013) states, "*Because invalid patents, by definition, never should have been issued, there is a shared understanding that a good-quality patent is at least a legally valid one*". This has led the way for discussions about additional factors that contribute to defining patent quality. A paper by Song and Li (2014) highlights other factors beyond legal validity in evaluating patent quality. In their work, they highlight the importance of principles that should guide the construction of quality indicators. One of these principles is that indicators should not only have strong theoretical support, but also apply to real data. They present various indicators for measuring patent quality, with the average number of claims being the most heavily weighted. According to their findings, a higher number of claims reflects broader technological coverage (Song & Li, 2014). This point of view is supported by Lerner (1994), who provided empirical evidence of the positive effect that patent breath or scope has on the value.

2.5 Quality Indicators

Several papers have focused on listing the most commonly used indicators of patent quality. van Zeebroeck (2011) highlights citations, grants, family size, and renewals as the main indicators. Squicciarini et al. (2013) provides a broader list of ten indicators, including patent scope, patent family size, grant lag, citations, and claims among the first five. Grant lag and renewals are the only indicators that directly show if a patent is granted. Since the EPO data includes both applications and granted patents, this analysis focuses on the other indicators: patent scope, patent family size, backward citations, NPL citations, and claims.

2.5.1 Patent Scope

Patent scope measures the technological breadth, reflecting how many technological areas it covers. This indicator is calculated using either the International Patent Classification (IPC) or Cooperative Patent Classification (CPC). Both schemes include technical sections A-H, with an additional section, Y, in the CPC. The Y section is used for general tagging of new technological developments, such as the LCE technologies. For example, the first letter of the code represents one of nine technical sections (e.g., "H" for Electricity), followed by characters denoting class, subclass, and group (e.g., "Y02E 10/50" for Solar photovoltaic energy).

Lerner (1994) argued for using four-digit IPC codes to analyze the patent scope, and the support from Matutes et al. (1996) focused on breath instead of length. The equation for Patent scope with adjustment from IPC to CPC used by Squicciarini et al. (2013) is:

$$\mathrm{SCOPE}_p = n_p; n \in \left\{\mathrm{CPC}_1^4, \ldots, \mathrm{CPC}_i^4, \mathrm{CPC}_j^4, \ldots, \mathrm{CPC}_n^4\right\} \quad \text{and} \quad \mathrm{CPC}_i^4 \neq \mathrm{CPC}_j^4 \tag{2.1}$$

n_p is the number of distinct four-digit CPC codes found in the patent p, CPC_i^4 is a specific four-digit CPC code, and the $CPC_i^4 \neq CPC_j^4$ ensures that only distinct four-digit CPC codes are included in the total patent scope $SCOPE_p$. A higher number of unique CPC codes indicates a broader technological scope.

2.5.2 Patent Family Size

Patent family size refers to the number of jurisdictions or countries in which a patent is filed. It gives an indication of the geographic and market reach of the invention. The family size is calculated by counting all patents within a family, which includes all related filings (such as priority applications, continuations, or translations) that stem from the same original invention.

Patent family size is a widely used indicator to measure patent quality. One of the first studies showing its positive relationship with patent value is by Putnam (1996). He argued that family size reflects the value through the willingness to pay the cost of filing patents in multiple jurisdictions or countries. These costs increase with market size, suggesting that applicants expect higher returns from broader market protection. Harhoff et al. (2003) supports this argument, showing that larger patent families correlate positively with patent value. Although broader filings may increase litigation risks, successfully protected patents in multiple jurisdictions tend to have higher value. Dernis and Khan (2004) proposed the measure of Triadic patents, meaning the same invention is filed with the EPO, the Japan Patent Office (JPO), and the United States Patent and Trademark Office (USPTO). Filing in all three offices is the most expensive approach, but it covers the largest markets and may highlight its value. In empirical analysis using patent data, filtering on triadic patents is a common method to exclude less valuable applications. Using this approach requires data from all three offices, increasing the complexity of the analysis.

When focusing on a single office such as the EPO, combining the size of the standard patent family with other indicators can still capture the patent value (Harhoff et al., 2003). This approach aligns with the methodology used by Squicciarini et al. (2013), which recommends combining indicators with the standard patent family to measure the quality of the patent.

2.5.3 Backward Patent Citations and NPL Citations

The paper by Squicciarini et al. (2013) categorizes citations into three groups: backward citations, NPL citations, and forward citations. Citations are divided into two types: those capturing how the patent builds on prior knowledge and those reflecting how it influences future inventions. Backward and NPL citations show how the patent references earlier knowledge to define the invention, while forward citations indicate how later inventions have built upon this patent. Forward citations reflect the patent value through the assumption that the patent that has been cited by others has influenced and contributed to future technological growth (Harhoff et al., 2003; van Zeebroeck, 2011). However, a limitation of forward citations is that they may not be fully recorded with the EPO until five to seven years after the patent is granted (Squicciarini et al., 2013). The value is updated continuously, which could increase uncertainty regarding when the actual value is captured. Such uncertainty may cause issues if the analysis uses on the earliest available patent data. The other two categories of citations are not affected in the same way since the count of backward and NPL citations is listed in the application. Findings by Harhoff et al. (2003) suggest that these citations have a positive correlation with value. The distinction between backward patent citations and NPL citations lies in their sources. Backward patent citations reference other patents, while NPL citations refer to academic articles, technical reports, or scientific publications. The higher the count of NPL found within a patent, the more likely it is to be driven by technological improvements. This is also one of the indicators used in the paper earlier mentioned, where Hirschey and Richardson (2004) found that patent quality could be useful for investors, especially a connection between stock price and the NPL citations count.

2.5.4 Patent Claims

Patent claims define the legal protection granted by a patent, outlining the invention's boundaries and specifying what aspects are protected. Companies often use multiple claims to secure broader protection. The number of claims is frequently associated with patent value, with more claims typically reflecting broader protection (Squicciarini et al., 2013). Claims are widely used in the literature as an indicator of patent quality. Tong and Frame (1994) found that claims provide a more precise measure of innovation and technological effort compared to patent application volumes. Similarly, van Zeebroeck and van Pottelsberghe de la Potterie (2011) examined patent applications and identified a positive relationship between the number of claims and patent value. Building on these findings, Grimaldi and Cricelli (2020) offered an overview of various methods to measure patent quality, highlighting claims through showing the breath of the patent. Grimaldi also pointed to spillover effects, noting that a higher claim count increases the likelihood of increased value in other indicators such as citations. Grimaldi and Cricelli (2020) further recommends using a combination of indicators to capture the true value when evaluating patents.

3 Data and Methodology

This section outlines the data and methodology used to analyze patent quality for energy-related technologies. The OECD Quality Indicator database is used to obtain values for each quality indicator. Publications made by the OECD must follow guidelines and provide freely available data that ensures its reliability. Since this database only includes information on patent applications and pre-calculated indicator values, the OECD REGPAT database is first used to filter for energy-related technologies. Both datasets are based on patent applications filed at the EPO and are updated annually. They are accessible by submitting an application through the OECD website and this thesis uses the September 2024 versions.

The methodology for classifying patents into energy-related technologies is then described. Finally, the section explains how weighting is applied to each technology. Since patents can be classified under multiple technologies, a weighted value is assigned to align the patent quality values for each indicator.

3.1 OECD REGPAT Database

When research aims to analyze patent applications in a region based on specific technologies, the REGPAT database is created in order to serve this purpose. The REGPAT database is created by the OECD that links patent data to regions. In addition to regionalised data, its structure allows to combine patent data with patent-based information such as citations and the classification of technological sectors (Maraut et al., 2008). In the REGPAT database, there are two classification schemes that group inventions by technological sectors. In addition to the IPC, which is used worldwide, there is the CPC. The CPC builds on the IPC but includes more detailed categories. Both schemes have technological sections A-H, with an additional section, Y, in the CPC. This Y section is used for general tagging of new technological developments, such as the cartography of LCE technologies presented in the paper by IEA (2021b). Patent information in the database covers the period from 1978 to 2023 and includes patent applications filed with the EPO, an office that examines and grants patents across European member countries. This thesis uses the REGPAT database by using classification schemes for selecting energy-related technologies and data on filing dates enable analysis of trends over time.

3.2 OECD Quality Indicator Database

When an analysis aims to measure patent quality, the OECD Quality Indicator database serves as a reliable tool. This data is based on the research presented in Squicciarini et al. (2013), which introduces ten indicators for measuring patent quality. These indicators are designed to apply to all patents, regardless of region or technology. While the paper by Squicciarini et al. (2013) focuses on specific technologies, the dataset in the OECD Quality Indicator database is unfiltered. Users of this data must apply their own filters to sort by technology. This data includes patent applications from the EPO with pre-calculated values for all ten quality indicators. Its reliability is supported by its publication through the OECD Publishing, a trusted source for statistics on environmental and economic development. Data from the OECD is freely accessible, ensuring transparency and reproducibility (OECD, 2015a). The values for each indicator can be calculated using data from the EPO, but this requires combining multiple datasets. This method of self-calculations creates more uncertainty on the results and increases the reliance on the users data filtering. Using the pre-calculated values for each patent quality indicator in the OECD Quality Indicator database ensures consistency and aligns with the purpose outlined by Squicciarini et al. (2013).

3.3 Classification of Energy-Related Technologies

The OECD REGPAT database categorizes patents across thousands of technological sectors. This thesis focuses on analyzing the quality of patents in energy-related technologies. The categorization is made possible using two reports created in collaboration between the EPO and the IEA: IEA (2021b) and IEA (2021a). These reports provide cartographies to classify LCE- and Fossil Fuel-related technologies based on the CPC schemes developed by the EPO, which are included in the REGPAT database. For LCE technologies, the cartography uses the EPO's dedicated classification schemes for climate change mitigation (Y02) and smart grid technologies (Y04S) (IEA, 2021b). These schemes divide LCE technologies into three sectors: LCE Supply, Enabling technologies, and End-use technologies.

This thesis focuses on LCE Supply and Enabling technologies, as the collapse in green innovation described earlier was mainly observed on the supply side. In addition, Gentile (2024)'s selection of energy-related technologies motivates our selection of only using LCE Supply, Enabling, and Fossil Fuel-related technologies. Within LCE Supply, only Solar and Wind sub-technologies are included from Table A.1. The IEA (2021b) highlights that these two technologies account for the highest volume of patenting activity between 2000 and 2019. According to figures in the report, patents related to Solar and Wind represent approximately 70 percent of all LCE Supply patents. Other reports show the current and future dominance of these technologies within LCE Supply (IEA, 2024c). This justifies the selection in the analysis. The technologies excluded from the cartography within LCE Supply are categorized as "other renewables", combustion technologies with mitigation potential, and nuclear energy, as listed in Table A.1.

End-use technologies are excluded from this analysis because most of the areas listed in the cartography from IEA (2021b) relate to driving energy demand rather than supply. For example, technologies in the building industry aim to improve energy efficiency but do not contribute to energy production, which is the focus of the other two sectors. All sub-technologies within Enabling that are listed in the cartography in Table A.1 are included in the analysis. The same report by the IEA highlights the role Enabling technologies play in supporting other LCE technologies. Batteries, CCUS, hydrogen and fuel cells, and smart grids are all mentioned for their role in facilitating the transition to Solar and Wind.

When analyzing the collapse in green innovation, this thesis includes Fossil Fuel-related technologies for comparison. Both LCE and Fossil Fuel-related technologies share the common purpose of supplying energy. As mentioned earlier, the classification is based on the cartography in the report by the IEA (2021a). Fossil Fuel-related covers Upstream, Processing and Downstream, and Transmission and Distribution. Since there are no dedicated CPC schemes for Fossil Fuel-related technologies, the IEA and the EPO have recommended a combined approach using CPC schemes and keyword filtering to ensure accurate classification.

3.4 Data Cleaning

Classification of patents in the REGPAT database for LCE Supply, Enabling, and Fossil Fuel-related technologies are based on cartography in Table A.1 and the report by the IEA (2021a). Classification is done by filtering using CPC schemes.[1] Apart from the classification of energy-related technologies, all other patents in the REGPAT database are classified as the Index. The Index includes patents across all technologies, both energy-related and unrelated. It provides a benchmark for evaluating the results of the analysis. Before combining the transformed REGPAT database and the OECD Quality Indicator database, we removed all patent applications not present in both. Patent applications registered from the last three years were removed due to incomplete data. This was a recommended approach to avoid giving false indicators of a decline in activity (Oldham, 2022). After data cleaning and transformation, the final dataset consists of 4.2 million patent applications.

3.5 Patent Classification and Weighting

Patents can include multiple CPC schemes, making them relevant to more than one selected technology sector or sub-technology. To ensure that each patent is appropriately categorized within a single technology sector or sub-technology, a percentage weight was assigned to each patent based on its CPC schemes. This weight is calculated as a proportion of the selected technological sectors and sub-technologies listed in Table A.1. For example, if a patent has one CPC scheme for Batteries, two for Solar, and one for Wind, its weights would be distributed as 0.25 for Batteries, 0.50 for Solar, and 0.25 for Wind.

CPC codes outside the Y-section are not included in the weighting. The Y-section is a general tagging classification that builds upon the A-H sections and is therefore already captured. Including them in the weighting would result in duplication, therefore excluded to ensure the weights accurately represent the selected technological sectors and sub-technologies. As a result, Table A.3 shows that 2.5 percent of the patents are distributed

[1] IEA's approach for classifying Fossil Fuel-related technologies includes both filtering on CPC codes and keyword analysis. It should be noted that the approach in this analysis may include additional patents that are not directly connected to Fossil Fuel-related technologies.

across two or more technology sectors.

Table 3.1: Overview of the weighted distribution of patents across LCE Supply, Enabling, Fossil Fuel-related technologies, and the Index between 1978 and 2020.

Technology	Total Patents (Weighted)
LCE Supply	41 337.20
Enabling	66 516.51
Fossil Fuel-related	53 017.29
Index	4 206 844.00

Table 3.1 shows the weighted distribution of patents across LCE Supply, Enabling, Fossil Fuel-related technologies, and the Index between 1978 and 2020. The weighted patent dataset was then merged with OECD's Quality Indicator Database to capture the quality indicators.

3.6 Trends in Energy-related Technologies

After steady volumes in patent applications up to the early 2000s, patent activity in LCE Supply and Enabling technologies experienced rapid growth between 2008 and 2011. After this period, LCE Supply and Fossil Fuel-related technologies saw a decline in patent activity. In contrast, Enabling technologies experienced only a temporary decline between 2012 and 2015, before returning to positive growth through 2020. As shown in Figure 3.1 the rapid decline in patent activity within LCE Supply, previously described as "the collapse in green innovation", is observed.[2]

Patent applications for sub-technologies show similar trends up until the early 2000s, followed by rapid growth between 2008 and 2011. While LCE Supply experienced afterward a rapid decline in activity, Figure 3.2 shows that this decline was primarily by Solar technologies. Although Wind technologies also experienced a decline, the volume was smaller. Wind later showed a period of positive growth, unlike Solar, which continued to decline. Figure 3.2 also shows that batteries have been the main drivers of growth within Enabling technologies. In contrast, CCUS and Other Enablers show negative or no

[2] The color combinations used for all plots in this thesis were selected based on the colorblind-friendly palettes recommended in the paper by Okabe and Ito (2008).

growth during the period after the rapid growth.

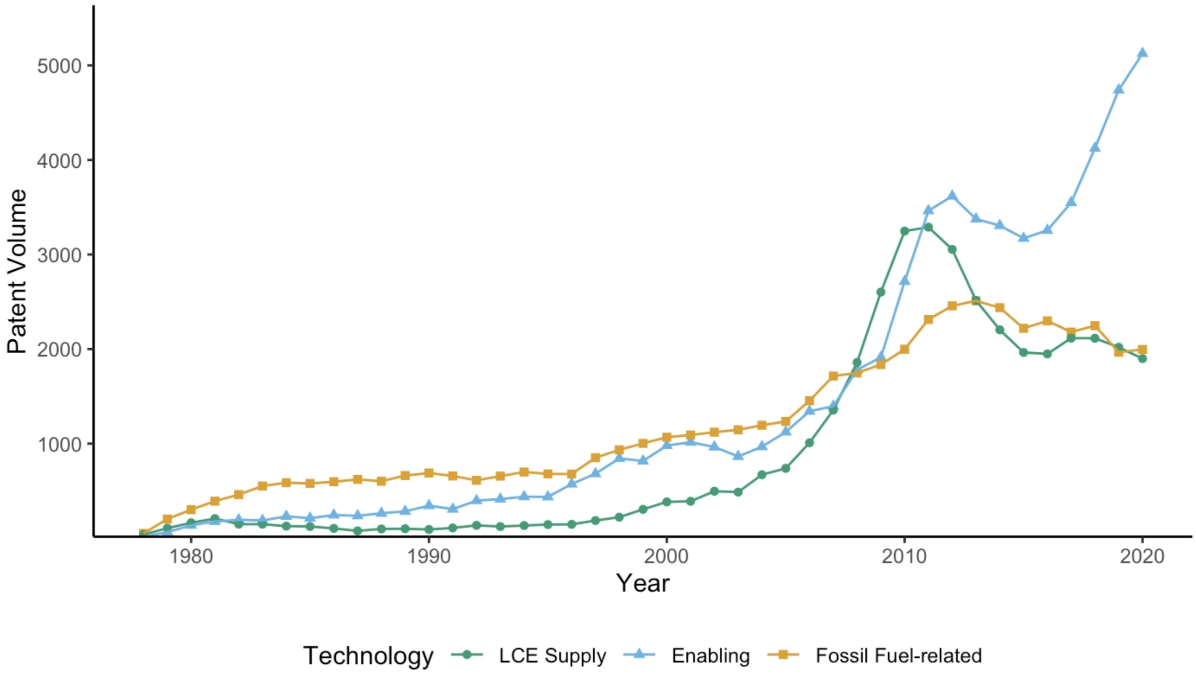

Figure 3.1: Patent application volumes for LCE Supply, Enabling, and Fossil Fuel-related technologies between 1978 and 2020.

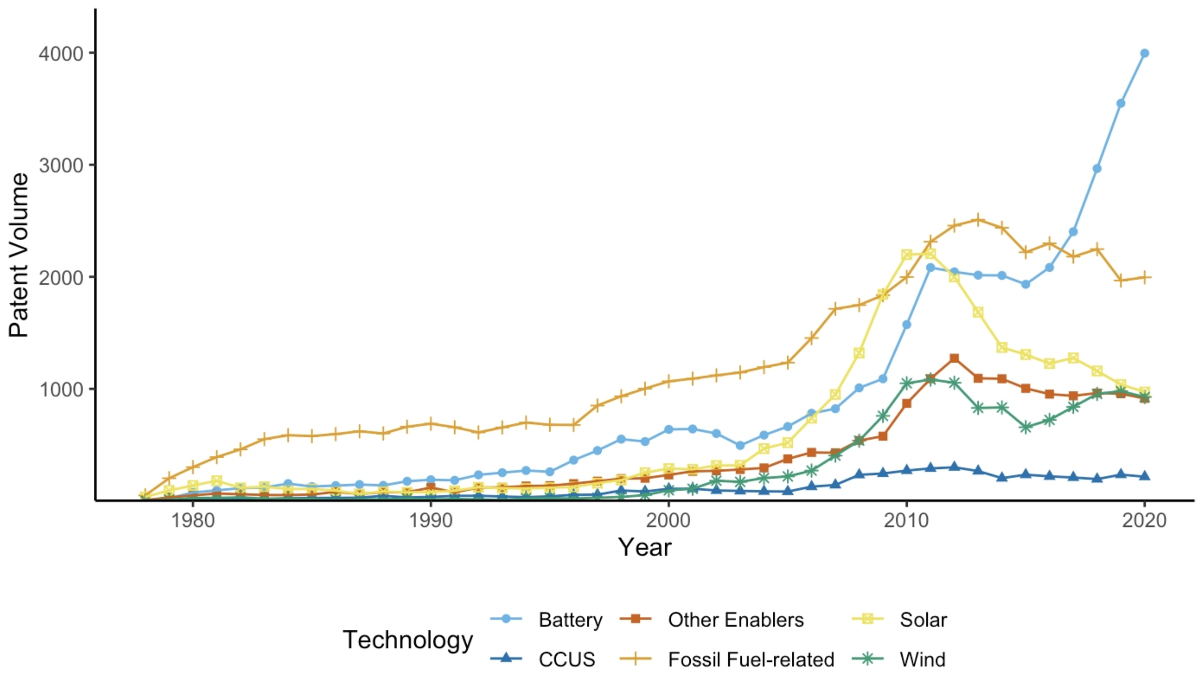

Figure 3.2: Patent application volumes for Solar, Wind, Battery, CCUS, Other Enablers, and Fossil Fuel-related technologies between 1978 and 2020.

4 Results

In this section, we present the results based on the methodology outlined in section 4. The findings are organized by each quality indicator, with one part focusing on the development of technology sectors and another examining the periodic progression of sub-technologies.

4.1 Quality Indicator: Patent Scope

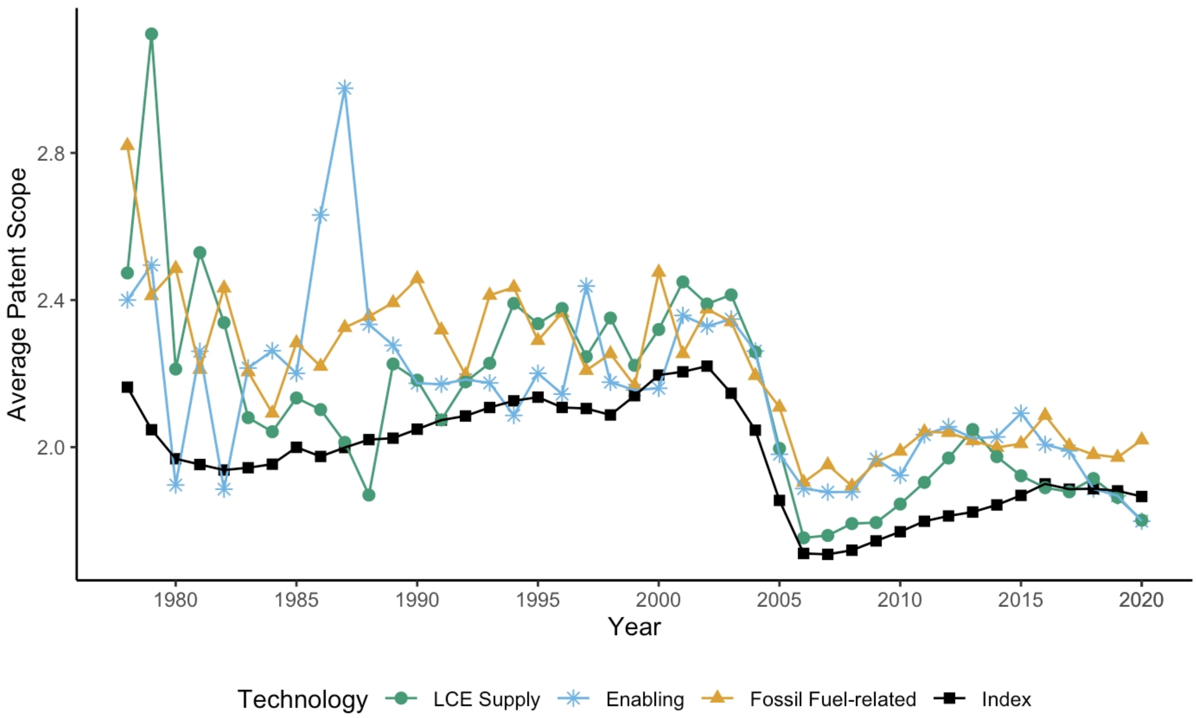

Figure 4.1: Average patent scope for LCE Supply, Enabling, Fossil Fuel-related, and Index from 1978 to 2020.

Figure 4.1 shows the average patent scope for LCE Supply, Enabling, Fossil Fuel-related, and the Index from 1978 to 2020. Up until the 2000s, the Index shows a stable value of around 2. After this, it experiences a sharp decline and stabilizes at just below 2 for the remaining period. The Index has the lowest values for most of the period compared to the other technology sectors. The other technology sectors follow a similar pattern, despite some fluctuations before the 2000s.

Figure 4.2 shows the average patent scope for each sub-technology across four five-year periods. CCUS has the highest average patent scope across all four periods, peaking in the initial period. All technologies reached their peak values during the initial period, followed by a period of negative growth, a recovery with positive growth, and a return to negative growth in the last period. However, the Index differs from this pattern, showing positive growth in the last two periods. Along with Battery and Wind, the Index had the lowest patent scope across all four periods. Technologies related to Wind were the only technology to have values below the Index in all four periods.

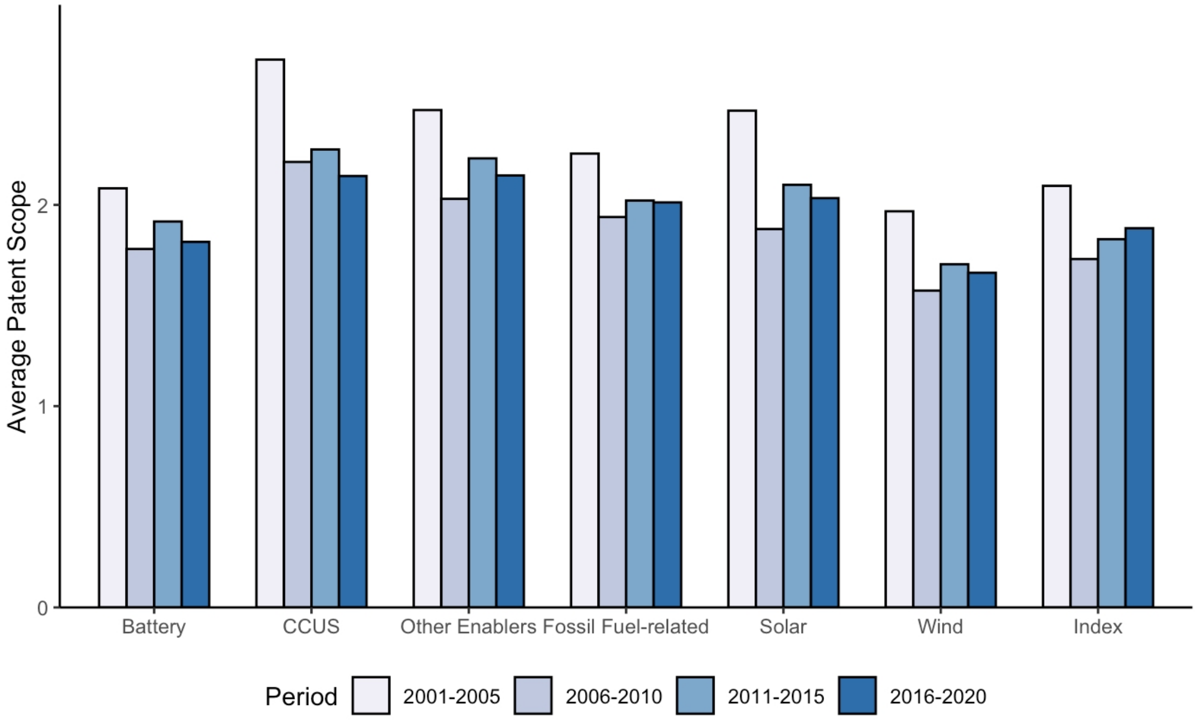

Figure 4.2: Average patent scope across sub-technologies Batteries, CCUS, Other Enablers, Fossil Fuel-related, Solar, and Wind over five-year periods from 2001 to 2020.

4.2 Quality Indicator: Patent Family Size

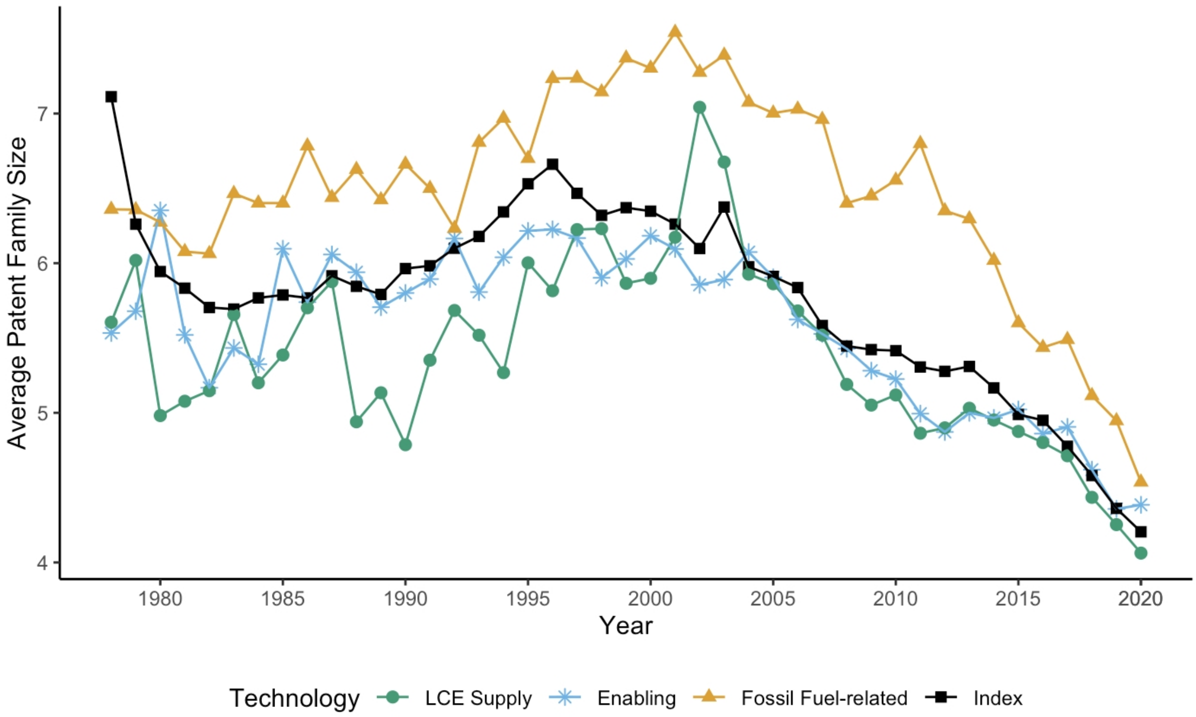

Figure 4.3: Average patent family size for LCE Supply, Enabling, Fossil-Fuel related, and Index from 1978 to 2020.

Figure 4.3 shows the average patent family size for LCE Supply, Enabling, Fossil Fuel-related, and the Index from 1978 to 2020. Up until the early 2000s, the Index shows a steady growth, followed by a continuous decline for the remaining period.

The other technology sectors follow a similar pattern, with average family sizes peaking in the early 2000s and declining thereafter. Before the 2000s, the figure shows fluctuations in the values for the technology sectors, with LCE Supply being the lowest for most of the period. Fossil Fuel-related technologies maintained the highest average family size for most of the time but also experienced the steepest decline after the peak. The highest recorded average patent family size was in 2001, with Fossil Fuel-related technology peaking at 7.5. Throughout the entire period, all technology sectors remain within the range of 7.5 to 4.

Figure 4.4 shows the average patent family size for each sub-technology across four five-year periods. CCUS had the highest average patent family size in two of the four periods. All technology sectors including the Index reached their peak values during the initial period, followed by consistent negative growth across subsequent periods. CCUS and

Fossil Fuel-related technologies were the only ones to maintain an average patent family size above the Index in every period. Although Wind had the highest average family size in the initial period, it experienced the steepest decline in the following period. Between the first and last period, the average family size for Wind drops by almost half. Along with Other Enablers, Wind ranks the lowest in average family size during the last two periods.

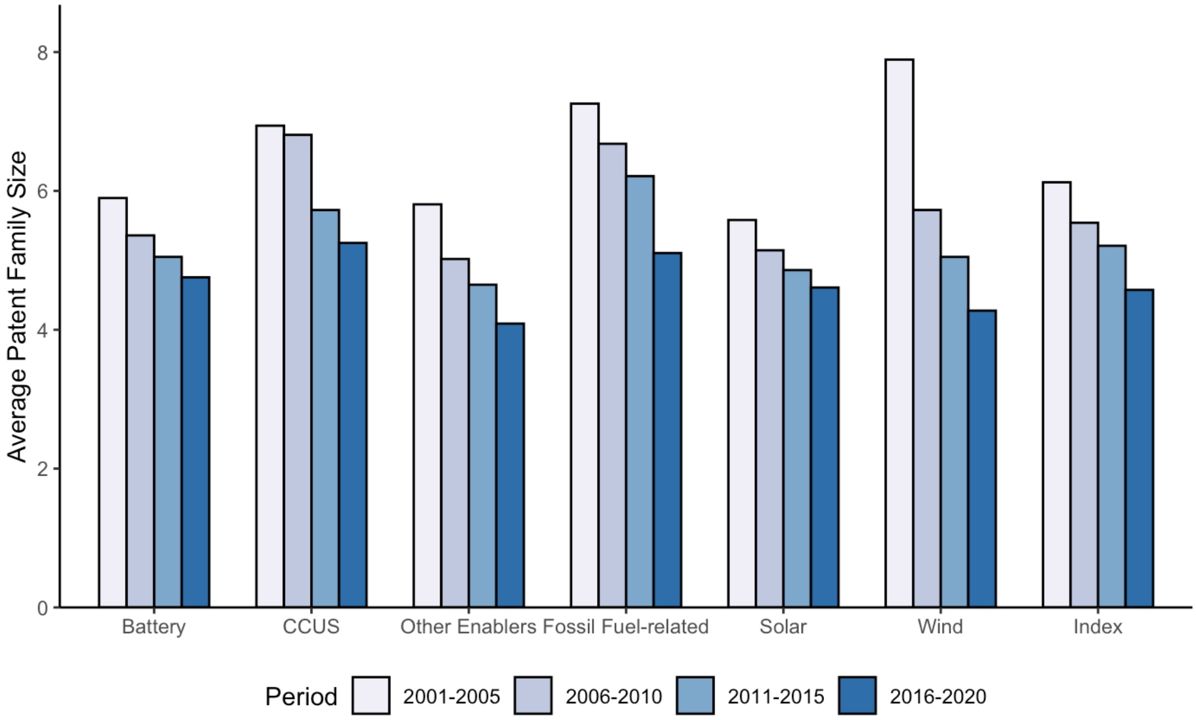

Figure 4.4: Average patent family size across sub-technologies Batteries, CCUS, Other Enablers, Fossil Fuel-related, Solar, and Wind over five-year periods from 2001 to 2020.

4.3 Quality indicator: NPL Citations

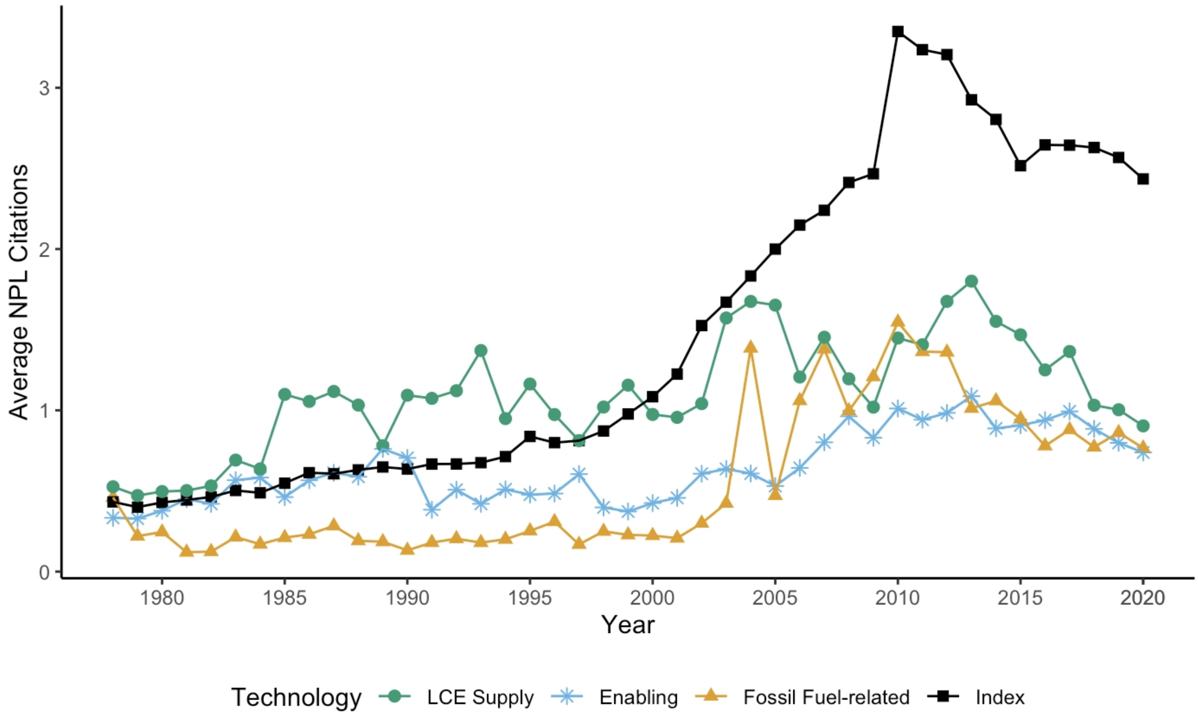

Figure 4.5: Average backward NPL citations per Patent for LCE Supply, Enabling, Fossil-Fuel related, and the Index each year from 1978 to 2020.

Figure 4.5 shows the average NPL citations per patent for LCE Supply, Enabling, Fossil Fuel-related, and the Index from 1978 to 2020. Up until the early 2000s, the Index shows a steady trend in NPL citations per patent before entering a period of continuous growth, peaking in 2010. After this, the Index declines slightly and stabilizes at just below 3 NPL Citations per patent. Throughout the 2000s, the Index maintained the highest average NPL citations per patent.

The other technology sectors remain within the range of 2 and 0 throughout the period. Up until the early 2000s. LCE Supply is the highest-ranked technology sector, maintaining a stable value of around 1. In contrast, Fossil Fuel-related technologies remain the lowest, with values closer to 0. During the 2000s, all technology sectors stabilize around 1, approximately half the value of the Index.

Figure 4.6 shows the average NPL citations for each sub-technology across four five-year periods. The Index had the highest average values in the first three periods, while CCUS had the highest in the last. The results highlight varying growth trends and a distinct separation between technologies above and below a value of 1. Battery, Fossil Fuel-related, and Wind remained below 1 in almost all periods, whereas CCUS, the Index, and Solar were closer to 2. CCUS was the only technology to show continuous positive growth across all periods, reaching the highest value in the final period. In contrast, Wind experienced continuous negative growth, recording the lowest average values across all technologies in the last three periods.

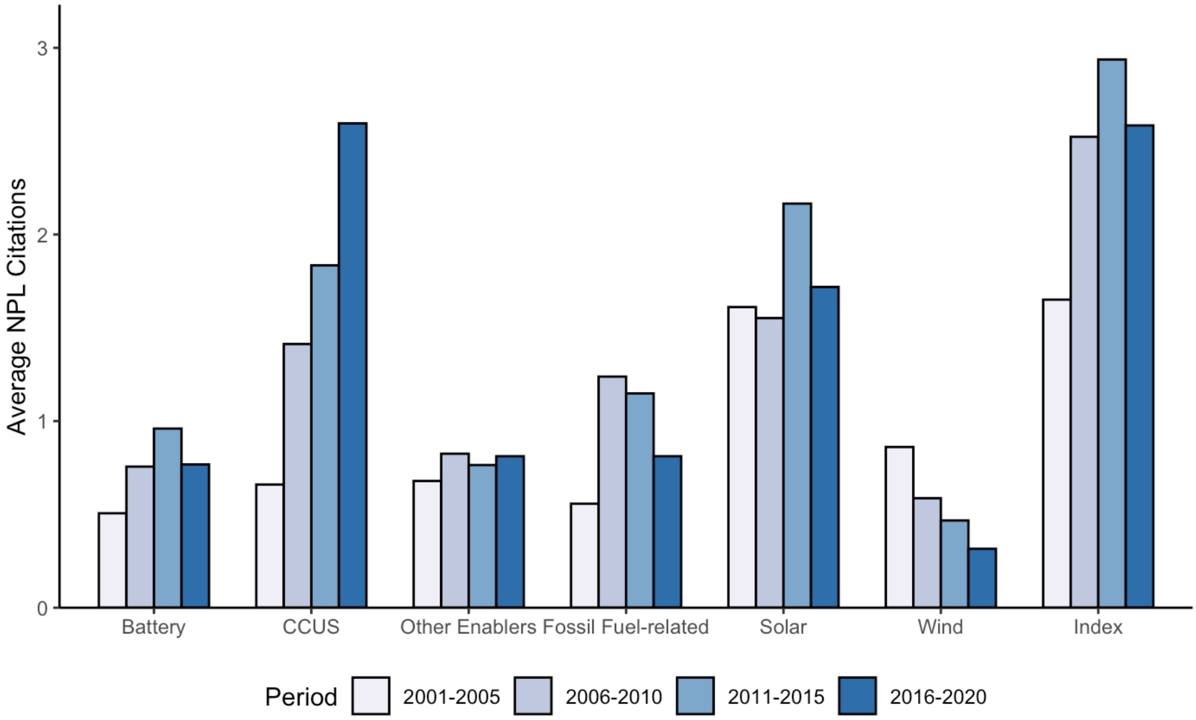

Figure 4.6: Average backward NPL citations across sub-technologies Batteries, CCUS, Other Enablers, Fossil Fuel-related, Solar, and Wind over five-year periods from 2001 to 2020.

4.4 Quality Indicator: Backward Patent Citations

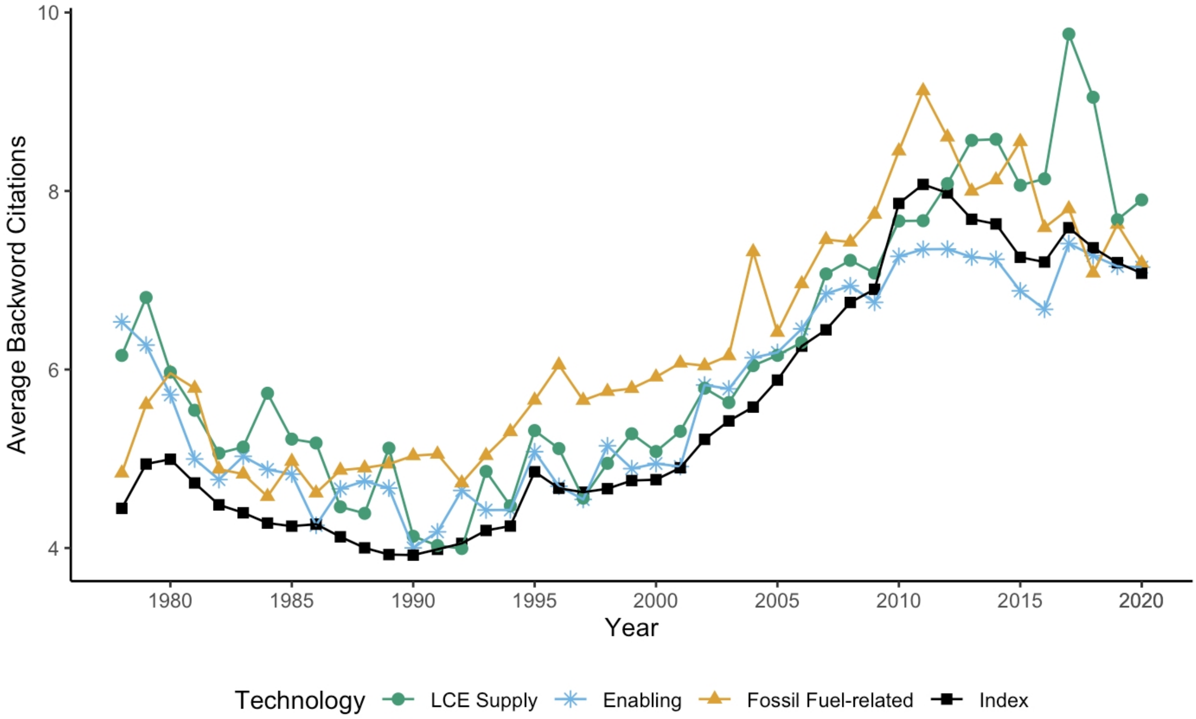

Figure 4.7: Average backward patent citations for LCE Supply, Enabling, Fossil-Fuel related, and Index each year from 1978 to 2020.

Figure 4.7 shows the average backward patent citations per patent for LCE Supply, Enabling, Fossil Fuel-related, and the Index from 1978 to 2020. Up until the early 2000s, the Index shows a steady trend in backward citations per patent before entering a period of continuous growth, peaking in 2011. After this, the Index declines slightly and stabilizes at around 7 backward citations per patent.

The other technology sectors follow a similar pattern as the Index. LCE Supply had the highest value, peaking in 2017. Throughout the entire period, all technology sectors remain within the range of 10 to 4.

Figure 4.8 shows the average backward patent citations for each sub-technology across four five-year periods. Fossil Fuel-related technologies had the highest average values in the first two periods, while Solar had the highest values in the last two periods. Solar and CCUS were the only technologies to show continuous growth across all periods, reaching the highest value in the final period. In contrast, Wind experienced continuous negative growth in the last three periods. The other technologies and the Index showed growth across the first three periods, followed by a decline in the final period.

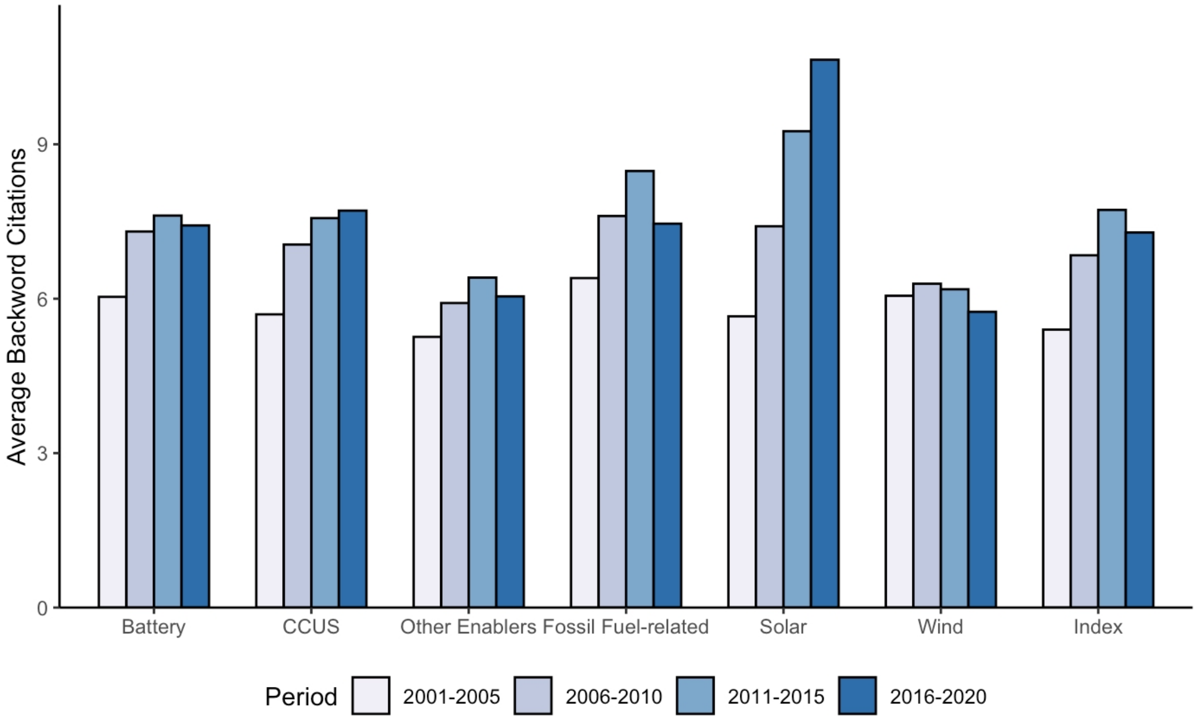

Figure 4.8: Average backward patent citations across sub-technologies Batteries, CCUS, Other Enablers, Fossil Fuel-related, Solar, and Wind over five-year periods from 2001 to 2020.

4.5 Quality Indicator: Claims

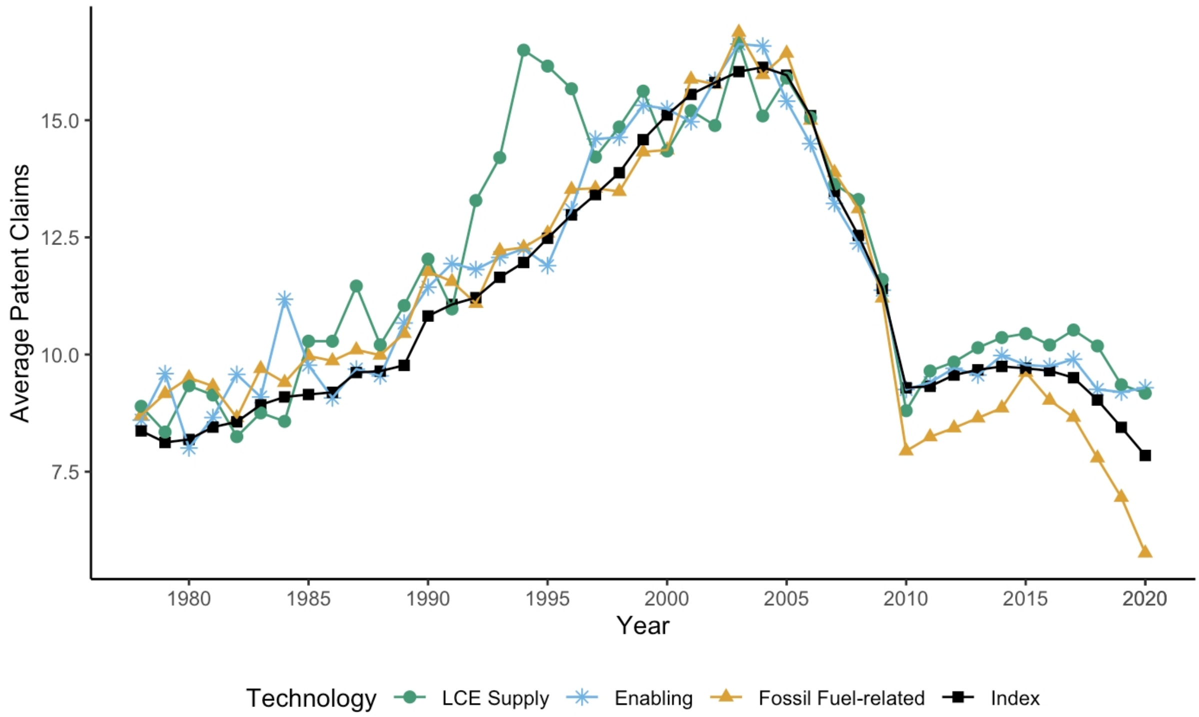

Figure 4.9: Average claims for LCE Supply, Enabling, Fossil-Fuel related, and Index each year from 1978 to 2020.

Figure 4.9 shows the average number of claims per patent for LCE Supply, Enabling, Fossil Fuel-related, and the Index from 1978 to 2020. Up until the early 2000s, the Index shows continuous growth. After this peak, it experiences a sharp decline and stabilizes at around 8 claims per patent after 2010. In the last five years, the Index has entered a new decreasing trend.

The other technologies follow a similar pattern to the Index. No single technology consistently has the highest value over the period, except between 1992 and 1997, when LCE Supply saw a short spike in this period. From that point, all technologies moved toward the Index until 2010. By the end of the period, Fossil Fuel-related technologies had the lowest average claims per patent.

Figure 4.10 shows the average number of claims for each sub-technology across four five-year periods. In the initial period, all technologies had their highest values, averaging around 15 claims. In the subsequent periods, average claims declined across all technologies, with the sharpest drop occurring between the first and second periods. Batteries and

Solar were the only sub-technologies showing positive growth in the last period. Solar, Wind and Batteries were higher than the Index in the last three periods. CCUS and Fossil Fuel-related technologies are below the Index in the last three periods.

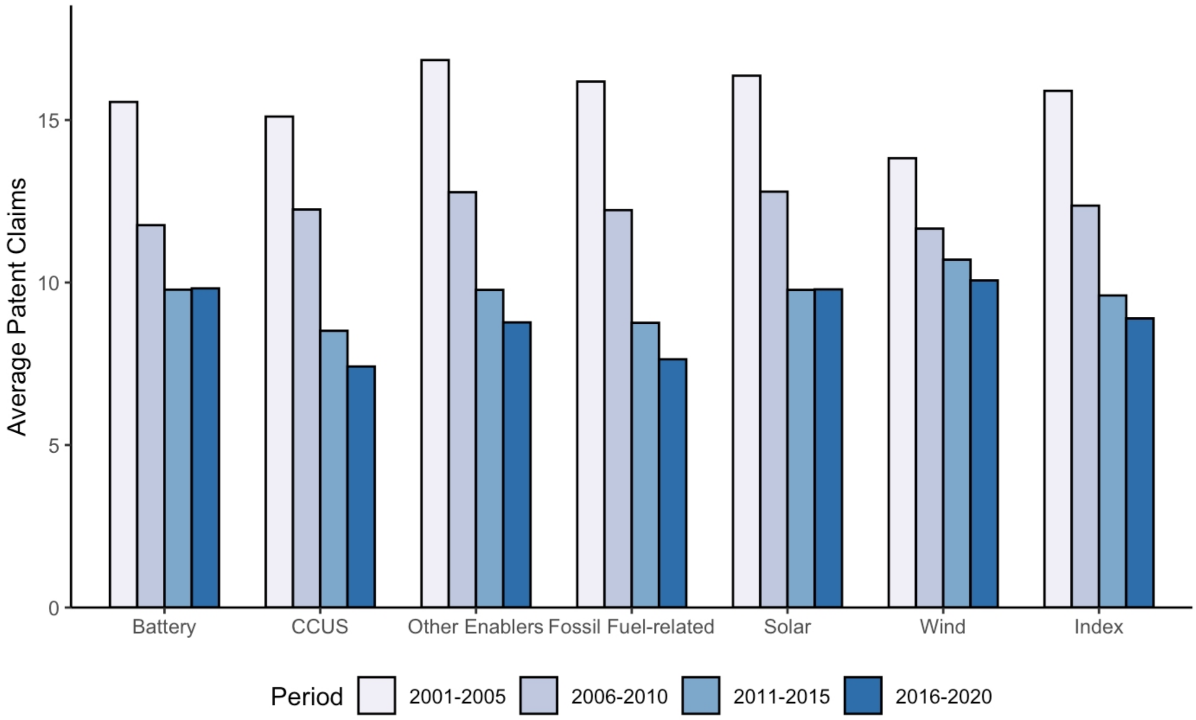

Figure 4.10: Average claims across sub-technologies Batteries, CCUS, Other Enablers, Fossil Fuel-related, Solar, and Wind over five-year periods from 2001 to 2020.

5 Discussion

In this section, we discuss whether the quality indicators reveal a collapse in green innovation, as reflected in the reduction of patent activity. We also explore potential explanations for the findings, such as including the role of public subsidies and the impact of patent offices on innovation activity and the value of innovations in the energy sector. Particular attention is given to LCE Supply, Batteries, and CCUS, as these findings differ notably from the others.

5.1 The Impact of Patent Offices

Rules and regulations regarding patents and patent offices are changing over time. This can make patent offices stricter or more lenient. Hall et al. (2004) discusses that an increase in patent applications can lead to more cursory controls. The increase in patent applications puts pressure on patent office resources, which may result in less thorough examination. Griliches (1990) argues that more lenient patenting standards often lead to an increase in the number of patents granted. According to this, a sharp increase in patent activity does not necessarily reflect greater innovation, as it can lead to the issuance of low-quality patents or incremental patents. Hall et al. (2004) states that a large number of low-quality patents increases legal uncertainty and the risk of costly litigation, which can hinder further innovation. He explains that fear of litigation may discourage smaller firms from entering technology areas dominated by large companies with large patent portfolios. The risk of legal disputes can discourage potential competitors from entering certain markets, reducing competition and slowing technological progress.

5.1.1 Stricter regulations affect the quality indicators

Figure 4.1 and 4.9 clearly show how changes in regulations at the EPO can impact the the patents quality. After 2003, patent claims and patent scope indicators declined and stabilized at lower levels across all technology sectors. This shift aligns with changes to EPO regulations and the amendment to Rule 29(2) EPC (now Rule 43(2)), implemented in January 2002 (EPO, 2003). The rule limited patents to one independent claim per category. Exceptions were allowed only under strict conditions, such as when multiple claims addressed distinct technical problems or effects. This change most likely reduced the breadth of patents, as applicants were discouraged from drafting broader claims. The drop in patent claims and patent scope after 2003 is therefore not considered a decline in value, but an adaptation to the new regulations.

5.2 Are Green Innovations Dependent on Subsidies?

Innovation is a key factor in driving economic growth. Schumpeter (1939) and Romer (1990) argued that technological progress is essential for sustaining long-term development. In the context of the energy transition, the IEA (2020) highlight that new innovations are necessary to achieve decarbonization goals. This highlights the importance of maintaining a sufficient level of innovation activity to ensure technological development. For sectors like LCE Supply, which are driven by governmental objectives, market forces alone may not be sufficient to stimulate innovation. Therefore, public support is often required to incentivize such investment.

Acemoglu et al. (2012) analyze the affect public subsidies has on the development of LCE Supply sector. They argue that subsidies are essential for stimulating innovation in these technologies, and points to the importance of the design or type of subsidy to reach the desired goal. Given that the energy transition's goal is to replace Fossil Fuel-related energy with clean energy, Acemoglu et al. (2012) suggest that an optimal subsidy would be temporary rather than continuous and "*ever-increasing*". Well-designed subsidies should therefore drive short-term innovation and allow technologies to reach a point where they can compete economically without ongoing public support. If subsidies are reduced too early the level of innovation activity may decline. Evidence from Johnstone et al. (2010) supports this claim, showing that public subsidies increase patenting activity for green technologies. This suggests a clear link between public subsidies and the rate of technological development in the LCE Supply sector.

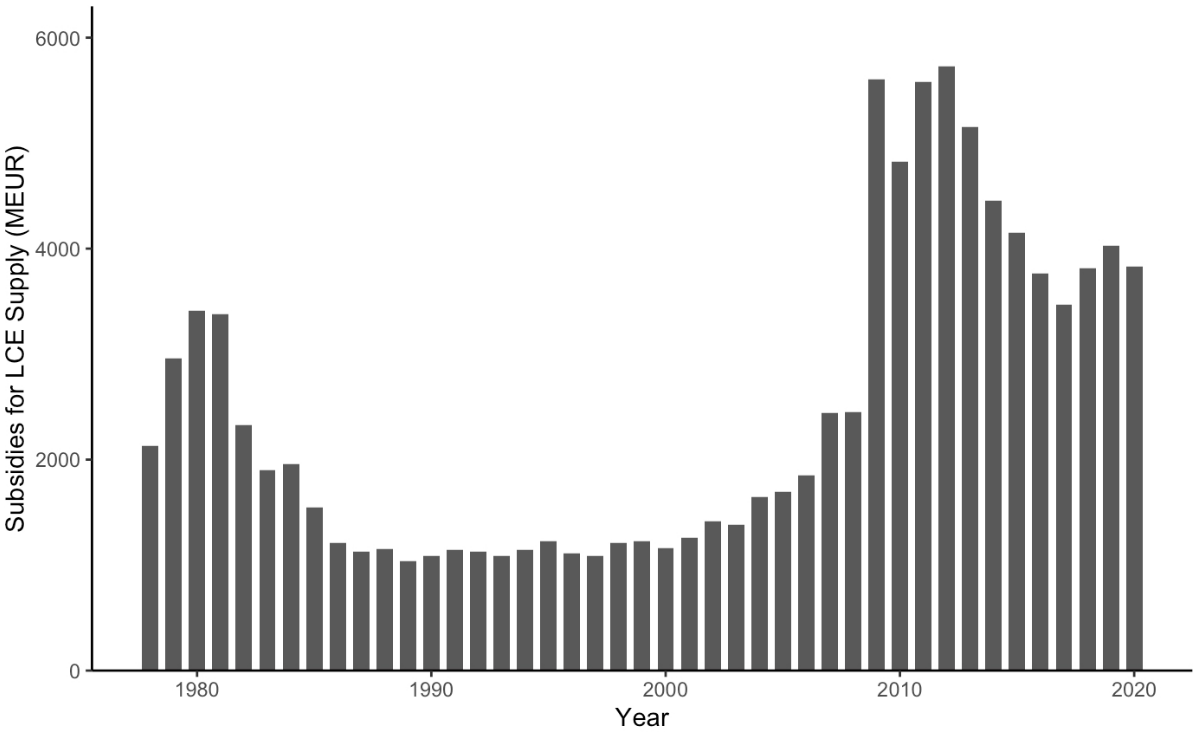

Figure 5.1: Overview of international public subsidies in MEUR for LCE Supply technologies between 1978 and 2020. Data retrieved from IEA (2024b).

Figure 5.1 provides an overview of international public subsidies for LCE Supply from 1978 to 2020. The trend in public subsidies closely aligns with the activity level in LCE Supply, as illustrated in Figure 3.1. This suggest that changes in subsidies may influence patent activity. Drawing on the argument from Acemoglu et al. (2012) and the assumption regarding the goal of the energy transition, this indicates that subsidies for LCE Supply sector may not be optimally designed. Increases in public support are associated with higher innovation activity, while reductions in subsidies correspond with declines in patenting. Popp et al. (2020) identified the "collapse in green innovation" after 2010, which agrees with a reduction in public subsidies. This suggests that LCE Supply remain dependent on public financial support. Despite the observed correlation between public subsidies and patent activity, it remains unclear whether the current level of innovation is the result of not optimal subsidies, early withdrawal of support, or a natural stabilization of activity after an initial increase in patent activity.

5.3 A Collapse in Green Innovation?

As mentioned, Popp et al. (2020) identified a sharp decline in LCE Supply patent activity beginning around 2010. This is described as a setback for the clean energy transition as it reflects a significant drop in innovation within the sector. The trend is referred to as the "collapse in green innovation". Despite this, the value of LCE Supply shows stable trends, with 4 out of 5 quality indicators aligning with the Index across all periods. The exceptions are some identified spikes that are considered as extreme values and therefore not relevant. The value of the LCE Supply sector has not decreased compared to the Index. In other words, the collapse in green innovation is not visually identified when looking at the quality of technology sectors.

Figure 3.2 illustrates the activity volumes of Solar and Wind separately over time. The figure shows that while the patent activity regarding Wind has increased in recent periods (a small decline in the last period), patent activity regarding Solar has declined. A possible reason could be the reduction in public subsidies from key contributing countries supporting Solar (Popp et al., 2020). This suggests that the collapse in green innovation based on patent activity may not include all LCE Supply sub-technologies. Solar shows stable and higher value compared to other sub-technologies, while Wind has the lowest in 3 out of 5 quality indicators. When comparing value to activity volumes, the results reveal opposite patterns: Wind shows increased activity but declining value, whereas Solar shows decreased activity but increasing value. A declining trend consistent with the "collapse in green innovation" can be observed for both Solar and Wind. This depends on whether the focus is on patent activity or value.

As mentioned earlier, the increase in patent activity for LCE Supply may be explained by increased subsidies. However, incorporating the observations of Hall et al. (2004) and Griliches (1990), rapid growth in patent activity may also be driven by changing standards and leniency at patent offices. A sudden increase followed by a collapse in green patent activity may reflect a period of more relaxed patenting criteria, followed by a stricter period. As Hall et al. (2004) suggests, rapid growth in patent activity may increase the proportion of low-quality patents, which could negatively affect innovation.

The consequences are reflected most clearly in the value trends for Wind. Despite the rise in patent activity, the value shows a decline. This finding aligns with Hall et al. (2004), suggesting a potential increase in the share of low-quality patents. Accordingly to Acemoglu et al. (2012), the result may suggest that subsidies driving innovations for LCE Supply are not optimal.

5.4 Batteries - High activity, average value

Gentile (2024) explains that the intermittency of LCE Supply requires Enabling technologies to ensure energy reliability. Technologies such as energy storage and smart grids are necessary to manage supply fluctuations and maintain grid stability. Scaling up the energy transition depends on the continued development of these technologies. The IEA (2020) highlights advancements in Batteries as essential for supporting grid flexibility and improving energy storage to scale up towards the energy transition. This positions Batteries as a key contributor to addressing the weaknesses that Gentile identifies in LCE Supply today.

The importance of Batteries are reflected by high patent activity. Figure 3.1 show that Battery technologies both have the highest increase and the highest volumes of patent activity throughout the period. Similar to LCE Supply, this increase appears to be driven by subsidies. Subsidies for storage technologies have grown steadily since the 2000s, coinciding with the rise in patent activity. This is shown in Figure A.7. The performance of Batteries across quality indicators remains around average, and therefor the value is not considered high. The high volumes of patent activity does not seem to have a significant impact on the value of Batteries. This suggests that subsidies do not necessarily have a positive effect on the value of Battery innovations, a pattern similar to what is observed for Wind. This outcome aligns with Acemoglu et al. (2012), who would view such subsidies as less optimal assuming the goal is to replace Fossil-Fuel technologies with LCE technologies. Despite this, the effect appears less significant than for Wind, since the value does not decrease.

A possible explanation for the average quality values, despite high activity, is the influence of the electric vehicle (EV) industry and other end-use technologies. Some studies suggest that the rapid growth in EV development and end-use consumer products has driven the activity in battery-related patents (IEA, 2020). These patents often focus on EV-specific features like energy density, charging speed, or safety, rather than contributing to broader energy storage advancements. While these developments improve batteries for EVs, they may not have benefits that extend to grid-scale storage or LCE Supply. These innovations align with the type of low-quality patents described by Hall et al. (2004) and Griliches (1990), as they are considered more incremental than breakthrough innovations. Despite this, the value of Battery innovations has not decreased, which may suggest a mix of high-quality patents and low-quality patents. This may also be a natural outcome during a phase of increasing innovation activity.

5.5 CCUS - Ahead in Value

Despite an overall decline in patent quality during the 2000s, the results show that CCUS ranks among the top sub-technologies for 3 out of 5 patent quality indicators across most periods. The only indicator where CCUS does not rank highest is the number of claims, which is primarily influenced by regulatory changes. The patent activity for CCUS remains steady and maintains one of the lowest volumes throughout the entire period. Unlike LCE Supply and Batteries, CCUS does not experience significant shifts in activity. The observed increase in patent value could therefore reflect actual technological development.

The IEA identifies innovation in CCUS as one of the key technologies for achieving the emission reductions needed to meet global climate-related targets. To reach the goals of the Paris Agreement, global CO2 emissions must be reduced by over 50 percent by 2050, with 14 percent of this reduction expected to come from CCUS (IEA, 2024c). Several factors may explain why CCUS during the period is of the highest value. In addition to being an enabling technology, CCUS is closely connected to Fossil Fuel-related industries, as it is frequently used in industries dependent on coal and fossil fuels. These industries face challenges in reducing emissions, with limited decarbonization options available. Examples include refining and manufacturing (cement, iron, and steel), which rank among the highest in CO2 emissions.

Figure A.4 highlights the turning point around 2008 for CCUS investments. Around this time, Europe installed its second CCUS project (Equinor, 2024), and financial incentives for climate-related actions began to grow. This shift led to exponential growth in CCUS investments, with nearly doubling between 2010 and 2017. During the 2000s, international carbon trading systems were also introduced and developed. This resulted in the establishment of a carbon pricing system. The price of emitting carbon has risen from around EUR 15 per tonne and reaching approximately EUR 80 per tonne by the end of 2021 (see Figure A.6).

The article by Haszeldine et al. (2018) illustrates that fossil fuel-related companies view CCUS investments as a strategic option. It enables them to continue fossil fuel production while reducing regulatory risks associated with climate commitment, like increasing carbon prices. They also discuss that these companies have several competitive advantages compared to renewable energy companies. A mature industry with financial strengths and infrastructure is key factors for the increasing possibility of developing CCUS technology. The IEA (2020) also highlights the motivation of companies to reduce CO2 emissions through CCUS technologies, noting that these firms have become some of the largest investors in their development. By applying the framework of Acemoglu et al. (2012) and the assumption that public incentives like carbon taxes aim to reduce emissions, the findings suggest that these incentives may be optimal for innovating CCUS. This is because the incentives motivate companies to innovate. The increasing value of CCUS indicates that the incentives are effective, as they may drive technological improvements reflected in higher value.

CCUS serves as an enabler for these companies in two ways. First it allow the companies to continue produce fossil fuels to maintain their income. Secondly it allow the companies to reduce their emission costs. If the goal is to reduce emissions, then continuous carbon taxes aligns with optimal incentives proposed by Acemoglu et al. (2012). A financially strong and motivated industry capable of change, may therefore help explain the increasing value of CCUS.

6 Limitations

This section discusses the limitations of the thesis. It focuses on the challenges associated with patent data, potential weaknesses of the quality indicators, and the strategic use of patents by companies.

6.1 The patent data

One of the challenges is accurately categorizing patent applications. Various methods exist for this task, and different methods give different categorizations for some of the patents. This is shown by Favot et al. (2023), the chosen method significantly influences which applications are identified as green patents. However, the primary focus of this thesis is to analyze how trends evolve across different technology sectors and sub-technologies. By creating a representative categorization based on CPC codes, it is reasonable to assume that the identified trends provide a reliable approximation of actual developments.

Another limitation involves the presence of incomplete data, as some patents lack key indicators, resulting in gaps within the dataset. Additionally, the dataset is focused on patent applications filed with the EPO. While this includes applications from companies worldwide seeking patent protection in Europe, it excludes patent applications filed in other regions. Collecting data from multiple patent offices is challenging due to variations in patent requirements, examination standards, and data storage practices. These inconsistencies can also affect patent quality indicators, such as family size, which reflects geographical coverage and may differ depending on whether offices like the United States Patent and Trademark Office (USPTO) or Japan Patent Office (JPO) are included. Gathering data across multiple offices is both resource- and time-intensive. Organizations such as the EPO and USPTO have already invested significant resources in standardizing their own data, making it impractical to replicate these efforts for the purposes of this thesis. Consequently, the analysis is limited to the available datasets, which remain representative.

6.2 The Quality Indicators

Patent quality indicators provide valuable perspectives on the innovations behind patents. Although, this cannot be directly transformed to the actual value of the innovations they protect. The indicators highlight specific aspects that may suggest higher value, but they have limitations. For instance, a breakthrough battery innovation might not build upon existing battery technology. This may give the patent a low number of backward citations, and indicating a low value. While the value of breakthrough technology might not be reflected in backward citations, it can be captured through other indicators, such as the number of claims or the patent scope.

Each quality indicator reflects a single perspective of the patent. A strong performance in one indicator does not necessarily imply that the overall quality or value of the innovation is high. Additionally, combining multiple indicators into a single index is not straightforward. There is no common agreement on whether all indicators are equally effective or if some should be weighted more heavily than others. Despite these challenges, the use of multiple quality indicators provides a well-rounded approach to assessing patents.

6.3 Patents as a strategic business tool

Patents are not only used to protect a company's innovations, but also a strategic tool used to influence competitors. On one hand, patents safeguard valuable innovations, preventing other companies from using or replicating them without permission. On the other hand, patent applications are public and reveal detailed information about the protected technology. This transparency may discourage some companies from patenting critical innovations, opting instead to keep them as trade secrets to avoid public exposure.

Another strategic use of patents is to block competitors' innovations. This is known as "patent blocking", and can wrongly impact the quality indicators because they do not necessarily reflect actual innovations. While this tactic is difficult to identify, certain patterns in quality indicators can suggest its use. Detecting patent blocking requires detailed, micro-level analysis of patent quality, which goes beyond the scope of this analysis.

7 Conclusion

This study analyzed the value of innovations within key technologies for the energy transition using patent quality indicators to track trends in innovation. The analysis examined whether LCE Supply experienced a decline in value during the "collapse in green innovation". Several studies points towards public subsidies when trying to explain the collapse. Given the role of public subsidies in the discussion regarding innovation in LCE technologies, we explore how subsidies impact the value.

Our results suggest a misalignment between patent activity and value. The findings indicate that the value of the LCE Supply has not declined in line with the "collapse in green innovation". A similar misalignment is observed when analyzing sub-technologies. Solar appears to be the main driver of the "collapse in green innovation", but this is not reflected with a decrease in value. In contrast, Wind shows increasing activity despite a decrease in value. This leads to contradictory conclusions depending on whether the focus is on patent activity volumes or value.

Subsidies seem to have a positive effect on patent activity, but the findings do not necessarily reveal a positive impact on value. Assuming that the goal of public subsidies is to replace fossil fuels, our findings suggest that current subsidies are not implemented or designed optimally. Subsidies also seem to be more effective for emission-reduction innovations like CCUS rather than for replacement technologies. This indicates a need for continuous subsidies.

The observed relationship between patent activity and the value of innovations aligns with the findings of Hall et al. (2004) and Griliches (1990). Rapid growth in patent activity may negatively affect the value, since it raises the likelihood of granting a higher proportion of low-quality patents. While public subsidies potentially contribute to this issue, Acemoglu et al. (2012) indicate that the problem do not lie in the use of subsidies themselves, but in their design. While this suggest that current subsidies do not produce the desired innovation effect, there is still uncertainty surrounding this conclusion. A more detailed analysis of how subsidies influence the share of low-quality patents is needed. Identifying which subsidies drive the development of high-quality LCE technologies will be important findings to support the energy transition.

References

Acemoglu, D., Aghion, P., Barrage, L., & Hémous, D. (2023). *Climate change, directed innovation, and energy transition: The long-run consequences of the shale gas revolution*. National Bureau of Economic Research. https://doi.org/10.3386/w31657

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). The Environment and Directed Technical Change. *American Economic Review*, *102*(1), 131–166. https://doi.org/10.1257/aer.102.1.131

Baregheh, A., Rowley, J., & Sambrook, S. (2009). Towards a Multidisciplinary Definition of Innovation. *Management Decision*, *47*. https://doi.org/10.1108/00251740910984578

Dernis, H., & Khan, M. (2004). Triadic Patent Families Methodology. *OECD Publishing*. https://doi.org/10.1787/443844125004

EPO. (2003). *Guidelines for Examination in the European Patent Office*. European Patent Office. Retrieved December 18, 2024, from https://link.epo.org/web/guidelines_2003_en.pdf

Equinor. (2024). Carbon capture, utilisation and storage. Retrieved December 18, 2024, from https://www.equinor.com/energy/carbon-capture-utilisation-and-storage

Favot, M., Vesnic, L., Priore, R., Bincoletto, A., & Morea, F. (2023). Green patents and green codes: How different methodologies lead to different results. *Resources, Conservation & Recycling Advances*, *18*, 200132. https://doi.org/10.1016/j.rcradv.2023.200132

Gentile, C. (2024). *Relying on Intermittency: Clean Energy, Storage, and Innovation in a Macro Climate Model*. Working Paper. Retrieved December 18, 2024, from https://www.carloalberto.org/wp-content/uploads/2023/12/JMP-Draft-Claudia-Gentile.pdf

Griliches, Z. (1990). Patent Statistics as Economic Indicators: A Survey. *Journal of Economic Literature*, *28*(4), 1661–1707. Retrieved December 18, 2024, from http://www.jstor.org/stable/2727442

Grimaldi, M., & Cricelli, L. (2020). Indexes of patent value: a systematic literature review and classification. *Knowledge Management Research & Practice*, *18*(2), 214–233. https://doi.org/10.1080/14778238.2019.1638737

Guellec, D. (2007). Patent desgin. In *The Economics of the European Patent System: IP Policy for Innovation and Competition* (pp. 114–152). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199216987.003.0005

Guerrini, C. J. (2013). Defining patent quality. *Fordham Law Review*, *82*, 3091–3142. Retrieved December 18, 2024, from https://heinonline.org/HOL/Page?handle=hein.journals/flr82&div=98&g_sent=1&casa_token=fXkckvSGxT4AAAAA:zKvI_qFrQ_yw-Etxc6waJEcXVXd8v_RTrT-1aGfOcPSm31vinf_5CBZR01bl5hSk7iavoZ-iXw&collection=journals

Hall, B. H., Graham, S., Harhoff, D., & Mowery, D. C. (2004). Prospects for Improving U.S. Patent Quality via Post-grant Opposition. *Innovation Policy and the Economy*, *4*, 115–143. https://doi.org/10.1086/ipe.4.25056163

Hall, B. H., & Harhoff, D. (2012). Recent Research on the Economics of Patents. *Annual Review of Economics*, *4*(1), 541–565. https://doi.org/10.1146/annurev-economics-080511-111008

Harhoff, D., Scherer, F. M., & Vopel, K. (2003). Citations, family size, opposition and the value of patent rights. *Research Policy*, *32*(8), 1343–1363. https://doi.org/10.1016/S0048-7333(02)00124-5

Haščič, I., & Migotto, M. (2015). Measuring environmental innovation using patent data. *OECD Publishing*, (89). https://doi.org/10.1787/5js009kf48xw-en

Haszeldine, R. S., Flude, S., Johnson, G., & Scott, V. (2018). Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *376*(2119). https://doi.org/10.1098/rsta.2016.0447

Hirschey, M., & Richardson, V. J. (2004). Are scientific indicators of patent quality useful to investors? *Journal of Empirical Finance*, *11*(1), 91–107. https://doi.org/10.1016/j.jempfin.2003.01.001

IEA. (2020). *Energy Technology Perspectives 2020*. International Energy Agency. Paris, France. Retrieved December 18, 2024, from https://www.iea.org/reports/energy-technology-perspectives-2020

IEA. (2021a). *Methodology for identifying fossil fuel supply related technologies in patent data*. International Energy Agency. Paris, France. Retrieved December 18, 2024, from https://iea.blob.core.windows.net/assets/d14427c6-2aa2-4422-9074-5a68940a5a96/Methodology_for_identifying_fossil_fuel_supply_related_technologies_in_patent_data.pdf

IEA. (2021b). *Patents and the Energy Transition*. International Energy Agency. Paris, France. Retrieved December 18, 2024, from https://www.iea.org/reports/patents-and-the-energy-transition

IEA. (2023). *Energy Technology Perspectives 2023*. International Energy Agency. Paris, France. Retrieved December 18, 2024, from https://www.iea.org/reports/energy-technology-perspectives-2023

IEA. (2024a). CCUS Projects Explorer. Retrieved December 5, 2024, from https://www.iea.org/data-and-statistics/data-tools/ccus-projects-explorer

IEA. (2024b). Energy Technology RD&D Budgets Data Explorer. Retrieved December 5, 2024, from https://www.iea.org/data-and-statistics/data-tools/energy-technology-rdd-budgets-data-explorer

IEA. (2024c). *World Energy Outlook 2024*. International Energy Agency. Paris, France. Retrieved December 18, 2024, from https://www.iea.org/reports/world-energy-outlook-2024

International Carbon Action Partnership. (2024). Icap allowance price explorer. Retrieved December 18, 2024, from https://icapcarbonaction.com/en/ets-prices

Johnstone, N., Haščič, I., & Popp, D. (2010). Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts. *Environmental Resource Economics*, *45*, 133–155. https://doi.org/10.1007/s10640-009-9309-1

Lerner, J. (1994). The Importance of Patent Scope: an Empirical Analysis. *The RAND Journal of Economics*, *25*(2), 319–333. https://www.jstor.org/stable/2555833

Maraut, S., Dernis, H., Webb, C., Spiezia, V., & Guellec, D. (2008). The OECD REGPAT Database. *OECD Publishing*, (02). https://doi.org/10.1787/241437144144

Matutes, C., Regibeau, P., & Rockett, K. (1996). Optimal patent design and the diffusion of innovations. *The RAND Journal of Economics*, *27*(1), 60–83. https://www.jstor.org/stable/2555792

Ménière, Y., Rudyk, I., Grilli, M., Wajsman, N., Kazimierczak, M., & Burgos, C. A. (2021). *Intellectual property rights and firm performance in the European Union*. European Patent Office. Retrieved December 18, 2024, from https://documents.

epo.org/projects/babylon/eponet.nsf/0/7120D0280636B3E6C1258673004A8698/$File/ipr_performance_study_en.pdf

Nagaoka, S., Motohashi, K., & Goto, A. (2010). *Patent Statistics as an Innovation Indicator*. https://doi.org/10.1016/S0169-7218(10)02009-5

OECD. (1997). *Proposed Guidelines for Collecting and Interpreting Technological Innovation Data: Oslo Manual: The Measurement of Scientific and Technological Activities*. https://doi.org/10.1787/9789264192263-en

OECD. (2015a). *OECD Style Guide: Third Edition*. Paris, France. https://doi.org/10.1787/9789264243439-en

OECD. (2015b). *The Innovation Imperative: Contributing to Productivity, Growth and Well-Being*. https://doi.org/10.1787/9789264239814-en

Okabe, M., & Ito, K. (2008). *Color Universal Design (CUD) - How to make figures and presentations that are friendly to Colorblind people*. Retrieved December 18, 2024, from https://jfly.uni-koeln.de/color

Oldham, P. (2022). *The WIPO Patent Analytics Handbook*. Retrieved December 18, 2024, from https://wipo-analytics.github.io/handbook/

Popp, D., Pless, J., Haščič, I., & Johnstone, N. (2020). *Innovation and Entrepreneurship in the Energy Sector* (Working Paper No. 27145). National Bureau of Economic Research. University of Chicago Press. https://doi.org/10.3386/w27145

Putnam, J. D. (1996). *The Value of International Patent Rights* [Doctoral dissertation, Yale University]. Retrieved December 18, 2024, from https://www.proquest.com/dissertations-theses/value-international-patent-rights/docview/304309879/se-2

Ratcliffe, S. (2016). *Oxford Essential Quotations* (4th edition). Oxford University Press. https://doi.org/10.1093/acref/9780191826719.001.0001

Ritchie, H., Rosado, P., & Roser, M. (2024). Energy Production and Consumption. *Our World in Data*. Retrieved December 18, 2024, from https://ourworldindata.org/energy-production-consumption

Rogers, M. (1998). *The Definition and Measurement of Innovation* (No. 10/98). Melbourne Institute of Applied Economic; Social Research. Retrieved December 18, 2024, from http://www.melbourneinstitute.com/wp/wp1998n10.pdf

Romer, P. M. (1990). Endogenous Technological Change. *Journal of Political Economy*, *98*(5), S71–S102. http://www.jstor.org/stable/2937632

Scherer, F. M., & Harhoff, D. (2000). Technology policy for a world of skew-distributed outcomes. *Research Policy*, *29*(4), 559–566. https://doi.org/10.1016/S0048-7333(99)00089-X

Schumpeter, J. A. (1939). Business Cycles: A Theoretical, Historical, and Statistical Analysis of the Capitalist Process. *McGraw-Hill*, *1*, 67–80.

Schumpeter, J. A. (1911/2017). *Teorien om økonomisk utvikling* (O. H. Poulssen, Trans.) [Original work published 1911]. Scandinavian Academic Press.

Song, H., & Li, Z. (2014). Patent quality and the measuring indicator system: Comparison among China provinces and key countries. *Berkeley Law Review*. Retrieved December 18, 2024, from https://www.law.berkeley.edu/files/Song_Hefa_IPSC_paper_2014.pdf

Squicciarini, M., Dernis, H., & Criscuolo, C. (2013). Measuring Patent Quality. *OECD Publishing*. https://doi.org/10.1787/5k4522wkw1r8-en

Tong, X., & Frame, J. (1994). Measuring national technological performance with patent claims data. *Research Policy*, *23*(2), 133–141. https://doi.org/10.1016/0048-7333(94)90050-7

van Zeebroeck, N. (2011). The puzzle of patent value indicators. *Economics of Innovation and New Technology*, *20*(1), 33–62. https://doi.org/10.1080/10438590903038256

van Zeebroeck, N., & van Pottelsberghe de la Potterie, B. (2011). Filing strategies and patent value. *Economics of Innovation and New Technology*, *20*(6), 539–561. https://doi.org/10.1080/10438591003668646

AI Tools Used in This Master Thesis

AI Tool(s): ChatGPT4o

Purpose of the Use of the Tool: Idea generating, data wrangling, data analysis and data visualization.

We are aware that we are responsible for all content of this master's thesis, including the parts where AI tools are used. We are responsible for ensuring that the thesis complies with ethical rules for privacy and publication

A Appendix

Table A.1: IEA Cartography of LCE Supply and Enabling Technologies. Retrieved from IEA (2021b).

Technologies	Sub-technologies		CPC codes
Low-carbon Energy Supply	Wind		Y02E10/70/LOW
	Solar	Solar PV	Y02E10/50/LOW
		Solar thermal	Y02E10/40/LOW
		Other solar	Y02E10/60
	Other renewables	Geothermal energy	Y02E10/10/LOW
		Hydro	FY02E10/20/LOW
		Marine	Y02E10/30/LOW
		Biofuels	Y02E50/10
	Combustion technologies with mitigation potential		Y02E20/00/LOW
	Energy generation of nuclear origin (electricity)		Y02E30/00/LOW
Enabling and cross-cutting energy systems	CCUS		Y02C20/00/LOW
	Batteries		Y02E60/10
	Hydrogen and fuel cells		Y02E60/30/LOW
	Other		Y02E60/00, Y02E60/13, Y02E60/14, Y02E60/16 Y02E70/00/LOW, Y02E60/60 Y02E40/00, Y02E40/10, 20, 30, 40, 50, 60
	Smart grids		Y04S

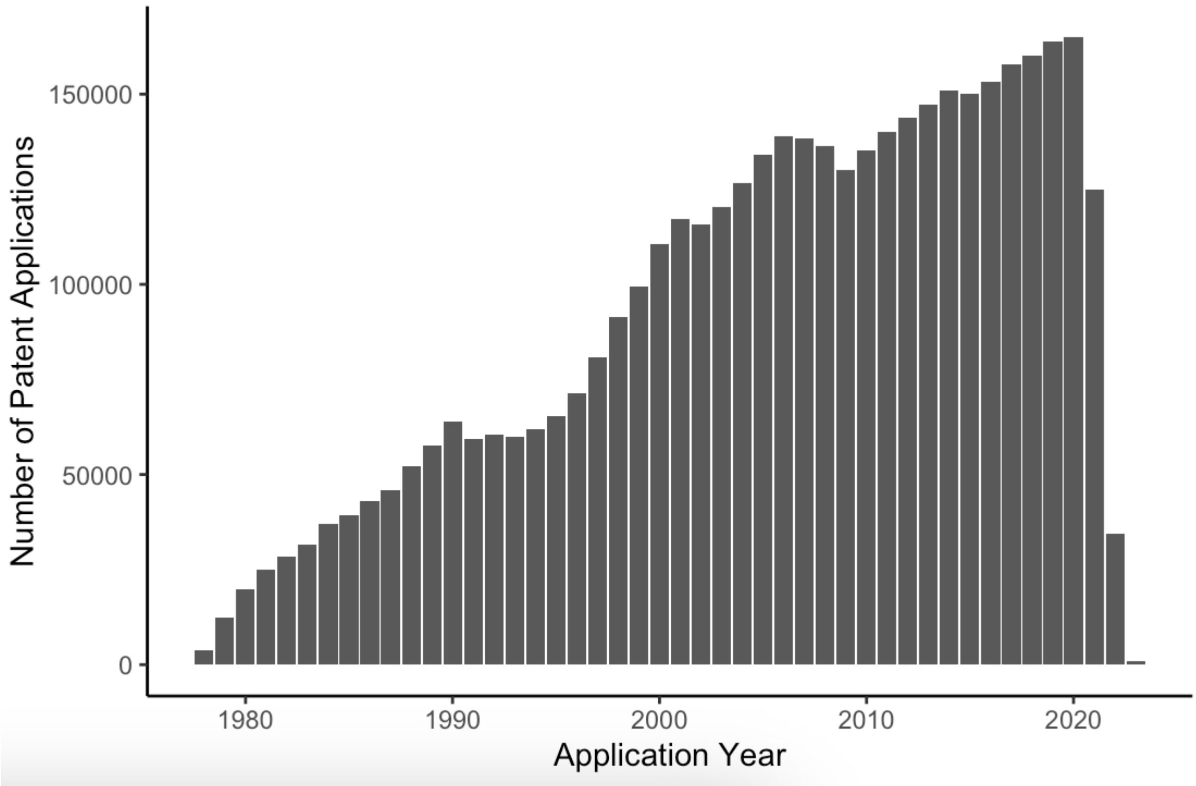

Figure A.2: Total Patent Application Volumes at the EPO from 1978 to 2023.

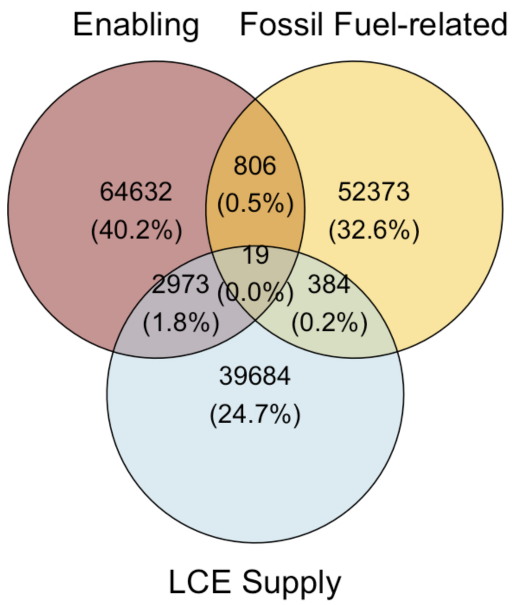

Figure A.3: Overview of the distribution of technologies across patent applications at the EPO from 1978 to 2021.

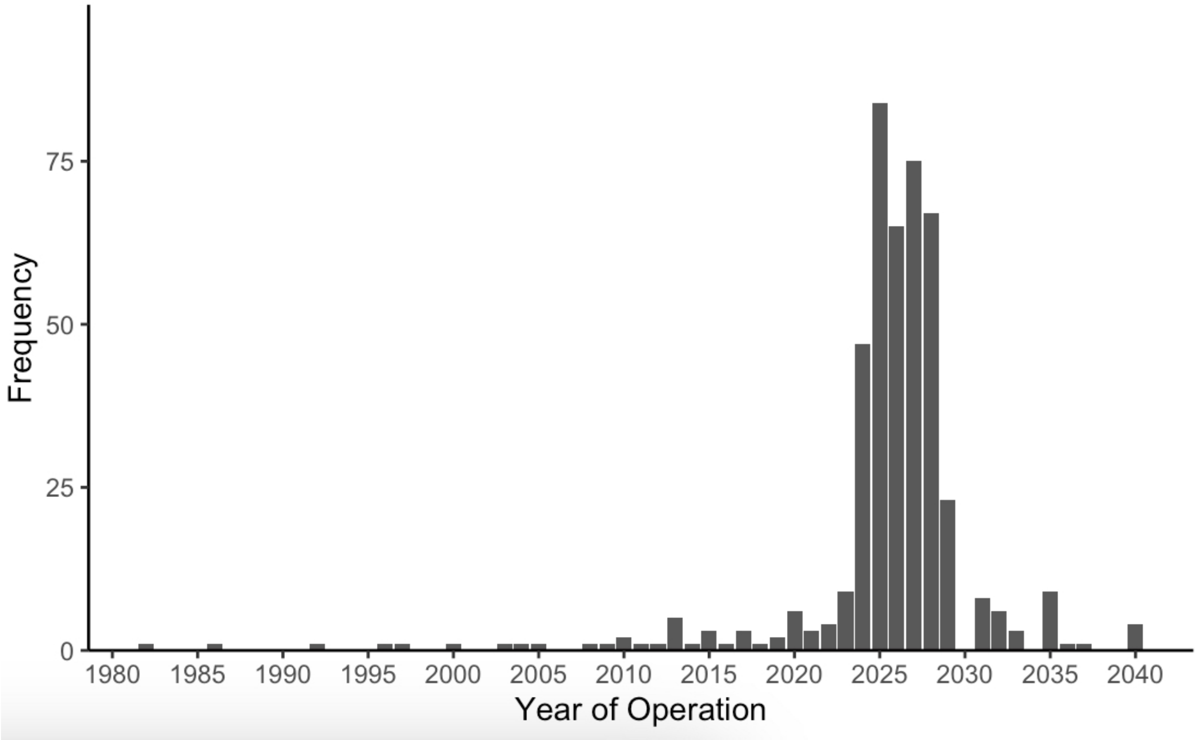

Figure A.4: Distribution of planned CCUS projects from 1978 to 2040. Data retrieved from IEA (2024a).

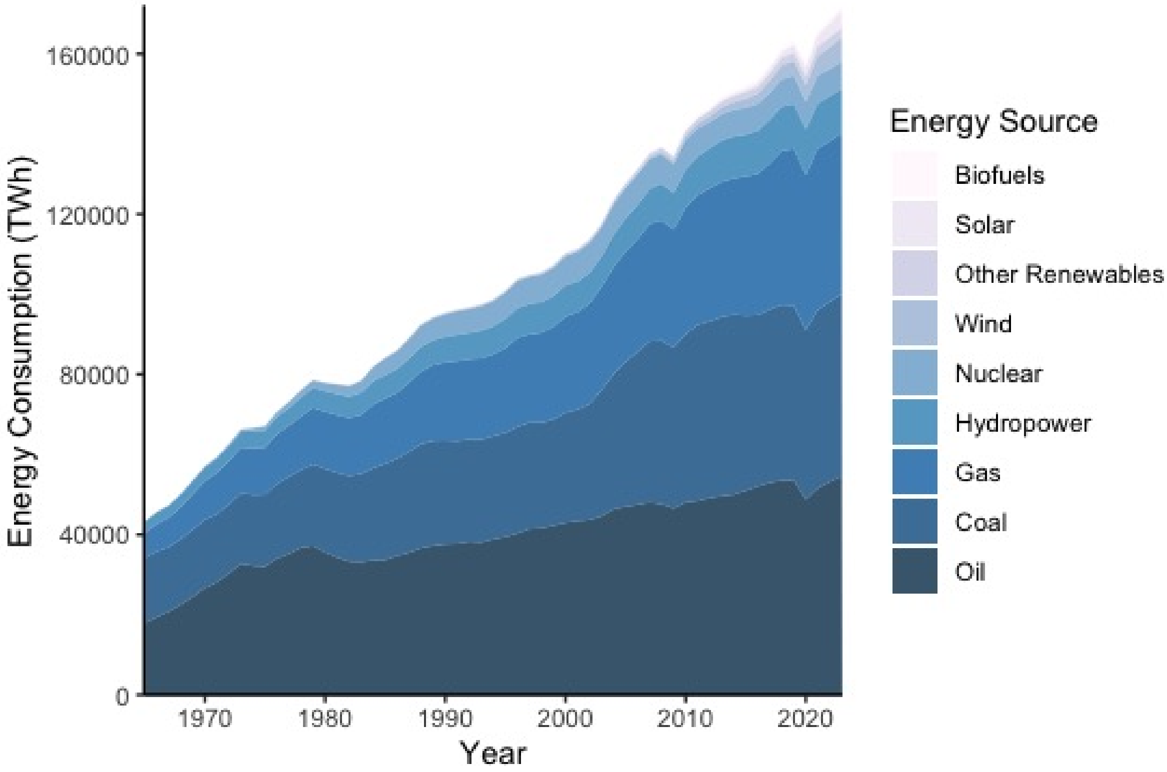

Figure A.5: Total energy consumption by source from 1965 to 2021, measured in terawatt-hours (TWh) of primary energy. Data retrieved Ritchie et al. (2024).

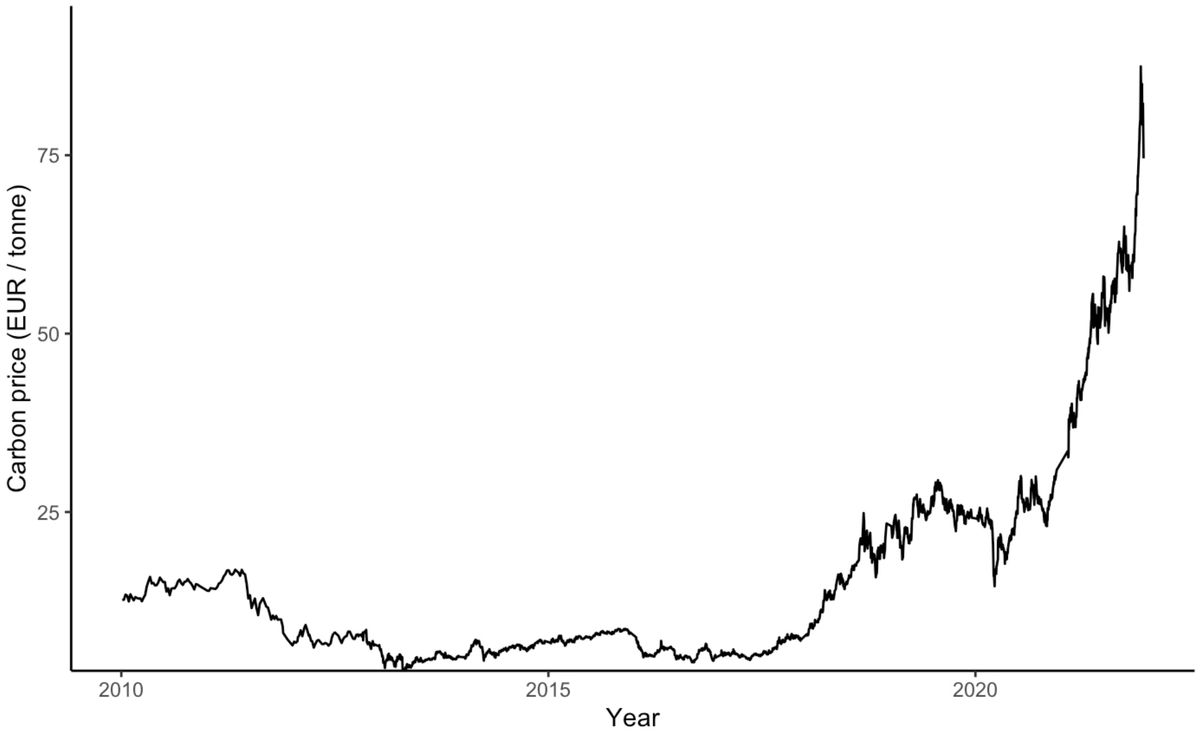

Figure A.6: EU carbon permits between 2010 and 2021. Data retrieved from the International Carbon Action Partnership (2024).

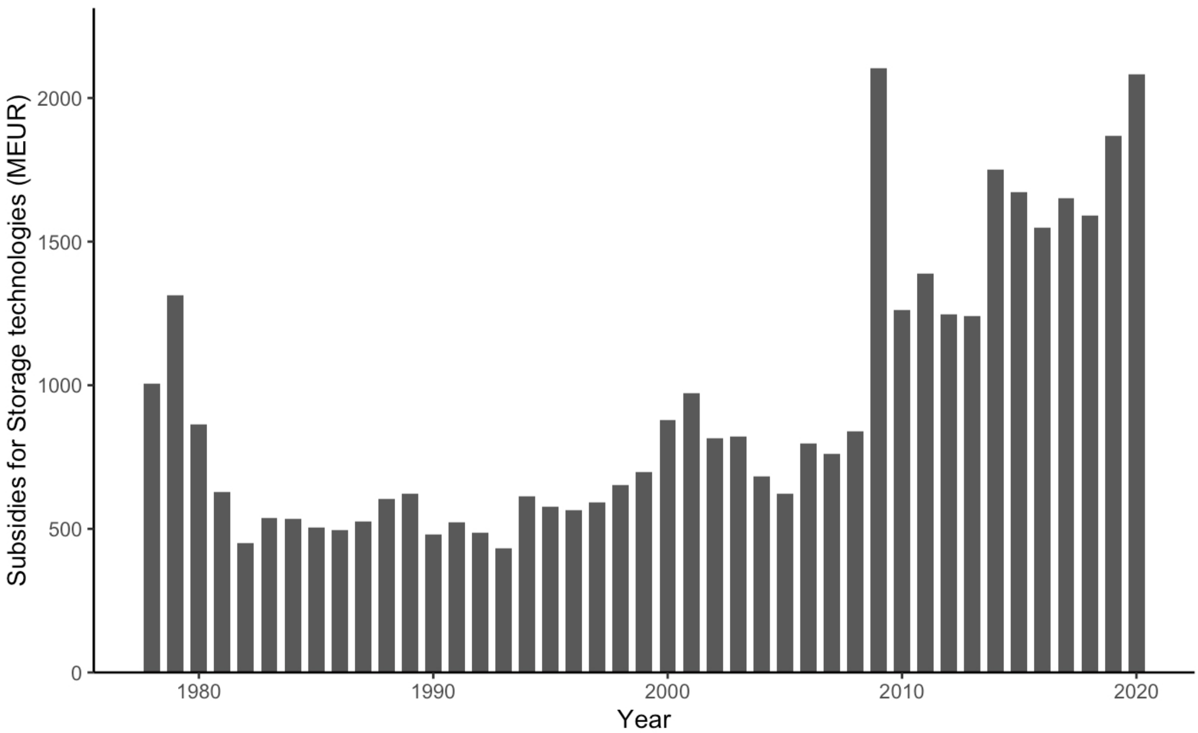

Figure A.7: Overview of international public subsidies for other power and storage technologies. Data retrieved from IEA (2024b).

NHH