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Exploring new metrics to measure environmental innovation

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Keywords: green innovation, innovation metrics, patent, transfer, assignment, licensing, venture capital, breakthrough innovation

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Abstract

Several efforts have been made to track progress on environmental innovations using very different approaches. However, many lack coverage, granularity, timeliness and may involve high data collection costs, especially when conducted on a large scale. In addition, traditional indicators like patent counts do not provide policy makers and scientists with the full picture of the innovation process overlooking commercialised innovation and breakthrough innovation. This issue is particularly relevant for environmental innovation, where scaling-up is considered key to address the climate, biodiversity and pollution crises. To fill this gap, the present paper first reviews potential metrics to measure commercialised climate change-related innovation and potential metrics to measure breakthrough environmental innovation. The paper explores innovative concepts and available data sources. By comparing the advantages and drawbacks of the potential new metrics, the paper selects two families of metrics to measure commercialised climate change-related innovation: one based on patent assignments and the other one based on licensing agreements. For breakthrough environmental innovation, the paper concludes that a family of metrics based on venture capital data is currently the most promising option to pursue. The paper then develops the selected new metrics, providing the data source and methodologies to analyse the data. Using these metrics, the paper also provides trends in environmental innovation over time, across sectors and when possible across countries. The paper concludes that while these new metrics provide important and useful information that help improve our understanding of innovation and facilitate the evaluation of innovation and environmental policies, additional data sources should be explored, including items such as government grants, loans and loan guarantees as well as new data on patent assignment. This would help extend the application of the proposed new metrics and develop additional metrics that together could provide a broader geographical coverage of green innovation.

Keywords: green innovation, innovation metrics, patent, transfer, assignment, licensing, venture capital, breakthrough innovation

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Résumé

Plusieurs efforts ont été faits pour suivre les progrès des innovations environnementales en utilisant des approches très différentes. Toutefois, nombre d'entre elles manquent d'exhaustivité, de granularité et de données récentes et peuvent être coûteuse en termes de collecte de données, en particulier lorsqu'elles sont menées à grande échelle. De plus, les indicateurs traditionnels tels que le nombre de brevets ne permettent pas aux décideurs politiques et aux scientifiques d'avoir une vue d'ensemble du processus d'innovation, en négligeant les innovations qui sont effectivement commercialisées et les innovations de rupture. Cette question est particulièrement pertinente pour les innovations environnementales, dont l'adoption à grande échelle est considérée comme essentielle pour faire face aux crises du climat, de la biodiversité et de la pollution. Pour remédier à ces limites, le présent document passe d'abord en revue les potentiels indicateurs permettant de mesurer l'innovation commercialisée liée aux changements climatiques et les potentiels indicateurs permettant de mesurer l'innovation de rupture dans le domaine de l'environnement. Le document explore des concepts novateurs et les sources de données disponibles. En comparant les avantages et les inconvénients des nouveaux indicateurs potentiels, le document sélectionne deux familles d'indicateurs pour mesurer l'innovation commercialisée liée aux changements climatiques : l'une basée sur les cessions de brevets et l'autre basée sur les accords de licence. Pour l'innovation environnementale de rupture, le document conclut que les indicateurs basés sur les données des investissements en capital-risque constituent actuellement l'option la plus prometteuse. Le document développe ensuite les nouveaux indicateurs sélectionnés, en fournissant la source de données et les méthodologies d'analyse des données. En utilisant ces nouveaux indicateurs, le document présente les tendances en termes d'innovation environnementale au cours du temps, dans les différents secteurs et, dans la mesure du possible, dans différents pays. Le document conclue que si ces nouveaux indicateurs fournissent des informations importantes et utiles qui contribuent à améliorer notre compréhension de l'innovation et qui facilitent l'évaluation des politiques d'innovation et des politiques environnementales, des sources de données supplémentaires devraient être utilisées, qui pourraient inclure les subventions, les prêts et les garanties de prêt gouvernementales, ainsi que de nouvelles données sur l'attribution des brevets. Cela permettrait d'étendre l'application des nouvelles mesures proposées et de développer d'autres mesures qui, ensemble, pourraient fournir une couverture géographique plus large de l'innovation verte.

Mots clés : innovation verte, indicateurs de l'innovation, brevet, transfert, cession de brevet, octroi de licence, capital-risque, innovation de rupture.

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Executive summary

Environmental innovation, sometimes called eco-innovation, is necessary to transition from carbon and material intensive economies to low carbon and resource efficient economies. Measuring environmental innovation is essential to measuring progress towards these objectives. Evidence-based policy making requires accurate indicators of innovation in order to promote green technologies.

Several efforts have been made to track progress on environmental innovations using very different approaches. Traditional indicators include patents, R&D expenditure and questionnaire-based surveys. However, these indicators often lack coverage, granularity, timeliness and may involve high data collection costs, especially when conducted on a large scale. In addition, these traditional indicators do not provide policy makers and scientists with the full picture of the current state of the innovation system as they each focus on specific innovation types and stages and generally overlook the commercialisation stages as well as breakthrough innovation. This issue is particularly relevant for environmental innovation, which upscale is considered key to address the climate, biodiversity and pollution crises.

To fill this gap, the present paper first reviews potential new metrics to measure (i) commercialised climate change-related innovation and (ii) breakthrough environmental innovation.[1] The paper explores innovative concepts and available data sources. By comparing the advantages and drawbacks of the potential new metrics, the paper selects two families of metrics to measure commercialised climate change-related innovation: one based on patent assignments[2] and the other one based on licensing agreements. For breakthrough environmental innovation, the paper compares two alternatives and concludes that a family of metrics based on venture capital data is currently the most promising option to pursue.

The paper then develops the selected new metrics, providing the data source and methodologies. For breakthrough environmental innovation, a multi-country analysis is performed, including more than 10 countries such as the United States, Canada, China, India and countries in western Europe. For commercialised climate change-related innovation, a case study on the United States is performed since harmonised US data are more easily accessible. Through the new metrics, the paper highlights main trends in environmental innovation over time, across sectors and when possible across countries. The following key results emerge from the analysis. First, commercialised climate change-related innovation, measured with patent assignment, increased in absolute terms in all sectors in the United States over the last two decades and is relatively more important in the energy and transport sector.[3] However, the relative importance of commercialised climate change-related innovation as a share of total innovation decreased between 2012 and 2018. Second, breakthrough environmental innovation effort, measured by venture

[1] Breakthrough innovation is defined in this paper as new, fast-growing, radical technologies that either introduces new products or processes with very high market potential, or that makes existing established technologies rapidly obsolete and dominate the market following Egli, Johnstone and Menon (2015[13]).

[2] A patent assignment is a transfer, by a seller to a buyer, of the rights, title and interest in one or more granted patents or patent applications.

[3] This part of the analysis focuses on the United States, which has available data on patent assignment.

capital (VC) funding, has been steadily increasing globally since 2008. Global green VC funding has reached USD 20 billion per year or 7% of all VC funding in 2019-2021 and is relatively important in transport, information and communication technology (ICT), manufacturing and energy. Green VC funding as a share of total VC funding peaked during the global financial crisis and decreased until 2015 after which it has been rising again.

The various metrics measure different green innovation trends because they focus on different stages and types of innovation. Most notably, commercialised climate-change related innovation has been decreasing in relative terms in the United States over the last decade likely driven by falling fossil fuel prices and increasing the technological maturity of some climate mitigation technologies. In contrast, effort in breakthrough climate change-related innovation as measured by the number of green venture capital deals relative to the total has been increasing since 2015 in nearly all the countries reviewed. This could suggest that the innovation focus in mature technological fields – as proxied by patent assignments - is slowing down while it is accelerating in high-risk, high-reward and potentially breakthrough green technologies.

The paper also illustrates how the metrics can be used with a case study of the electric car sector in the United States. The case study shows that new metrics are more correlated with actual technology deployment but that there is a time lag of several years between innovation effort, patent assignment and the market penetration of electric cars.

The results of the paper have important policy implications. First, the evidence-based assessment of environmental and economic policies should to the extent possible measure green innovation with various metrics capturing different stages and types of innovation. Only relying on one metric can potentially lead to important trends being overlooked and to failures of capturing the full effect of policies. Second, assessing the effect of environmental policies on green innovation requires looking at various time horizons depending on the metrics used. Third, looking beyond environmental policies and taking into account other factors or policies that drive the emergence of green innovation should properly be accounted for when evaluating environmental policies. For example, the amount of VC in green firms also depends on fiscal policies, market fragmentation, monetary policies and stimulus packages. Assigned patented inventions also depends on intellectual property rights regime and policies. Taking these other policies into account is potentially important to create synergies and consistency with environmental policies to favour the emergence of green innovation.

The new metrics proposed in this paper provide important and useful information that help improve our understanding of innovation and facilitates the evaluation of innovation and environmental policies

However, the findings in this paper are somewhat limited by availability of data. For commercialised innovation, the usefulness of the new metrics could be improved by adding data sources that offer a more comprehensive geographical coverage. This could include additional commercial patent databases. For breakthrough innovation, tracking innovation funding, measured through venture capital investments, is shown to be an important metric for several countries. However, since the means of funding new ventures vary across countries, additional data would be beneficial in order to be able to better compare and assess innovation policy across countries. As a next step it could therefore be useful to add sources for grants, loans and loan guarantees.

1 Introduction

Environmental innovation, sometimes called eco-innovation, is necessary to transition from carbon- and material-intensive economies to low-carbon and resource-efficient economies. Both incremental innovation, improving the effectiveness and lowering the cost of existing green technologies, and breakthrough innovation, that dramatically changes the way we produce, consume and transport, are key ingredients to address the triple climate, biodiversity and pollution crisis. Moreover, as environmental policy will become more stringent, firms will see their competitiveness be increasingly linked to their ability to innovate and to secure their access to technologies bringing environmental benefits to them or to their customers. Additionally, there is a growing demand by customers and society as a whole for firms to adopt and develop green technologies to respond to climate change, biodiversity loss, and material scarcity (Ganda, 2019[1]).

Despite the general agreement on the need to scale-up efforts to accelerate the emergence and deployment of environmental innovation, it is still unclear how to achieve this in the most effective way. In particular, more information is needed on how to assess the effectiveness of various policy measures in driving and directing environmental innovation.

In this context, improving the ability to measure environmental innovation is essential. Evidence-based environmental policy making requires accurate indicators of innovation in order to promote green technologies. Previous OECD work has extensively addressed the issue of how to collect and interpret data on innovation, including to facilitate international comparability (OECD/Eurostat, 2018[2]). In the environmental field, several efforts have been made to track progress on environmental innovations using very different approaches. One approach consists in tagging patents that protect inventions with environmental benefits (Haščič, 2011[3]; Haščič, Silva and Johnstone, 2015[4]). Another approach relies on large scale and multi-country surveys such as the Community Innovation Surveys (CIS) that collect information on firms' environmental innovation activities. Furthermore, several dedicated indicator systems have been created in the past to measure different dimensions of eco-innovation such as 'inputs', 'activities' and 'outcomes' on a regular basis. Examples are the Eco-innovation Observatory (EIO) established in 2010 by the European Commission (EC) for its Member States, the ASEM SME Eco-Innovation index for 50 countries in Europe and Asia established by the Asia-Europe Meeting (ASEM), and the Global Cleantech Innovation Index (GCII) established by the Cleantech Group for 40 countries including Latin American countries. Environmental innovation has also been measured in specialised studies focusing on particular sectors or technologies, for instance through the work of the IEA on Tracking Clean Energy Innovation (IEA, 2022[5]; Kemp et al., 2020[6]).

However, traditional indicators based on patents, R&D expenditure and questionnaire-based surveys often lack coverage, granularity, timeliness and may involve high data collection costs, especially when conducted on a large scale (Nagaoka, Motohashi and Goto, 2010[7]; Squicciarini, Dernis and Criscuolo, 2013[8]). For example, R&D expenditures are often private data and not available at an adequate level of detail. They also capture only innovation input that might not translate into innovation output and technological change. Surveys asking firms about their innovation activities are useful but rely on self-reporting which can be subjective. Patents have been used notably because they offer important technological fields granularity but they are intermediate outputs and sometimes their classification fails to capture the contribution of specific technologies to environmental goals (Pless, Hepburn and Farrell, 2020[9]). For instance, many information technologies (IT) that have generic applications are breakthrough in energy systems or for circular business models. One example is the use of blockchain smart contracts between recycling companies and manufacturers. Moreover, as not all patents are associated with commercialised technologies, relying exclusively on patents can overestimate innovation that is actually valuable and deployed in the real world.[4] Recently, trademarks have been used to measure green innovation (Dussaux and Agrawala, 2022[10]; Amoroso et al., 2021[11]). However, the descriptions of trademark available can be too broad and do not always allow the identification of some technologies precisely, especially those pertaining to process innovation.

Measuring environmental innovation properly also requires defining it and setting benchmarks. Nevertheless, most frameworks do not include an explicit baseline, target or benchmark that must be exceeded to qualify as an environmental innovation (Kemp et al., 2020[6]). Consequently, these traditional indicators do not provide policy makers and scientists with the full picture of the current state of the innovation system. This issue is particularly relevant for measuring environmental innovation, especially in light of the increasingly pressing need to rapidly address the triple climate, biodiversity and pollution crisis (García-Granero, Piedra-Muñoz and Galdeano-Gómez, 2020[12]).

This paper adds to this literature by framing and developing new metrics to measure environmental innovation. The first main contribution of the paper is to frame new metrics on environmental innovation by assessing the feasibility and potential of different options. More specifically, the paper explores new metrics to measure two different types of environmental innovations. The paper first focuses on commercialised climate change-related innovations[5] because indicators of climate change-related innovations that are not necessarily commercialised are already well developed. These traditional indicators such as those based on patents can overestimate the actual number of innovations that are ultimately adopted and that bring about environmental benefits. Therefore, by focusing on commercialised innovations, the potential new metrics assessed in this paper can provide more relevant policy insights.

The second type of innovation that the paper focusses on are breakthrough innovations related to all environmental issues including those related to climate change. Breakthrough innovations such as a technology that can store large amount of electricity at a reasonable cost will be necessary to reach carbon neutrality by 2050. Therefore, it is important to understand how these breakthroughs occur and it requires being able to identify and measure them. Yet, to the best of the authors' knowledge, there has been limited work on measuring and identifying breakthrough environmental innovation. Egli, Johnstone and Menon (2015[13]) suggest new criteria to identify breakthrough low carbon innovation using patent data. The present paper suggests alternative measures that are more directly related to investment and market outcome such as venture capital investment. Bioret et al. (forthcoming[14]) and IEA (2022[5]) also use venture capital investment to track innovation but IEA (2022[5]) focuses exclusively on the energy sector.

This paper identifies the following metrics as potential options to measure adopted or commercialised climate change-related innovations:

- Metrics based on licensing deals;
- Metrics based on patent assignments;
- Metrics based on web scraping websites of firms to identify environmental innovations;
- Metrics based on linkage between products and patents;

Further, the paper identifies the following metrics as potential options to measure breakthrough environmental innovation:

- Metrics based on high-growth firms using employment and sales data controlling for patent activity;

[4] It should be nonetheless recognised that the value of a patent does not simply relate to its commercialisation. For example, the knowledge included in a patent becomes available to other researchers to build upon.

[5] In this report, climate change-related innovation regroups innovation in climate change mitigation and in climate change adaptation.

- Metrics based on venture capital data.

The paper then compares the advantages and drawbacks of these different candidate metrics to select the most promising to develop. For commercialised climate change-related innovations, the paper concludes that metrics based on patent assignments and licensing deals should be developed in priority because both product and process innovations are covered, historical data are available and the identification of climate change-related technologies is clear. For breakthrough environmental innovation, the analysis concludes that metrics based on venture capital data is the most promising to pursue because the identification of environmental technologies does not depend on patent data, recent historical data are available in several countries and available data cover both small and large companies.

The second main contribution of this paper is to develop the new families of metrics based on the most promising options identified in the framing phase. To achieve this, the paper describes a methodology for data collection and aggregation and the construction of a dataset for each selected new metric. Another key contribution of the paper is to develop a novel methodology based on the analysis of keywords in firms' description to measure breakthrough green innovation effort. The method allows the breakdown of green VC funding in many detailed environmentally technological fields – from climate change mitigation and adaptation to technologies related to air pollution, water pollution, waste management, soil remediation and environmental monitoring – and a direct comparison with existing patent metrics.

The paper then provides trends in environmental innovation over time, across sectors and when possible across countries. For commercialised climate change-related innovation, trends are analysed for the United States, for which data are currently available. The empirical analysis leads to several key results. First, commercialised climate change-related innovation increased in absolute terms in all sectors in the United States over the last two decades and is relatively more important in the energy and transport sector. However, the relative importance of commercialised climate change-related innovation as a share of total innovation decreased between 2012 and 2018, the last year of available data. This decline, also found by Probst et al. (2021[15]) for high value patented inventions, is attributed to falling fossil fuel prices, low carbon prices and increasing the technological maturity of some climate mitigation technologies. While a similar decline can also be observed for climate-change related patents in general, commercialised climate change-related patented inventions declined at a faster rate than non-commercialised patented inventions.

The second key result is that breakthrough environmental innovation effort – as measured by VC funding in green companies – is on the rise globally. The analysis shows that VC funding raised by green firms has been constantly increasing since 2008 and has now reach USD 20 billion per year or 7% of all VC funding at the global level. The most important sectors for green VC funding are transport, ICT, manufacturing and energy. Green VC funding is concentrated in a few countries and the United States and China account for 78% of the total. Green VC funding as a share of total VC funding peaked during the global financial crisis and decreased until 2015 after which it has been rising again. This could suggest that the innovation focus is shifting from mature technological to high-risk, high-reward and potentially breakthrough green technologies.

The remainder of this paper is structured as follows. Section 2Section and 3 frame and assess the feasibility and potential of new metrics to measure respectively commercialised climate change-related innovation and breakthrough environmental innovation. Section 4 illustrates a new family of innovation metrics based on patent assignment data and a new family of metrics based on licensing agreements to measure commercialised innovations in climate change mitigation technologies. Section 5 develops a new family of metrics to measure breakthrough environmental innovation effort based on venture capital data. Section 6 summarises the main trends in the relative importance of environmental innovation across the various metrics developed and illustrates how they can be used in empirical analysis. Section 7 concludes.

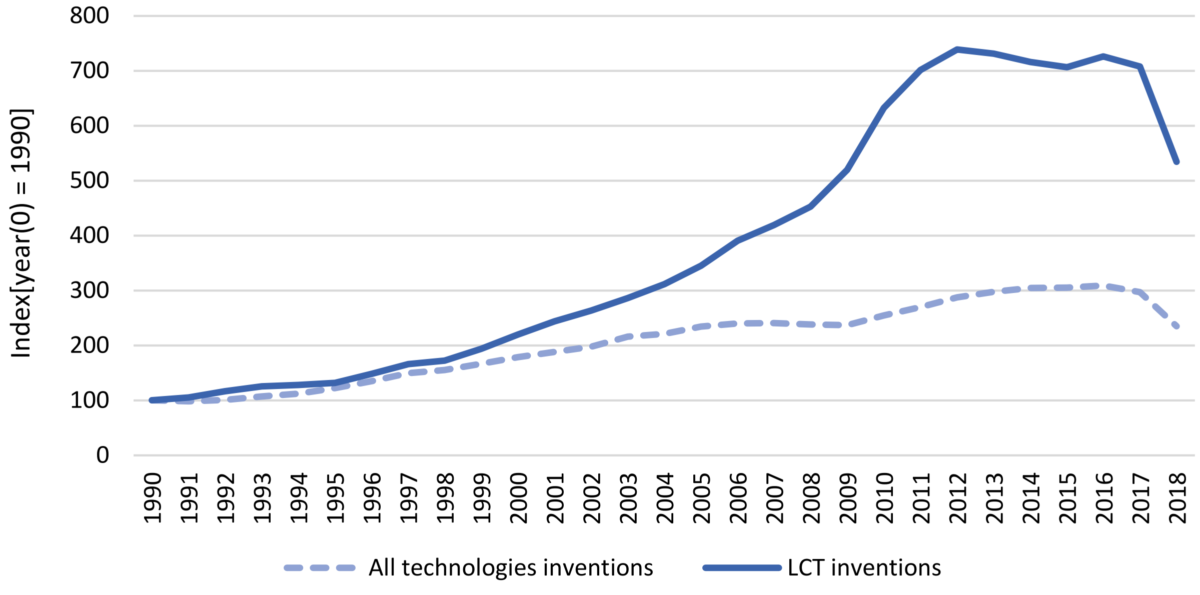
Part I Framing new green innovation metrics

2 Framing new metrics to measure commercialised innovation in climate change-related technologies

2.1. Metrics based on licensing deals

Recent work by (Pigato et al., 2020[16]) shows that patenting activities in low carbon technologies (LCT) have been increasing since the 1990s and that this rising trend has started to slow down since the beginning of the 2010s. Figure 2.1 shows that LCT patenting activity has been growing at a higher rate than the average technology but that this growth has stalled in recent years. In addition to this, a key question is whether this surge in LCT patenting activity has also led to an increased deployment or commercialisation of new LCT technologies.

Figure 2.1. Global growth of inventions in LCTs and all technologies, 1990-2018



Note: The index is a normalised to 100. The Y variable equals 100 * (number of patented inventions / number of patented inventions in year 1990). Low-carbon technology (LCT) includes only mitigation technologies. A patented invention is defined as an international patent family, i.e. a group of patents covering a single invention that have been filed in more than one country. Data for 2018 is still not final.
Source: Authors calculation based on the OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, January 2023.

One method to examine the uptake of these technologies is to measure licensing deals involving LCT patents (or any patent of relevant for environmental innovations). Licensing deals are closer to commercialisation than patents and show a signal of economic interest in a particular technology.

Results of a patent licensing study done by the European Commission have shown that on average 55% of European firms licensed technology out between 2008 and 2011 (see Table 2.1). This rate is even higher in the oil, gas, and general industries which are more likely linked to LCT technologies. These results suggest that there is potentially a decent share of licensing activity in LCT technologies.

Table 2.1. Breakdown of licensing activity by sector

Size class	Out-licensing		Not out-licensing	
	n	%	n	%
TOTAL	175	55	144	45
…Oil, gas, basic materials, utilities	30	71	12	29
…General industries	29	58	21	42
…Industrial engineering	31	53	27	47
…Consumer goods	23	45	28	55
…Health Care	34	67	17	33
…Technology-ICT	28	42	39	58

Source: European Commission (2014[17]) based on Technopolis survey, n = 319 in 19 European countries.

2.1.1. Commercial databases as sources for patent licensing

The availability of data specifically focussing on patent licensing is low. Nevertheless, licensing deals based on intellectual property can be examined with the use of specific surveys or commercial licensing databases. Surveys on patent licensing behaviour are not conducted regularly and do not allow to conduct in-depth analysis over time. There are a few US licensing databases available which can give information on the type of technology that is licensed. The most well know sources are ktMINE (https://www.ktmine.com/ip-data/licensed-patents/) and Royalty Source (https://www.royaltysource.com/). Both commercial databases have access to a large set of licensing deals and information within such deals. To the authors' knowledge no similar databases exist for other markets outside the United States.

Both sources have been contacted to explore their potential. After a few interactions with Royalty Sources it became clear that this source does not have the information of interest as it has no information on trends in green technology licensing over time. On the other hand, ktMINE's database and software is an excellent data source which would allow the construction of a new set of metrics measuring licensing deals based on green related technologies.

2.1.2. ktMINE database on IP statistics

Through a proprietary process, ktMINE gathers innovation and intangible asset data from publicly available sources such as the Securities and Exchange Commission, United States Patent and Trademark Office (USPTO), hundreds of news sources, as well as Freedom of Information Act requests. The objective of ktMINE is to find, analyse, and add any public document with viable innovation and intangible asset information into their database while making the search and review process for this information fast and accurate. ktMINE database links several different sources, such as the USTPTO patent database, the USTPTO patent assignment database, Securities and Exchange databases (SEC) (where firms report IP transactions) and other databases and sources as well. All of these sources are linked with a software tool developed by ktMINE. The software tool allows users to search for particular technologies, agreements, controlling for several variables such as industry, Cooperative Patent Classification) (CPC) codes etc. Their database consists of more than 120 000 agreements of which about 20 000 contains information on royalty rates. The database covers the time period from about 1980 to date.

There are different types of license agreements for which ktMINE has data of which: asset purchases, distribution, joint development, cross license, franchise, manufacturing or process. Of note, a license agreement can be of more than one type, having for instance a manufacturing and distribution element. Each record includes a filing date and an entry into effect date, allowing for a trend analysis of licensing deals related to environmental innovation technologies.

Of importance is to determine the representability of the data and how the ktMINE database compares to other data sources. The only other source that collects information on licensing deals is, as previously reported, Royalty Source but this source does not have information to examine trends over time. KtMINE mainly collects data about publicly available deals and therefore any analysis based on these data should recognise this limitation. In addition to this, even when a licensing deal is public, it is not always possible to trace back the deal to the patent number of the respective patent that gets licensed. When this happens, it is more difficult to associate the licensing deals to a specific technological field such as the CPC codes. As a result, while the data collected by ktMINE provide significant information on licensing deals, they come with limitations, most notably the fact that the database only covers a fraction of all licensing deals.

2.1.3. ktMINE access options and steps forward

ktMINE has several access options but the most common are a bulk data request or a subscription. There is also an option of a quarterly subscription with limitations for the number of data exports.

The bulk data approach would provide everything related to green technologies based on fixed queries. For example, it would provide information on the licensee and licensor, filing dates, geographical scope, every rate in the document and an exhaustive list of CPC codes. With the subscription method (most often used) the user can set up queries themselves and export the results.

Table 2.2 summarises the potential new indicators that could be developed based on licensing deals data, their comparative advantages and drawbacks as well their coverage in terms of technologies and countries. The next steps to collect the data and develop new metrics are also described.

Table 2.2. New environmental innovation metrics using licensing deals data (ktMINE database)

Indicators	1. Climate change-related licensing deals as a share of total licensing deals 2. The change in value of climate change-related technologies based on royalty rates (increase in royalty rate over time indicates greater value of the technology)
Comparative advantages	1. Hard factual data 2. Ability to identify trends over time 3. Licensing deals are a good indicator of commercially viable technologies both products and processes
Comparative drawbacks	1. Not publicly available 2. Since many transactions remain in the private domain one cannot fully assure representability of the data. However, ktMINE has data for a large number of years across many different sectors which does allow to conduct useful analysis based on a sample of the total population of licensing deals. 3. US only coverage 4. Only a few deals disclose a patent number
Coverage: technological fields, countries and time period	Technological fields: All technological fields are covered Geographical: US markets only Time period: 1980s to date
Next steps to develop new metrics	Build a dataset with detailed information on licensing deals that have a reference to the CPC classification Y02 that includes information of the effective date, economic region, patent number, patent CPC and where available royalty rates including the agreement.

Source: Authors' own elaboration.

2.2. Metrics based on patent assignments

Another option to measure commercialised climate change-related innovation is to examine patent assignments. An assignment is a transfer, by a seller to a buyer, of the rights, title and interest in one or more granted patents or patent applications. A reassignment describes a new transfer of these rights.

Patent assignments can be used to measure high value innovations, which are more likely to be commercialised and therefore used than the average patented invention. Serrano (2010[18]) shows that patents with a higher number of forward citations and of backward patent citations show a significant increase in the average likelihood of being traded. In addition, De Marco A. et al. (2017[19]), who found similar results as Serrano (2010[18]), also show that patents that protect inventions characterised by higher degree of technological uncertainty, measured as closeness to basic research (emerging technologies), are more likely to be traded.

A potential drawback of using patent assignments is that in some cases, the motive for trade is not related to the deployment and use of the protected technology but rather for strategic or purely commercial reasons. One example includes "killer acquisitions" where firms acquire other firms and their patents to stop their innovation process or the development of acquired products (Cunningham, Ederer and Ma, 2021[20]). Another example is patent trolling or hoarding, an activity that consists in acquiring patents to enforce patent rights far beyond the patent's actual value without manufacturing products or supply services related to the patent in question. Therefore, there is a risk that the number of assignments and reassignments overestimates the actual amount of interest in a technology. While it is difficult to detect which assignments constitute patent trolling, one way to mitigate this issue is to build an indicator based on the number of traded patents.

2.2.1. Data sources on patent assignments

Patent owners are not required to disclose patent transactions to patent offices. However, they are offered incentives to do so for legal reasons. For example, section 261 of the US Patent Act states that patent owners facing litigation in court are only protected against subsequent assignments if they have recorded the transfers of patents at the USPTO. These recordings are registered by the USPTO and made available through the USPTO Patent Assignment Dataset (UPAD). The UPAD contains detailed information on 8.6 million patent assignments and other transactions recorded at the USPTO since 1970 involving roughly 14.9 million patents and patent applications. While other patent offices also keep record of patent assignments, the USPTO makes this data publicly available and user-friendly by applying a methodology categorising patent assignments according to the "nature of conveyance" (Marco et al., 2015[21]). For this reason, the present section only focusses on the United States.

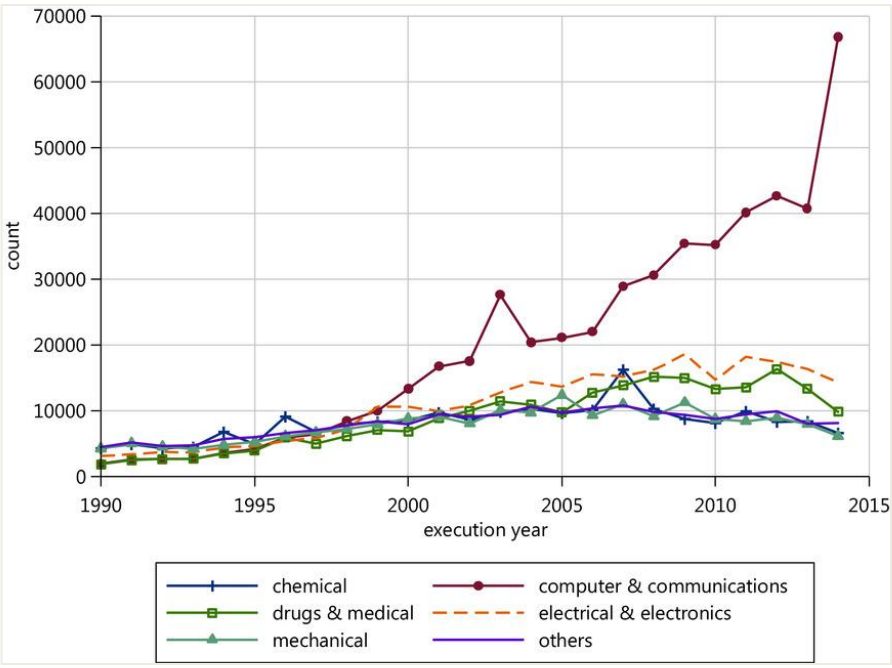
There are several patent-asset conveyances recorded including assignment or re-assignments, mergers and acquisitions, licenses to government and several other types (see Graham et al., (2018[22]) for an overview). Many of the USPTO assignment records reflect assignments conducted in the ordinary course of business, between inventor employees and their firm employers (employer assignments) or to different units of a multinational. However, there is a substantial amount of patent right transfers to other firms. Graham et al., (2018[22]) identified about 700 000 of such patent right transfers to other organisations for the time period 1970 to 2014. When the Patent Assignment dataset is linked with the USPTO Patent Dataset, one can obtain the number of patent assignments by technological research fields (see Figure 2.2). More importantly, it is possible to identify climate mitigation patent assignments through the CPC code provided by the USPTO Patent Dataset.

In the case of Europe, while firms and patent owners can record an assignment at the European Patent Office (EPO), there is no legal obligation to do so. However, as recording a patent at the EPO has several advantages including establishing a public record of the change in ownership, useful for clarity and to provide evidence of ownership in case of any disputes or legal proceedings, such data would have value even if incomplete.

Unfortunately, there is relatively little ready to use, low cost and harmonised data on patent assignments in European countries. This is because tracking reassignments of European patents is challenging in several ways (Ciaramella, Martínez and Ménière, 2017[23]). First, legal events regarding European patents may be recorded at the EPO and or in national patent offices, which can lead to duplicate assignments due to non-harmonised names and different inscription dates. Second, the legal status codes under which the change of ownership is registered in each office can differ.

Ciaramella, Martínez and Ménière (2017[23]) developed a methodology to efficiently track transfers of ownership of European patents using Patstat but they apply it exclusively for medical technologies. In addition, there exist fee-based private sector databases that include information on patent assignment for other countries than the United States. For example, PatSnap and LexisNexis collect data on legal invents including patent transfer for all jurisdictions along with original assignees and current assignees, which names are standardized. Another example is WIPS Global that has patent assignment data for China and Korea in addition to the United States. Similar to the USTPO UPAD, these datasets cover only patent transfers or assignments that have been recorded, disclosed and published.

Figure 2.2. Patent properties involved in a recorded Reassignment, annual counts, by technology category and execution year, 1990–2014



Source: Graham et al. (2018).

2.2.2. Access options and steps forward

The USPTO Patent Assignment Dataset (UPAD) data are publicly available from the USTPO.[6] The UPAD dataset itself includes several information points but no information on CPC (or US) patent classifications.

[6] Link to all the data: https://www.uspto.gov/learning-and-resources/electronic-data-products/patent-assignment-dataset.

For such analyses, a link has to be established with the UPAD and USPTO dataset or PATSTAT.[7] For each assignment, the USPTO patent application number is provided, allowing to establish a link between the USPTO and UPAD databases. In addition, ktMINE has linked its database with the UPAD dataset allowing analysis of licensing data with assignment data. Table 2.3 summarises the potential new indicators that could be developed based on patent assignment data, their comparative advantages and drawbacks as well their coverage in terms of technologies and countries. The next steps to collect the data and develop new metrics are also described.

[7] The API to access USPTO data can be found here: https://assignment-api.uspto.gov/documentation-patent/.

Table 2.3. New environmental innovation metrics using patent reassignment data (USPTO UPAD dataset)

Indicators	1. The annual number of assigned patented inventions in the field of climate change-related technologies. 2. Share of climate-change related assigned patented inventions as percentage of total assigned patented inventions 3. Share of assigned patented inventions as percentage of total climate-change related patented inventions
Comparative advantages	1. Hard factual data 2. Ability to identify trends 3. Patent reassignments can identify commercially viable technologies, both products and processes 4. Representability of the data, i.e. good coverage of the US market 5. Microdata linking directly with ktMINE data on licensing
Comparative drawbacks	1. Transferred patent signals value but not necessarily actual technology use and deployment 2. Firms are not required to disclose patent transactions but given legal reasons is not likely they will not inform the USPTO 3. Only covers the United States
Coverage: technological fields, countries and time period	Technological fields: All technological fields are covered Geographical: US market only Time period: 1980 to date
Next steps to develop new metrics	After selecting a relevant time period, using the PATSTAT database, bulk data downloads can be performed of patents granted at the USPTO. This file will then have to be linked with the UPAD database to control for relevant CPC classifications.

Source: Authors' own elaboration.

2.3. Metrics based on web scraping

Recently, there have been efforts to identify innovations by scraping websites (e.g. Kinne and Bernd (2018[24])). This research is mostly based on identifying product launches related to innovations by searching for newly published items on websites and identifying them with a set of keywords. This approach has some clear advantages as one can identify firms that innovate in a relatively granular set of fields through the choice of keywords. Additionally, identified time series can be collected by tracking product launches over time. Another advantage of this approach is that with web scraping, capturing the diffusion of a technology is possible by tracking the use of new technologies through key-word identification on companies' websites. However, the quantified innovation depends on when the website is being visited to extract information and whether or not the firm updates the website with new innovation activities. The work of Kinne and Bernd (2018[24]) who formed the company ISTARI.AI is presented below to show the potential of using web-scraping analysis for identifying and quantifying environmental innovations.

2.3.1. Web scraping data from ISTARI.AI

ISTARI.AI is a spin-off firm of the German research institute ZEW. This company is currently developing a firm-level web-based indicator on whether a company is "green" in the DACH region that includes Germany, Switzerland and Austria. At the time of writing, the identification procedure is under development. The start-up is continuously identifying companies using a broad concept of 'green SMEs' (energy use, production of "green" goods, circular economy etc.). The first step of this procedure is to extract text from firms' websites. In a second step, a Machine Learning algorithm assesses the extracted texts using keywords such as energy use, production of "green" goods, circular economy, etc. and predicts if the companies introduced a new environmental innovation. More specifically, the approach works on a single indicator to identify 'green SMEs' using a multilingual Text-Analysis Model. The identification of 'green SMEs' is then cross-checked against traditional (aggregate) indicators and manual checks.

In their previous work, ISTARI.AI researchers Jan Kinne and David Lenz use webscraping and deep learning to identify product innovators in all fields. In that study, they use information from the Mannheim Innovation Panel (MIP), a questionnaire-based innovation survey of firms, to label the websites of surveyed firms as associated to either a product innovator firm or a non-innovator. This labelled data set is then used to train a deep neural network to predict the probability of firms to be product innovators based solely on their website text. Figure A.1 outlines their approach. The predicted product innovator probabilities can be interpreted as a continuous firm-level indicator of innovation.

Their results showed that if the model classifies a firm as a product innovator, it is correct in roughly 4 out of 5 cases (81% precision for the product innovator class). The model retrieves 64% of all product innovator firms and 91% of all non-innovator firms in the test dataset. The overall success rate of the model is 80%. In addition, Jan Kinne and David Lenz checked their results against firm-level patent statistics for 2017 from the European Patent Office. By using regression analysis they showed that product innovator probabilities predicted by their machine learning algorithm are strongly related to the number of patents held by firms. This provides some evidence that the algorithm captures innovation aspect that is also captured by patent data. This is reassuring but does not mean that the algorithm does not add information that are not measured by patent data.

2.3.2. Discussions and steps forward

Following the analogy of the model presented in Figure A.1 a similar approach can be taken for environmental innovations but relying on the core aspects of the algorithm developed by ISARI.AI. The algorithm would differ by being only trained on recognising firms with green innovation activities. In a first step, all possible firms with unknown environmental innovation activities will be web scraped and the text information from their website will be stored in a database. In a second step the website text will go through an algorithm to identify firms with environmental innovations (climate change mitigation technologies for instance). Finally, the output of the algorithm is a binary probability of whether a company is green or not. This algorithm can be trained using firm-level databases with traditional environmental innovation indicators and manual checks that have determined the green innovativeness of firms. The algorithm could be developed further to count the number of innovative products and processes reported by the identified green firms.

Big data analyses such as web scraping, deep learning and artificial intelligence show great potential. Their main advantage is that they allow to perform timely up-to-date analysis to research areas of interest. The main drawback of these approaches is that they focus only on product innovations and do not capture process innovations, which are relevant in low-carbon technologies. Moreover, these methods mainly capture recent data and it is uncertain if companies consistently use their websites for product launches. Therefore, the possibility to analyse innovation over large periods of time using these data are quite limited.

summarises the potential new indicators that could be developed based on web scraping data, their comparative advantages and drawbacks as well their coverage in terms of technologies and countries. The next steps to collect the data and develop new metrics are also described.

Table 2.4. New environmental innovation metrics using web scraping data

Indicators	1. The number of firms reporting an innovation in the field of climate change mitigation technologies 2. The share of firms reporting an innovation in the field of climate change mitigation technologies 3. The number of climate change mitigation innovation reported by firms
Comparative advantages	1. Live and up-to-date data 2. Ability to identify recent trends 3. Good coverage of markets as databases with website can be purchased using commercial parties or use Orbis 4. Ability to search for specific keywords (see PPMI study) 5. Microdata linkage 6. With existing data sources such as patent databases or survey data, cross and validity checks are possible
Comparative drawbacks	1. Focus on product innovations (product launches) and not on process innovations 2. Propensity to announce use of technology launches can change over time 3. Germany, Austria and Switzerland only
Coverage: technological fields, countries and time period	Technological fields: All technological fields are covered Geographical: Germany, Austria and Switzerland only Time period: only present-day data (live data). Data have been stored since Q4 2020. Scraping web archives could provide historical data but it has not been developed yet.
Next steps to develop new metrics	An agreement will have to be made with ISARI.AI to use of their services.

Source: Authors' own elaboration.

2.4. Metrics based on patent-product linkage

IProduct is a recent research project that links products to patents using virtual patent marking[8] data of US products.[9] Virtual patent marking has become an alternative to physical marking that allows the printing onto the article or its packaging of the word "patent" followed by an address of a posting on the Internet that associates the patented article with the patent number (USPTO, 2014[25]). Data collection and enrichment is done through user contributions. Users identify patent markings on products and a match is made with the relevant patent numbers. Additional source data comes from virtual patent marking sources, which are then linked with patent statistics based on the patent identification number(s) on the end-product.

The current version of the database contains products associated with 30,000 patents but it is projected to grow to at least 100,000 patents over the next 12 months. To the best of our knowledge, no other database offers such a correspondence between products and patents. The dataset has already been used to track the real impact of the research funded by the Novonordisk foundation. Of 2,238 patent documents that cite the Novonordisk foundation funded journal articles from 1994 to 2017, 95 patents were identified and matched to the Novonordisk foundation funded research, which resulted in the identification of 48 commercial products from 23 companies around the world (Novo Nordisk Foundation, 2019[26]).[10]

[8] Virtual marking of patented articles is an alternative to physical marking. While physical marking involves placing the word "patent" along with the patent number on the article itself, virtual marking allows to affix onto the article a posting on the internet associating the patented article with the patent number (USPTO, 2014[76])

[9] IPRoduct data platform - https://iproduct.io/app/#/public/page/home.

[10] SOCIETAL IMPACT of the Novo Nordisk Foundation's grant activities Annual Impact Report 2019.

The identification of low-carbon technologies is straightforward by extracting patents under CPC code Y02. Box 2.1 shows five products that are protected by patents to illustrate the data contained in IProduct. In an older version of the IPRoduct database it was found that about 2 percent of the US patents in IPRoduct are "green".

Box 2.1. Examples of low-carbon products linked to patent in the IProduct dataset

Industrial equipment Power Wave® welding platform, protected by US8581147B2

(Y02P80/10 Efficient use of energy, e.g. using compressed air or pressurized fluid as energy carrier)

Tablet Computer Google Nexus 9, protected by US7672219B2

(Y02D30/50 Reducing energy consumption in communication networks in wire-line communication networks, e.g. low power modes or reduced link rate)

Crop Vistive® Gold Soybeans, protected by US7566813B2

(Y02E50/10 Biofuels, e.g. biodiesel)

Laser scanner Granit 1280i, protected by US5805474A

(Y02D10/00 Energy efficient computing, e.g. low power processors, power management or thermal management)

Medical apparatus StrykeVac 3 Smoke Evacuation System, protected by US7761188B2

(Y02P90/02 Total factory control, e.g. smart factories, flexible manufacturing systems [FMS] or integrated manufacturing systems [IMS]

Source: IProduct dataset

The main advantage of this approach is that we can directly compare existing indicators based only on patent data with new metrics based on patent and product linkage. Moreover, it is a promising approach that would allow to quantity how many patents in a given particular green technology field have actually delivered an innovative product to the market. However, this early research is still in a beta-phase and covers only US patents.[11] Therefore, data and results are not fully available yet. In addition, there is some evidence that not all patents are equally likely to be virtually marked. For example, de Rassenfosse (2018[27]) finds that firms are more likely to mark their products if they have a higher chance of being infringed, if they pursue an active branding strategy and if they need larger external financing. Finally, many environmentally relevant inventions are process innovations that are less likely to be virtually marked.

Beyond identifying cases of successful commercialisation of green technologies, IPRoduct could be used to produce a series of metrics related that can address different key questions including:

- Commercialisation time lag. Do green patents take longer to be commercialised than non-green patents?
- Commercialisation success. Are green patents more or less likely to be commercialised than non-green patents?
- Co-dependent technologies. What are the non-green technologies that enables (within product) green technologies?

[11] To the authors' knowledge no similar databases exist for other markets outside the United States.

Table 2.5 summarises the potential new indicators that could be developed based on IProduct data, their comparative advantages and drawbacks as well their coverage in terms of technologies and countries. The next steps to collect the data and develop new metrics are also described.

Table 2.5. New environmental innovation metrics using linkage between patents and products

Indicators	1. The annual number of products in the market based on climate change mitigation related patents 2. The share of products in the market related to climate change as percentage of all products 3. Commercialisation time lag 4. Commercialisation success 5. Co-dependent technologies (detailed technology level filtering is possible)
Comparative advantages	1. Fully captures commercialised innovation 2. Operationalisation works two-ways: o By identification of patents of interest one can determine the use of the patents in the commercial market. o Products that have proven to be green efficient can be cross-checked which (if any) patented technology is used in its development.
Comparative drawbacks	1. The data are driven from the virtual markings and their connection to patents. Impact on data unclear at this stage (i.e. direction of potential bias). 2. Likelihood of LCT and other relevant technologies to be virtually marked is likely small as the use of environmental innovations is more prevalent in process innovations.
Coverage: technological fields, countries and time period	Technological fields: All technological fields are covered Geographical: US markets. Time period: annual statistics possible, time period not known but trend analysis from early 90s should be possible
Next steps to develop new metrics	An agreement will have to be made with IPRoduct to use of their services.

Source: Authors' own elaboration.

2.5. Selecting the new metrics to develop

The previous sections present potential new metrics that could be used to measure commercialised climate change-related innovation. The question now is which of these options are feasible and which is the most promising to pursue. To address this, we summarise the key advantages and drawbacks of these potential metrics and assess their suitability and technical feasibility (see Table 2.6).

Several insights emerge from this comparison. First, for most of the potential metrics, except the web scraping approach, there is a clear way to identify low-carbon technologies that allows for direct comparison with indicators based on patent data. Second, only the licensing deals and patent reassignments approaches permit to measure not only product innovation but also process innovation that represents a significant share of low carbon innovations. Third, only the licensing deals and patent reassignments approaches allow to analyse historical trends in innovation.[12] Therefore, metrics based on licensing deals and patent reassignments seem to be the most suitable candidates at present. The metric based on licensing deals could be considered slightly superior because the patent reassignments can capture activities that do not necessarily reflect actual technology use in theory. However, in practice data for patent assignment are much more representative than data on licensing agreements. Finally, both

[12] For the web scraping approach historical data could be reconstructed based on web archives but it would require the development of a new tool.

approaches are technically feasible at least for the United States. Patents reassignment data are publicly available and licensing data can be purchased from ktMINE. Both metrics are developed in Section 4.

Table 2.6. Comparing key advantages and drawbacks of potential new metrics of commercialised climate change-related innovation

Potential metric	Key advantages	Key drawbacks	Suitability	Feasibility
Licensing deals	- Good indicator of commercialised technologies - Straightforward identification of low-carbon innovation - Ability to analyse trends over time - Clear identification of low-carbon technologies	- Many transactions remain in the private domain - Only covers the United States	Excellent	Very good
Patent reassignments	- Indicator of patent value (positively correlated with commercialisation) - Publicly available - Clear identification of low-carbon technologies	- Transferred patent signals value but not necessarily actual technology use and deployment - Only covers the United States	Very good	Excellent
Web scraping	- Access to recent and live data - Good coverage of markets/technologies	- Covers only product and not process innovations - Historical trends cannot be analysed yet - Only covers Germany, Switzerland and Austria	Fair	Good
Linking products to patents	- Direct link of patent information and commercialised products on the market - Clear identification of low-carbon technologies - Global geographical coverage	- Covers only product and not process innovations - Historical trends cannot be analysed - Only covers the United States	Good	Poor

Source: Authors' own elaboration.

3 Framing new metrics to measure breakthrough environmental innovations

3.1. Defining breakthrough innovations

Innovative breakthroughs are the basis of change in scientific and technological ideas leading potentially to significant modifications in social and individual economic value. There are several definitions of breakthrough in the literature. Della Malva et al. (2015[28]) define it as "rare events which introduce new concepts with the potential to generate new markets". Ahuja and Lampert (2001[29]) describe it as "rare, valuable, and potentially inimitable source of competitive edge". Egli et al. (2015[13]) define breakthrough as new, fast-growing, radical technologies that either introduces new products or processes with very high market potential, or that makes existing established technologies rapidly obsolete and dominate the market. Lastly, in the environmental innovation backstop technologies literature, breakthrough technologies are defined as a "new technology producing a close substitute to an exhaustible resource" (Dasgupta and Heal, 1974[30]).

3.2. Previous efforts measuring breakthrough innovations

Most of the research on breakthrough "innovations" uses patent data to focus on breakthrough inventions (Ahuja and Morris Lampert, 2001[29]; Della Malva et al., 2015[28]; Egli, Johnstone and Menon, 2015[13]; Capponi, Martinelli and Nuvolari, 2022[31]). In a recent study, for example, Capponi, Martinelli and Nuvolari (2022[31]) develop a methodology to identify breakthrough innovations that looks at award-winning innovations that have been successfully commercialised. For the period 1976–2013, in a sample of 138 467 USPTO patents, they identify 17 176 breakthrough innovations representing 12% of total innovation. Differently, Egli, Johnstone et al. (2015[13]) identify breakthrough technologies based on a list of attributes that are consistent with the notion of a ground-breaking and subsequently widely diffused invention.

Other studies analysed the determinants of breakthrough innovations but they heavily focus exclusively on the pharmaceutical industry (Dunlap-Hinkler, Kotabe and Mudambi, 2010[32]; Arnold and Troyer, 2016[33]).

A challenge identified by Stiller (2019[34]) is the delineation between a breakthrough and an incremental innovation. Several studies have tried to identify breakthrough and incremental innovation using surveys of corporate managers, retrospective determination by panel of experts (Sorescu, Chandy and Prabhu, 2003[35]), patent citation statistics (Phene, Fladmoe-Lindquist and Marsh, 2006[36]; Liu et al., 2012[37]), regulatory assessment particularly relevant for pharmaceutical drugs with priority review considered as breakthrough (Arnold and Troyer, 2016[33]) and pharmaceutical drug price reimbursement data, where the price is positively correlated with the contribution of the innovation (Suzuki and Methé, 2014[38]).

These methods have advantages and drawbacks. The survey and expert panel approach are subjective approaches prone to various biases. The other measurement approaches are more objective but also have their limitations. Patent statistics for instance capture inventions, but not necessarily innovations.[13] Many studies include assumptions of the future commercialisation possibilities of patents based on patent statistics, however, a scientific breakthrough captured via patent statistics do not necessarily make it into commercial breakthroughs. Finally, the regulatory drug approval assessment and reimbursement prices of pharmaceutical drugs are limited to a specific sector and have limited data availability.

Many studies investigate the determinants of innovative breakthroughs and a few of them draw on theories of recombination, that is, the relationship between creativity and knowledge (Weisberg, 1999[39]). In the relationship between creativity and knowledge, one domain can potentially hinder the other. For instance, a lack of creativity can lead researchers into only one way of thinking. Achieving high economic values through breakthrough innovations requires recombination of both knowledge and creativity (Ahuja and Morris Lampert, 2001[29]).

When analysing innovative patents, studies consistently find strong evidence for various forms of recombination as the main mechanism producing breakthroughs (Fleming, 2001[40]; Hall, 2002[41]). To measure breakthroughs, these studies look at patent citation counts, which have been found to be correlated with measures of economic value (Griliches, 1990[42]), such as inventors' or other experts' estimates of future financial value (Harhoff et al., 1999[43]), patent renewal fee payments (Hegde and Sampat, 2009[44]), filing patents for the same invention in multiple jurisdictions (Lanjouw and Schankerman, 2004[45]), and firms' stock market values (Hall, Jaffe and Trajtenberg, 2005[46]).

However, while citations successfully measure the value or usefulness of the patented invention, they do not necessarily fully capture the innovation that includes the implementation of the invention in the market. Kaplan and Vakili (2015[47]) try to address this issue by developing a measure of cognitive novelty. They argue that scientific ideas are embedded in vocabularies, and therefore shifts in ideas can be detected in shifts in language. Through topic modelling, Kaplan and Vakili (2015[47]) highlighted latent topics in a collection of documents. They capture breakthroughs by identifying a formation of new topics in patent data. Kaplan and Vakili (2015[47]) find that patents that originate new topics are more likely associated with local search[14], whereas economic value is the product of broader recombination and novelty.

To identify inventions related to breakthrough in low-carbon technologies, Egli et al. (2015[13]) go beyond patent citation counts by developing patent quality attributes that are consistent with an invention that is ground-breaking and subsequently widely diffused. They assess to which extent the quality attributes affect the long-term effects of different classes of inventions. Egli et al. (2015[13]) note that, ideally, the climate mitigation contribution of an invention should be measured through marginal cost of abatement and market penetration rates but that this kind of data are not available.

Among the different patent quality attributes developed by Egli et al. (2015[13]), "industrial generality", an original measure of the sectoral breadth of the utilisation of a patent technological class by private companies, is strongly and robustly correlated with later rapid diffusion of a given technology. Therefore, inventions with a high level of industrial generality are more likely to be breakthrough innovations.

The next sections contribute to the literature by proposing potential new metrics that do not rely exclusively on patent data and that do not rely on auxiliary data such as regulatory approval assessments and data on reimbursement prices that are only applicable to the pharmaceutical sector.

[13] While the terms innovation and invention look alike, they are not synonyms. Innovation is the implementation of an invention in the market.

[14] That is not coming from the recombination of distant or diverse knowledge but rather from development of deep knowledge in particular domains.

3.3. New breakthrough metrics based on high-growth firms

A firm that introduces a breakthrough innovation should experience a large and rapid change in their activities, such as increases in turnover and or employment. Although breakthrough innovation faces more uncertainty than incremental innovation, it also tends to be associated with a larger boost in revenues originating from the new opportunities created by the new technology. Although the literature on the topic is still scarce, Shen and Yang (2022[48]) find that breakthrough innovation positively contributes to a firm's capacity utilisation and that its impact is stronger than the one of incremental innovation. There are also anecdotal evidence supporting this idea. For example, the US company Uber launched in 2012 experienced an exponential growth going from 1 billion trips in March 2016 to 10 billion trips in September 2018.[15] Uber's application that allows car drivers and people looking for a ride to connect directly was not necessarily a very complex technology, but its core idea was a breakthrough in terms of commercial potential.

Based on the idea that the development of breakthrough innovation can engender exceptionally high growth, we can capture breakthrough innovation by first identifying firms experiencing high growth. High growth firms are defined by the OECD/Eurostat (2008[49]) as: "All enterprises with average annualised growth greater than 20% per annum, over a three-year period, and with ten or more employees at the beginning of the observation period. Growth is measured by the number of employees and by turnover". Firms experiencing rapid and large growth can be identified using micro data statistics on individual enterprises. For example, the Orbis database developed by Bureau van Dijk allows such micro data analysis and identification of high growth firms – although data remains limited for smaller firms (Bajgar et al., 2020[50]).

3.3.1. Identifying green high-growth firms based on their sector

To capture high-growth firms that likely introduce a green breakthrough innovation, we can use industry classifications available in Orbis, such as the Statistical classification of economic activities in the European Community (NACE) or the standard industry classification (SIC) . For example, firms operating in NACE 33 "repair and installation of machinery and equipment", NACE 38 "waste collection, treatment and disposal activities; materials recovery" and NACE 39 "remediation activities and other waste management services" can easily be considered green. This is also the case of firms manufacturing bicycles and railway locomotives. However, this approach has two drawbacks. First, firms operating in non-green sectors such as electricity generation can be greener than their competitors. Second, firms operating in green sectors can produce green products with a significant environmental footprint. Relying solely on the sector does not allow to identify a great proportion of green firms. Hence, a more appropriate indicator is suggested below.

3.3.2. Identifying green high-growth firms based on their patents

Firms that filed a high proportion of green patents can be considered green. Combining information on green patent and revenue growth can help to identify firms that introduce environmental breakthrough innovation. To achieve that, it is possible to match the Orbis and PATSTAT datasets, respectively collecting information on firms' economic performance and patent data. Several methodologies have been published to match Orbis and PATSTAT (EPO, 2013[51]).

The suggested methodology to measure breakthrough environmental innovation using patent data is three-fold. First, green firms are extracted from PATSTAT if they filed a high proportion of their patents in a

[15] As reported by Uber Technologies, Inc. in the form S-1 filed to the United States Securities and Exchange Commission on 11 April 2019.

technology field (CPC code) that is environmentally relevant. This high proportion could be defined in relative terms. For example a given firm in a given sector could be considered green if its stock of green patents as a share of total is above the median value computed in the same sector. Second, the revenues of green firms extracted from PATSTAT are collected from Orbis for each year. The last step consists in computing the share of green high-growth firms by industry and country as discussed above.

Table 3.1 summarises the potential new indicators of breakthrough environmental innovation that could be developed based on high-growth firms, their comparative advantages and drawbacks as well their coverage in terms of technologies and countries. The next steps to collect the data and develop new metrics are also described.

Table 3.1. New environmental breakthrough innovation metrics based on high-growth firms

Potential data source	Orbis & PATSTAT data
Indicators	1. The share of high growth firms that filed a high proportion of patents under an environmentally relevant CPC code (after data linkage with PATSTAT)
Advantages	1. Measures based on economic performance are closely related to breakthrough innovation output 2. Ability to analyse historical trends
Drawbacks	1. Firms' revenue is not necessarily fully correlated with the environmental contribution of the innovation. 2. The identification of environmental innovation relies on patent data 3. Orbis data has missing datapoints, in particular for small firms. 4. The matching of the Orbis and PATSTAT datasets is not perfect.
Coverage: technological fields, countries and time period	Technological fields: All technological fields are covered Geographical: 2.8 million companies in 36 countries Time period: yearly data from 2000 to 2019
Next steps to develop new metrics	Establish data linkage between Orbis and PATSTAT.

Source: Authors' own elaboration.

3.4. New breakthrough metrics based on venture capital data

Both R&D Ventures and Corporate Ventures have been identified as determinants of breakthrough innovations (Hess and Siegwart, 2013[52]). R&D Ventures are projects where two or more firms join together to form a third, often with a particular (research) project in mind. Corporate Ventures are large companies investing money in a smaller company. Most of the research conducted in this field is based on ex post case-studies. Venture capital investments have been notably used to measure the financing of start-ups involved in the development of low-carbon technologies (IEA, 2022[53]). Nevertheless, venture capital trends can also be used to identify ex ante future trends. Data on venture capital are becoming more and more available through a wide range of commercial sources.[16] These private data sources track venture capital investments and project future revenues controlling for (broad) technologies and markets.

A notable example of data on innovative firms and especially start-ups is the Crunchbase database that has become a primary source of data for investors (Dalle, Besten and Menon, 2017[54]). Crunchbase gathers data on businesses, including founding year, funding raised, funding rounds, number of investors, acquisitions, etc. As of May 2019, Crunchbase included records on 708 000 companies, 122 000 investors, 263 000 funding rounds, 890 000 people, 17 000 initial public offerings (IPO) and 90 000 acquisitions (Ferrati and Muffatto, 2020). There is some evidence that Crunchbase is a representative source of data. Aggregated data are consistent with the OECD Entrepreneurship Financing Database based on data compiled by national or regional Private Equity and Venture Capital Associations (Dalle, Besten and

[16] Crunchbase, Invest Europe, CB Insights, Angellist, MatterMark, Owler and many more.

Menon, 2017[54]). Furthermore Crunchbase has been used by a growing number of researchers in economics (Dalle, Besten and Menon, 2017[54]).

More importantly for the purpose of this paper, it is possible to identify environmental start-ups by searching for specific terms in the description of the firm activity or to identify firms active in green sectors e.g. renewables, green tech, electric vehicles, etc. Cojoianu et al. (2020[55]), for example, use Crunchbase to analyse the effect of environmental policies on new venture creation in climate change mitigation technologies across 24 OECD countries over the period 2001-2013.

Another source of venture capital data is Invest Europe that has data on more than 1,400 European private equity firms, covering 86% of the EUR 782 billion in capital under management in Europe. Invest Europe offers reviews of fundraising, investment and divestment trends for European private equity and venture capital activity. Specific data are only available through a subscription.

Another source specifically related to environmental innovation is the CleanTech commercial database. CleanTech offers a wide range of services including commercial industry data named i3, grouped into two datasets 1) sector insights, which examines innovation themes and analyses value chains and 2) investment insights, which includes investment trend analysis on emerging investment themes including M&A, IPOs and investor activity. Research using this dataset has been conducted by Criscuolo and Menon (2014[56]). They link (the funded) company information in the CleanTech database with patent data from PATSTAT using string-similarity algorithms following Egli et al. (2015[13]). This linkage allows them to calculate the total amount of investments for each technological class and year.

While venture capital can be used to measure the amount of resources put into promising technologies that can produce breakthrough innovations, it is not a direct indicator of breakthrough innovation output. Therefore, metrics based on venture capital are rather a measure of innovation effort in high-risk high-reward technologies.

Another challenge with venture capital data is that venture capital as an investment vehicle is used differently across countries. Notably, venture capital has been well established in the United States and Israel as a way to finance start up and innovation. In contrast, venture capital is not as developed in European countries where innovation is mainly financed via grants, loans and loan guarantees. In 2016, venture capital investments in the United States amounted to USD 66.6 billion or 86% of total venture capital investments in the OECD while venture capital investments in Europe amounted to USD 4.7 billion (OECD, 2017[57]). Therefore, international comparison based on the absolute amount of venture capital investment should be interpreted with caution. However, there is some evidence that venture capital investments are increasingly more evenly distributed across countries (IEA, 2022[53]). This trend is likely to continue as venture capital markets are growing outside of the United States, meaning that this challenge might become less important over the years. Moreover, indicators based on the ratio between green venture capital and total venture capital can be used to mitigate this issue when comparing countries with one another.

Table 3.2 summarises the potential new indicators of breakthrough environmental innovation that could be developed based on venture capital data, their comparative advantages and drawbacks as well their coverage in terms of technologies and countries. The next steps to collect the data and develop new metrics are also described.

Table 3.2. New environmental breakthrough innovation metrics based on venture capital data

Indicators	1. Share of venture capital spent on green firms (Crunchbase) 2. Estimated total amount of investment for patent classes (Cleantech & PATSTAT)
Advantages	1. Hard factual data on the value or potential of a particular technology 2. Trend analysis over time is possible 3. Identification of environmental innovation does not depend on patent data 4. Dataset has global coverage, although it is more comprehensive for the US market
Drawbacks	1. Not publicly available 2. Capture breakthrough innovation effort and not innovation output 3. The reliance on VC funding varies across countries
Coverage: technological fields, countries and time period	Technological fields: All technological fields are covered Geographical: Highly comprehensive for US markets but data exist for 200 countries. Time period: since 2007 (both Crunchbase and Invest Europe)
Next steps to develop new metrics	• Purchase access to Crunchbase • Develop a list of keywords to extract venture capital data relevant to environmental innovation.

Source: Authors' own elaboration.

3.5. Selecting the new breakthrough metrics to develop

Similarly to the new potential metrics to measure commercialised climate change-related innovation, we find that not all new potential breakthrough metrics have the same potential. Table 3.3 compares key advantages and drawbacks of potential new metrics of environmental breakthrough innovation. Metrics based on high growth firms are more closely related to breakthrough innovation *output* but rely on patent data to identify environmental innovation and have poor coverage of small firms. In comparison, metrics based on venture capital data cover both small start-up and large companies and do not rely on patent data. While there exist historical data for both metrics, venture capital data offers near real time data while the metrics based on high-growth firms rely on patent data which are only available 4 years after.[17] The main drawback of venture capital data is that it measures breakthrough innovation *effort*, not output. Therefore, it appears that these two families of metrics are complementary and could be both developed. Yet, the metrics based on venture capital data has a clear comparative advantage over the metrics based on high-growth firms. Therefore, the metrics based on venture capital data is pursued in Section 5

[17] In addition, it is not necessarily straightforward to track firms over time in Orbis, which can translate into missing data point for some years that prevent the computation of growth rates.

Table 3.3. Comparing key advantages and drawbacks of potential new metrics of environmental breakthrough innovation

Potential metric	Key comparative advantages	Key comparative disadvantages	Suitability	Feasibility
High-growth firms using Orbis and PATSTAT linking	- Measures based on economic performance are closely related to breakthrough innovation output	- Economic performance does not necessarily signal environmental performance - The identification of environmental innovation relies on patent data - Poor coverage of small firms	Good	Good
Venture capital data	- Hard factual data on the value or potential of a particular technology - Identification of environmental innovation does not depend on patent data	- Capture breakthrough innovation effort and not innovation output	Good	Excellent

Source: Authors own elaboration.

Part II Developing new families of green innovation metrics

4 New metrics to measure commercialised climate change-related innovation based on patent assignments and technology licensing

Traditional indicators such as those based on patents can overestimate the actual amount of innovation that is ultimately deployed in the economy and therefore overestimate the environmental benefits deriving from it. One way to overcome this issue is to analyse trends in commercialised innovation. By focussing on successful inventions which attract commercial interest from other parties, metrics based on commercialised innovation can provide more relevant policy insights and a measurement of innovation output.

In this section, commercialised innovations are proxied by inventions whose patent rights are transferred. Two common ways to transfer the rights over an invention are:

- The transferring of ownership from the holder of a patent to another entity through a patent assignment; and
- The licensing of the patent to entities which can benefit from the technology, often in exchange for the payment of a royalty fee.

The two following sections will analyse trends in green innovation using data on patent assignments and patent licensing agreements.

4.1. Measuring commercialised green innovation through patent assignments

This section describes a new family of metrics to measure commercialised innovation related to climate change in the United States using patent assignment data. This section focuses on the United States as harmonised data on patent assignment in the United States were more complete and readily available than other regions, as discussed above (see section 2.2.1). The underlying assumption of this new metrics is that patent assignments can be used to measure high value innovations, which are more likely to be commercialised and therefore used than the average patented invention.

4.1.1. Methodology and data source

The new metric is based on the number of patent families in climate change-related technologies that undergo one or several assignments. A patent assignment is a transfer, by a seller to a buyer, of the rights, title and interest in one or more granted patents or patent applications. A patent family is a collection of patent documents that covers a single invention. Analysing the number of patent families rather than the total number of individual patents better captures the number of innovations that are assigned or re-assigned by avoiding double counting.[18] For clarity, the term patented inventions will be used to describe patent families.

Patent assignment data come from the USPTO Patent Assignment Dataset (UPAD), an organised relational database of assignments and other transactions associated with US patent documents (both applications and grants).[19] UPAD data are derived from the recording of patent transfers by parties with the USPTO. A legally valid assignment transfers all or part of the right, title, and interest in a patent or application from an existing owner (an assignor) to a recipient (an assignee).[20] Patent assignments differ from licensing agreements insofar licensing agreements do not entail a change in ownership.

The USPTO allows parties to record assignments of patents and patent applications in order to maintain a complete history of claimed interests in a patent (Marco et al., 2015[58]). The UPAD dataset employed in the present paper contains detailed information on more than 9 million patent assignments and other transactions recorded at the USPTO between 1970 and 2020. It includes identifying information for the assignor(s) and assignee(s), the date of transaction recorded at the USPTO, patent and application numbers, and a self-asserted, by the USPTO, "nature of conveyance" (e.g., assignment, merger, security agreement, or license). The nature of conveyance categories are based on a keyword search done by USPTO (Marco et al., 2015[58]).[21] The conveyance categories relevant for the present paper are the ones reflecting a change in ownership, notably 'assignment' (ownership transferred to another entity) or 'merger' (ownership change due to merger) (Marco et al., 2015[58]). For clarity, inventions undergoing a change in ownership will be referred to as "assigned inventions" in the present paper.

There are several reasons why the UPAD dataset can be considered representative. While federal recording of an entire or partial patent assignment is not mandatory, patent owners have strong incentives to record assignments and patent attorneys strongly recommend this practice (Dykeman and Kopko, 2004[59]). There is no expressed legal requirement for parties to disclose assignments to the USPTO; however, both patent statute and federal regulations provide some incentive for recording (Marco et al., 2015[58]). By statute, failure to record an assignment in the USPTO renders it void against any subsequent purchaser or mortgagee.[22] This implies that if an assignment is not recorded, the assignor can sell the patent to another buyer and if that assignment is recorded, it will take priority.

[18] Since the UPAD dataset does not contain patent family IDs, the OECD Intellectual Property Database was used to trace back grant IDs in the UPAD Dataset to DOCDB inventions.

[19] Available for download at: https://www.uspto.gov/ip-policy/economic-research/research-datasets/patent-assignment-dataset, (last retrieved Oct. 4, 2021).

[20] USPTO Manual of Patent Examining Procedure (MPEP)

[21] More precisely, the USPTO assigns in the UPAD dataset all entries to the different conveyance type categories using key search terms such as 'assignor's interests', 'government interest' or 'merger' for pattern matching (Marco et al., 2015[58]).

[22] "An assignment, grant, or conveyance shall be void as against any subsequent purchaser or mortgagee for a valuable consideration, without notice, unless it is recorded with the Patent and Trademark Office within three months from its date or prior to the date of such subsequent purchase or mortgage." 35 U.S.C. 261 (2021) (US law).

In this paper assignments of patent families that are related to climate change are identified using Y02 codes of the Co-operative Patent Classification (CPC) described as 'technologies or applications for mitigation or adaptation against climate change' (henceforth 'climate change-related')[23]. A patented invention is classified as climate change-related when it is tagged with at least one Y02 code.

This section analyses the evolution in the number of assigned patented inventions in climate change-related technologies over time and compares this trend to traditional patent metrics and to other sectors. Notably, the trends in climate change-related assigned patented inventions are compared with:

- Trends for other assigned patent families, which are not climate change-related; and
- Trends for non-assigned patented inventions, looking both at climate change-related and other types of technologies.

This trend comparison analysis allows to examine whether climate change-related innovation tend to become more commercialised than innovation that are not related to climate change. To be able to compare the evolution of assigned inventions and non-assigned inventions over time, the application year of the first patent in the family is used to compute the count in both types of inventions. Moreover, to analyse trends across diverse economic sectors, patented inventions are classified along six economic sectors, namely agriculture, construction, energy, information & communication technologies, manufacturing and transport. The classification is based on an ad-hoc methodology using CPC codes to assign an invention to the respective economic sector (see Table A.1 in the Annex).

A similar trend comparison analysis is then conducted to examine the relationship between patent assignment that is a proxy for commercialised patented inventions and the number of patent citation that is a standard proxy for the value and quality of patented inventions.

4.1.2. Trends in assigned climate change-related patented inventions in the United States

Most commercialised climate change-related innovation occurs in the manufacturing and energy sectors

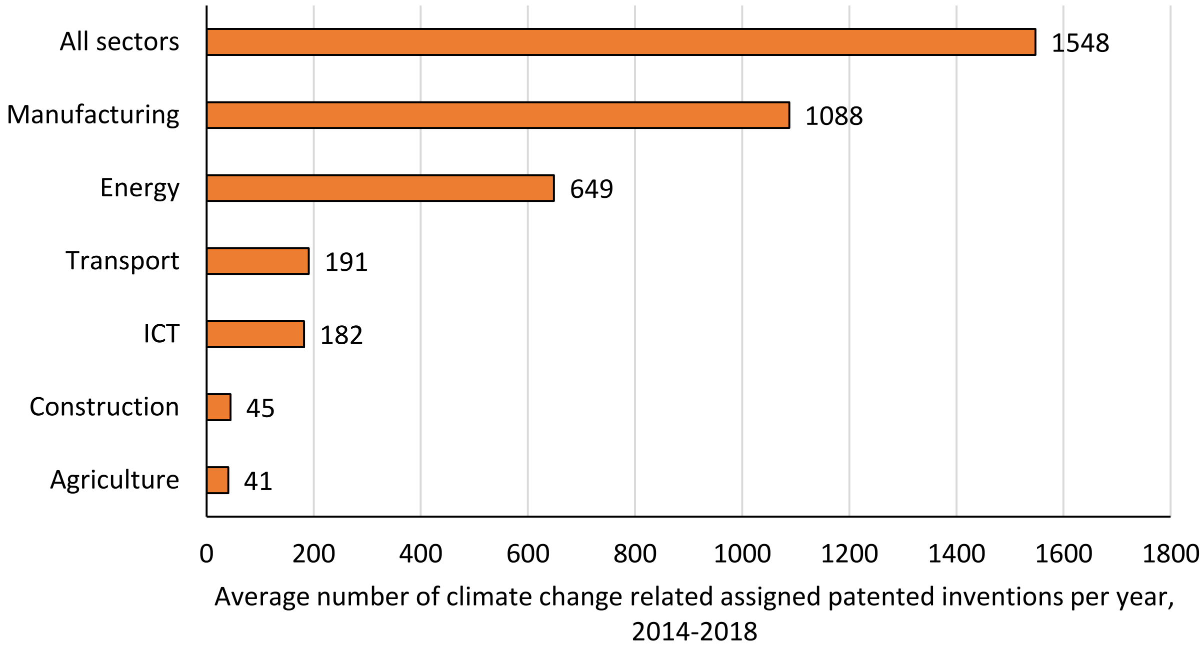
A total of 1 543 patented inventions related to climate change per year[24] were assigned in the United States on average between 2014-2018. The amount of commercialised climate change-related innovation measured by the number of assigned patented inventions varies significantly across sectors (Figure 4.1). Most climate change-related innovation occurs in the manufacturing sector with 1 088 assigned inventions per year, which is consistent with the predominant size of the manufacturing sector.[25] The next largest amount of commercialised low carbon innovation occurs in the energy (649 per year), transport (191 per year) and ICT (182 per year). Construction and agriculture exhibit a lower amount of climate change-related innovation with respectively 45 and 41 assigned inventions per year.

[23] As patents usually have several CPC classes, this analysis examines inventions tagged with at least one Y02 class.

[24] The year considered is the priority application year. Patents with a more recent priority year have a lower probability of being assigned.

[25] The transport sector shown in Figure 4.1 is also included in the manufacturing sector. It is shown to allow a comparison of the metrics based on patent assignments with traditional patents metrics because transport related climate change mitigation technologies are reported separately under the CPC Y02 tagging system.

Figure 4.1. Climate change-related assigned patented inventions per sector per year



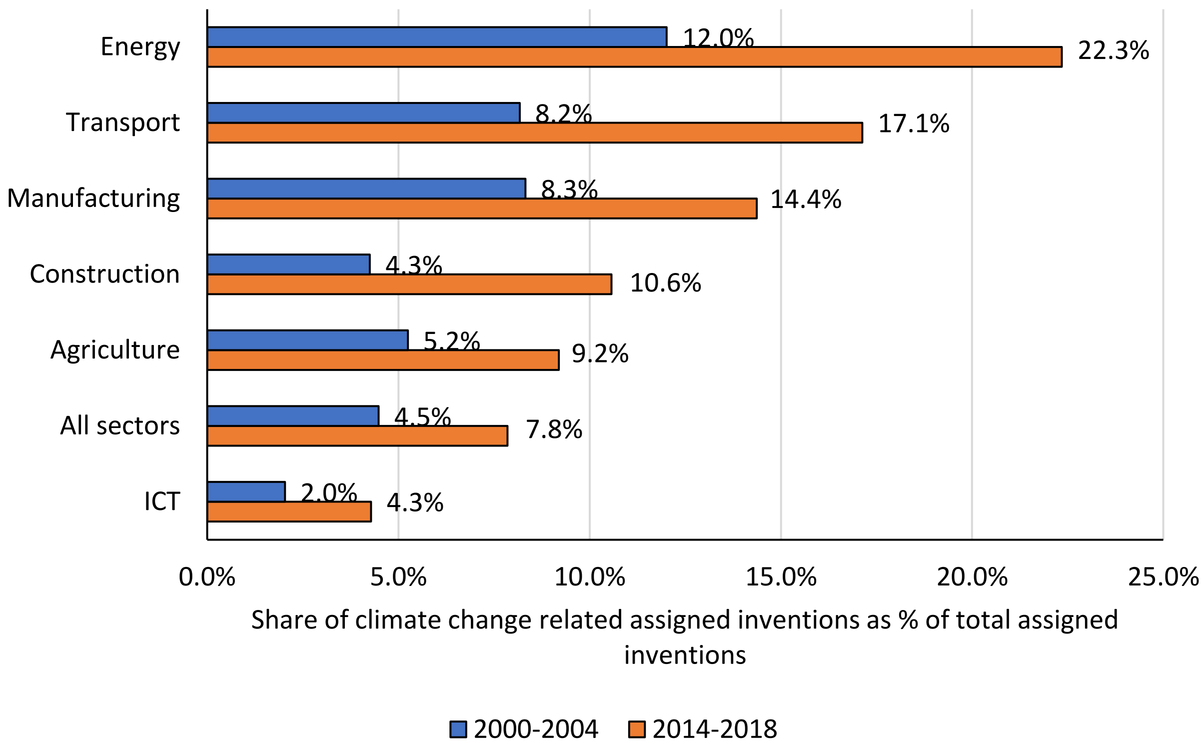
Note: Climate change-related patented inventions are defined as patent families having at least one Y02 code. Assignments are defined as change in ownership, notably 'assignment' (ownership transferred to another entity) or 'merger' (ownership change due to merger). To avoid double counting, only the first assignment of each patent family is counted. The total "all sectors" is not equal to the sum across all individual sectors because some inventions appear in different sectors. Patented inventions are classified along six economic sectors, namely agriculture, construction, energy, information & communication technologies, manufacturing and transport. The classification is based on an ad-hoc methodology using CPC codes to assign an invention to the respective economic sector (see Table A.1 in the Annex).
Source: Authors calculation based on the UPAD dataset and OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, May 2022

Commercialised climate change-related innovation increased in all sectors and is relatively more important in energy and transport

The amount of commercialised climate change innovation is proportional to the size of the different sectors. Figure 2.2 shows the share of climate change-related assigned inventions as % of the total number of assigned inventions related or not to climate change for two periods of time: 2000-2004 and 2014-2018. The relative importance of climate change-related innovation varies importantly across sectors. Between 2014 and 2018, commercialised climate change-related innovation was relatively more important in the energy sector in which 22% of assigned inventions are related to climate change. Commercialised climate change innovation is relatively higher in transport (17%), manufacturing (14%) and construction (11%) and relatively lower in agriculture (9%) and ICT (4%).

Climate change-related innovation increased significantly over the last two decades (Figure 4.2). Between 2014 and 2018, 7.8% of assigned inventions were related to climate change against only 4.5% between 2000 and 2004. This increase is observed in all sectors but is especially important in the energy sector where the share of commercialised inventions related to climate change rose from 12% in 2000-2004 to 22% in 2014-2018. The second and third largest increase occurred in the transport and construction sectors where commercialised climate change-related innovation respectively rose by 9 percentage points and 6 percentage points. Commercialised low carbon innovation remains relatively low in ICT because many innovations in these sectors are completely unrelated to climate change.

Figure 4.2. Share of climate change-related assigned patented inventions as % of total assigned inventions, by sector



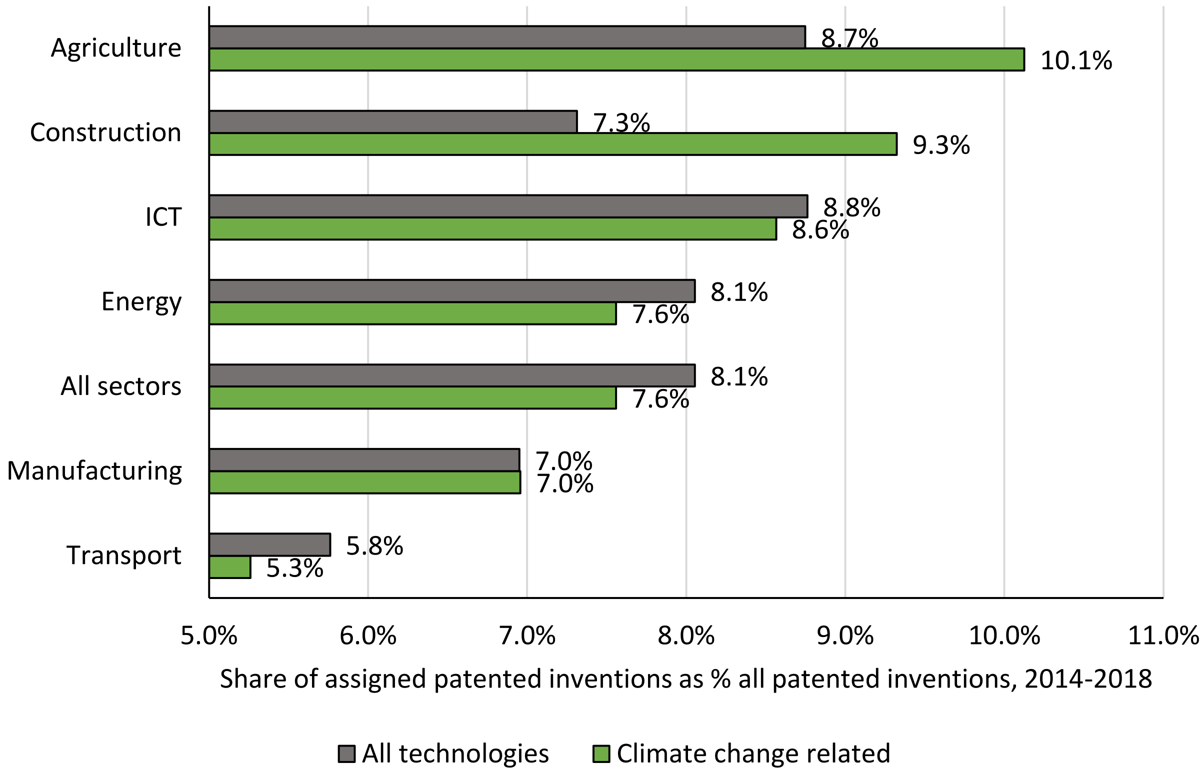
Note: The year for non-assigned patented inventions correspond to the application year of the first patent in the family. Only patent family's first assignment is included. Climate change-related patented inventions are defined as patent families having at least one Y02 code. Assignments are defined as change in ownership, notably 'assignment' (ownership transferred to another entity) or 'merger' (ownership change due to merger). To avoid double counting, only the first assignment of each patent family is counted. The total "all sectors" is not equal to the sum across all individual sectors because some inventions appear in different sectors. Patented inventions are classified along six economic sectors, namely agriculture, construction, energy, information & communication technologies, manufacturing and transport. The classification is based on an ad-hoc methodology using CPC codes to assign an invention to the respective economic sector (see Table A.1 in the Annex).
Source: Authors calculation based on the UPAD dataset and OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, May 2022

The degree of commercialisation of climate change-related innovation varies across sectors

The degree of commercialisation of climate change-related technologies, measured by the share of inventions that have been assigned at least once, is slightly lower to what can be observed for all kinds of technologies (Figure 4.3). In recent years, 7.6% of all patented inventions related to climate change have been assigned at least once while this is 8.1% of all patented inventions, related or not to climate change.

The degree of commercialisation of climate change-related innovation varies across sectors. Compared to all technologies, climate change-related innovations are relatively more commercialised in agriculture (10.1% against 8.7%) and construction (9.3% against 7.3%). In transport and energy, climate change-related innovation tends to be slightly less commercialised than the average technology (5.3% against 5.8%). In manufacturing and ICT, the degree of commercialisation does not differ significantly between climate change-related technologies and the average technology.

Figure 4.3. Degree of commercialisation of patented inventions

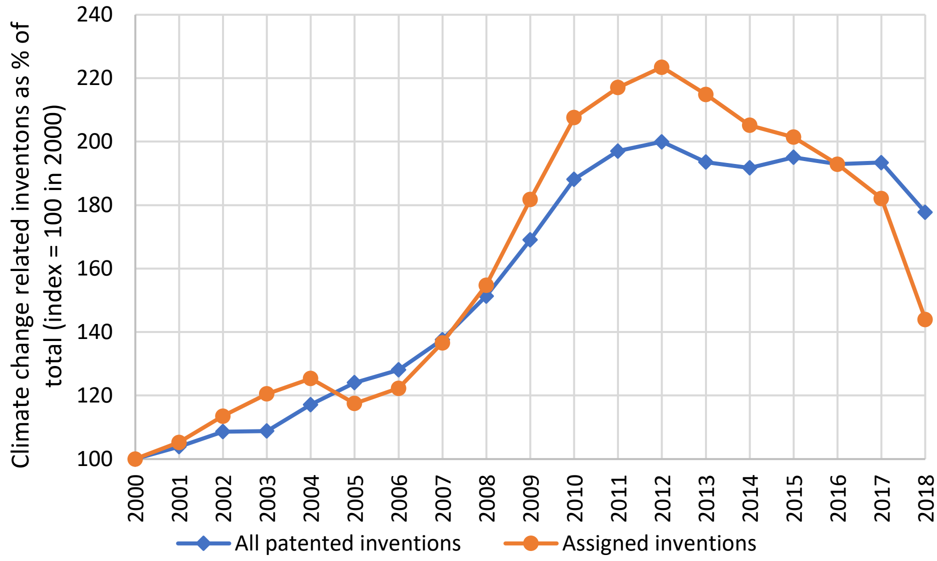


Note: The year for non-assigned patented inventions correspond to the application year of the first patent in the family. Only patent family's first re-assignment is included. Climate change-related patented inventions are defined as patent families having at least one Y02 code. Assignments are defined as change in ownership, notably 'assignment' (ownership transferred to another entity) or 'merger' (ownership change due to merger). To avoid double counting, only the first assignment of each patent family is counted. The total "all sectors" is not equal to the sum across all individual sectors because some inventions appear in different sectors. Patented inventions are classified along six economic sectors, namely agriculture, construction, energy, information & communication technologies, manufacturing and transport. The classification is based on an ad-hoc methodology using CPC codes to assign an invention to the respective economic sector (see Table A.1 in the Annex).
Source: Authors calculation based on the UPAD dataset and OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, May 2022

After several years of increase, the share of commercialised climate change-related technologies decreased in recent years

Commercialised innovation related to climate change measured by patent assignments and total innovation (commercialised or not) measured by the total number of patented inventions follows a similar trend over time. Figure 4.4 shows the growth of the share of assigned patented inventions related to climate change and the growth of the share of patented inventions (assigned or not) related to climate change between 2000 and 2018. Unsurprisingly, the two trends are highly correlated since the greater the number of patented inventions, the higher the number of potentially commercialised inventions. However, these growths differed several times. Between 2008 and 2015, the share of climate change-related inventions among commercialised inventions grew more than the share of climate change-related inventions among all patented inventions. In contrast, the share of climate change-related technologies that are commercialised has sharply decreased since 2016 compared to the share of climate change-related inventions. This declining trend is also found by Probst et al. (2021[15]) for high value patented inventions. Falling fossil fuel prices, low price for carbon emissions and the maturity of several technologies like solar photovoltaics are likely culprits although no causal evidence could be derived yet.

Figure 4.4. Share of climate change-related innovation over time, measured by a traditional patent metric and by patent assignments



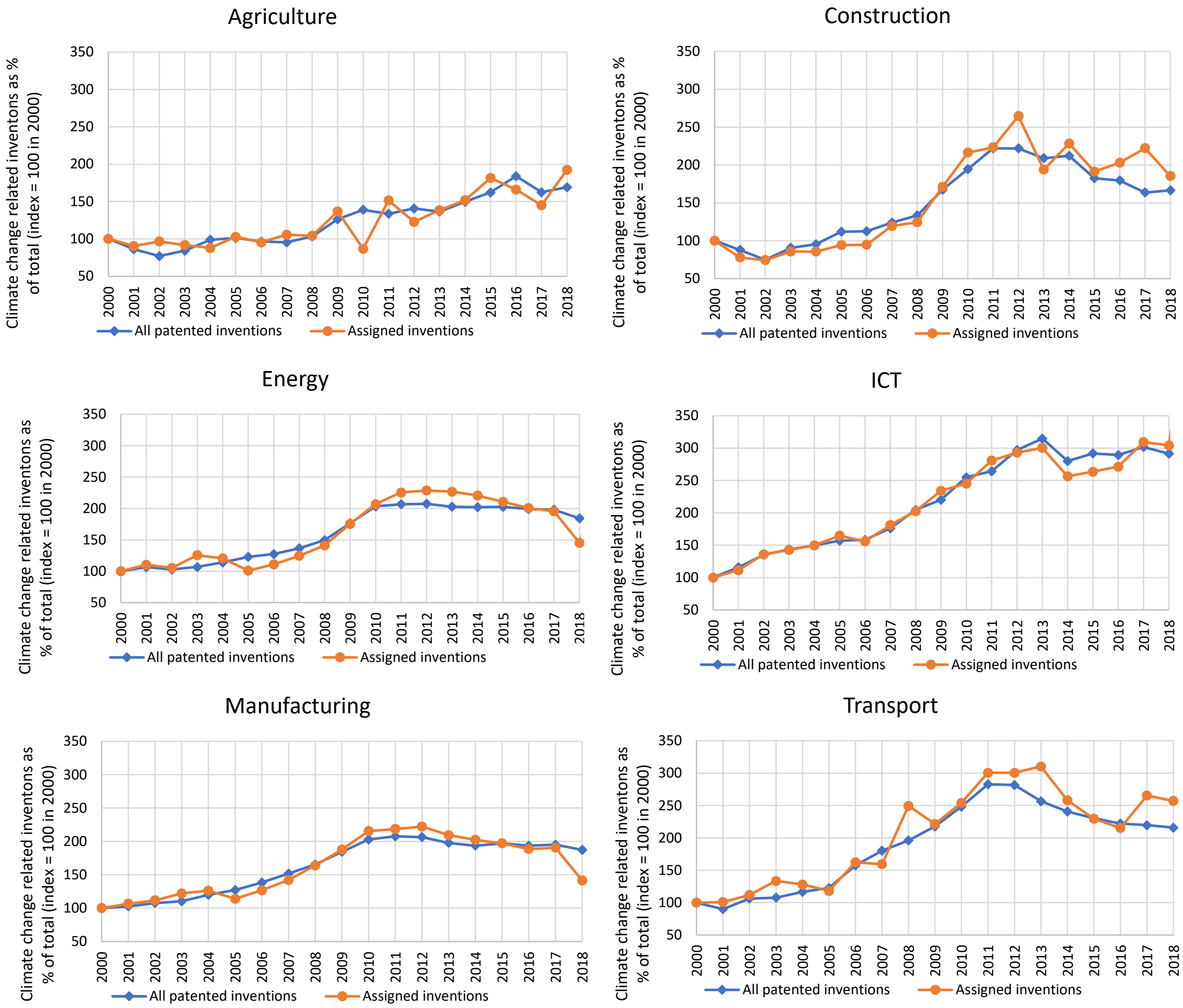
Note: The year for non-assigned patented inventions correspond to the application year of the first patent in the family. Only patent family's first re-assignment is included. Climate change-related patented inventions are defined as patent families having at least one Y02 code. Assignments are defined as change in ownership, notably 'assignment' (ownership transferred to another entity) or 'merger' (ownership change due to merger). To avoid double counting, only the first assignment of each patent family is counted. The total "all sectors" is not equal to the sum across all individual sectors because some inventions appear in different sectors.
Source: Authors calculation based on the UPAD dataset and OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, May 2022

Commercialisation of climate change-related technologies became more important in transport and construction in recent years

The aggregate trends presented in Figure 4.4 sums some heterogeneity across sectors. The growth of the share of assigned patented inventions related to climate change and the growth of the share of patented inventions (assigned or not) related to climate change follows a highly similar trend between 2000 and 2018 in most sectors (Figure 4.5). However, in construction and transport, the share of commercialised climate change-related inventions has been growing more rapidly than the share of climate change relative inventions (assigned or not) since 2015 and 2016 respectively. In other words, the degree of commercialisation of technologies related to climate change recently increased in these two sectors.

This result illustrates that patent assignment data, in contrast to traditional patent indicators, can be used to assess the relative interest of firms in green technologies, but also to capture differences between scale and commercialisation effects. In particular, green innovation metrics based on patent assignments allow to assess to what extent firms are trading knowledge around green technologies and whether this mechanism will eventually become more or less relevant.

Figure 4.5. Share of climate change-related innovation over time by sector



Note: The year for non-assigned patented inventions correspond to the application year of the first patent in the family. Only patent family's first re-assignment is included. Climate change-related patented inventions are defined as patent families having at least one Y02 code. Assignments are defined as change in ownership, notably 'assignment' (ownership transferred to another entity) or 'merger' (ownership change due to merger). To avoid double counting, only the first assignment of each patent family is counted. Patented inventions are classified along six economic sectors, namely agriculture, construction, energy, information & communication technologies, manufacturing and transport. The classification is based on an ad-hoc methodology using CPC codes to assign an invention to the respective economic sector (see Table A.1 in the Annex).
Source: Authors calculation based on the UPAD dataset and OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, May 2022

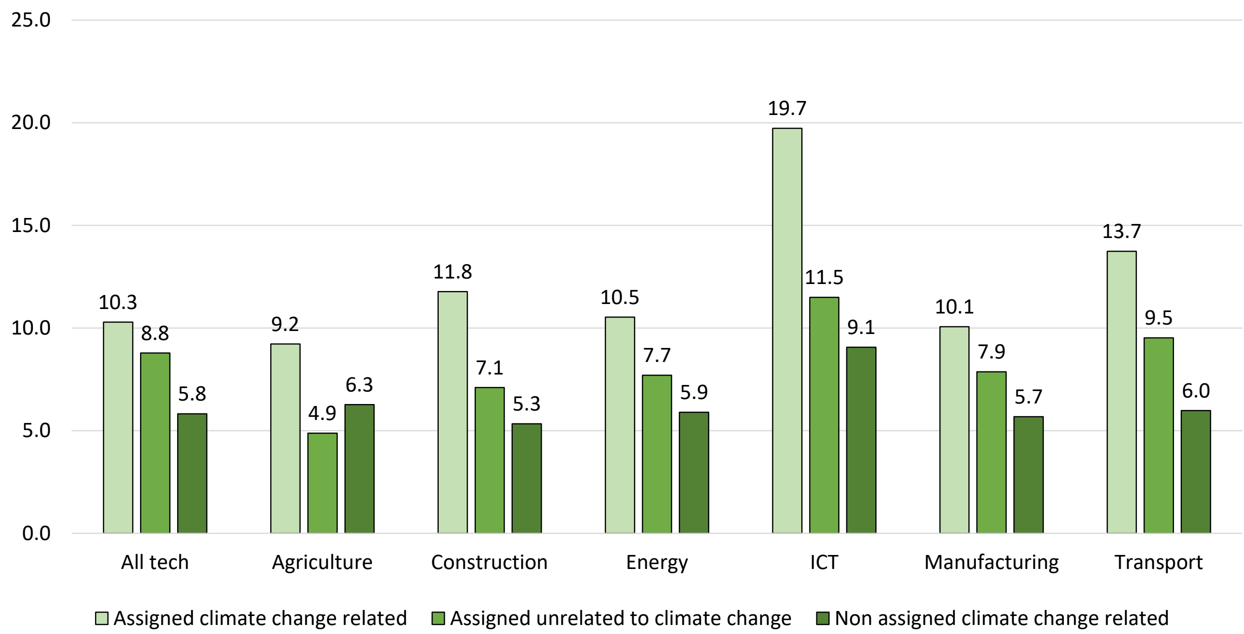
Assigned climate change-related inventions tend to be more valuable

Commercialised inventions exhibit features that could point to higher commercial value. Figure 4.6 shows the average number of forward citations for assigned climate change inventions, assigned (commercialised) inventions unrelated to climate change and for non-assigned climate change-related inventions by sector. The number of forward citations is a commonly used proxy to capture value of patented inventions (Hall, Jaffe and Trajtenberg, 2005[60]). Commercialised climate related inventions have a statistically higher average number of citations (10.3) than commercialised inventions that are unrelated to climate change (8.8). Similar differences are also observed in every sector. The largest differences are observed in agriculture, ICT, transport and construction.

In addition, climate change-related inventions that are commercialised also have a statistically higher number of citations (10.3) than climate change-related inventions that are *not* commercialised (5.8). The same difference is observed in all sectors.

These results suggest that while assigned climate change-related inventions are highly correlated with the overall level of climate change-related patenting activity in the United States, metrics based on patent assigned measure inventions of higher value. Therefore, analyses could use such metrics to investigate the effects of environmental and innovation policies on climate change-related innovations that have higher value and higher degree of commercialisation. Innovations that ultimately get commercialised contribute ultimately to a larger impact on climate change mitigation and adaptation.

Figure 4.6. Average number of citations of patented inventions by sector, 2014-2018



Source: Authors calculation based on the UPAD dataset and OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, May 2022. The total "all tech" is not equal to the sum across all individual sectors because some inventions appear in different sectors. Patented inventions are classified along six economic sectors, namely agriculture, construction, energy, information & communication technologies, manufacturing and transport. The classification is based on an ad-hoc methodology using CPC codes to assign an invention to the respective economic sector (see Table A.1 in the Annex).

4.2. Measuring commercialised green innovation through licensing agreements

Another method to examine commercialised climate change-related innovation is to measure license agreements involving patents with underlying climate-change related technologies (or any patent of relevant for environmental innovations). As described above, licensing deals are closer to commercialisation than patents and show a signal of economic interest in a particular technology.

Licensing deals based on intellectual property can be examined with the use of commercial licensing databases. This section describes the methodology and dataset used to develop a new metric to measure commercialised climate change-related innovation using license agreement data.

4.2.1. Methodology and data source

This section analyses the evolution in the number of license agreements in climate change-related technologies over time and compares this trend to traditional patent metrics and to other sectors. Notably, the trends in climate change-related license agreements are compared with:

- Trends for other license agreements, which are not climate change-related; and
- Trends by sector, looking both at climate change-related and other types of technologies.

This trend comparison analysis allows to examine whether climate change-related innovations tend to become more commercialised than innovations that are not related to climate change.

The present analysis uses licensing data from KtMINE, which collects several information on each licensing agreement (see Section 2.1 for more details). For most agreement, ktMINE provides information on filing date and entry into effect date, type of IP involved, patent number, industry sector and CPC codes.

For this analysis, two ktMINE databases were used. The first dataset used in this analysis includes detailed information on 913 agreements involving climate change-related technologies. This database has information on the actors involved in the transactions, the year in which the licensing deal came into effect, the patent number of the technology and the economic region over which the license was transferring exploitation rights. A synopsis of the license agreement including the terms and conditions of the agreement and the source of the license agreement e.g., SEC or USPTO is also available.

For some climate change-related license agreements, information on the modifier or payment structure of the licensing deal is available. There are different payment structures that can be involved in a single license agreement. For this study, the royalty rate is of interest as a separate metrics able to capture the value of a specific technology. Other payment structures include upfront or annual payments, cost sharing, service fees or commission. The database includes information on the royalty rate for 234 license agreements involving a climate change-related technology.

The second database from ktMINE includes information on 7 028 license agreements pertaining to all technologies (not only climate-change related) and, for each of them, provides the associated CPC codes. Detailed CPC information is available up until the sub-class level (e.g., Soil working in agriculture or forestry (A01B), climate change adaptation (Y02A), climate change mitigation in buildings (Y02B) etc.). This database is useful to compare climate change-related licensing deals with other technological classes.

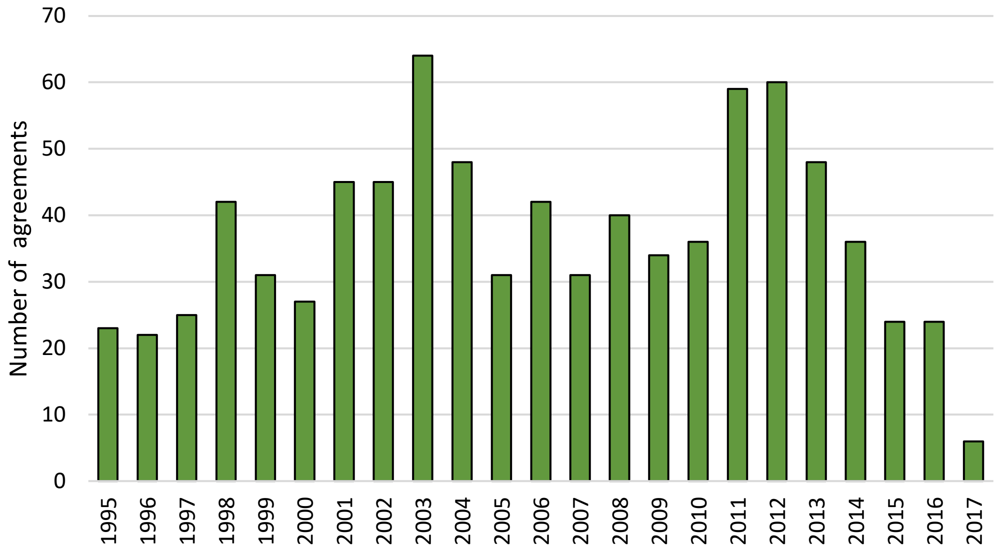
Some caveats concerning the ktMINE database should be flagged before delving into the data analysis. First, both ktMINE databases used in the analysis include mainly publicly available licensing deals. Second, the ktMINE datasets used in the present analysis only includes information on licensing deals which disclosed a patent number and for which a CPC code could identified. Relying on the CPC code was the only way to separate climate and non-climate related deals. This limitation significantly restricts the amount of licensing information that could be collected and could undermine the representativity of the sample. In addition, while the datasets collect information up to 2021 the number of observations for the recent years is very low, a drawback that also exist for patent metrics.

4.2.2. Trends in climate change-related licensing agreements in the United States

Available data suggests that the number of climate change-related licensing agreements remained stable over time

The number of licensing deals in climate change-related technologies remained relatively stable over time since the 1990s, except for two peaks in 2001-2004 and in 2011-2013 (see Figure 4.7). After 2012, the number of licensing deals declined significantly, although data for more recent years could be less comprehensive. However, these absolute figures should be taken with precaution as ktMINE covers only publicly available licensing deals that account for a small fraction of the licensing deals that actually occur in the market.

Figure 4.7. Number of climate change-related licensing agreements in KtMINE

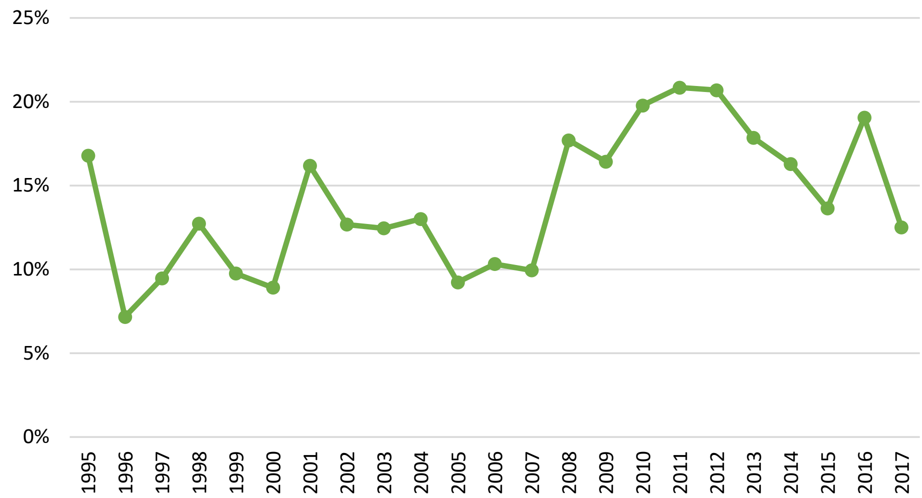


Source: Calculations of the authors based on ktMINE data.

The share of climate change licensing agreements raised during the global financial crisis

Considering that ktMINE data contains a fraction of total licensing deals, looking at the relative share of climate change-related deals rather than at the absolute number provides more useful insights. The share of climate change-related deals has fluctuated between 7% and 21% between 1995 and 2017 (see Figure 4.8). The most consistent surge took place during the global financial crisis, between 2007 and 2012, consistent with findings for other metrics presented in this paper (see Section 2.2). Despite the overall economic downturn, the share of licensing deals in climate-change related technologies has increased from 12% in the years before 2007 to 17% from 2008.

Figure 4.8. Climate change-related deals as a share of total deals

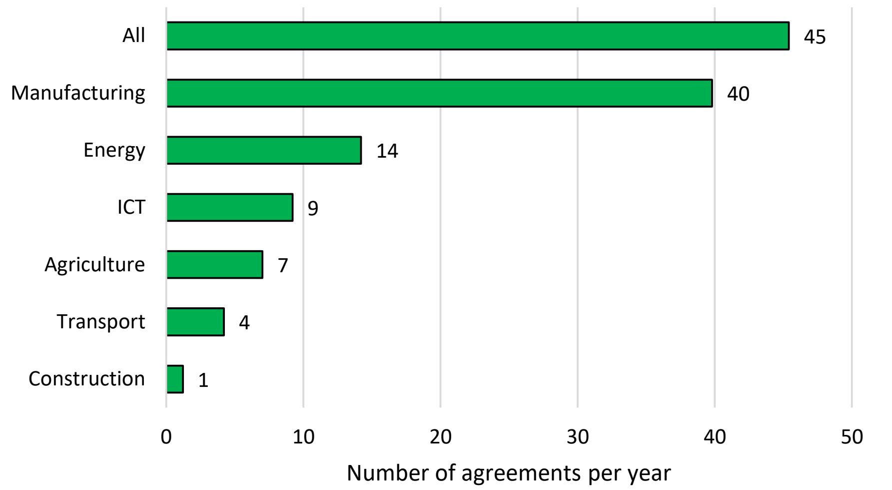


Source: Calculations of the authors based on ktMINE data.

Manufacturing and energy are the most important sectors in terms of climate change-related licensing deals

The number of agreements by sector suggests that manufacturing and energy are the most important sectors in terms of climate change-related licensing deals, while construction and transport are the ones with the lowest number of agreements (see Figure 4.9). Over the period 2011-2015, 40 climate change-related licensing agreements per year involved manufacturing technologies, 14 for energy technologies and only 1 for technologies used in the construction sector.

Figure 4.9. Number of climate-related licensing agreements per year, by sector (2011-2015)

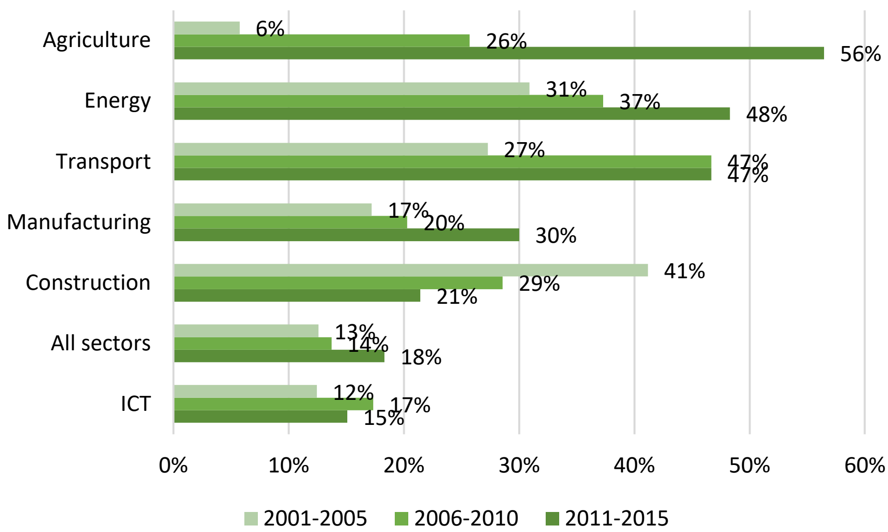


Source: Calculations of the authors based on ktMINE data.
Note: All climate-change related licensing agreement is not equal to the sum of sector level climate-change related licensing agreement because companies can be active in several sectors. The total "all" is not equal to the sum across all individual sectors because some inventions appear in different sectors. Licensing agreements are classified along six economic sectors, namely agriculture, construction, energy, information & communication technologies, manufacturing and transport. The classification is based on an ad-hoc methodology using CPC codes to assign an invention to the respective economic sector (see Table A.1 in the Annex).

The share of climate change-related licensing agreements increased in most sectors

The absolute number of licensing agreements presented in Figure 4.9 also reflects the size of the respective sectors in the economy. Therefore, it is useful to analyse the share of climate-change related licensing agreements out of total to better gauge the greenness of commercialised innovation at the sector level. While only 13% of all licensing agreements involved a climate change-related technology in 2001-2005, the share increased to 18% in 2011-2015, signalling an increased interest in climate change-related technologies relative to other non-climate technologies but also reflecting the increasing share of climate-related patents in total patents available to license (see Figure 4.10). The share of climate-change related licensing agreements out of total increased in most sectors including agriculture, energy, transport, and manufacturing. In the energy sector, for instance, the share of climate change-related licensing agreements increased from 31% in 2001-2005 to 48% in 2011-2015. On the contrary, in the construction sector the share declined from 41% in 2001-2005 to 21% in 2011-2015, signalling a decline in the interest in low carbon construction technologies relative to non-low carbon technologies.

Figure 4.10. Share of climate-related licensing agreements, by sector and time period



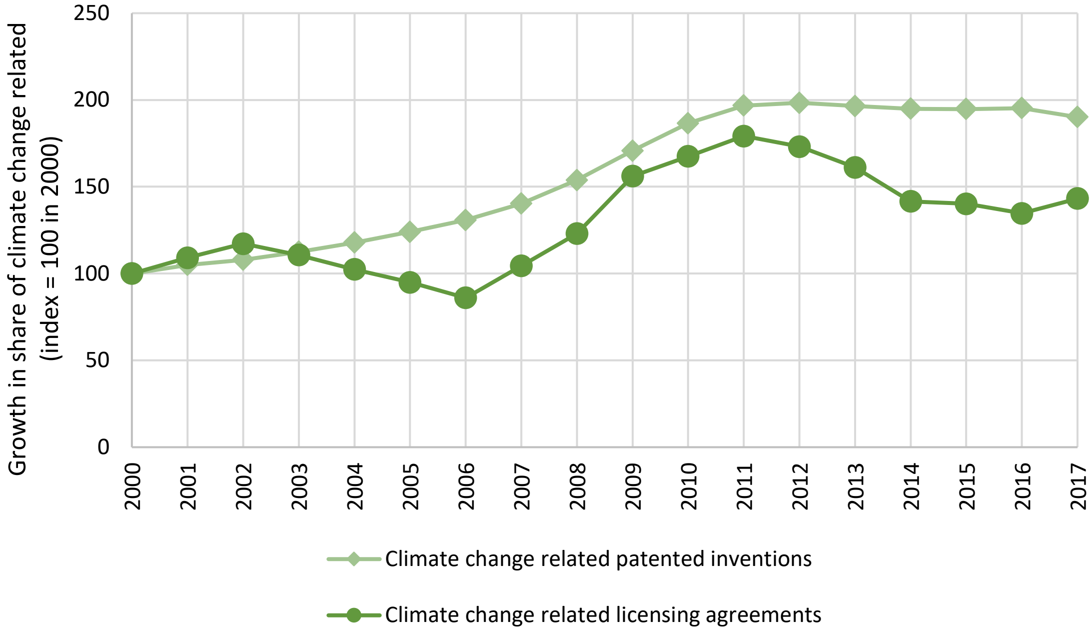
Source: Calculations of the authors based on ktMINE data. The total "all sectors" is not equal to the sum across all individual sectors because some inventions appear in different sectors. Licensing agreements are classified along six economic sectors, namely agriculture, construction, energy, information & communication technologies, manufacturing and transport. The classification is based on an ad-hoc methodology using CPC codes to assign an invention to the respective economic sector (see Table A.1 in the Annex).

4.2.3. Comparison with traditional patent metrics

Traditional patent statistics show a more sustained increase in the climate change-related innovation relative to licensing deals

Comparing the growth in the total number of climate change-related patents and in climate change-related licensing agreements suggests that they measure different dynamics (see Figure 4.11). The share of climate change-related patented inventions increased at a constant rate up until the early 2010s and has then started to decline. By contrast, the share of climate change-related licensing agreements has first declined between 2002 and 2006, it has significantly increased between 2007 and 2011 and it has finally started to decline again afterwards. Overall, the share of climate related licensing deals displayed a lower growth relative to its 2000 value compared to patents. This suggests a relative decrease over time in the degree of commercialisation of climate change-related innovation that is not consistent with the findings of the patent assignment analysis. This difference might be due to two factors. First, licensing and assignment captures different dynamics. Second, the result from the licensing data suffers from lower data availability. Therefore, the result based on patent assignment is considered to be more robust.

Figure 4.11. Growth in share of climate related licensing agreements compared to growth in share of climate-related patented inventions



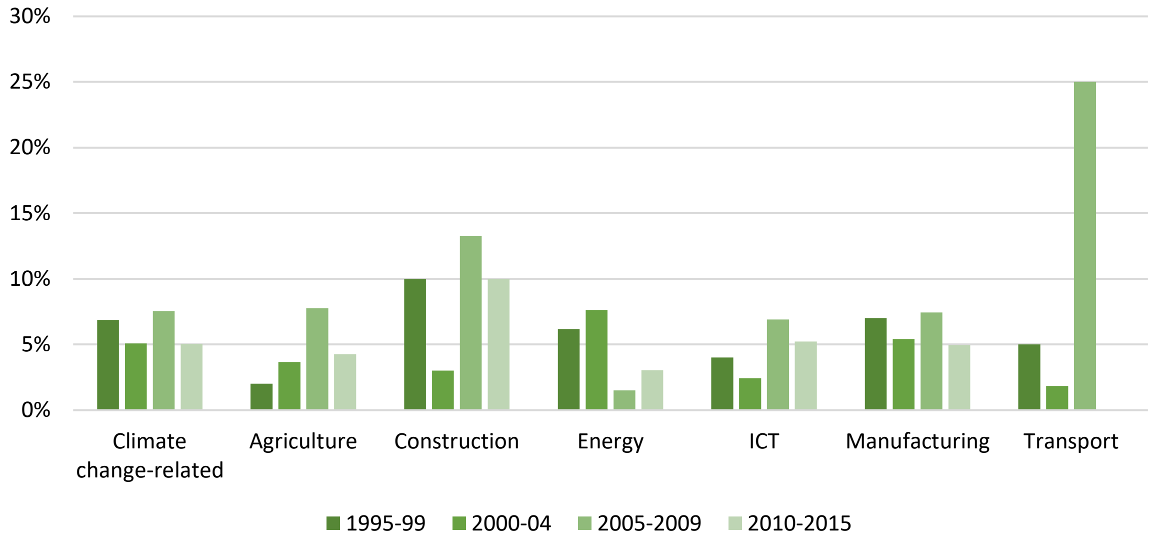
Source: Calculations of the authors based on ktMINE and "OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, September 2022".
Note: Patents correspond to patent families. A patent family is a collection of patent documents that covers a single invention. Analysing the number of patent families rather than the total number of individual patent applications better captures the amount of innovation and avoid double counting.

4.2.4. Measuring the value of commercialised climate change-related innovations using royalty rate in licensing agreements

Climate change-related innovation were more valuable during the global financial crisis

The ktMINE database allows to collect information on royalty rates of climate change-related licensing deals. A royalty payment is a payment made by a licensee to the licensor, for the right to use of the licensed asset. Royalties are typically set upon as a percentage of revenues derived from the use of an asset but can also be defined as a fixed price per unit sold of an item of such. Royalty rates can be a proxy of the commercial value of a specific technology. Figure 4.12 shows the average royalty rates of climate change-related licensing agreements by sector for four periods of time. Average royalty rates for climate change-related technologies in all sectors except energy increased significantly during the global financial crises and then decreased in 2010-2015.

Figure 4.12. Average royalty rates across climate change-related technologies



Source: Calculations of the authors based on ktMINE data.
Note: Royalty rate is defined as % of sale from the use of the licensed asset. Licensing agreements are classified along six economic sectors, namely agriculture, construction, energy, information & communication technologies, manufacturing and transport. The classification is based on an ad-hoc methodology using CPC codes to assign an invention to the respective economic sector (see Table A.1 in the Annex).

5 New metrics to measure breakthrough green innovation effort using Venture Capital data

This section describes a new family of metrics to measure breakthrough green innovation using venture capital (VC) investment data collected by Crunchbase, a commercial database collecting business information on public and private companies. By capturing investors' interest in innovative firms, this new metric has the potential to capture innovation effort in breakthrough, high risk – high reward innovation.

5.1. Methodology and data source

The new metrics of green breakthrough innovation is based on venture capital (VC) funding in green firms that are firms engaging in activities mitigating environmental impacts and adapting to climate change-related hazards.

VC is an intermediary in financial markets consisting of dedicated pools of capital focussing on equity or equity-linked investments in privately held, high growth companies (Gompers and Lerner, 2001[61]). VC is a way of financing high-risk firms, which are generally small, young, and highly innovative. These companies routinely need to complete various funding rounds before getting to the initial public offering stage. The initial investment, known as pre-seed or seed funding, is followed by several other rounds, known as series A, B, C, etc. This analysis considers all funding rounds from pre-seed to series J as VC funding.[26]

5.1.1. Methodology

This section analyses the evolution in VC funding in green firms over time – both in terms of number of VC deals and in terms of total amounts raised. While the number of deals provide information on the intensity of VC activity in green firms, the total funding provides a proxy of the value associated with the investment, i.e., its expected returns. The analysis also compares these trends to traditional patent metrics and to other sectors. Notably, the trends in VC funding are compared with:

- Trends for non-green VC funding – both in terms of total amounts raised and in terms of number of deals; and
- Trends for traditional patent statistics, looking both at green patents and other types of technologies.

[26] The following Crunchbase categories of investment type are classified as VC in the current study: angel, pre-seed, seed, series_A, B, C, D, E, F, G, H, I, J, convertible_note, product_crowdfunding, venture - series unknown, equity_crowdfunding.

This trend comparison analysis allows to examine whether trends capturing venture capital funding green firms capture different dynamics compared to traditional patent statistics.

To analyse trends across diverse economic sectors, patented inventions are classified along six economic sectors, namely agriculture, construction, energy, information and communication technologies, manufacturing, and transport. The classification is based on Crunchbase sector classification and can be consulted in Table A.1.

5.1.2. The Crunchbase database

The analysis uses VC data from Crunchbase. Founded in 2007, Crunchbase has fast grown into one of the most widely used data sources in the venture capital industry, while also becoming prominent among scholars and academic researchers (Dalle, den Besten and Menon, 2017[62]). Initially developed to track tech companies and start-ups, its scope and coverage has increased significantly over the past few years and now contains information on a wide range of companies on a global scale.

Crunchbase collects a wide array of firm-level information, including company description, industry classification, founding date, funding raised, funding rounds, mergers, and acquisitions, etc. As of July 2022, Crunchbase included records on over 2 000 0000 companies, 225 000 investors and 352 000 funding rounds in 220 countries. Data is sourced from companies and investment firms themselves, through machine learning, through Crunchbase's in-house data team and, finally, through crowdsourcing from members of the Crunchbase community. Differently from other commercial databases, this system of data collection allows for data to be updated daily and continuously validated by users themselves.

There is some evidence that Crunchbase is a representative source of data. Aggregated data are consistent with the OECD Entrepreneurship Financing Database based on data compiled by national or regional Private Equity and Venture Capital Associations (Dalle, Besten and Menon, 2017[54]). Furthermore, Crunchbase has been used by a growing number of researchers in economics (Dalle, Besten and Menon, 2017[54]).

5.1.3. Identifying green firms in Crunchbase

The Crunchbase database does not provide an immediate way to identify green firms.[27] The database, however, provides several useful firm-level information that can be exploited to identify which firms are involved in green activities, such as a detailed company description outlining key information on the company's main activities.

The present analysis relies on firm-level descriptions and sector classification of Crunchbase to identify green firms. Firm-level descriptions and the sector classification of Crunchbase allow to precisely assess to what extent a firm is active in green activities or not and to further disaggregate the green firm classification. The methodology used in this study disaggregates green companies into companies active in (i) environmental management, (ii) climate change mitigation and (iii) climate change adaptation.

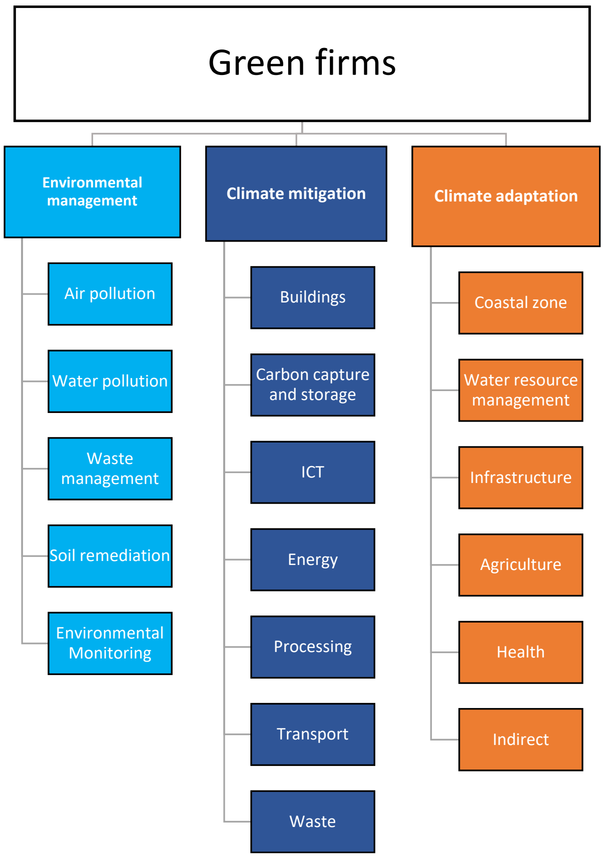
The strategy to identify green firms builds on the work by Haščič, and Migotto (2015[63]), which identified environmentally relevant technologies based on the Co-operative Patent Classification System. Figure 5.1 provides a stylized description of the categories along which green firms were categorised. The climate

[27] The database employs a company classification system based on specific industry groupings. Each firm in the database can belong to multiple industries. Among these industry groupings, it is possible to identify some which clearly contribute to green economic activities (e.g. clean energy, green buildings, water purification, etc.). Nonetheless, industry groupings alone do not allow to capture all green companies nor further disaggregate them into more granular subfields. In addition to this, many industry groupings, which intuitively could be assigned to environmental technologies such as renewable energy, are often associated with companies without any clear environmental focus such as oil and gas companies with a renewable energy portfolio..

change mitigation and adaptation categories of the present paper mimic the CPC Y02 classification. The environmental management category captures additional activities aimed at pollution control and environmental monitoring. Following this logic, a key advantage of this methodology is to enable a direct comparison between the new metric based on VC data and traditional patent statistics, which results are outlined in the following sections.

The methodology employed to identify green firms uses a two-pronged approach. Firstly, a list of keywords related to climate and environmental technologies was extracted from CPC descriptions. This list was complemented by a targeted web search on environmental and climate technologies. This allowed to obtain a comprehensive set of keywords covering all climate and environmental technologies. Secondly, in line with the work of Bioret et al. (forthcoming[14]), the Crunchbase sector classification was utilised in addition to the keywords to identify green firms which was not possible to capture through the keyword search. The methodology also includes a list of "brown" and "white" sectors pertaining respectively to the fossil fuels and mining industries or the medical sector, which are automatically excluded from the green classification. The methodology was perfected through several rounds of validation until a level of accuracy of 95% was reached. Further details on the methodology can be consulted in Table A.1.

Figure 5.1. Green firms' categorization scheme



Source: Authors based on Haščič, and Migotto (2015[63]).

5.2. Unpacking trends in breakthrough green innovation

5.2.1. VC funding for green firms has been increasing and now accounts for 7% of all VC funding

Total VC funding for green firms is on an increasing trend. Since 2007, total VC funding for green firms in constant prices has significantly increased, from USD_{2015} 4 billion per year over the triennium 2007-2009 to USD_{2015} 20 billion per year over the triennium 2019-2021.[28] This trend is driven by the total number of deals involving green firms, which increased from approximately 230 per year to 1 450 per year over the same period (Figure 5.2).

While on an increasing trend, green VC funding has not kept up with the rate of growth in total VC funding, until recently. Figure 5.2 shows the evolution in the share of green VC funding as a share of total VC funding, both in terms of amounts raised and number of deals. The amount of green VC funding relative to total funding peaked in 2008 and then declined until 2015. The peak in relative terms during the Global Financial Crisis coincides with the general economic downturn and the anticipation of stricter climate policies by investors in the United States, which account for a large share of VC deals. It was still important following the American Recovery Act of 2009 that leveraged private investment in clean technologies (Aldy, 2012[64]; Council of Economic Advisors, 2016[65]). After 2015, the share of green VC funding out of total funding has been increasing and reached 7.4% in 2021, coinciding with the years following the signing of the Paris Agreement.[29]

Similarly, the share of green VC deals also peaks in 2008, followed by a decline until 2015. As the share in total funding, the number of green VC deals out of total VC deals has been increasing since 2016 and reached 7.0% in 2021.

5.2.2. The size of VC deals for green firms are lower than the ones for non-green firms

The size of VC deals can serve as a proxy for the value investors view in allocating funds in certain sectors. As shown in Figure 5.3, the median amount raised per deal by green firms peaked in relative terms in 2007 driven by investors in the United States and then declined until 2014.[30] Since then, median VC deal value has been consistently increasing and reached its second peak value in 2021 at USD_{2015} 1.7 million per deal. The trend in the median size of deal among all firms followed a similar tendency, declining from 2007 to 2014 and then increasing until 2021.

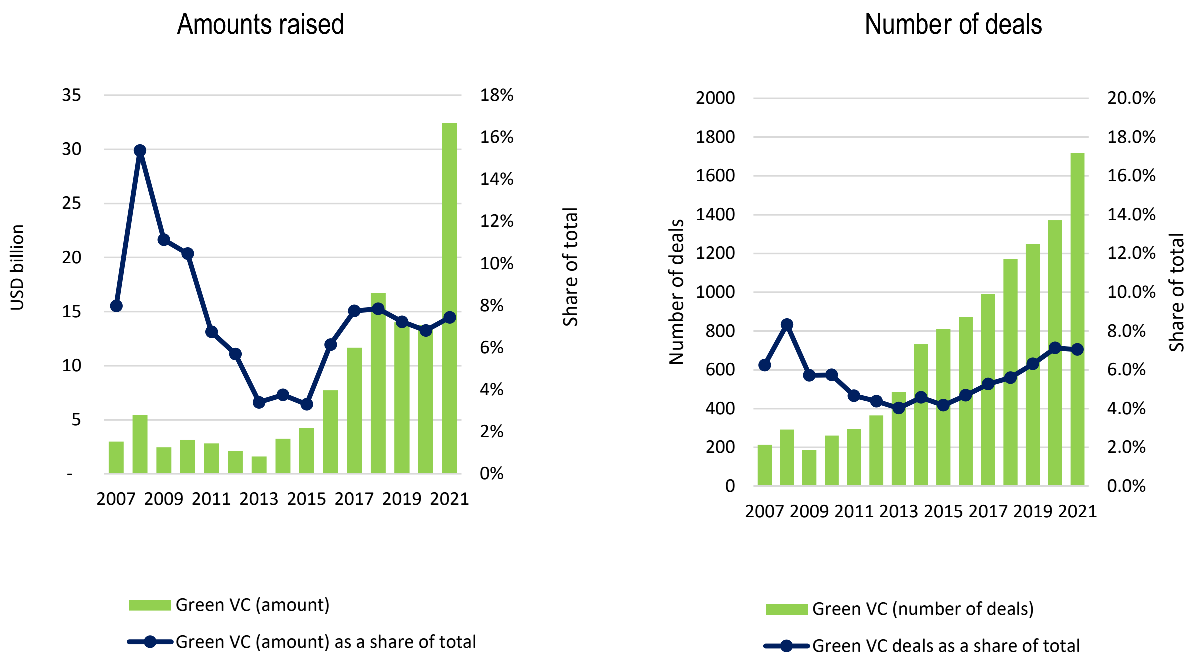
Looking at the difference in VC deal size between green firms and non-green firms can provide valuable insights into the relative appetite investors have for firms engaging in activities that mitigate environmental impacts and support climate change adaptation efforts. While green firms received larger VC deals compared to non-green firms between 2007 and 2013, the trend has reversed in recent years. Figure 5.4 shows the difference in median deal size between green firms and non-green firms, as well as the same value for the 25th and the 75th percentiles. Over the period 2014-2021, non-green firms benefitted from VC deals of larger size than green firms, potentially signalling lower expected returns from investing in green companies relative to other non-green companies.

[28] The starting year (2007) coincides when the founding year of Crunchbase. Amounts expressed in USD were converted to constant 2015 prices using the OECD GDP deflator (output approach) retrievable at https://stats.oecd.org/#.

[29] This does not imply that the Paris Agreement has a causal effect on green VC.

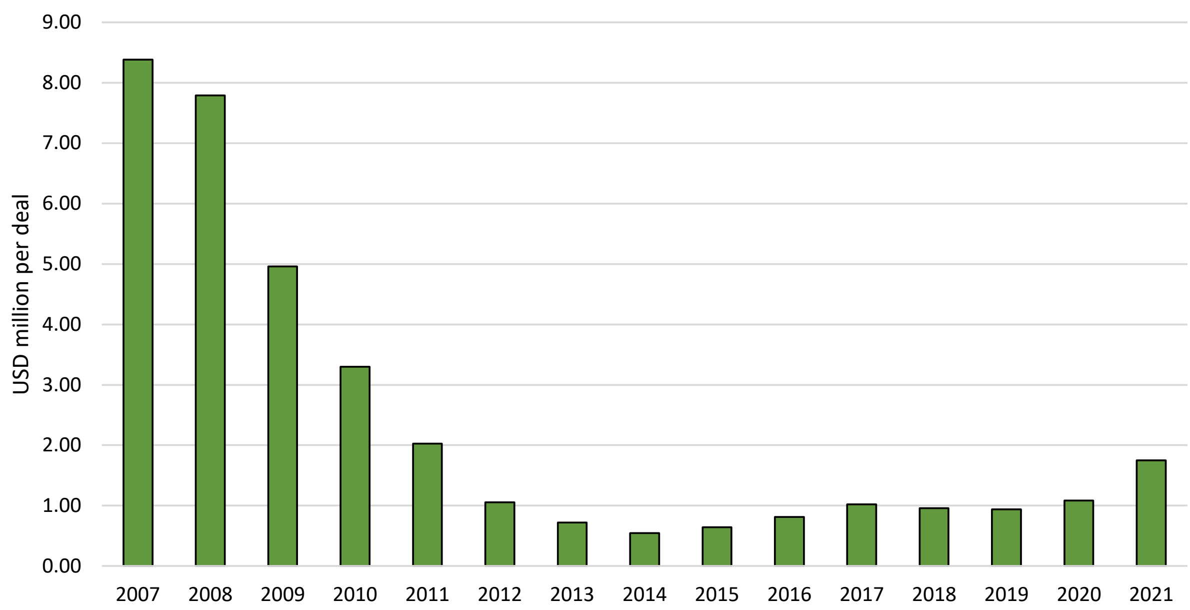
[30] The median is actually more relevant than the average as a large minority of deals drives the average value.

Figure 5.2. Worldwide VC funding for green firms (2007 – 2021)



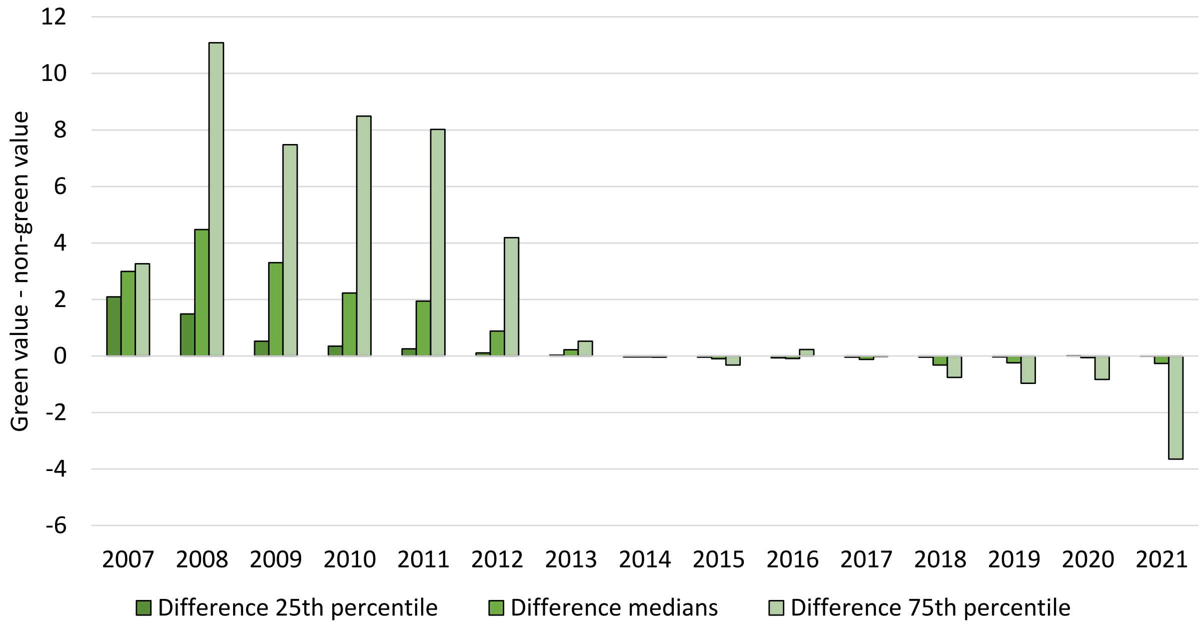
Source: Crunchbase based on Authors' methodology described in Section 5.1. VC funding is measured in constant 2015 USD.

Figure 5.3. Median size of green VC deals



Source: Crunchbase based on Authors' methodology described in Section 5.1.

Figure 5.4. Difference between green and non-green VC deal size



Source: Crunchbase based on Authors' methodology described in Section 5.1.

5.2.3. The majority of green VC funding targets transport, ICT, manufacturing, and energy

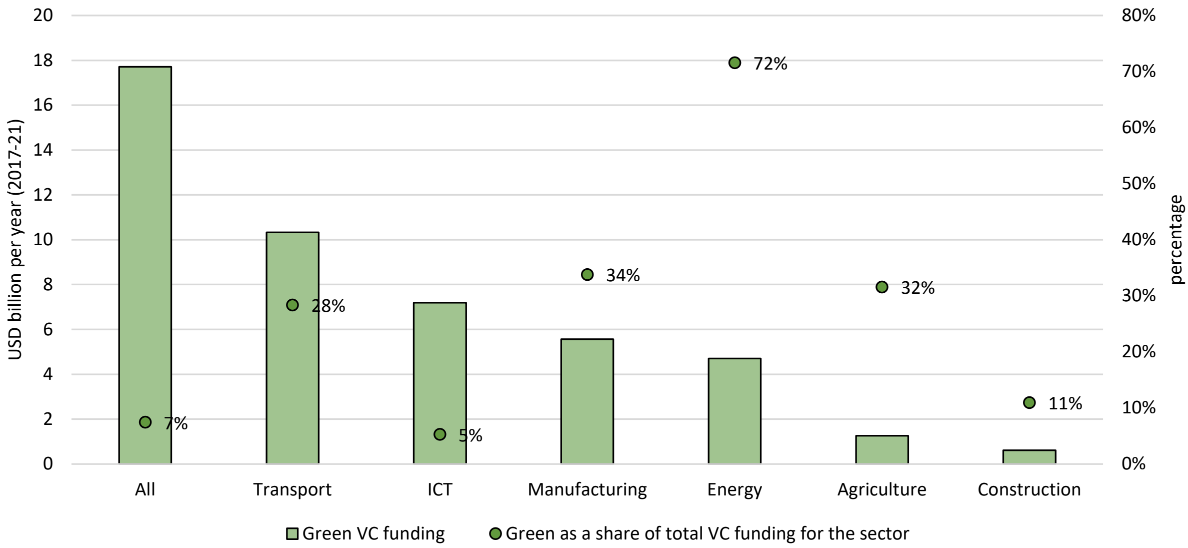
The transport sector attracted the highest amount of green VC funding of the green VC funding over the period 2017-21 with USD_{2015} 12 billion per year followed by ICT (USD_{2015} 10 billion), manufacturing and energy (USD_{2015} 8 billion) (see Figure 5.5). The evolution in the absolute amount of green VC funding for specific sectors can provide information about the evolution of the focus of VC investors on different environment-relevant economic sectors. On the contrary, a comparison between absolute amounts of different sectors is less informative due to the general propensity of certain sectors to receive more VC funding with respect to others, for example, because of their size in the overall economy or their funding model more based on VC funding.[31]

Comparing the share of VC funding targeting green firms at the sector level can provide a better understanding of the focus of investors on the greening of certain sectors compared to others. While the ICT sector is the second most targeted sector in terms of absolute amounts of green VC funding, only a small share of total funding to ICT went to green firms (5%). In 2017-2021, the largest share of green VC was in the energy and manufacturing sector where 72% and 34% of total VC funding respectively targeted green firms.[32] In contrast, ICT and construction received the lowest shares of green VC funding out of the total, amounting to 5% and 11% respectively. Being the largest sector in the database in terms of VC funding received (57% of the total over 2017-2021), ICT drives down the overall share of green VC funding out total funding in all sectors, which in 2017-2021 amounted to 7%.

[31] This is typically the case for ICT which attracts a very large amount of VC.

[32] The high share in energy is not explained by companies operating in fossil fuel energies since they are excluded from the selection.

Figure 5.5. Green VC funding by sector (2017-21)

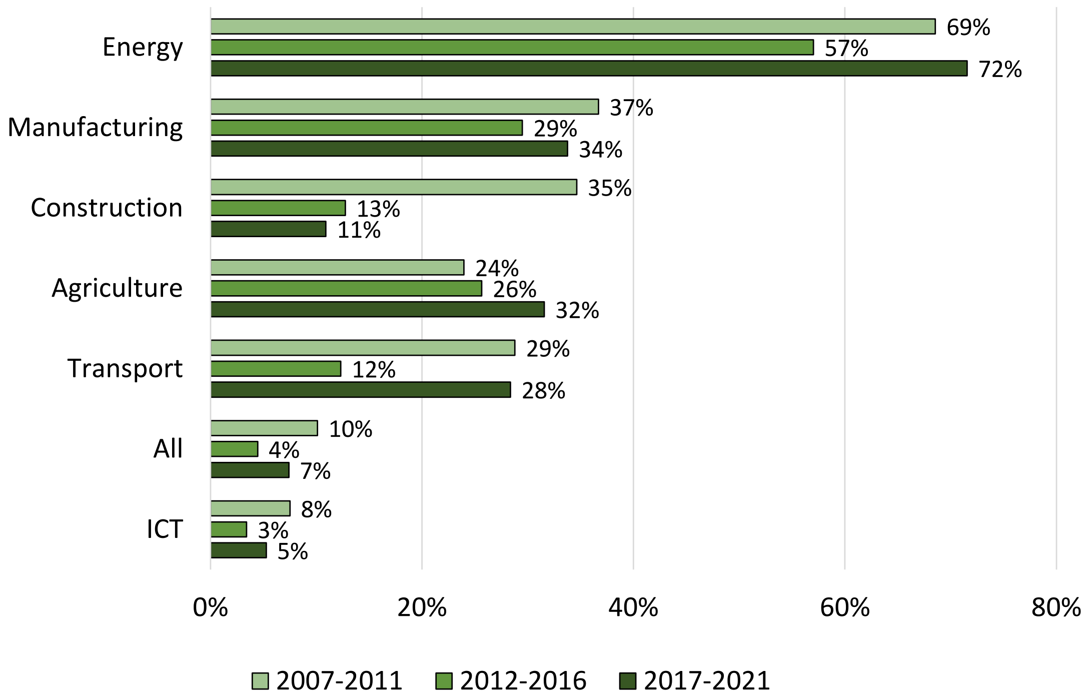


Source: Crunchbase based on Authors' methodology described in Section 5.1.
Note: All green VC funding is not equal to the sum of sector level green VC funding because companies can be active in several sectors.

5.2.4. After decreasing in all sectors, the share of green VC funding is bouncing back

In all sectors analysed, the share of green VC funding out of total VC funding has declined between the 2007-2011 period and the 2017-2021 period (Figure 5.6). At the global level, the share of green funding declined significantly, moving from 10% on average in 2007-11 to 7% in 2017-21, mainly due to a decline in green VC funding in the United States in the years following the peak that occurred during the financial crisis recovery phase. As shown in Figure 5.6, the share in green funding declined between 2007-2011 and 2012-2016 but has increased again since 2015. This U-shaped trend was observed in most sectors, except for agriculture and construction. In the agriculture sector in particular, the share of green funding out of the total has constantly increased over the three period.

Figure 5.6. Green VC funding as a share of total, by sector



Source: Crunchbase based on Authors' methodology described in Section 5.1. All green VC funding is not equal to the sum of sector level green VC funding because companies can be active in several sectors.

5.3. The geography of breakthrough green innovation effort

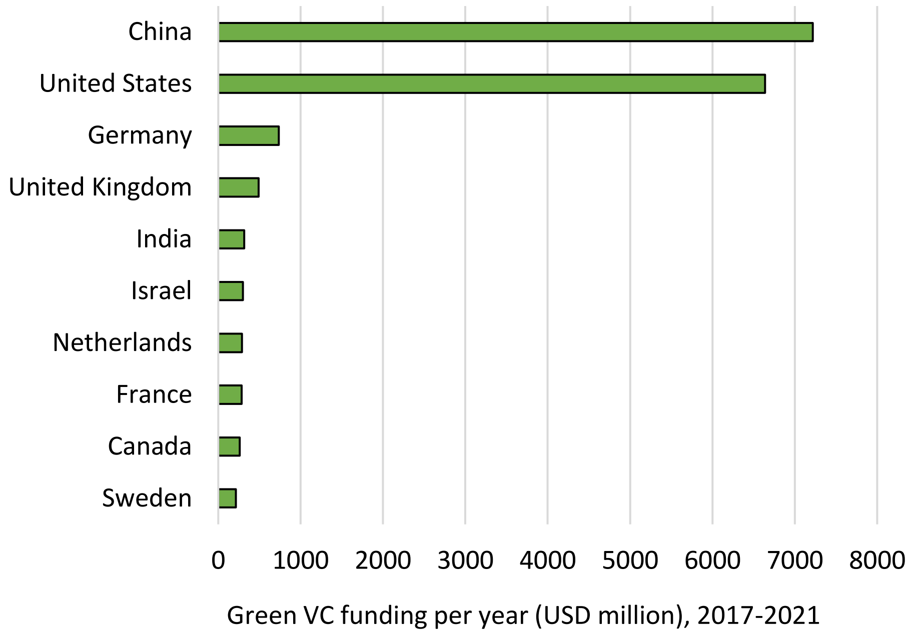
5.3.1. Green VC funding is concentrated in a few countries

Green VC funding is highly concentrated in a few countries (Figure 5.7). In 2017-2021, China and the United States combined represented 78% of green VC funding. Over this period, green firms in these two countries received USD 6.6 billion and USD 7.2 billion of VC funding per year respectively. The remaining share of green VC funding was allocated to firms based in other countries, such as Germany (4% of total green VC funding) and the United Kingdom (3%). The European Union accounts for approximately 10% of green VC funding.[33] The top 10 recipients of VC funding received 94% of total green VC funding, while only 92% of total (green and non-green) VC funding, signalling a higher geographical concentration of the former.

It is important to note that the reliance on venture capital as a vehicle for investment in start-ups and high-risk, high-reward technologies can differ markedly from one country to another. Most notably, venture capital markets are more developed and mature in the United States compared to other countries. Therefore, actual breakthrough green innovation effort is likely less concentrated than the green VC funding as shown by Figure 5.7.

[33] This is probably a lower bound estimate since Crunchbase has historically focused more on US markets in terms of data collection.

Figure 5.7. Geographical distribution of green VC funding (2017-2021)



Source: Crunchbase based on Authors' methodology described in Section 5.1. Note that the amount reported for the European Union is probably a lower bound estimate since Crunchbase has historically focused more on US markets in terms of data collection.

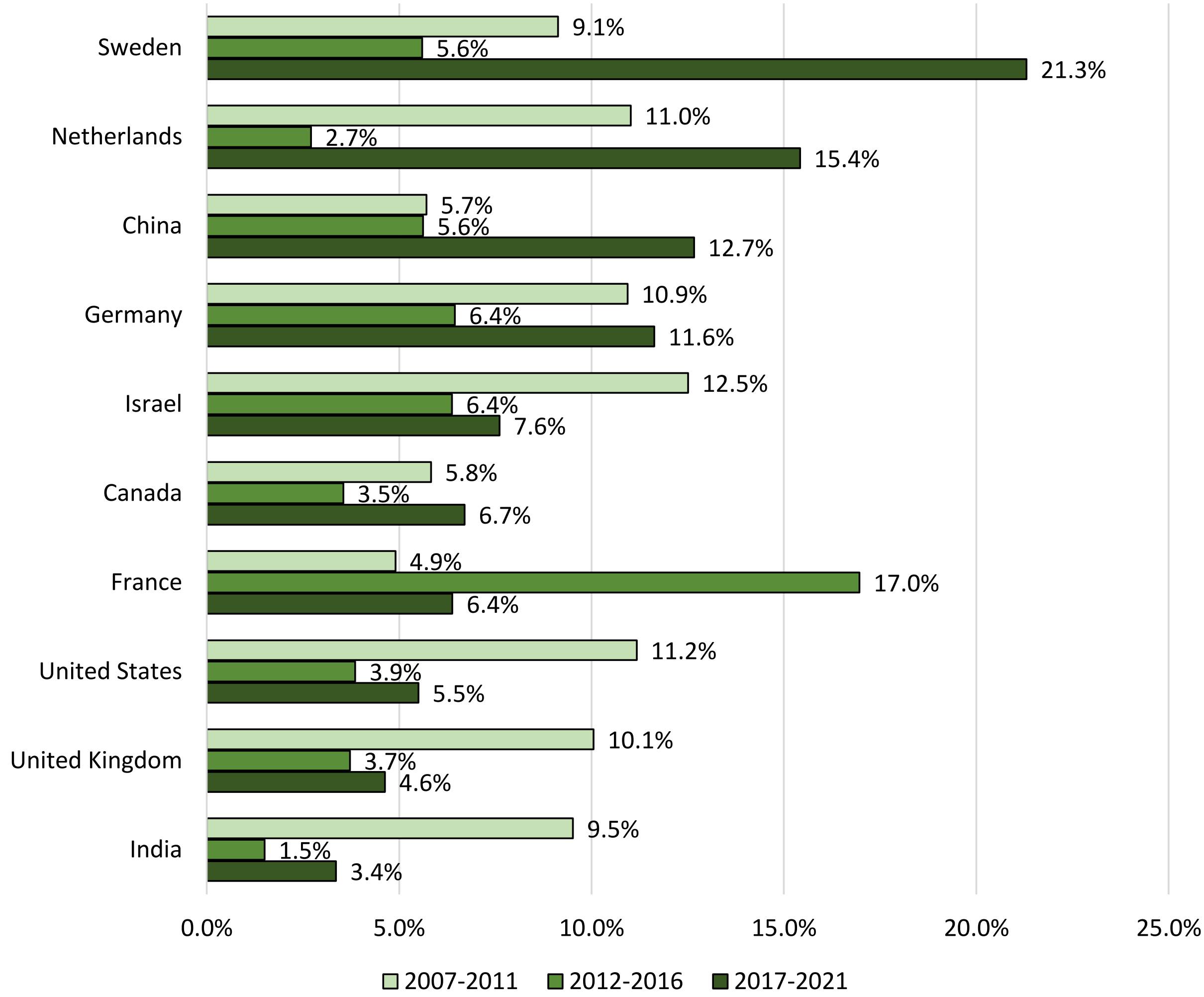
5.3.2. The share of green VC funding and its evolution over time varies significantly across countries

Because the reliance on VC as an investment vehicle differs across countries, international comparison based on absolute amount of green VC funding is challenging. Instead, looking at green VC funding as a share of total VC funding partially mitigates this issue as both numerator and denominator are equally affected by the reliance on VC funding.

The share of total VC funding benefitting green companies varies markedly between countries (Figure 5.8). In 2017-2021, among the 10 top recipients, the share of green VC funding out of total VC funding ranged between 3% in India and 21% in Sweden. Following Sweden, other countries with large shares of VC funding out of total VC funding are the Netherlands (15%), China (13%) and Germany (12%).

Countries differ also in the evolution of the share of green VC funding out of total. In most countries the share of green VC funding declined between 2007-2011 and 2012-2016 but then started increasing again over the period 2017-2021. In France, the share of VC funding was allocated to green companies peaked in the period 2012-2016 driven by late-stage investment in share mobility start-ups such as Bla Bla Car, Cityscoot and Navya. The large decrease in the United States over the three periods is mostly explained by the exceptional peak of VC funding in green companies during the great financial crisis and the following years.

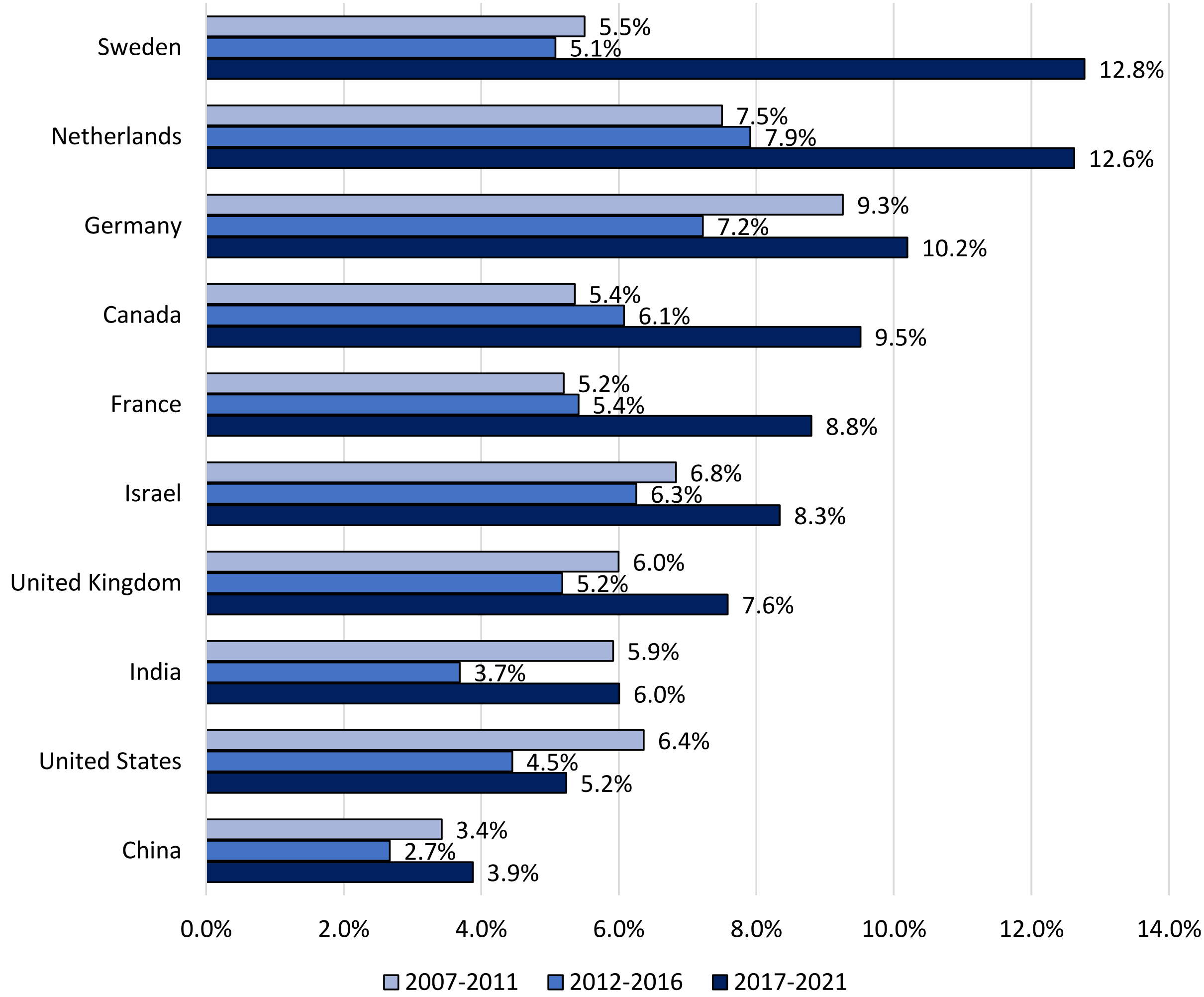
Figure 5.8. Green VC funding amounts as a share of total, by country



Source: Crunchbase based on Authors' methodology described in Section 5.1.

Since the share of green VC values might be influenced by a few large investments, looking at the share of the number of green VC deals by country can provide additional information. Overall, the share of green VC deals out of total in 2017-2021 ranged between 4% in China and 13% in Sweden (Figure 5.9). One key difference with respect to total VC funding amounts is that the share of green VC deals has been the highest in the most recent period, except for the United States. Similarly to the share of green VC funding, there was also a decline in the share of green VC deals in many countries between 2007-2011 and 2012-2016, including the two largest players, China and the United States.

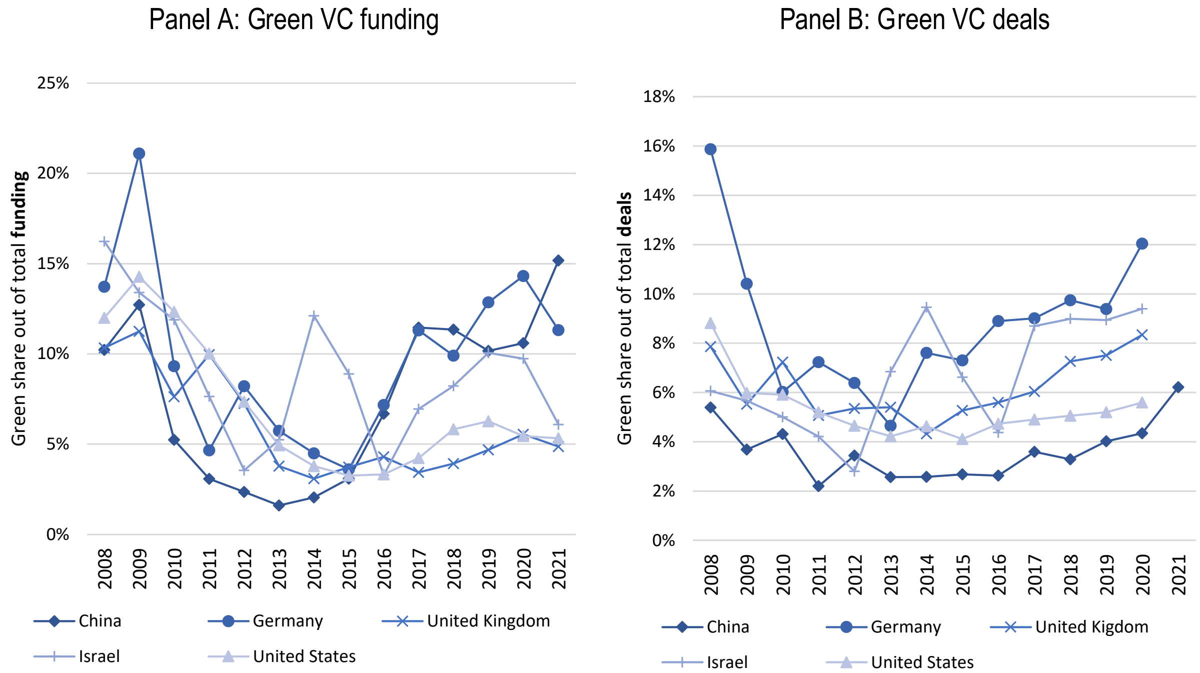
Figure 5.9. Green VC deals as a share of total, by country



Source: Crunchbase based on Authors' methodology described in Section 5.1.

These new metrics can also help track over the years the greening of venture capital at the country level as illustrated by Figure 5.10. Since 2015, Germany and China have been increasing their share of green VC funding (Panel A). On the contrary, the United States decreased its share of green VC funding until 2014, and then stabilised around 5%. In terms of green deals, Germany, United Kingdom, and China have increased their share of green deals, while the United States displays a stable trend (Panel B).

Figure 5.10. Evolution of share of green VC funding and green deals by country



Note: Shares for both amount of funding and number of deals is computed using a two-year moving average.
Source: Crunchbase based on Authors' methodology described in Section 5.1.

5.4. Comparison with traditional patent metrics

5.4.1. Green venture capital and green patents capture different aspects of innovation

Traditional patent statistics and metrics based on VC funding capture innovation differently. Simple counts of patent families do not distinguish between incremental and breakthrough innovation output while VC funding mostly focus on high value and high-risk innovation effort. The comparison between these two metrics provides insights into the different evolution of incremental and breakthrough innovation in environmental technologies.

Metrics based on VC funding deals are different from metrics based on patent statistics also because they measure innovation at different stages of a technology life cycle. Patent families measure innovation at the point in time when an invention is first registered by its inventor. VC deals in a green company, on the other hand, measures innovation effort when an innovative company has not yet commercialised its potentially breakthrough invention or is in the early stages of commercialisation. Patents can play an important role in helping to attract VC funding (Häussler, Harhoff and Müller, 2012[66]; Hoenig and Henkel, 2015[67]) but this is not always their main objective. Some patents, for example, are regularly filed later on when firms are mature to protect their intellectual property.

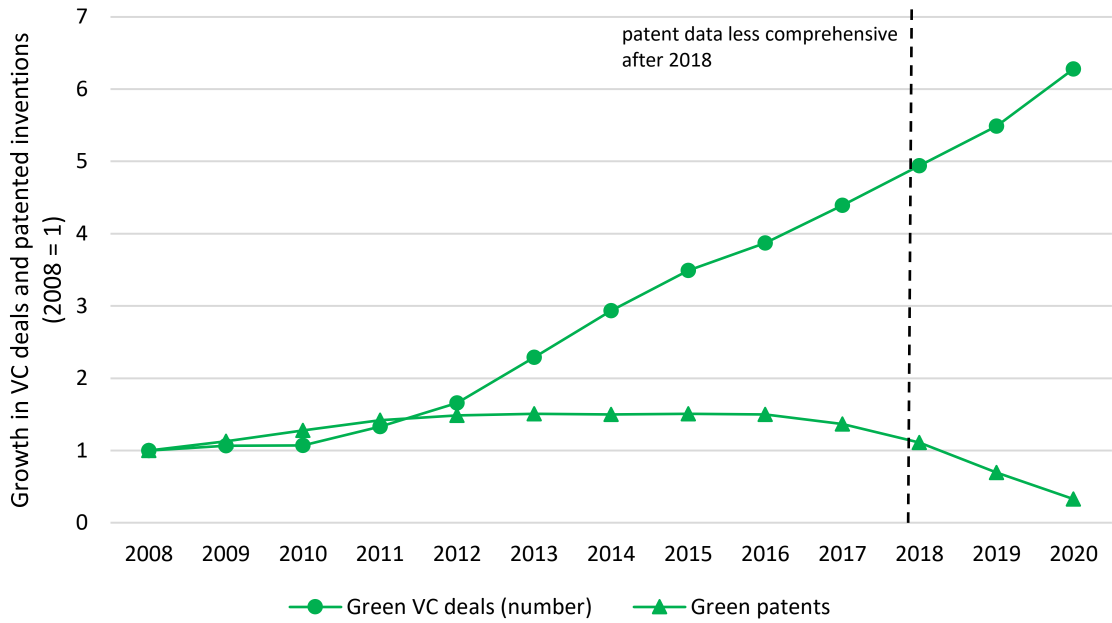
A third difference between patent statistics and metrics based on VC funding is the timing at which information becomes available. Patent data are updated and made available to the public with a lag, which hamper the analysis of the trends of innovation until several years after the date of the patent application. This makes it harder to draw conclusions on the effectiveness of specific policy measures in a timely manner. In contrast, information on VC funding is available in close-to-real time, which can allow to track the impact of policy measures more rapidly.

5.4.2. Green venture capital deals have grown much faster than green patents

From the comparison between patents statistics and new metrics based on the number of VC deals it appears that the number of green venture capital deals[34] has been growing much faster than the number of new patents in recent years. Figure 5.11 shows the different growth trends in patent families and number of VC deals over the period 2008-2020. While green patents have only slightly grown from 2008 to 2013 reaching a plateau until 2016 and then decreasing, the number of green VC deals has continued to increase since 2011. The higher growth rate of green VC deals compared to green patents is consistent across all sectors (Figure 5.12).

In addition, in recent years green VC deals have outpaced the growth experienced by VC deals overall, while the opposite trend can be found for green patents. Figure 5.13 shows the evolution in green VC deals as a share of total VC deals and in green patents as a share of total patents. While the share of green patents out of total has been decreasing since 2012, pointing to a decreased level of innovation intensity, the share of green VC deals has been on a consistent growing trend since 2015. This trend holds true even when only seed transactions – the ones in more unripe technologies - are considered.

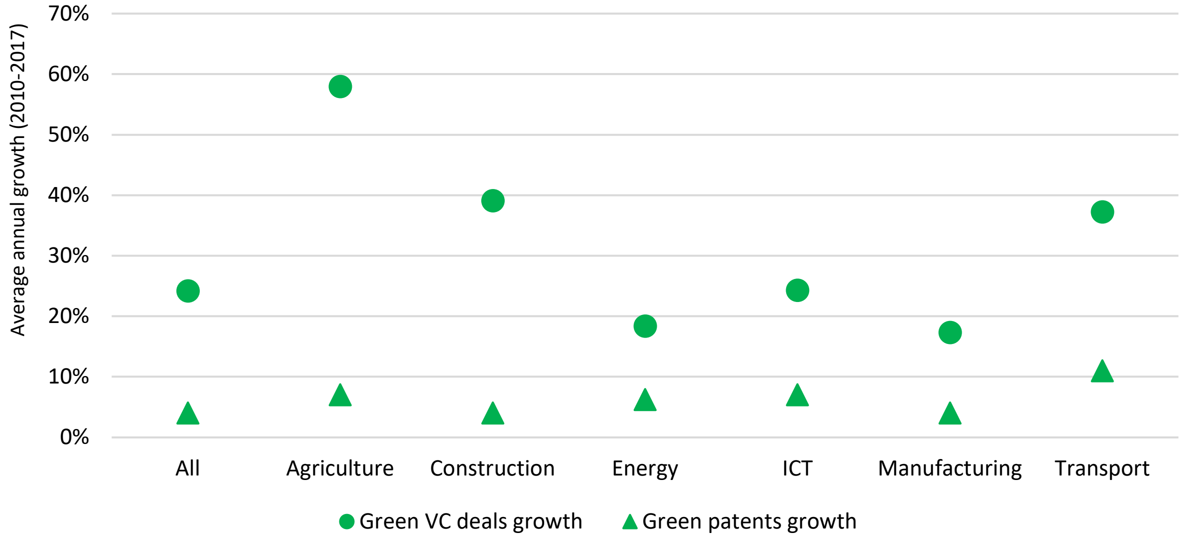
Figure 5.11. Comparison between the growth in green patents and in the number of VC deals



Source: Crunchbase based on Authors' methodology described in Section 5.1 and "OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, September 2022".
Note: The index for both patents and number of VC deals is computed using 3-year moving average. Patents correspond to patent families. A patent family is a collection of patent documents that covers a single invention. Analysing the number of patent families rather than the total number of individual patent applications better captures the amount of innovation and avoid double counting.

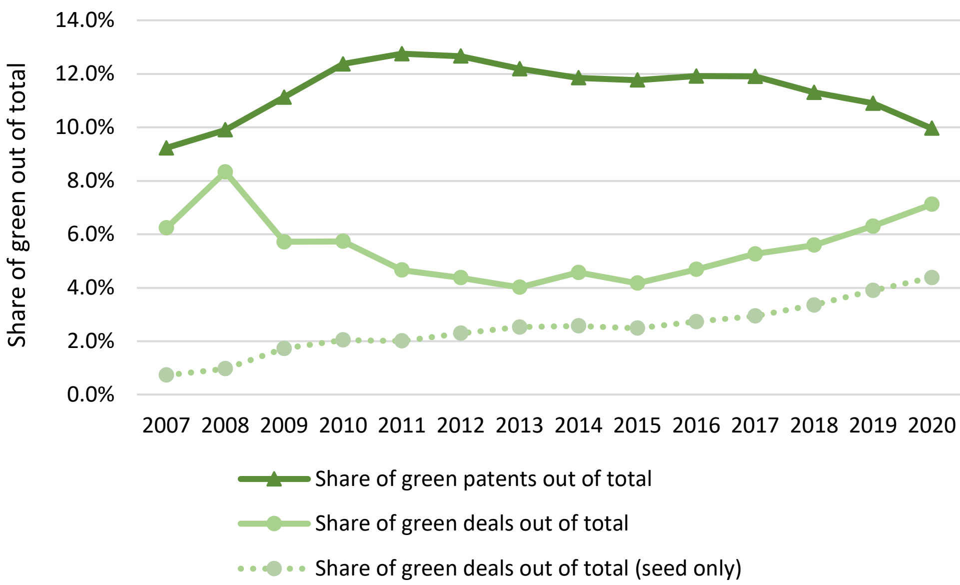
[34] Using the number of VC deals rather than total VC funding provides a better comparison with respect to patent statistics than total green funding. Just like the number of patents, the number of VC deals does not assign a value to these transactions. On the contrary, green funding should be proportional to the value investors see in a specific company.

Figure 5.12. Average annual growth rate (green patents vs number of green VC deals), 2010-2017



Source: Crunchbase based on Authors' methodology described in Section 5.1 and "OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, September 2022".
Note: Patents are aggregated at the patent family level. A patent family is a collection of patent documents that covers a single invention. Analysing the number of patent families rather than the total number of individual patents better captures the amount of innovation.

Figure 5.13. Share of green patents and green VC deals out of total



Source: Crunchbase based on Authors' methodology described in Section 5.1 and "OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, September 2022".

These opposite trends in green patents and VC deals in green firms indicate that the two metrics capture different dynamics, potentially tracking different types of innovation type (incremental versus breakthrough) and innovation stages (early-stage versus commercialisation). As a result, tracking the evolution of the two can give a more comprehensive representation of green innovation trends.

6 Summarising trends in green innovation using new metrics

6.1. Summary of the general green innovation trends across metrics

This paper develops three new families of green innovation metrics based on patent assignment, technology licensing agreement and venture capital that are described in greater details in the previous sections. Table 6.1 summarises the main characteristics of these new innovation metrics and of traditional patent metrics including the stage of innovation, the type of the innovation and the technological fields.

Table 6.1 also shows the main trends in the greenness of innovation between 2008 and 2021 for the United States and at the global level. Focusing on the share rather than on the absolute value of green innovation allows to control for the scale effects that are specific to all metrics and permits to compare metrics in the same unit. The comparison of these trends leads to several findings.

First, the metrics can be divided in two groups based on the shape of the general trends measure. The share of green innovation based on patent assignment, technology licensing and traditional patents exhibit an inversed U-shape relationship (∩-shape). For these metrics, the relative importance of green innovation increased from 2008 until 2012 where it peaked then decrease until more recent years. In contrast, the share of green innovation based on VC funding and VC deals exhibits a U-shape relationship. The amount of VC in green technologies was the highest during the global financial crisis then decreased until around 2015 where it started bouncing back possibly driven by the adoption of the Paris Agreement.[35] The different shapes of the trends across the two groups of metrics are capturing fundamentally different innovation dynamics, which is not surprising considering that they focus on different types and stages of innovation. Assigned patented inventions and licensing agreement measure commercialised innovation while venture capital measure innovation effort at earlier stage of technology development.[36]

Second, while metrics based on patent assignment, technology licensing and traditional patents share a similar inversed U-shape relationship in terms of share of green innovation, the increase and decrease around the peak year vary significantly across metrics. This is consistent with the findings presented in the previous sections that patent assignment and technology licensing captures something new compared to traditional patent metrics.

Third, climate change-related innovation and green innovation in general tend to follow similar dynamics. However, the share of climate change-related innovation tends to fluctuate more than the share of green

[35] Note that there is no evidence yet on the causal link between the Paris Agreement and green VC.

[36] Another difference might come from the difference in the propensity to rely on patent assignment and venture capital across sectors. For example, in the United States, total VC (green or not) is ten times more important in ICT than in manufacturing while the total number of assigned patented inventions is twice as more important in manufacturing as in ICT. However, this difference is partially controlled for when looking at green innovation as a share of total innovation in the respective sectors.

innovation in general as illustrated by patented inventions, VC funding and VC deals where the comparison is possible. One possible explanation is that climate has been seen as a more and more urgent issue to tackle among investors and creators of technologies relatively to other environmental fields.

Finally, the share of green innovation in the United States is increasing less rapidly than the share of green innovation measured at the global level across all metrics where the comparison is possible. Future work should examine more carefully what drives cross country differences in green innovation indicators.

Table 6.1. Recent trend in green innovation since the global financial crisis across different metrics

Green innovation as a share of total innovation, 2008-2021

Metric	Innovation stage	Type of innovation	Technological field	Trends in share of total innovation from 2008 and from the pivotal year	
				World	United States
Patented inventions	Innovation commercialised or not	Inventions of all value	All green	∩-shape Increased (+28%*) and peaked in 2012 then decreased (-21%**)	∩-shape Increased (+28%) and peaked in 2012 then decreased (-33%)
Patented inventions	Innovation commercialised or not	Inventions of all value	Climate change adaptation and mitigation	∩-shape Increased (+32%) and peaked in 2012 then decreased (-26%)	∩-shape Increased (+32%) and peaked in 2012 then decreased (-37%)
Assigned patented inventions	Commercialised innovation	Inventions of higher value	Climate change adaptation and mitigation	Not available	∩-shape Increased (+42%) and peaked in 2012 then decreased (-36%)
Licensing	Commercialised innovation	Inventions of higher value	Climate change adaptation and mitigation	Not available	∩-shape Increased (+17%) and peaked in 2012 then decreased (-39%)
Venture capital funding	Innovation effort	High reward high risk (breakthrough)	Climate change adaptation and mitigation	U-shape Decreased (-78%) after the GFC but increasing since 2016 (+126%)	U-shape Decreased (-82%) after the GFC but increasing since 2015 (+86%)
Venture capital deals	Innovation effort	High reward high risk (breakthrough)	Climate change adaptation and mitigation	U-shape Decreased (-52%) after the GFC but increasing since 2016 (+72%)	U-shape Decreased (-54%) after the GFC but increasing since 2016 (+29%)
Venture capital funding	Innovation effort	High reward high risk (breakthrough)	All green	U-shape Decreased (-79%) after the GFC but increasing since 2016 (+124%)	U-shape Decreased (-82%) after the GFC but increasing since 2016 (+91%)
Venture capital deals	Innovation effort	High reward high risk (breakthrough)	All green	U-shape Decreased (-50%) after the GFC but increasing since 2016 (+69%)	U-shape Decreased (-53%) after the GFC but increasing since 2016 (+31%)

Note: * The evolution is given in percentage change from 2008 and not in terms of percentage point change to allow for comparison across metrics. ** The evolution is given in percentage change from the peak year.
Source: Calculations of the authors based on "OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, September 2022", USPTO, ktMINE and Crunchbase data.

6.2. Using new green innovation metrics for empirical analysis: the case of the car sector

The market for electric cars illustrates how the green innovation metrics developed in this paper can be used in empirical analysis. Notably, the new green innovation metrics are found to be more correlated to the future commercialisation of green technologies than traditional patent metrics (Table 6.1).[37]

Table 6.1 shows, for the United States, the growth in the share of car-related patented inventions for electric cars (Panel A), the growth in the share of all car-related assigned inventions for electric cars (Panel B) and the share of transport-related VC deals related to electric cars on the right axis (Panel C). These trends are compared with the growth in the share of electric cars as percentage of all cars sold in the United States on the left axis using data from IEA (2022[68]). The growths in the shares are normalised to 100 in 2011 to allow for the comparison of the trends over time.[38]

The metric based on assigned patented inventions is the most correlated with the market penetration of electric cars (Table 6.1, Panel B). It is found that assigned patented inventions precede the sales of electric vehicles. More specifically, there is a lag of 5 years between the first peak in assigned patented inventions in 2009 and the first peak in market penetration in 2014 while there is a lag of 4 years between the second peak in assigned patented inventions in 2014 and the second peak in market penetration in 2018. The metric based on VC deals is less correlated than the metric based on patent assignment (Table 6.1, Panel C). However, there is a peak in VC deals related to electric cars during the global financial crisis that also precede the jump in electric car market penetration in later years. In comparison, the metrics based on patented inventions is relatively flat and appears to be uncorrelated to electric car market penetration (Table 6.1, Panel A).

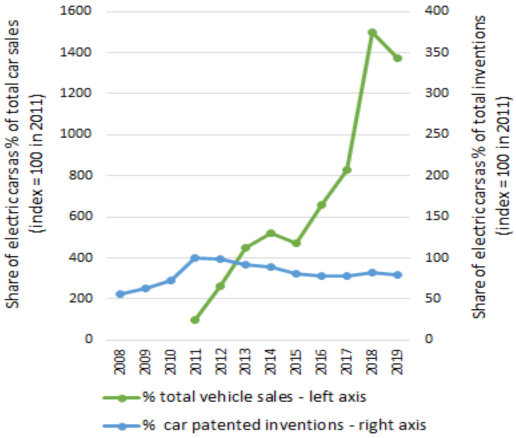
This case study shows that new green innovation metrics, such as those based on patent assignments and VC in green firms, are more correlated to future commercialisation of green technologies than traditional patent metrics. However, these empirical relationships should be taken with precaution. Deriving causal effects requires an adequate empirical setting and additional research.

[37] This correlation does not necessarily imply a causal effect, which is left for further research.

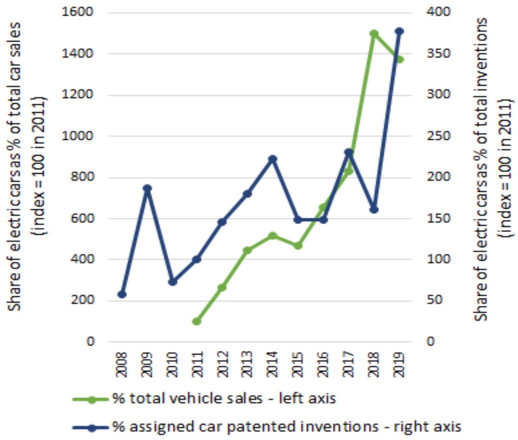
[38] The base year is 2011 because the share of vehicles sales related to electric cars is not available before.

Figure 6.1. New green innovation metrics and sales of cleaner cars in the United States

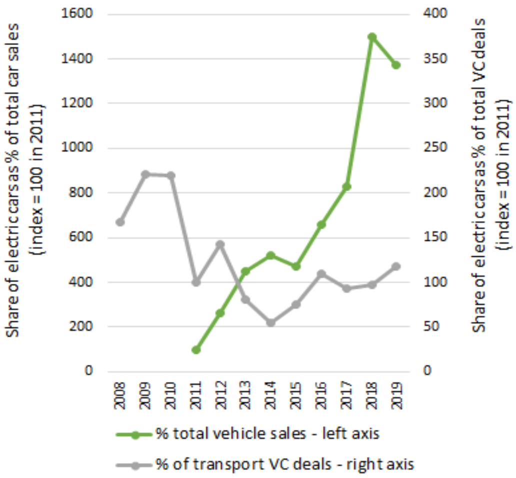
Panel A



Panel B



Panel C



Note: The year for non-assigned patented inventions correspond to the application year of the first patent in the family. Only patent family's first re-assignment is included. Climate change-related patented inventions are defined as patent families having at least one Y02 code. Assignments are defined as change in ownership, notably 'assignment' (ownership transferred to another entity) or 'merger' (ownership change due to merger). To avoid double counting, only the first assignment of each patent family is counted.
Source: Authors calculation based on the UPAD dataset and OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, May 2022. Sales of electric cars that include battery cars and plug-in hybrid electric cars come from IEA (2022[68]). Sales of all cars are collected from various form 10-K of car manufacturing compagnies available from the United States Securities and Exchange Commission.

7 Conclusions and policy implications

This paper reviewed potential new metrics to measure (i) commercialised climate change-related innovation (Section 2) and (ii) new metrics to measure breakthrough green innovation (Section 3). For commercialised climate change-related innovation, the paper identifies four different families of indicators based on: licensing deals, patent assignments, web scraping, and patent-product linkage that overcome some issues associated with metrics based on traditional indicators such as patent data, R&D expenditures or survey data. The comparison of the different advantages and drawbacks of these different candidates concludes that metrics based on licensing deals and patent reassignments are the most promising to develop to measure commercialised climate change-related innovation.

Regarding breakthrough green innovation, the paper identifies two different families of indicators based on high-growth green firms and green venture capital (VC) funding. The comparison of the different advantages and drawbacks of these different candidates concludes that green venture capital funding is the most appropriate metrics to develop because available data cover both small and large companies and that the identification of environmental innovation does not rely on patent data.

New metrics to measure commercialised climate change-related innovation based on patent assignment and licensing deals are developed (Section 4). The methodology is described and various trends are analysed for the United States, for which data are currently available. Commercialised climate change-related innovation increased in absolute terms in all sectors over the last two decades and is relatively more important in the energy and transport sector. However, the relative importance of commercialised climate change-related innovation as a share of total innovation decreased between 2012 and 2018. In addition, the paper shows that data on patent licensing is still very scarce and only covers a small fraction of total licensing deals. Extending the new metrics based on patent assignment to other countries is possible but would require an additional amount of data work to merge and harmonise patent assignments recorded in various patent offices, each having their specific recording system or would require purchasing additional commercial datasets.

The paper also develops a new family of metrics to measure breakthrough green innovation effort based on the analysis of keywords in VC data (Section 5). The methodology allows to measure innovation effort in climate change adaptation and mitigation but also in technologies related to air pollution, water pollution, waste management, soil remediation and environmental monitoring. The analysis shows that green VC funding has been constantly increasing since 2008 and has now reach USD_{2015} 20 billion per year or 7% of all VC funding at the global level. The most important sectors for green VC funding are transport, ICT, manufacturing and energy. Green VC funding is concentrated in a few countries and the United States and China account for 78% of the total, partially reflecting the reliance of VC funding as an investment vehicle for start-ups. Green VC funding as a share of total VC funding peaked during the global financial crisis and decreased until 2015 after which it has been raising again since.

The various metrics measure different green innovation trends because they focus on different innovation stage and type of innovation (Section 6). Most notably, climate-change related assigned patented inventions has been decreasing in relative terms over the last decade likely driven by falling fossil fuel prices and increasing the technological maturity of some climate mitigation technologies. On the contrary, climate-change related VC funding has been increasing since 2015. This could suggest that the innovation focus is moving from mature technological fields towards high-reward high-risk and potentially breakthrough green technologies.

The results of the paper have important policy implications. First, the evidence-based assessment of environmental and economic policies should to the extent possible measure green innovation with various metrics capturing different stages and types of innovation. Only relying on one metric can potentially lead to overlooking important trends and to the failure of capturing the full effect of policies. Second, assessing the effect of environmental policies on green innovation requires looking at various time horizons depending on the metrics used. Third, the other factors or policies that drive the emergence of green innovation should also be accounted for when evaluating environmental policies. For example, the amount of VC in green firms likely also depends on fiscal policies, market fragmentation, monetary policies and stimulus packages. Assigned patented inventions also depends on intellectual property rights regime and policies. Taking these other policies into account is potentially important to create synergies and consistency with environmental policies to favour the emergence of green innovation.

These new metrics have strong advantages against traditional patent metrics and offer new perspective on measuring various forms of green innovation as illustrated by the case study on the US electric car market. However, it is worth mentioning existing limitations. First, the new metrics developed to measure commercialised climate-change related innovation are only available for the United States for which raw data are most readily accessible. Data on licensing agreements are scarcer and currently focus on publicly available deals. This is not the case of the new family of metrics to measure breakthrough green innovation effort based on VC data that is becoming more and more available for various countries. Second, data for recent years (2018-2021) are, similarly to traditional patent metrics, not fully available for the metrics based on assigned patented inventions and licensing agreements. In comparison, VC data are available in near real time. Third, metrics based on green VC funding focus on breakthrough green innovation effort, which does not always become actual breakthrough in terms of environmental impacts as not all ventures are successful and as economic success does not automatically translate into environmental benefits. Further research should be done to link VC funding and indicators of environmental impacts. Further research on developing metrics more directly related to innovation policies such as grants, loans and loan guarantees and public R&D subsidies is also recommended in order to cover the innovation cycle more broadly and better reflect the universe of innovation funding available in different countries and to facilitate improved ex post assessments of public innovation policies.

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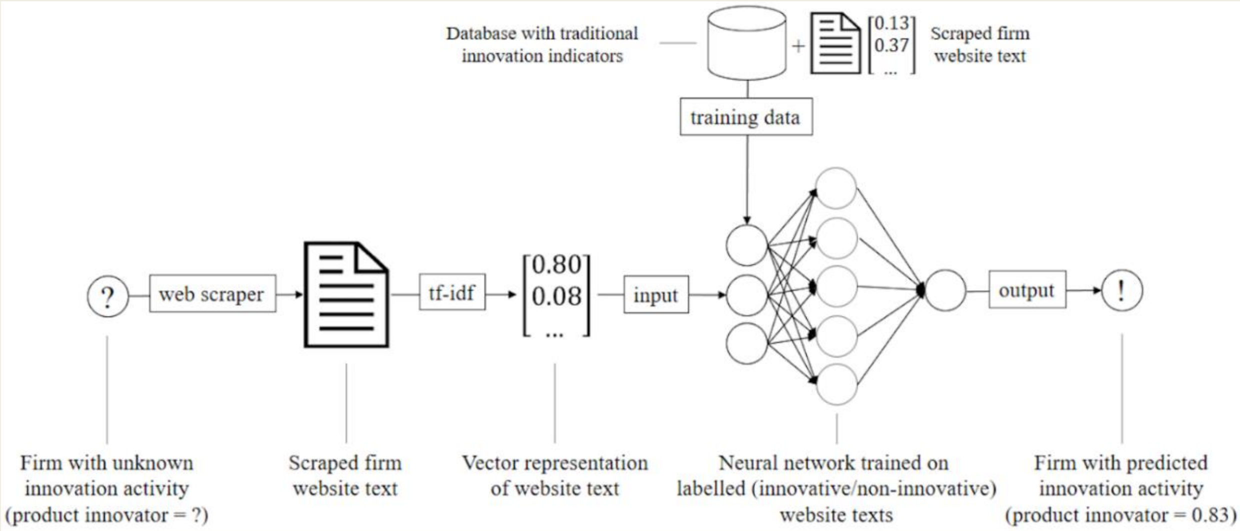
Annex A. Additional material

Figure A.1. Product innovator prediction framework Kinne and Lenz (ISARI.AI)



Source: Kinne and Lenz (2021[69])

Table A.1. Definition of economic sectors industries used in Section 4

Sector	Cooperative Patent Classification Code
Agriculture	A01: agriculture; forestry; animal husbandry; hunting; trapping; fishing
Construction	E01: construction of roads, railways or bridges E02: hydraulic engineering, aviation, soil shifting E03: water supply, sewerage E04: building E05: locks; keys; window or door fittings; safes E06: doors, windows, shutters, or roller blinds in general; ladders
Energy	H01: basic electric elements H02: generation; conversion or distribution of electric power
ICT	G11: information storage G16: information and communication technology [ict] specially adapted for specific application fields H04: Electric communication techniques
Manufacturing	A21: baking; edible doughs A22: butchering; meat treatment; processing poultry or fish A23: foods or foodstuffs; treatment thereof, not covered by other classes A24: tobacco; cigars; cigarettes; simulated smoking devices; smokers' requisitesa24 A41: wearing apparel A42: headwear A43: footwear A44: haberdashery; jewellery A45: hand or travelling articles A46: brushware A47: furniture; domestic articles or appliances; coffee mills; spice mills; suction cleaners in general B21: mechanical metal-working without essentially removing material; punching metal B22: casting; powder metallurgy B23: machine tools; metal-working not otherwise provided for B24: grinding; polishing B25: hand tools; portable power-driven tools; manipulators B26: hand cutting tools; cutting; severing B27: working or preserving wood or similar material; nailing or stapling machines in general B28: working cement, clay, or stone

B29: working of plastics; working of substances in a plastic state in general
B30: presses
B31: making articles of paper, cardboard or material worked in a manner analogous to paper; working paper, cardboard or …
B32: layered products
B33: additive manufacturing technology
B41: printing; lining machines; typewriters; stamps
B42: bookbinding; albums; files; special printed matter
B43: writing or drawing implements; bureau accessories
B44: decorative arts
B60: vehicles in general
B61: railways
B62: land vehicles for travelling otherwise than on rails
B63: ships or other waterborne vessels; related equipment
B64: aircraft; aviation; cosmonautics
B65: conveying; packing; storing; handling thin or filamentary material
B66: hoisting; lifting; hauling
B67: opening, closing or cleaning bottles, jars or similar containers; liquid handling
B68: saddlery; upholstery
B81: microstructural technology
B82: nanotechnology
C01: inorganic chemistry
C02: treatment of water, waste water, sewage, or sludge
C03: glass; mineral or slag wool
C04: cements; concrete; artificial stone; ceramics; refractories
C05: fertilisers; manufacture thereof
C06: explosives; matches
C07: organic chemistry
C08: organic macromolecular compounds; their preparation or chemical working-up; compositions based thereon
C09: dyes; paints; polishes; natural resins; adhesives; compositions not otherwise provided for; applications of materials …
C10: petroleum, gas or coke industries; technical gases containing carbon monoxide; fuels; lubricants; peat
C11: animal or vegetable oils, fats, fatty substances or waxes; fatty acids therefrom; detergents; candles
C12: biochemistry; beer; spirits; wine; vinegar; microbiology; enzymology; mutation or genetic engineering
C13: sugar industry
C14: skins; hides; pelts; leather
C21: metallurgy of iron
C22: metallurgy; ferrous or non-ferrous alloys; treatment of alloys or non-ferrous metals
C23: coating metallic material; coating material with metallic material; chemical surface treatment; diffusion treatment of …
C25: electrolytic or electrophoretic processes; apparatus therefor
C30: crystal growth
C40: combinatorial technology
D01: natural or man-made threads or fibres; spinning
D02: yarns; mechanical finishing of yarns or ropes; warping or beaming
D03: weaving
D04: braiding; lace-making; knitting; trimmings; non-woven fabrics
D05: sewing; embroidering; tufting
D06: treatment of textiles or the like; laundering; flexible materials not otherwise provided for
D07: ropes; cables other than electric
D10: indexing scheme associated with sublasses of section d, relating to textiles
D21: paper-making; production of cellulose
F01: machines or engines in general; engine plants in general; steam engines
F02: combustion engines; hot-gas or combustion-product engine plants
F03: machines or engines for liquids; wind, spring, or weight motors; producing mechanical power or a reactive propulsive …
F04: positive - displacement machines for liquids; pumps for liquids or elastic fluids
F05: indexing schemes relating to engines or pumps in various subclasses of classes f01-f04
engineering in general
F15: fluid-pressure actuators; hydraulics or pneumatics in general
F16: engineering elements and units; general measures for producing and maintaining effective functioning of machines or installations; thermal insulation in general
F17: storing or distributing gases or liquids
F21: lighting
F22: steam generation
F23: combustion apparatus; combustion processes
F24: heating; ranges; ventilating
F25: refrigeration or cooling; combined heating and refrigeration systems; heat pump systems; manufacture or storage of ice; liquefaction solidification of gases
F26: drying
F27: furnaces; kilns; ovens; retorts

	F28: heat exchange in general F41: weapons F42: ammunition; blasting H01: Basic electric elements
Transport	B60: vehicles in general B61: railways B62: land vehicles for travelling otherwise than on rails B63: ships or other waterborne vessel B64: aircrafts, aviation, cosmonautics

Source: Authors' own elaboration based on the Cooperative Patent Classification available on espacenet: https://worldwide.espacenet.com/classification.

Table A.2. Definition of economic sectors and industries used in Section 5

Sector	Crunchbase industry groupings
Energy	Battery, Biofuel, Biomass Energy, Clean Energy, Electrical Distribution, Energy, Energy Efficiency, Energy Management, Energy Storage, Fossil Fuels, Fuel, Fuel Cell, Oil and Gas, Power Grid, Renewable Energy, Solar, Wind Energy
Agriculture	Agriculture, AgTech, Animal Feed, Aquaculture, Equestrian, Farming, Forestry, Horticulture, Hydroponics, Livestock
Manufacturing	3D Printing, Advanced Materials, Foundries, Industrial, Industrial Automation, Industrial Engineering, Industrial Manufacturing, Machinery Manufacturing, Manufacturing, Paper Manufacturing, Plastics and Rubber Manufacturing, Textiles, Wood Processing
Transport	Air Transportation, Automotive, Autonomous Vehicles, Car Sharing, Courier Service, Delivery Service, Electric Vehicle, Ferry Service, Fleet Management, Food Delivery, Freight Service, Last Mile Transportation, Limousine Service, Logistics, Marine Transportation, Parking, Ports and Harbors, Procurement, Public Transportation, Railroad, Recreational Vehicles, Ride Sharing, Same Day Delivery, Shipping, Shipping Broker, Space Travel, Supply Chain Management, Taxi Service, Transportation, Warehousing, Water Transportation
ICT	App Discovery, Apps, Consumer Applications, Enterprise Applications, Mobile Apps, Reading Apps, Web Apps, Artificial Intelligence, Intelligent Systems, Machine Learning, Natural Language Processing, Predictive Analytics, Computer, Consumer Electronics, Drones, Electronics, Google Glass, Mobile Devices, Nintendo, Playstation, Roku, Smart Home, Wearables, Windows Phone, Xbox, 3D Technology, Application Specific Integrated Circuit (ASIC), Augmented Reality, Cloud Infrastructure, Communication Hardware, Communications Infrastructure, Computer Vision, Data Center, Data Center Automation, Data Storage, Drone Management, DSP, Electronic Design Automation (EDA), Embedded Systems, Field-Programmable Gate Array (FPGA), Flash Storage, GPS, GPU, Hardware, Industrial Design, Laser, Lighting, Mechanical Design, Network Hardware, NFC, Optical Communication, Private Cloud, Retail Technology, RFID, RISC, Robotics, Satellite Communication, Semiconductor, Sensor, Sex Tech, Telecommunications, Video Conferencing, Virtual Reality, Virtualization, Wireless, Business Information Systems, CivicTech, Cloud Data Services, Cloud Management, Cloud Security, CMS, Contact Management, CRM, Cyber Security, Data Integration, Data Mining, Data Visualization, Document Management, E-Signature, Email, GovTech, Identity Management, Information and Communications Technology (ICT), Information Services, Information Technology, Intrusion Detection, IT Infrastructure, IT Management, Management Information Systems, Messaging, Military, Network Security, Penetration Testing, Reputation, Sales Automation, Scheduling, Social CRM, Spam Filtering, Technical Support, Unified Communications, Video Chat, VoIP, Cloud Computing, Cloud Storage, Darknet, Domain Registrar, E-Commerce Platforms, Ediscovery, Internet, Internet of Things, ISP, Location Based Services, Music Streaming, Online Forums, Online Portals, Product Search, Search Engine, SEM, Semantic Search, Semantic Web, SEO, SMS, Social Media, Social Media Management, Social Network, Vertical Search, Visual Search, Web Browsers, Web Hosting, Meeting Software, Wired Telecommunications, Android, iOS, mHealth, Mobile, Mobile Payments, App Discovery, Application Performance Management, Billing, Bitcoin, Browser Extensions, CAD, Consumer Software, Cryptocurrency, Database, Developer APIs, Developer Platform, Developer Tools, E-Learning, EdTech, Embedded Software, Enterprise Resource Planning (ERP), Enterprise Software, Facial Recognition, File Sharing, IaaS, Image Recognition, Linux, macOS, Marketing Automation, MOOC, Open Source, Operating Systems, PaaS, Presentation Software, Presentations, Productivity Tools, Product Management QR Codes, SaaS, Simulation, SNS, Software, Software Engineering, Speech Recognition, Task Management, Text Analytics, Transaction Processing, Virtual Assistant, Virtual Currency, Virtual Desktop, Virtual Goods, Virtual World, Web Development,Android, Facebook, Google, Tizen, Twitter, WebOS, Windows
Construction	Architecture, Building Maintenance, Building Material, Commercial Real Estate, Construction, Facility Management, Green Building, Home and Garden, Home Improvement, Home Renovation, Home Services, Janitorial Service, Landscaping, Property Development, Real Estate, Residential,Smart Building, Smart Cities, Smart Home,

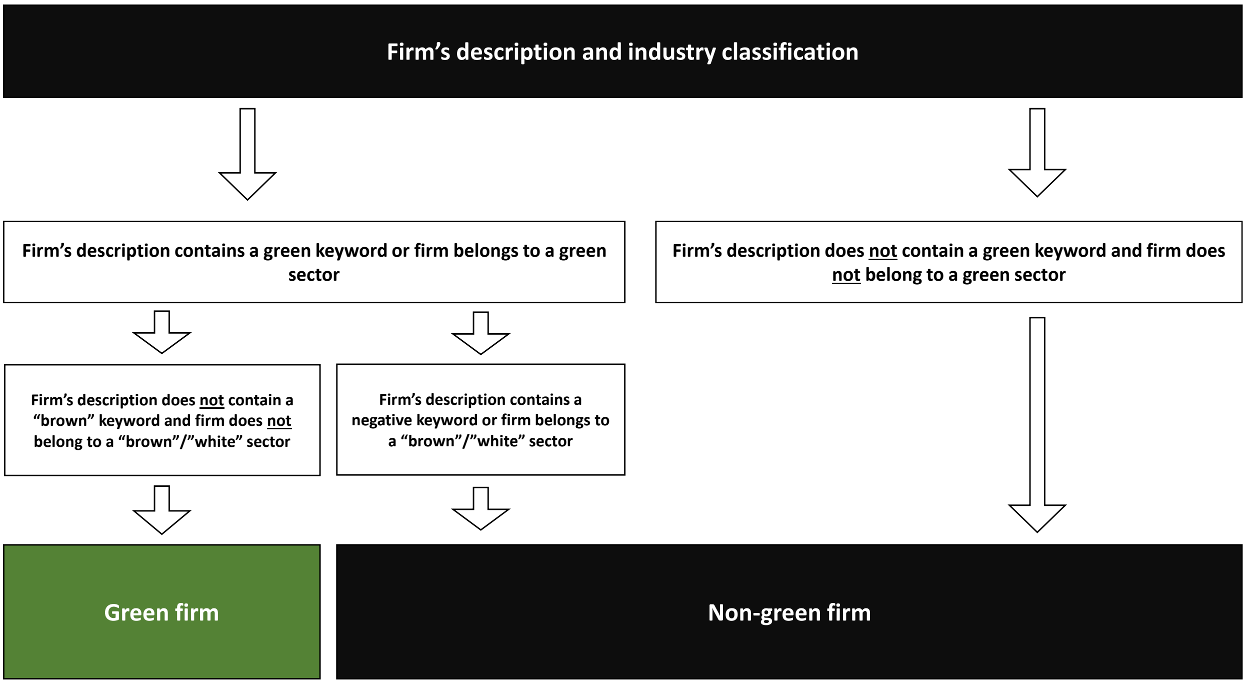
Source: Authors' own elaboration based on Crunchbase industry grouping available on https://support.crunchbase.com/hc/en-us/articles/360043146954-What-Industries-are-included-in-Crunchbase-

Annex B. Methodology to identify green firms in Crunchbase

The analysis presented in section 5 relies on a new methodology developed to identify green firms in the Crunchbase database. The Crunchbase database does not provide an immediate way to identify green firms. The database, however, provides several useful firm-level information that can be exploited to identify which firms are involved in green activities, such as a detailed firm description outlining key information on the firm's main activities and a company classification system based on specific industry groupings.

The methodology used in the paper adopts a two-pronged approach to identify green firms. It combines a keyword search on company's descriptions and the use of industry categories (Figure B.1). In line with the work of Bioret et al. (forthcoming[14]), the methodology also introduces several exclusion criteria targeting firms active in "brown" sectors (e.g. oil and gas and mining) and "white" sectors (e.g. healthcare) and negative keywords. The methodology was improved through several rounds of validation where 100 firms' descriptions that were randomly selected were read to ensure that the algorithm select green companies only. Of all the firms that get categorized as green firms through this methodology, it was estimated that approximately 95% are correct.

Figure B.1. Methodology to identify green firms in Crunchbase



Source: Own elaboration of authors.

Identifying green firms through a keyword search

As a first step, it was necessary to identify which descriptive information to consider among the one available. The Crunchbase database provides several firm-level descriptive information. It provides a firm's common name (*name*), a firm's legal name (*legal_name*), a short description of the firm's activities (*short_description*), a long description (*long_description*), a list of industry groups to which the company belongs (*category_groups_list*), and a list of more granular industry sub-groups (*category_list*). For the purpose of this analysis, only firms' short and long descriptions were considered valuable descriptive information and they were merged in a single string of text.

To minimise mistakes and homogenise text, special characters and other uninformative strings were removed from the new variable and all strings were transformed into lower case only. The number of characters contained in the final, cleaned description variable ranges between 0 and 10,000, with a mean number of characters of 300. While the quality of firms' descriptions can vary significantly, such a volume of descriptive information allows to broadly identify the company's main activity.

To identify green firms, a list of keywords was developed based on environmental and climate technologies listed in CPC Patent Classification System. The keyword search was developed building on the work by Haščič, and Migotto (2015[63]), which identified environmentally relevant technologies based on the Co-operative Patent Classification System. Figure 5.1 provided a stylized description of the categories along which green firms were categorized. The climate change mitigation and adaptation categories mimic the CPC Y02 classification. The environmental management category captures additional activities aimed at pollution control and environmental monitoring.

Keywords were extracted from the different CPC descriptions. In addition, this list was complemented through specific web search on environmental and climate technologies. This allowed to obtain a comprehensive set of keywords covering all climate and environmental technologies. In order to maximise accuracy, some keywords were combined with other keywords. Table B.1 presents a sample of the keywords used for each of the three indicators.

Finally, to limit the number of false positive results, a list of negative keywords was developed. This list targets a number of keywords which would commonly lead to mistakes (e.g. cleaning industry) or associated with activities that undermine environmental and climate goals (e.g. fossil fuels, oil and gas, etc.).

Table B.1. Sample of green keywords used

Sector	Sub-sector	Keyword	In combination with
Adaptation	Adaptation - Agriculture	salt tolerant	agriculture
Adaptation	Adaptation - General	climate adaptation	.
Adaptation	Adaptation - General	extreme weather	.
Adaptation	Adaptation - Agriculture	crop insurance	.
Adaptation	Adaptation - Agriculture	soil erosion	.
Adaptation	Adaptation - Agriculture	micro irrigation	.
Adaptation	Adaptation - Agriculture	precision agriculture	.
Adaptation	Adaptation - Coastal	cliff stabiliz	.
Adaptation	Adaptation - Coastal	sea level rise	.
Adaptation	Adaptation - Coastal	coastal erosion	.
Mitigation	Mitigation - General	cleantech	.
Mitigation	Mitigation - General	carbon footprint	.
Mitigation	Mitigation - General	net-zero emission	.
Mitigation	Mitigation - Buildings	double glazed window	.
Mitigation	Mitigation - CCS	carbon storage	.
Mitigation	Mitigation - Energy	energy efficiency	.
Mitigation	Mitigation - Energy	heat recovery	.
Mitigation	Mitigation - transport	lithium-ion batter	.
Mitigation	Mitigation - transport	electric vehicle	.
Mitigation	Mitigation - General	co2	emission/abatement/filtration/air quality/air pollution
Environment	Environment - Monitoring	air quality	.
Environment	Environment - General	biodiversity	.
Environment	Environment - Waste	waste management	.
Environment	Environment - Waste	bioplastic	.
Environment	Environment - Water	rainwater collection	.
Environment	Environment - Water	river restoration	.
Environment	Environment - Waste	water treatment	.
Environment	Environment - Ocean	marine conservation	.
Environment	Environment - General	environmental monitoring	.
Environment	Environment - Air	ghg	emission/abatement/filtration/air quality/air pollution

Source: Own elaboration of authors

Identifying green firms through industry groupings

Crunchbase employs a company classification system based on specific industry groupings. Crunchbase categorizes firms using more than 700 industries divided in more than 40 industry groups. Each firm in the database can belong to multiple industries.

Among industry groupings, it is possible to identify some which clearly contribute to green economic activities (e.g. clean energy, green buildings, water purification, etc.). Nonetheless, industry groupings alone do not allow to capture all green companies nor to further disaggregate them into more granular subfields. In addition to this, many industry groupings, which intuitively could be assigned to environmental technologies, are often associated with companies without any clear environmental focus (e.g., companies active both in renewable energy and oil and gas) or are the result of mistakes.

In line with the work of Bioret et al. (forthcoming[14]), the methodology used in the analysis identifies a list of industry groupings that could be categorized as green sectors. As a second step, a validity check is run on 50 firms per each industry in order to assess the accuracy of the industry categorization. The results of the validity check are illustrated in Table A.2. As a rule of thumb, a sector was considered valid when the share of false positive was 15% or lower. When it was higher and a clear explanation could be found, the sector was included with some caveats (e.g. additional exclusion criteria). Finally, when the sector produced a high rate of false positives due to mistakes in the categorisation, the sector was not included as a green sector. Potentially green sectors that were not retained include biomass, car sharing, clean tech, energy management, green consumer good, power grid, and ride share.

Table B.2. Validity checks on potentially green sectors

Industry grouping	False positive	Total observations sampled	Share of false positive	Include as green sector
Battery	4	50	8%	Yes
Biofuel	5	50	10%	Yes
Biomass	22	50	44%	No
Car sharing	28	50	56%	No
Clean energy	8	50	16%	Yes if oil and gas is excluded
Clean tech	11	50	22%	No
Electric vehicle	5	50	10%	Yes
Energy efficiency	8	50	16%	Yes if oil and gas is excluded
Energy management	18	50	36%	No
Energy storage	8	50	16%	Yes if oil and gas is excluded
Environmental consulting	6	50	12%	Yes
Environmental engineering	9	50	18%	Yes
Fuel cell	6	50	12%	Yes
Green building	7	50	14%	Yes
Green consumer good	10	50	20%	No
Green tech	3	50	6%	Yes
Nuclear	14	50	28%	Yes if medical sector is excluded
Pollution	1	50	2%	Yes
Power grid	24	50	48%	No
Recycling	6	50	12%	Yes
Renewables	17	50	34%	Yes if oil and gas is excluded
Ride share	18	50	36%	No
Solar	4	50	8%	Yes
Waste management	5	50	10%	Yes
Water purification	10	50	20%	Yes if bottled water-related words are excluded
Wind power	4	50	8%	Yes

Source: Own elaboration of authors.

Applying exclusion criteria

To limit the volume of false positive results and to ensure that no company active in economic activities that undermine the achievement of environmental and climate goals are captured as green firms, the methodology also includes a list of "brown" and "white" sectors. These sectors pertain respectively to the fossil fuels/mining industries and to the medical sector. In line with the work of Bioret et al. (forthcoming[14]), firms belonging to any of these sectors are automatically excluded from the green firm classification. "Brown" and "white" industry groupings are presented in Table B.3.

Table B.3. Exclusion criteria

White industry groupings	Brown industry groupings
Alternative Medicine	Fossil Fuel
Assisted Living	Mining
Assistive Technology	Mining Technology
Biopharma	Foundries
Cannabis	Precious Metals
Child Care	Fuel
Clinical Trials	Oil and Gas
Cosmetic Surgery	.
Dental	.
Diabetes	.
Dietary Supplements	.
Elder Care	.
Electronic Health Record	.
Emergency Medicine	.
Employee Benefits	.
Fertility	.
First Aid	.
Funerals	.
Genetics	.
Health Care	.
Health Diagnostics	.
Home Health Care	.
Hospital	.
Medical	.
Medical Device	.
mHealth	.
Nursing and Residential Care	.
Nutraceutical	.
Nutrition	.
Outpatient Care	.
Personal Health	.
Pharmaceutical	.
Psychology	.
Rehabilitation	.
Therapeutics	.
Veterinary	.
Wellness	.

Source: Bioret et al. (forthcoming[14]).