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Knowledge for a warmer world: A patent analysis of climate change adaptation technologies

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ABSTRACT

Technologies can help strengthen the resilience of our economy against existential climate-risks. We investigate climate change adaptation technologies (CCATs) in US patents to understand (1) historical patterns and possible drivers of innovation; (2) scientific and technological requirements to develop and use CCATs; and (3) CCATs' potential technological synergies with mitigation. First, in contrast to mitigation, innovation in CCATs only slowly takes off, indicating a relatively low awareness of investors for solutions to cope with climate risks. We discuss how historical trends in environmental regulation, energy prices, and public support may have contributed to patenting in CCATs. Second, CCATs form two main clusters: science-intensive ones in agriculture, health, and monitoring technologies; and engineering-intensive ones in coastal, water, and infrastructure technologies. Analyses of technology-specific scientific and technological knowledge bases inform directions for how to facilitate advancement, transfer and use of CCATs. Lastly, CCATs show strong technological complementarities with mitigation as more than 25% of CCATs bear mitigation benefits. While not judging about the complementarity of mitigation and adaptation in general, our results suggest how policymakers can harness these technological synergies to achieve both goals simultaneously.

1. Introduction

Climate change poses an existential threat to human livelihoods (Bellprat et al., 2019; Ornes, 2018). Recent extreme weather events have demonstrated the immediate need for significant adaptations driven by technological innovation to help communities adjust to these new climatic conditions (IPCC, 2018). For instance, technological innovation plays an important role in addressing this challenge (Ferreira et al., 2020; Dechezlepretre et al., 2020): climate-smart agriculture could help communities to adapt to droughts, floods, and increasing threats of pest infestation (Kuhl, 2020; Adenle et al., 2015); new types of hazard defense and weather prediction tools help protect infrastructure and human lives from storms, floods, and heatwaves (UNFCCC, 2006); water conservation and catchment technologies help address water scarcity (Conway et al., 2015); vaccines, new drugs, and preventive public health inventions strengthen people's resistance against infectious diseases and heatwave-induced risks that become more prevalent under climate change (Guo et al., 2018; Caminade et al., 2019). Alongside nature-based solutions and behavioral changes, adaptation technologies are needed to cope with current and future climate risks (UNFCCC, 2006; UNEP, 2021).

Under the Paris Agreement, several governments committed to strengthening their adaptation capacities, including technological solutions. However, any progress made towards achieving this goal has rarely been evaluated in a comprehensive manner Berrang-Ford et al. (2019) and Lesnikowski et al. (2017). It is vital to measure this progress so that any gaps in adaptation can be identified, along with enabling impact assessments of adaptation strategies. This contributes to a mutual understanding as decision-makers share their own experiences with adaptation efforts. In this paper, we systematically assess existing technologies for adaptation using patent data, addressing three questions: *(1) To what extent have these technologies been developed and which were possible drivers of innovation? (2) How can governments support the development and adoption of these technologies? (3) How do technologies for adaptation interact with climate change mitigation?*

Existing studies on climate change adaptation technologies (CCATs) predominantly dedicate their focus to specific regions, technologies, or climate risks. To date, systematic analyses of innovation in CCATs have been limited (Popp, 2019; Dechezlepretre et al., 2020), not least because, until 2018, there was no classification of CCATs in patent

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databases. The most closely related study was made by Dechezlepretre et al. (2020) who investigated the diffusion of CCATs using patent data.

Leveraging the recent Cooperative Patent Classification (CPC) of 'climate change adaptation technologies' (Angelucci et al., 2018), we investigated how innovation in various adaptation technologies has changed over time. We analyzed the composition of the scientific and technological knowledge bases of CCATs to show which scientific and technological capabilities are needed to advance, adopt, and utilize CCATs. We further identified technological complementarities between adaptation and mitigation showing in which areas both targets can be achieved at the same time. To the best of our knowledge, this is the first systematic analysis of the current state of technological knowledge for adaptation. From our analysis of CCATs, we have documented five key insights:

1. Despite increased awareness of climate change, patenting in most adaptation technologies has not experienced a surge in the past two decades, much unlike patenting in climate change mitigation which has been increasing significantly.
2. Adaptation technologies form two clusters: those that are science-intensive (health-related adaptation, agriculture, and indirectly enabling technologies for weather forecasting and natural resource assessment) and those that are engineering-based (adaptation in coastal, infrastructure, and water supply). The qualitative details of the knowledge base reveal scientific and technological requirements needed to develop, adopt, and utilize these technologies and inform policy makers how to facilitate advancement and transfer of adaptation technologies.
3. Invention in various CCATs greatly differ by magnitude: Adaptation related to human health has the highest number of patented inventions (>16k patents), followed by agriculture (8k). Coastal adaptation has the lowest number of patented inventions (<0.9k).
4. Since mid-2000s, more than 40% of adaptation patents have been reliant on government support, which is about 10% higher than average (Fleming et al., 2019b). For most mitigation technologies, the reliance on government support is much lower during the same period, except for nascent mitigation technologies such as carbon capture and storage (CCS).[1]
5. 26% of all adaptation technologies simultaneously help with mitigation. The highest overlap exists in infrastructure, where 70% of adaptation patents also help reduce emissions. Many of these inventions likely came as byproducts of innovations developed to cope with environmental regulation and high energy prices.

The observation that 26% of adaptation technologies simultaneously contribute to mitigation is of high theoretical and practical importance. In many theoretical discourses, climate change adaptation and mitigation were treated as substitutes (Barrett, 2020; Reyer et al., 2017). Our results question this perspective. We argue that well-designed policy can encourage innovations that meet the twin goals of adaptation and mitigation simultaneously.

We documented a substantial scope for technological complementarity between certain adaptation and mitigation options. While not promising a universal solution for all adaptation and mitigation options, we illustrate examples of how emission-increasing *maladaptation* can be avoided (Barnett and O'Neill, 2010).[2] For example, thermal insulation in buildings achieves both: adaptation to heatwaves and emission-reduction through energy savings, while air-conditioning would be an example of maladaptation. Energy-intensive desalination to cope with water scarcity, another example of maladaptation, can be complemented with the integrated use of solar PV. Our analysis identifies additional cases, for example in agriculture, infrastructure, and clean production where public R&D support can encourage inventions that meet adaptation and mitigation goals at the same time.

As technological development is path-dependent (Arthur, 1994; Ruttan, 1997), subsequent technological development cumulatively builds on pre-existing technology and knowledge. Technology choices in the early phase of development are essential to prevent lock-in effects in adaptation options that undermine mitigation efforts or in mitigation strategies that increase vulnerability against climate change.

The remainder of this paper is structured as follows: In the next Section 2, we offer an introduction to the economics of adaptation, mitigation, and technology. In Section 3 we describe the methodology and data. Section 4 outlines the results, first documenting innovation trends in adaptation (Section 4.1), continuing with an analysis of the technological and scientific base (Section 4.2), and ending with an analysis of adaptation–mitigation complementarity (Section 4.3). Section 5 concludes.

2. Background

2.1. Adaptation and the role of technology

Governments typically employ a portfolio of different actions to adapt to climate change. For instance, these portfolios can comprise of behavioral and nature-based solutions, technological adaptation of physical infrastructure, and insurance-like mechanisms that facilitate the economic recovery after the occurrence of an extreme event (Berrang-Ford et al., 2019).

Behavioral solutions can comprise of awareness and information campaigns that strengthen the risk-preparedness in the face of wildfires, storms, and floods; or teach the population about appropriate behavior during heatwaves (van Valkengoed and Steg, 2019). Nature-based solutions for adaptation either strengthen the resilience of ecological systems, such as through biodiversity protection, or leverage the provision of ecosystem services for water supply or green zones to alleviate heatwaves in urban areas (Seddon et al., 2020; Sharifi, 2021). Technologies for adaptation comprise both high-tech and low-tech solutions, and even non-patented technological solutions (Dechezlepretre et al., 2020; IPCC, 2022; UNFCCC, 2006). Next to these, financial instruments and social safety nets play a crucial role, as financial and economic capabilities are essential to enable recovery after extreme weather events. These instruments consist of, for example, weather insurances in agriculture or real-estate, but also public recovery schemes. Furthermore, poverty reduction is an effective adaptation strategy, which is most prevalent in low-income countries (Linnerooth-Bayer and Hochrainer-Stigler, 2015).

However, these adaptation options interact and mutually enhance their effectiveness. Behavioral risk-preparedness is easier to achieve if technologies provide reliable weather forecasts (van Valkengoed and Steg, 2019), and the costs of financial insurance schemes can be significantly reduced if technological adaptation strengthens the resilience of physical assets against extreme weather (Mills, 2007).

In this study, we focus on patented technological solutions for adaptation. Technological solutions are appealing when other adaptation options are prohibitively expensive or infeasible, and they bear the potential to overcome some of the limits to adaptation. For example, two-thirds of the world's cities are located on coastlines, which are vulnerable to sea level rise. Relocating assets and citizens is often infeasible or prohibitively expensive due to financial and social constraints (Fankhauser and McDermott, 2016). Many nature-based solutions like the restoration of mangroves for flood protection, agroforestry dealing with water scarcity, or green zones in cities to alleviate

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[1] The technology class CCS also includes the capture and storage of non-carbon greenhouse gases such as SO_2 or SF_6. We use the term CCS to simplify the notation.

[2] Note that the definition of maladaptation goes beyond emission-increasing adaptation but includes any adaptation action with adverse side effects. In this article, we refer to subset of emission-increasing adaptation when using the term maladaptation.

heatwaves, only work provided that extreme weather events are sufficiently moderate (Thomas et al., 2021). In a world with ongoing climate change as currently projected (Steffen et al., 2018; IPCC, 2018), societies need to prepare for weather events that exceed these limits. In these situations, technological solutions can play an important role (Tompkins et al., 2018; IPCC, 2022).

2.2. *Adaptation and mitigation: Substitutes or complements?*

Although it has been said that – given our current knowledge – mitigation remains the cheapest and best adaptation, climate change is already happening today at a worrying pace and societies need to adapt to these unavoidable changes.

In the literature, the relationship between climate change mitigation and adaptation is an interesting controversy. Theoretical studies suggest that mitigation and adaptation efforts can be considered as strategic substitutes, as increased mitigation efforts reduce the need for future adaptation, while future adaptation may compensate for the lack of mitigation today (Barrett, 2020; Reyer et al., 2017; Buob and Stephan, 2011; van Vuuren et al., 2011). Game theoretical considerations suggest that policymakers' ambitions to mitigate climate change may be undermined by the prospect of future technological solutions that neutralize the negative impact of climate change (Barrett, 2020; Buob and Stephan, 2011).

This line of argument was believed to undermine the progress of international climate negotiations about mitigation and underpinned ethical concerns about research on climate engineering (Svoboda, 2017) and adaptation (Reyer et al., 2017). The controversy about adaptation–mitigation trade-offs is of very practical relevance today, acknowledging that adaptation is a necessity of both today and the future (IPCC, 2022; Barnett and O'Neill, 2010). Research has shown that short-term mitigation policies may undermine the future adaptation. For example, the production of carbon-neutral biofuels or rapid deforestation to sequester carbon may come with the cost of biodiversity losses, which may be essential to assist ecological systems in adapting to changing climatic conditions (Jeswani et al., 2020; Chisholm, 2010). Other examples of maladaptation are emission-increasing solutions for adaptation, such as energy-intensive desalination techniques to improve water supply or air-conditioning in response to heatwaves (Barnett and O'Neill, 2010).

However, theoretical models upon which the trade-off considerations build are difficult to calibrate for three major reasons:

(1) The models explore a trade-off between current costs of mitigation compared to future costs of adaptation. This valuation is highly sensitive to the appropriate choice of the discount rate which is empirically controversial (Gollier and Hammitt, 2014). Moreover, those making decisions about adaptation and mitigation may be disparate as adaptation benefits are mostly locally specific, and often private, while climate change mitigation contributes to a global (uncertain) public good (Abidoye, 2021).

(2) The economic impact of climate change is subject to uncertainty: Once tipping thresholds in the climate system are crossed, it may become unpredictable and an existential threat to human livelihood, which may be beyond the scope of any available and expected technological solutions (Lenton et al., 2019).

(3) Existing models suggest that investments made in mitigation cannot be spent on adaptation and vice versa. However, empirically mitigation and adaptation are not necessarily mutually exclusive and examples exist where adaptation efforts contribute to mitigation and vice versa (Sharifi, 2021; Spencer et al., 2017; Berry et al., 2015).

We provide evidence that the trade-off consideration may need to be reconsidered as we identify adaptation–mitigation complementarities in R&D and show in which areas these co-benefits can be harnessed. In addition, we state that some examples of emission-increasing maladaptation can be a matter of technology choice, for example in desalination or air-conditioning (see Barnett and O'Neill, 2010).

3. Methods

3.1. *Data sources*

We used US patent data from the US Patent and Trademark Office (USPTO) and GooglePats compiled for an earlier project (Hötte et al., 2021b,a). We used USPTO data since most high-value inventions are filed in the US, and US patents can be regarded as a good proxy for the global technological frontier (Albino et al., 2014). To ensure the uniqueness of inventions, we used the patent DOCDB family ID of patents downloaded from PATSTAT (Spring 2021 version) as the unit of analysis (Kang and Tarasconi, 2016; Office, 2021).[3] We supplemented the patents with CPC classifications obtained from the master classification file (April 2021 version) provided by USPTO.[4] To identify adaptation and mitigation technologies, we used the CPC Y02-tags (Angelucci et al., 2018; Su and Moaniba, 2017).

We obtained 37,341 unique patents that are tagged as *technologies for adaptation to climate change* as indicated by the CPC tag Y02A. We categorize them as patents for coastal adaptation (Y02A1), water supply and conservation (Y02A2), infrastructure resilience (Y02A3), agriculture (Y02A4), human health protection (Y02A5), and indirectly enabling technologies such as weather forecasting, monitoring, and water-resource assessment (Y02A9) (see A.1 for a detailed overview). We also sourced mitigation-related patents distinguishing technologies at the 4-digit level (buildings (Y02B), CCS (Y02C), energy-saving ICT (Y02D), clean energy (Y02E), clean production (Y02P), clean transportation (Y02T), and clean waste (Y02W) (see Veefkind et al., 2012; Angelucci et al., 2018). The tagging scheme for climate change mitigation and adaptation technologies is based on the search algorithms that identify mitigation- and adaptation-related CPC symbols, IPC symbols, and keywords (see Veefkind et al., 2012; Angelucci et al., 2018). Our analysis relies on the CPC version from April 2021.

The USPTO regularly re-classifies patents whenever a new version of the CPC system becomes available. Hence, old and new patents are assigned to technology classes according to uniform principles (Lafond and Kim, 2019). This enables the identification of the technological ancestors of today's inventions. For example, early patented inventions in windmills are the technological ancestors of today's high-tech wind turbines (cf. Hötte et al., 2021b). An adaptation-related example is health-related patents for improvements in medical compounds developed in the late nineteenth century to fight cholera. These inventions build the foundations of today's technology to fight infectious diseases. Similarly, many inventions in agriculture (e.g. ecological buffer zones or organic fertilizers), water conservation, and insulation in buildings have their origins in the nineteenth century.

Some of the patents in our data serve multiple adaptation purposes. We double-counted these patents, arguing that knowledge is non-rival and patents that serve multiple adaptation purposes contribute equally to the knowledge base of these CPC 6-digit categories. This argument is further supported by the high variation in the value of patents: patents with a higher number of co-classifications tend to represent more valuable inventions (Lerner, 1994; Sun et al., 2020; Méndez-Morales et al., 2021). In our data, 295 out of 37,341 unique patent families are multi-purpose adaptation technologies, i.e. are assigned to two or more 6-digit Y02A-classes.[5]

We further supplemented the data with information on the reliance of individual patents on governmental support (Fleming et al., 2019b,a). Patents are defined as being reliant on governmental support if at least one of the following five conditions hold: (1) The patent

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[3] Throughout this document, we use simple DOCDB patent families as the unit of analysis, but we use 'patent' for 'patent family' as shorthand.

[4] https://bulkdata.uspto.gov/data/patent/classification/cpc/.

[5] Note that we applied the same double-counting rule for mitigation patents that are classified into multiple 4-digit subclasses of Y02.

is directly owned by a governmental institution. (2) Governmental support is explicitly acknowledged in the patent document. (3) The patent cites a patent owned by a governmental institution or that acknowledged governmental support. (4) The patent cites research published by a governmental institution. (5) The patent cites research where governmental support is mentioned in the acknowledgments. The first two conditions are related to the patents created by direct financial support of the government and the last three conditions are related to the patents being reliant on prior knowledge created by financial support of the government. Although there can be other routes of governmental support such as human- or facility-based ones, we focus on the direct financial support and prior knowledge base support, main areas of governmental support that can be captured comprehensively at the patent-level.

To analyze the technological and scientific knowledge base, we used data on (1) citations from patents to patents from Pichler et al. (2020) and (2) citations from patents to science provided by Marx and Fuegi (2020b).

3.2. The scientific base

To describe the scientific base of adaptation, we used data on citations from patents to science. Citations in a patent can be made in the text body or at the front page of a patent, and can be added by the applicant or patent examiner. We included all types of citation into our analyses. Marx and Fuegi (2020c) extracted the citation links using a sequential procedure based on text recognition and matched the data with the scientific database Microsoft Academic Graph (MAG) (Sinha et al., 2015). The matching procedure is probabilistic. Marx and Fuegi (2020c) tagged citation links with a so-called confidence score, which indicates the precision and recall rate of the matching (more detail available in Marx and Fuegi, 2019, 2020a). We only included patents with a confidence score > 4 which is associated with a precision rate of more than 99%. The citation links are complemented with meta-information on the scientific paper that is cited, e.g. title, DOI (if available), outlet, publication year, and scientific field of research.

We analyzed the scientific base in two ways: (1) We computed time series of the share of the number of citations to papers to the number of total citations to patents and papers. The data are aggregated into 5-year bins gathering all patents classified as certain adaptation technology that were granted during the considered period. (2) We provided a qualitative description of the science base. Every paper is tagged by the Web-of-Science (WoS) category into which the article is classified. The assignment of WoS categories to papers is made on the paper level (further explanations are provided in Hötte et al., 2021b). We used this information to show, for each type of adaptation technology, the six most often cited WoS fields as a share in all scientific citations during the different time periods.

3.3. Adaptation–mitigation complementarities

Analyzing the technological base of patents relies on the hierarchical CPC system, which classifies patents into broad sections (A-H, Y) which are sequentially sub-divided into classes, sub-classes, groups, and sub-groups. The section 'Y' is a special, cross-sectional tagging scheme that is used to identify climate-related technologies. We removed 'Y10'-tags from our analysis because these tags are assigned to patents for technical reasons (for example to ensure compatibility with other classification systems).

Patents can be classified into multiple CPC classes. Co-classification indicates interdependence among different technologies. We used co-classification data to identify patents that are tagged as adaptation *and* mitigation technologies. We call these patents 'dual purpose' technologies.

To better understand overlaps in the knowledge base of adaptation and mitigation technologies, we used backward citations. The cosine similarity of two technology types is computed as the normalized dot product of the vectors of backward citation shares made to 4-digit CPC classes for the technological similarity and to WoS-fields for scientific similarity. We rely on the methodology used in Hötte et al. (2021b) to create similarity networks. We illustrated the pairs of 6-digit mitigation and adaptation complements that show strong overlaps in their technological and scientific knowledge base.

4. Results

4.1. A slow start for adaptation

We analyzed the technological frontier in climate change adaptation by looking at patents granted by the USPTO that are tagged as *technologies for adaptation to climate change*. This leads to a population of 37,341 unique patent families that are explicitly recognized as technologies that help in climate change adaptation. We also collected 408,348 unique patent families related to climate change mitigation to explore the technological relationship between mitigation and adaptation.

Currently, there are six main categories of climate change adaptation patents: (1) coastal adaptation, (2) water supply and conservation, (3) infrastructure resilience, (4) agriculture, (5) human health protection and (6) indirect adaptation i.e. measurement technologies such as weather forecasting, monitoring invasive species, and water-resource assessments (see UNFCCC (2006) and A.1 for details).

In Fig. 1, we show on the left-hand side the evolution of patents in mitigation and adaptation technologies as identified by 4-digit CPC codes. At the right-hand side, we show analogous figures for different adaptation technologies at the more disaggregate 6-digit level. The upper two Figs. 1(a) and 1(b) show the number of annually granted patents since the mid-nineteenth century. In the mid row, we show these time series measured as a share in all annually granted USPTO patents.

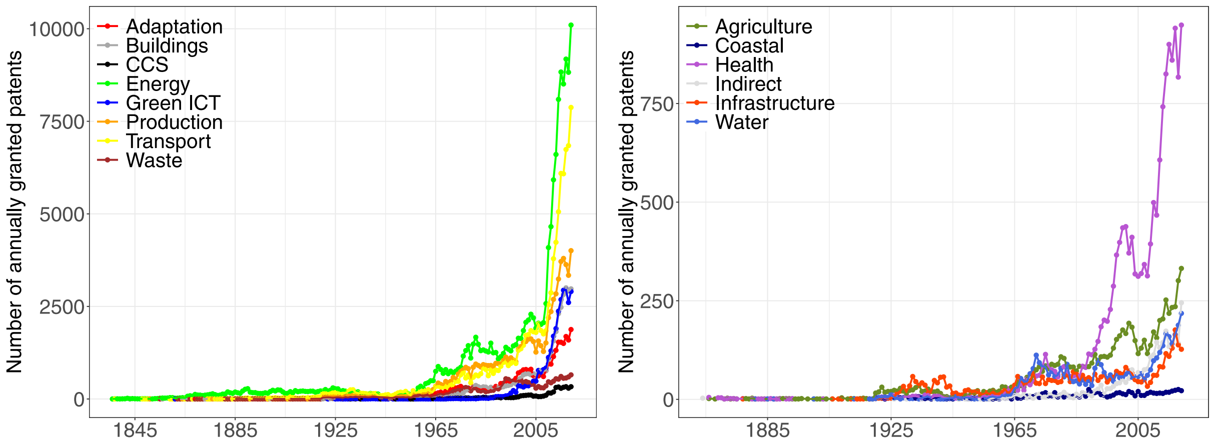
Until the second half of the twentieth century, patenting in mitigation and adaptation ranged at very low levels, both in absolute patent counts and measured as a share. The only exception is renewable energy with a share of up to 4% already in the late nineteenth century. This share corresponds to the level of clean energy inventions today. The historically high share is in line with previous research and historical accounts showing that patenting for energy technologies like windmills and water wheels was already very prevalent in the nineteenth century (Hötte et al., 2021b).

Since the early twentieth century, we observe the number of annually granted patents in mitigation and adaptation to grow slowly. However, when showing these inventions as a share in all US inventions, we find the growth of green inventions to be non-monotonous.

Patenting in climate change mitigation began growing after the 1950s. After then, patenting in mitigation technologies experienced several periods of acceleration, such as during the Oil Crisis of the 1970s (Geels et al., 2017; Grubler et al., 2012). Since the 2000s, patenting in climate change mitigation (especially in energy and transportation) increasingly took off.

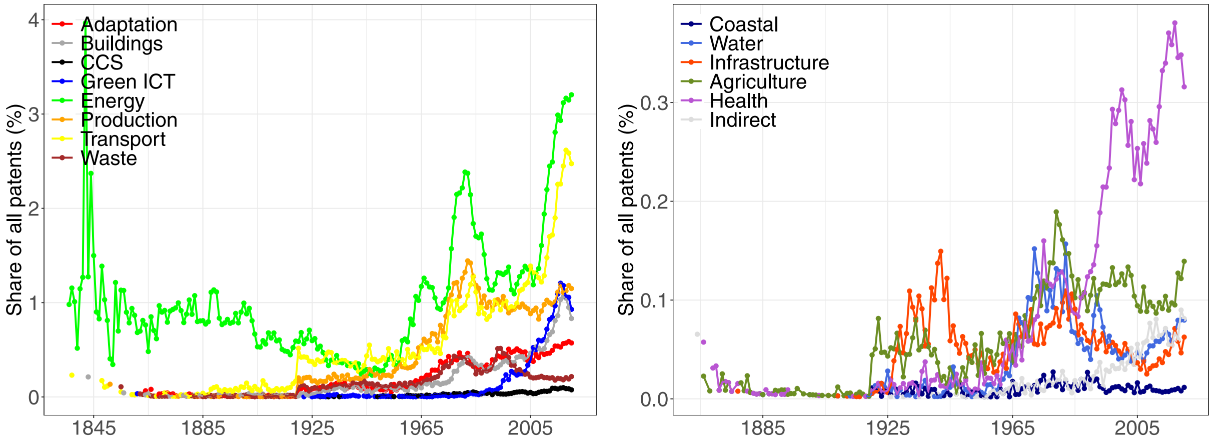
For adaptation, we find that inventions have not increased substantially over time except for the category of health-related technologies (Fig. 1(d)). Adaptation has seen only modest increases in the aftermath of the Oil Crisis and in the subsequent decades. In 2020, about 0.5% of all US patents were classified as being helpful for adaptation, while green energy and transport patents account for more than 3% and 2.5% and exhibited a steep increase since the 2000s (Figs. 1(c), 1(d)).

Among the adaptation technologies, health-related adaptation dominates by the number of patents. With more than 16,300 unique patents over the full time horizon, health accounts for more than twice as many patents as agriculture (8,089 patents), which is the second largest category. Coastal adaptation is the smallest category with only 857 unique patents (Table A.1). These differences may not only reflect high levels of innovative activity in health-related adaptation but also the



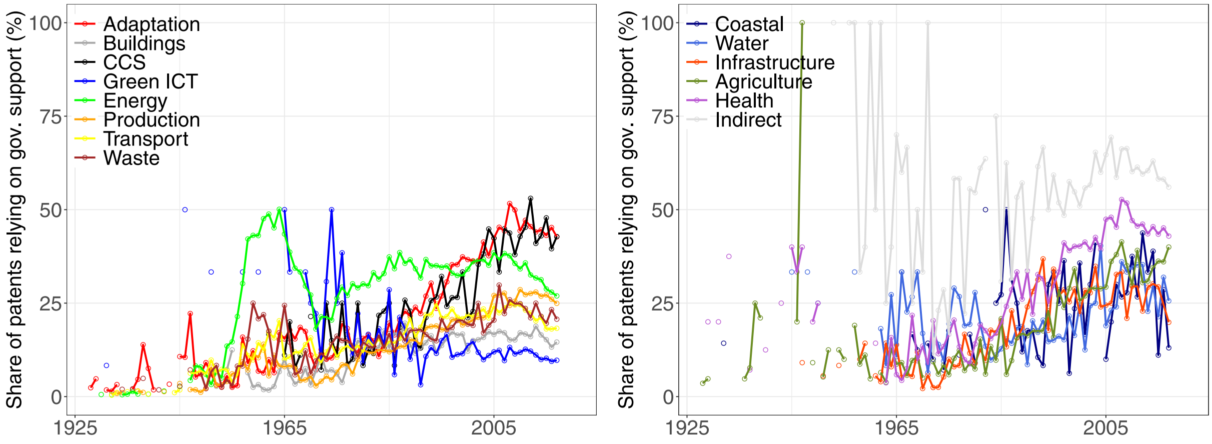
(a) Mitigation & adaptation counts

(b) Adaptation patents counts



(c) Mitigation & adaptation shares

(d) Adaptation technology shares



(e) Reliance on public support

(f) Adaptation's reliance on public support

Fig. 1. Patented inventions in adaptation technologies over time.
Fig. 1(a) 1(b) shows the number of annually granted US patents (unique by DOCDB patent family) in 4-digit mitigation and adaptation (6-digit adaptation) technologies since 1836. Fig. 1(c) 1(d) shows the number of 4-digit mitigation and adaptation (6-digit adaptation) patents as a share of all US patents. Fig. 1(e) 1(f) shows the share of these patents that relies on governmental support in 1935-2017 (see Section 3.1 for a definition). Note that the axes may differ in scale due to differences in the data by time coverage and scale.

fact that these technologies can be more effectively protected through patents compared to the other technologies (Cohen et al., 2000). Moreover, as coastal adaptation has public goods characteristics which may explain that private incentives for innovation – and patenting – can be relatively dampened. Patenting in adaptation related to water and infrastructure peaked in the 1980s but subsequently tapered off.

4.1.1. Drivers of innovation in adaptation and mitigation

Previous research has shown that innovation and patenting in green technologies respond to price signals and the size of the market for the technology (Popp, 2002; Acemoglu et al., 2012). The market size of a technology can grow through an increased demand, for example induced by environmental disasters (Miao and Popp, 2014) or regulatory pressure (Andreen, 2003; Kemp et al., 2000). These drivers may explain patterns in the time series data.

Health- and water-related adaptation rose in the aftermath of the first regulatory initiatives by the US government to reduce the pollution of the air and water resources by industrial processes (e.g. the Clean Air Act in 1963 and Clean Water Act in 1972). Many of the water- and health-related adaptation technologies have a pollution control functionality. For example, technologies that help control air pollution contribute to public health and thereby are counted as health-related adaptation. Technologies for waste water treatment, leakage control, and filtration not only help reduce pollution through waste water from industrial processes, but also help improve water supply in response to climate pressure. Therefore, these technologies are labeled as water-related adaptation technologies (see A.1). These specific technologies exhibited a steep rise during the 1960s–80s as we illustrate and discuss in more detail in A.2.2. This observation is in line with previous research which has shown that innovation in pollution control technologies is one response to regulatory pressure (Andreen, 2003; Kemp et al., 2000,?). The rising number of patents for pollution control technologies may reflect the response to the regulations and has been contributing to an enhanced technological capacity for water- and health-related adaptation as a byproduct.

We further observe a rise in infrastructure adaptation in the post 1970s. One plausible explanation for this rise is the Oil Crisis. Other research has shown that increased energy costs in response to that crisis were an important driver of energy-saving innovations (Popp, 2002; Hassler et al., 2021). Patents for infrastructure adaptation comprise many energy-saving insulation technologies, for example preserving thermal comfort in buildings or making power lines for energy transmission more robust (see A.1).

Mazzucato (2013) extensively discussed that innovation may be also triggered by an *entrepreneurial state* that actively engages in basic and applied research and creates markets for novel technological solutions. This may have also been a driver of innovation behind many of the early inventions in low-carbon energy technologies during the 1950s and 1960s which timely coincide with upcoming government-led initiatives in nuclear energy (Cowan, 1990) and renewable energy technologies emerging from early US government initiatives from the Department of Energy and the US space program (Mazzucato, 2013).

4.1.2. Reliance on public support

Patenting in adaptation shows a strong reliance on governmental support with over 40% of patents since mid-2000s being linked directly or indirectly to government support (Fig. 1(e)). This is about 10% higher than the value for average patents in the US (cf. Fleming et al., 2019b). Indirect adaptation and health-related adaptation show the highest levels of reliance on public support (Fig. 1(f)). For many climate change mitigation technologies, by contrast, we observe a lower reliance on public support today compared to earlier periods. Especially clean energy and green ICT were heavily supported in the past, but have seen a significant private-sector take off. Mitigation technologies with insufficient market demand (e.g. CCS) show comparably high levels of public support as adaptation technologies.

The reliance on public support can serve as an indicator of the stage of market development: if sufficient market demand for a technology exists, innovators have a commercial interest to develop these technologies and the reliance on public support is low. In contrast, if markets are underdeveloped (as in the case for adaptation and CCS), the public sector can play a critical role in stimulating innovation (cf. Mazzucato, 2013).

Reliance on public support does also include the reliance on government-funded research. As we shall see below in 4.2 and A.2.3, some adaptation technologies are more science-reliant than many other technologies. This partly explains the relatively higher reliance on public support of adaptation technologies, but the time trends suggest that science-reliance is not sufficient to explain the high reliance on public support. For example, for both clean energy and green ICT, the science reliance increased over time, but we observe a decreasing reliance on public support. Moreover, among the different categories of adaptation technologies, we also find that technologies like coastal, water-related, and infrastructure adaptation exhibit relatively higher shares of reliance on public support despite low levels of scientificness.

4.2. The knowledge base of adaptation

To study the knowledge base of adaptation technologies, we combine data on patent citations, co-classifications (Hötte et al., 2021a), and science citations (Marx and Fuegi, 2020c). Citations from patents to science indicate the scientific origins of patented inventions (Meyer, 2000; Ahmadpoor and Jones, 2017). Similarly, citations from patents to other patents describe technological base of patented inventions (Jaffe and De Rassenfosse, 2019; Verhoeven et al., 2016).

4.2.1. Reliance on science: Two clusters

We find that adaptation technologies, as reflected by patents, can be grouped into two clusters: (i) science-intensive technologies (agriculture, health, and indirect adaptation); and (ii) engineering-based technologies (coastal, water, and infrastructure).

We measure the scientificness of adaptation technologies by the share of patent citations to science over the sum of citations to other patents plus citations to science. This ratio indicates to which extent a patent relies on science rather than applied technological development as encoded in patent citations (see Hötte et al., 2021b). The evolution of the CCATs' scientificness over time since 1976 is shown in Fig. 2. Coastal, water, and infrastructure adaptation technologies exhibit low shares of citations to science (0%–5%) while health, agriculture, and indirect adaptation are highly science-intensive (50%–80%). This reflects the idiosyncratic nature of different technologies. To be specific, science-intensive adaptation technologies include, for example, crops that are climate resilient, treatments for diseases that will become more prevalent in hotter temperatures, and complex early warning and monitoring systems. By contrast, engineering-based adaptation, which relies significantly less on science, includes technologies such as fixed construction to provide flood defense, cliff stabilization, water purification, and methods to strengthen the resilience of infrastructure.

The rise in share of citations to science for agriculture and health in the 1970s-1980s coincides with the rise of the US biotechnology. This period was characterized by many spin-offs from universities and public research laboratories that undertook innovation in basic necessities (Powell et al., 1996, 2005). Even within the engineering-intensive adaptation technologies such as water and infrastructure adaptation, we observe that these technologies became more science-intensive. We find that this phenomenon is related to the increased scientificness of chemistry-reliant water-conservation technologies (such as desalination, reverse osmosis), advances in material sciences for infrastructure adaptation, and increased interactions between developments in science-reliant solar photovoltaics with water and infrastructure adaptation, for example to supply energy for water treatment or heating and cooling in buildings.

Coastal adaptation, the smallest category in our sample, did not show an increase in its reliance on science. This is exceptional as an increasing reliance on science is a general trend in innovation during the second half of the twentieth century (Hötte et al., 2021b). This indicates that other knowledge sources rather than science are important for patented technologies in coastal adaptation, although interpretations must be made with caution due to the low number of patents.

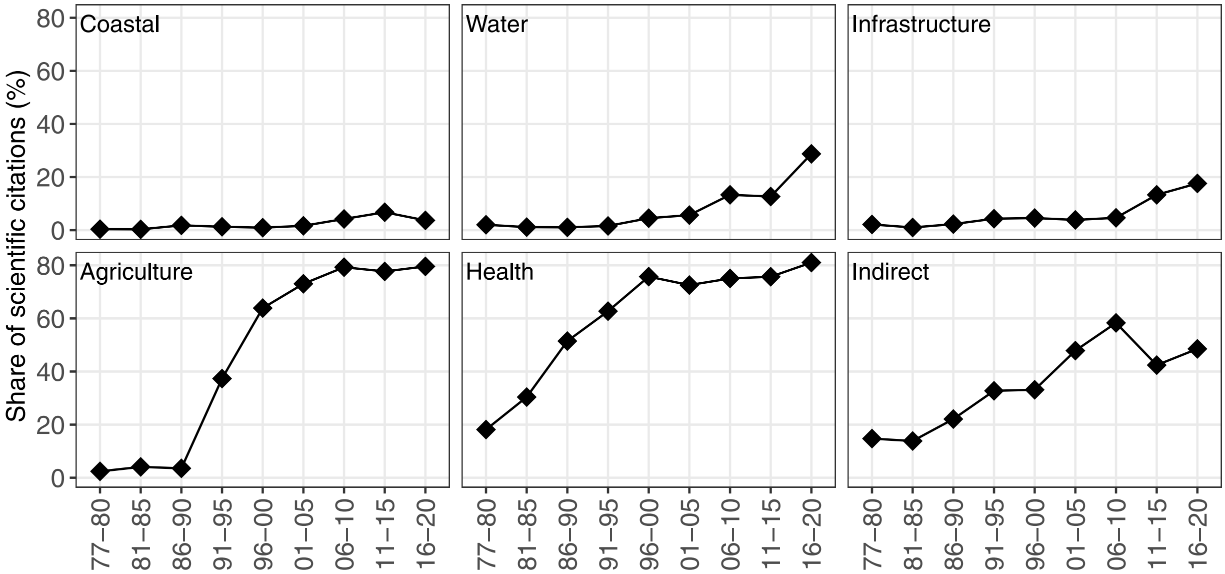


Fig. 2. Science intensity of adaptation technologies.
Notes: Science-intensity of different adaptation patents measured by the share of citations to science in the number of total citations (sum of citations to other patents and scientific articles).

4.2.2. Composition of the scientific base

We studied the knowledge base of adaptation showing which fields of science are cited by adaptation technologies over time (Fig. 3). This gives an idea of the scientific disciplines policymakers can support to strengthen innovation in adaptation technologies. Complex technologies require a so-called *absorptive capacity* to be effectively used and further developed (Cohen and Levinthal, 1990; Caragliu and Nijkamp, 2012; Criscuolo and Narula, 2008). In many environmental technologies, off-the-shelf solutions available on global markets require adaptive innovation to become useful under locally specific conditions (Popp, 2020). Hence, having expertise in scientific fields that are relevant for adaptation can spur the adoption, adaptation, and indigenous development of CCATs and ensure their maintenance. This can facilitate the efficient transfer of CCATs to regions where being exposed to climate risk, which is particularly urgent in many developing countries (Huenteler et al., 2016; Adenle et al., 2015; Lema and Lema, 2016). These regions can stimulate adoption of adaptation technologies by investing in laboratories of local universities or public research institutions having relevant scientific understanding and thereby stimulate the transfer of adaptation skills to the local community.

Distinguishing between applied and basic research following Persoon et al. (2020), we find that science-intensive CCATs (agriculture, health, and indirect adaptation) rely mostly on basic research, while adaptation technologies with a low science-intensity (coastal, water, and infrastructure) build to a higher extent on applied research.

Among the science-intensive CCATs, both health and agriculture largely build on biochemistry and molecular biology. Health adaptation further relies on immunology, oncology, and virology, while agricultural adaptation further relies on plant sciences. Indirect adaptation technologies which cover monitoring, assessment, and forecasting technologies rely on physics-related areas such as electrical engineering and optics, which form foundations of sensor and measurement technologies. Further, they build on biology-related areas such as biochemistry and immunology. Manual inspections of patents reveal that indirect adaptation technologies cover not only weather forecasting and monitoring technologies but also bioinformatics technologies for medicine and chemical assessment. Therefore, university or public research laboratories in the field of biochemistry or molecular biology would be a good starting point for transferring many of the science-intensive adaptation technologies to the regions in need of such skills and knowledge (Adenle et al., 2015).

In engineering-based CCATs, applied sciences dominate. Coastal adaptation relies on several different types of engineering (civil, electric, environmental, and geological), but it also has weak linkages to some basic research of meteorology, maths, geosciences and environmental science. Water-related adaptation also relies on engineering but also basic research in chemistry, which is relevant for water conservation, filtration, recovery, and desalination that make use of chemical processes. The scientific knowledge base of infrastructure adaptation consists of material science, thermodynamics, construction, and electrical engineering, among other fields. To sum up, to transfer the engineering-based CCATs to the regions in need, the role of laboratories in the engineering department of local universities will be particularly important, though basic science is also necessary in some fields. For example, in regions at high risk of sea level rise, civil engineers, and geologists in local universities may work together to efficiently adopt and advance technologies for coastal adaptation, and to adapt them to locally-specific conditions. Similarly, in regions where water adaptation is urgent, chemical engineers in the local universities may play a pivotal role in facilitating the adoption and further development of water adaptation technologies.

4.2.3. Technology co-classifications

A single patent can belong to multiple technology classes, reflecting a combinatory nature of knowledge creation (Nelson and Winter, 1985). Investigating co-classification patterns of adaptation patents can reveal technological capabilities other than Y02 A that are needed to develop each type of CCAT. In addition, the co-classification patterns can be also interpreted as reflecting the promising fields of technological convergence with adaptation technologies (e.g. Jee et al., 2019).

Therefore, organizations equipped with capabilities in fields frequently co-classified with Y02 A can be understood as being in a competitive position in developing and exploiting adaptation technologies. Motivating these organizations, particularly in the private sector, to engage in the development of adaptation technologies can be a reasonable direction to spur innovation in climate change adaptation. In addition to encouraging the supply side, governments can also stimulate targeted foreign direct investments (FDI) or foreign licensing and connect these organizations with potential regions where demand exists, the regions being exposed to a higher risk of a certain type of

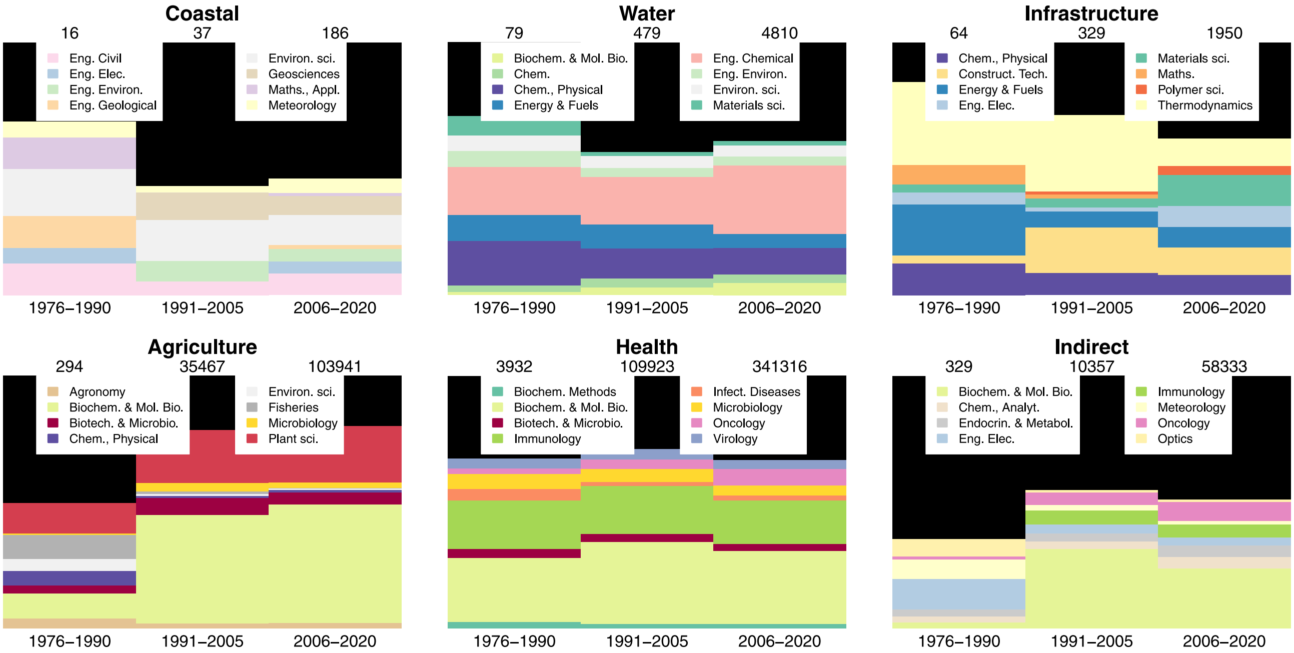


Fig. 3. Composition of scientific knowledge base by scientific fields.
Notes: These figures show the 8 most often cited scientific fields (by Web-of-Science categories). The numbers on top of each bar indicate the number of papers cited by patents granted in the respective time period. The size of the colored fields in each bar plot indicates the share of citations that goes to the respective WoS field. Black color is used for the residuum of fields that are cited less often than the 8th most often cited field. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

climate change (Ferreira et al., 2020; Popp, 2020; Saggi, 2002). Targeted technology-transfer policy may not only stimulate the diffusion of environmentally related technologies, but also spur technological learning and indigenous innovation by local firms.

Fig. 4 shows the overall patterns of co-classification for each type of CCAT. For example, we can see that the vast majority of coastal adaptation patents are co-classified as fixed constructions technology.[6] The results imply that firms with fixed construction engineering skills are in a good position to develop and utilize coastal adaptation technologies. Targeted government support on these firms to motivate their investment in coastal adaptation technologies and to match them with regions with high risk of sea level rise would play an important role in stimulating innovation in coastal adaptation.

Many indirect adaptation patents are co-classified as physics (see Fig. 4). In-depth analysis with further technological details (see SI.2) shows that this is due to technological interdependencies between indirect adaptation and applied physics including measurement, detection, and prediction technologies. Therefore, to stimulate innovation in indirect adaptation, governments can incentivize firms with advanced skills in measurement, detection, and prediction to invest in indirect adaptation technologies, as well as connect these firms to regions where precise, timely sensoring and forecasting of climate disaster are critical.

Fig. 4 also shows the extent to which different categories of adaptation patents are labeled as mitigation patents, indicated by purple color. The next section explores this duality in more detail.

4.3. Complementarities with mitigation

We next focus on complementarities between adaptation and mitigation technologies to inform technology-choices that help achieve climate change mitigation and adaptation at the same time. We use two different approaches: (1) analyzing patents that are co-classified as adaptation and mitigation technologies to identify 'dual purpose' technologies, and (2) examining the extent to which adaptation and mitigation technologies rely on similar technological and scientific knowledge (i.e., cite the same patents and papers). The knowledge base similarity of adaptation and mitigation technologies helps understand how mutual knowledge spillovers between adaptation and mitigation can be stimulated. For example, public support may be directed towards the fields in which both adaptation and mitigation rely on.

4.3.1. Adaptation technologies with mitigation co-benefit

Starting off with co-classifications, we find that many adaptation patents except for those in indirect adaptation include a significant proportion of dual purpose patents helping in not only adaptation but also mitigation (purple bars in Fig. 4). In total, 26% of adaptation patents are co-classified as mitigation patents, showing that more than a quarter of adaptation technologies have the potential to be used in both adaptation and mitigation areas (Table 1). The highest overlap is in infrastructure adaptation where 70% of the patents are co-classified as mitigation technologies. For example, thermal insulation in buildings achieves both adaptation and mitigation purposes: it preserves thermal comfort during extreme temperature events, but it may also help reduce energy consumption and associated emissions. This is an example of how maladaptation relying on the intensified use of air-conditioning to cope with heatwaves can be avoided (Barnett and O'Neill, 2010). Other illustrative examples are extreme weather resistant electricity grids that rely on insulation technologies that help reduce energy losses during the transmission through the grid, or integration of production and use of renewable energy into buildings for heating and cooling purposes.

For health-, agriculture-, and water-related adaptation, roughly 20% of patents simultaneously serve mitigation purposes (Table 1). Co-benefits in health adaptation arise for example from clean transportation that reduce emissions. This represents a preventive intervention improving public health as air pollution control helps prevent respiratory and cardiovascular diseases. Research has shown that these diseases increase the vulnerability to heatwaves and some infectious

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[6] Coastal adaptation significantly relies on solutions that are difficult to patent as well, such as mangrove reforestation and nature-based solutions. We should note that Fig. 4 includes a bias towards coastal adaptation solutions that are patentable, rather than the hard to be patented solutions.

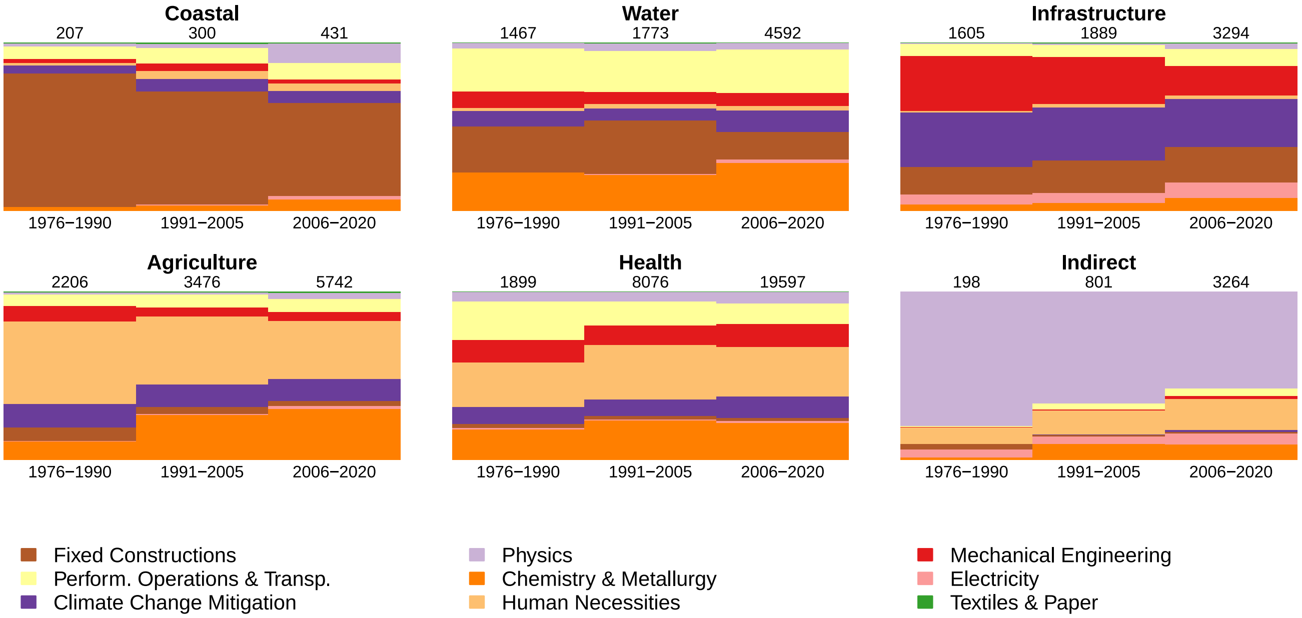

Fig. 4. Co-classification of adaptation technologies.
Notes: These figures show the co-classification of adaptation technologies at the CPC section level (1-digit). The numbers on top of each bar indicate the number of patents granted in each sub-period. Note that the bar plots rely on the number of co-classifications. Patents that serve multiple adaptation purposes, i.e. are classified into multiple adaptation technology types, are double-counted. The size of the colored fields in each bar plot indicates the share of co-classifications for different subgroups by adaptation technology type.

Table 1
Overview statistics of dual purpose patents.

	Total patents	Share dual purpose	Citing/total patents	Share gov. supported
Dual purpose adaptation technologies				
Coastal	71	0.08	0.11	0.30
Water	926	0.20	0.25	0.32
Infrastructure	3276	0.70	0.10	0.17
Agriculture	1768	0.22	0.21	0.23
Health	3668	0.22	0.19	0.20
Indirect	39	0.01	0.54	0.69
Gov. support (No)	6440	0.27	0.10	
Gov. support (Yes)	1657	0.17	0.41	
All	9645	0.26	0.23	0.20
Dual purpose mitigation technologies				
Buildings	3033	0.07	0.09	0.16
CCS	429	0.08	0.44	0.46
Green ICT	15	0.00	0.67	0.36
Energy	920	0.01	0.24	0.31
Production	1356	0.02	0.25	0.23
Transport	2821	0.03	0.12	0.14
Waste	1071	0.05	0.24	0.27
Gov. support (No)	6440	0.02	0.10	
Gov. support (Yes)	1657	0.02	0.41	
All	9645	0.02	0.29	0.20

Notes: This table summarizes the subsets of dual purpose patents, i.e. patents that are simultaneously classified as adaptation and mitigation technology. The upper part of the table shows these patents from the angle of adaptation, the lower part from the angle of mitigation technologies. Column *Share dual purpose* shows the share of dual purpose patents in all patents. Column *Citing/total patents* shows the ratio of patents that cite at least one scientific paper over the number of all patents. Column *Share gov. supported* shows the share of patents that benefited from governmental support. The rows *Gov. support: Yes* and *No* show statistics for the subset of patents that do and do not rely on public support, respectively. Sum of the number patents in each sector is not exactly same with the number of all patents because a patent can be classified into multiple sectors at the same time.

diseases (Harlan and Ruddell, 2011), including Covid-19 (Domingo and Rovira, 2020).

In agriculture, we find technologies that improve the climate resilience of plants can simultaneously sequester carbon. Some technologies that contribute to an improved handling of bio-related waste or energy efficiency of greenhouses can simultaneously be used in cooling systems for food storage.

In addition, some adaptation technologies used for water treatment, purification, and desalination also help reduce emissions in wastewater and solid waste treatments. Barnett and O'Neill (2010) mentioned energy-intensive desalination as an example of emission-increasing maladaption. Our analysis shows that mitigation-friendly alternatives exist, combining renewable energy with desalination.

By contrast, the occurrence of dual purpose technologies is relatively weak in coastal (8%) and indirect adaptation technologies (1%).

When examining the degree to which mitigation patents can be co-classified as adaptation patents, we find that CCS, clean buildings, and waste management-related mitigation technologies include 8%, 7%, and 5% of dual purpose patents, respectively. By the number of patents, clean transportation, efficient production, and low-carbon energy patents have significant co-classification with adaptation. However, due to the large number of patents in these categories the share of co-classification is low, ranging between 1%–3%.

The fact that some adaptation technologies bear mitigation co-benefits does not tell us much about the climate impact of the remainders beyond examples mentioned in the literature on maladaptation. We cannot say – based on our analysis – whether mitigation technologies that are not co-classified as adaptation have a negative or positive impact on the economy's climate resilience. While not judging whether adaptation and mitigation are complements in general, we show that some adaptation–mitigation options are complementary. Complementarity may be a matter of technology choice and our analysis identifies areas that are promising to achieve adaptation–mitigation co-benefits.

Although our analysis shows the technological potential to achieve both adaptation and mitigation goals, the absence of co-benefits does not necessarily imply an inferior technology choice. Other factors such as competing policy objectives, economic constraints, different time horizons, and locality of events may constrain the set of available technology options. For example, health-related adaptation technologies to cope with risks from vector borne diseases are urgent in some developing countries although disconnected from any mitigation technology. For nuclear energy, in some countries, political objectives to achieve short-term mitigation may weigh higher than the long-term resistance to climate change. At least in the short term, adaptation co-benefits of nuclear energy are absent and there is good reason to believe that these technologies rather undermine than strengthen the vulnerability against extreme climate shocks (Hanski et al., 2018; Jordaan, 2018). Nevertheless, short term mitigation benefits of this technology are strong and – assuming a positive mitigation impact – it also contributes to adaptation in the long run if it helps reduce the impact of climate change.

4.3.2. Potential knowledge spillovers between mitigation and adaptation

We investigate the extent to which different mitigation and adaptation technologies build on a common knowledge base. To identify domains of shared knowledge, we analyze similarities of the technological and scientific knowledge base for pairs of different adaptation and mitigation technologies. Previous research has shown that similarities enable knowledge spillovers across technologies at the organizational, regional, and national level, and they are an indicator of absorptive capacity as it is easier for firms, industries, and countries to adopt a new technology if the adopter has pre-existing relevant knowledge (Cohen and Levinthal, 1990; Caragliu and Nijkamp, 2012; Criscuolo and Narula, 2008). This also matters for policy: if two technologies build on the same knowledge sources, R&D policy may focus on these areas to support the development of both technologies at the same time.

In Fig. 5, we illustrate knowledge similarities through network plots and correlation charts. Similarities are measured via backward citation patterns: two technologies are more similar if they rely more on common sources of knowledge. This is measured by the cosine similarity based on shares of citations to CPC 4-digit technology classes (Fig. 5(a)) and citations to scientific Web of Science (WoS) fields (Fig. 5(b)).

The upper two figures show similarity networks. A link between a pair of technologies indicates the cosine similarity of their references to scientific fields and technology classes, respectively. For clarity, only the most significant links are shown.[7] The widths of connecting edges are proportional to the degree of similarity and the node sizes are proportional to the number of patents. The node colors indicate the 4-digit technology class (i.e., red for adaptation, gray for buildings, black for CCS, blue for green ICT, green for energy, orange for production, yellow for transport, and brown for waste).

The lower two figures illustrate the numerical values of the cosine similarity of adaptation (columns) and mitigation (rows) technologies at the 6-digit level. The letters in the beginning indicate the type of mitigation technology (B for buildings, C for GHG disposal, D for green ICT, E for energy, P for production, *T* for transport, and W for waste). Our similarity analysis shows:

(1) Citing similar patents, mitigation technologies for energy efficiency in buildings and green ICT have a similar technological knowledge base to infrastructure-related adaptation technologies. Technologies that reduce transmission losses and improve the energy efficiency of ICTs rely on similar technological knowledge as technologies that strengthen the resilience of physical infrastructure to extreme weather events. The same holds for insulation, efficient heating, and renewable energy in buildings.

(2) Clean energy, especially clean combustion and bio-fuels, exhibits strong scientific similarities with science-intensive adaptation technologies such as agriculture, health, and indirect adaptation. This is particularly due to their common reliance on chemistry (see Section 4.2 and for more detail Fig. SI.3–SI.5, SI.8 in the Supplementary Material).

(3) Water-related adaptation technologies exhibit a high degree of scientific similarity with clean industrial processing technologies for metal and oil, with waste treatment, and CCS. This can be explained by their joint reliance on chemistry. We also observe a high potential for scientific and technological knowledge spillovers between water adaptation and clean energy that mostly arise from interactions with non-fossil fuels and renewables. Our data shows that examples of energy intensive water treatment technologies like desalination explicitly make use of photovoltaics, which explains their reliance on the same science (see Fig. SI.4–SI.5 in the Supplementary Material).

(4) We observed the rise in mitigation technologies for clean production that have adaptation co-benefits (see orange node in Fig. 5 and SI.4–SI.8). Not surprisingly, the spillover potential is highest in between adaptation and mitigation in agricultural production. In addition, we observe a large potential for technological knowledge spillovers between enabling technologies in production and various fields of adaptation. This suggests that there is a high potential to harness knowledge spillovers and to realign efforts to mitigate emissions in production processes with adaptation goals.

This analysis suggests that many adaptation and mitigation technologies in various domains share a common knowledge base. The reliance on similar technological and scientific knowledge suggests that R&D investments in one area have positive side effects on another. Economically, the existence of positive knowledge spillovers is a justification for higher levels of public support, as the social returns of these investments exceed those from investments in technologies that show a lower spillover potential (Aldieri et al., 2019).

5. Discussion

Despite the urgency of climate change and the substantial long-term economic benefits of adaptation (Tall et al., 2021), the study of innovation in adaptation has attracted relatively little scholarly attention (Popp, 2019; Dechezlepretre et al., 2020) and markets for adaptation technologies seem underdeveloped given their benefits (Dechezlepretre et al., 2020). However, this is likely to change: the requirement of countries to disclose their adaptation plans under the Paris Agreement (Lesnikowski et al., 2017; Berrang-Ford et al., 2019), increasing awareness of firms' climate risks and efforts by regulators to make risk disclosures mandatory will incentivize the public and private sector to take action towards adaptation (Goldstein et al., 2019; Smith,

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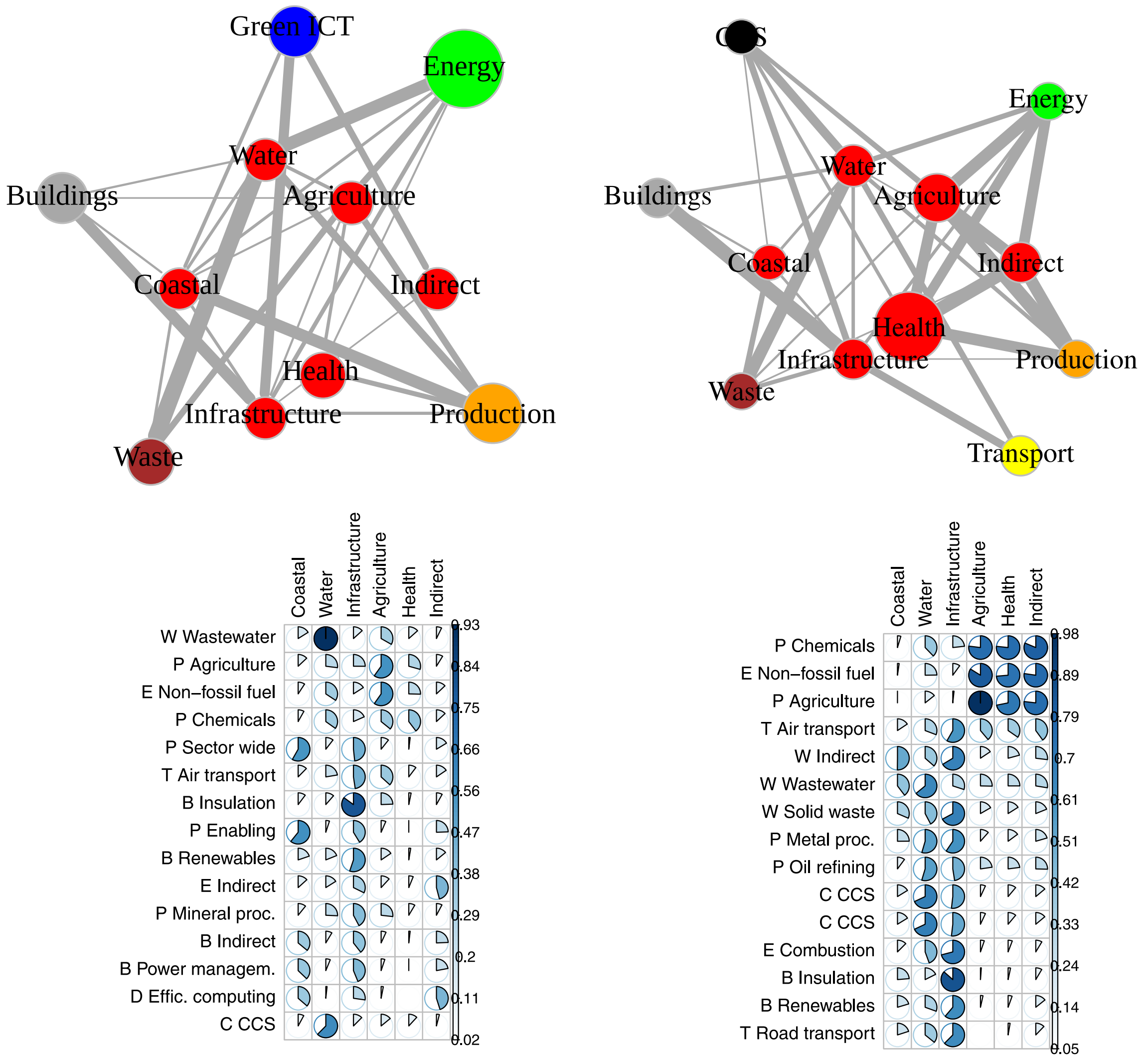
[7] We use the median weight of connecting links as significance threshold and show only those links whose weight is larger than that.



(a) Technological similarity

(b) Scientific similarity

Fig. 5. Technological and scientific similarity among CCATs and CCMTs.
Notes: These figures illustrate technological similarities of different types of adaptation and mitigation technologies that are complements, i.e. simultaneously classified as adaptation and mitigation technologies. The figures are based on shares of (a) citations to CPC 4-digit technology classes and (b) citations to scientific fields (WoS). The upper two figures show similarity networks. A link between a pair of technologies indicates the cosine similarity of their references to scientific fields and technology classes, respectively. For clarity only the most significant links are shown. The widths of connecting edges are proportional to the degree of similarity and the node sizes are proportional to the number of patents. The node colors indicate the 4-digit technology class (i.e., red for adaptation, gray for buildings, black for CCS, blue for green ICT, green for energy, orange for production, yellow for transport, and brown for waste). The lower two figures illustrate the numerical values of the cosine similarity of adaptation (columns) and mitigation (rows) technologies at the 6-digit level. The letters in the beginning indicate the type of mitigation technology (i.e., B for buildings, C for GHG disposal, D for green ICT, E for energy, P for production, *T* for transport, and W for waste). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2021). This study offers the first systematic analysis of adaptation technologies and their knowledge base addressing three questions.

First, we asked: *To what extent have these technologies been developed, and which were the drivers of innovation?* We find that patenting in most adaptation technologies did not increase substantially over the past decades, with the exception of health-related and indirect adaptation. Historically, we observed several phases of increased inventive activity, especially since the late 1960s and during the Oil Crisis in the 1970s. The 1960s were the starting date of many environmental initiatives including regulatory measures such as the Clean Air Act from 1963 and Clean Water Act from 1972. As discussed above, many adaptation technologies, especially in water and health, interacting with pollution control bear a positive externality improving the environmental quality. Despite not providing causal evidence, the rise in certain water and health adaptation technologies we observe might have been a byproduct of environmental regulatory policy.

Similarly, our analysis revealed that many solutions for adaptation, especially in infrastructure and agriculture, have the potential to simultaneously improve energy efficiency. Many other technologies integrate off-grid renewable energy into their processes, for example for desalination, food processing and conservation, or cooling and heating in buildings. High prices for fossil fuel energy during the Oil Crisis stimulated investments in energy efficiency and the demand for alternative energy solutions, which offers one explanation for the rise adaptation, again as a byproduct of the seemingly unrelated energy price.

Second, we addressed the question: *How can governments support the development and adoption of these technologies?* Our analysis has further revealed that public R&D support may be supportive for early-stage technological development. This is particularly important for science-intensive technologies, as private sector incentives to engage in basic research with uncertain returns are limited. Agriculture, health, and indirect adaptation technologies are highly science-intensive, while adaptation for coastal defense, infrastructure, and water is rather engineering-based.

Analyzing the scientific base of adaptation, we have further discussed that science-intensive CCATs rely more heavily on basic rather than applied sciences. This gives insights into policies for transferring adaptation technologies to regions in need. Local universities and public research institutions equipped with relevant scientific knowledge base (e.g., biochemistry and molecular biology for science-intensive CCATs) can be key actors in facilitating technology transfer, as they contribute to the regional absorptive capacity for science-intensive technologies. An analysis of co-classification patterns of adaptation patents helps identify organizations with complementary technological capabilities, which can be used to develop and exploit different adaptation technologies, for example firms with construction skills for coastal adaptation. Above, we discussed directions in which the government should provide targeted support for both supply and demand of adaptation solutions to stimulate innovation in climate change adaptation.

Finally, we wanted to find out: *How do technologies for adaptation interact with climate change mitigation?* From a technological perspective, climate change mitigation and adaptation are complements: on average, 26% of adaptation technologies also help in mitigation. In some sub-fields such as infrastructure-adaptation, the complementarities are particularly large, with 70% of adaptation patents simultaneously contributing to climate change mitigation. Well-designed policy may exploit and strengthen these complementarities to ensure that climate change technologies serve the twin goals of adaptation and mitigation.

Adaptation–mitigation co-benefits have been recognized in many adaptation case studies (Kabisch et al., 2017; Sharifi, 2021; Berry et al., 2015). Our analysis shows that this can be also seen systematically in aggregate data. This enables a systematic understanding of the drivers of innovation behind adaptation and shows many examples of how adaptation and mitigation efforts can be aligned. We have also seen that adaptation technology development often came as a byproduct of other economic trends. Identifying complementarity with other larger technological developments, for example in artificial intelligence and biotechnology, may help to make R&D for adaptation more effective. Furthermore, systematic analyses of technological overlaps of adaptation with response strategies to major shocks such as Covid-19, the Ukraine war, or financial crises can also mobilize additional financial resources to create a resilient economy.

6. Conclusion

In this paper, we have taken stock of the current technological frontier of adaptation technologies. We have shown that – compared to mitigation – innovation in the field of adaptation has not yet taken off. In the analysis, we have identified and discussed major drivers of innovation in adaptation such as responses to regulation and shocks in the market, but we also highlighted a prominent role of the government stimulating the development of these technologies.

Our analysis has further shown how governments can effectively stimulate the development and adoption of technologies through targeted investments in scientific and technological capacities, and we discussed how this can help enable technology transfer to countries where adaptation needs are high.

Finally, we addressed the nexus between climate change mitigation and adaptation and have shown that – from a technological perspective – mitigation and adaptation efforts can be complementary in certain technological areas. This is a matter of technology choice and our analysis may provide guidance on how these choices can be made to achieve mitigation and adaptation objectives at the same time.

This study is limited to the technological frontier of adaptation as reflected in patent data. Although the granted patents capture inventions that have high (perceived) market value, patent data as a measure of innovation has well-documented limitations (OECD, 2009) being biased towards the technological frontier solutions and being silent about other aspects such as nature-based or behavioral solutions. Furthermore, our analysis is descriptive and not causal. The drivers of innovation and the suggestions for how governments can support innovation in adaptation are based on descriptive analyses and insights from the existing literature. Our analysis may serve as a basis for future research that identifies factors affecting the development and diffusion of climate change adaptation technologies. Another promising avenue for future research is to develop measures for these other solutions of adaptation that can be systematically compared to the technologies analyzed in this paper. This would help understand the multiple trade-offs and synergies among different solutions for adaptation and their interaction with mitigation, which is highly relevant to address the climate challenge in an efficient way.

CRediT authorship contribution statement

Kerstin Hötte: Developed the research idea, Study design, Visualized the results, Wrote the initial draft, Compiled and analyzed the data, Contextualized the results, Writing - review & editing. **Su Jung Jee:** Compiled and analyzed the data, validated the results, Contextualized the results, Writing - review & editing.

Declaration of competing interest

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

Data availability

The data is published under a CC-BY 4.0 license and available here: https://doi.org/10.4119/unibi/2958327.

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Appendix

A.1. Y02A Classes and definitions

This list is downloaded from: https://worldwide.espacenet.com/classification?locale=en_EP#!/CPC=Y02A [April 2021].

Y02A

CPC COOPERATIVE PATENT CLASSIFICATION

Y **GENERAL TAGGING OF NEW TECHNOLOGICAL DEVELOPMENTS; GENERAL TAGGING OF CROSS-SECTIONAL TECHNOLOGIES SPANNING OVER SEVERAL SECTIONS OF THE IPC; TECHNICAL SUBJECTS COVERED BY FORMER USPC CROSS-REFERENCE ART COLLECTIONS [XRACs] AND DIGESTS**

(NOTES omitted)

Y02 **TECHNOLOGIES OR APPLICATIONS FOR MITIGATION OR ADAPTATION AGAINST CLIMATE CHANGE**

(NOTES omitted)

Y02A TECHNOLOGIES FOR ADAPTATION TO CLIMATE CHANGE

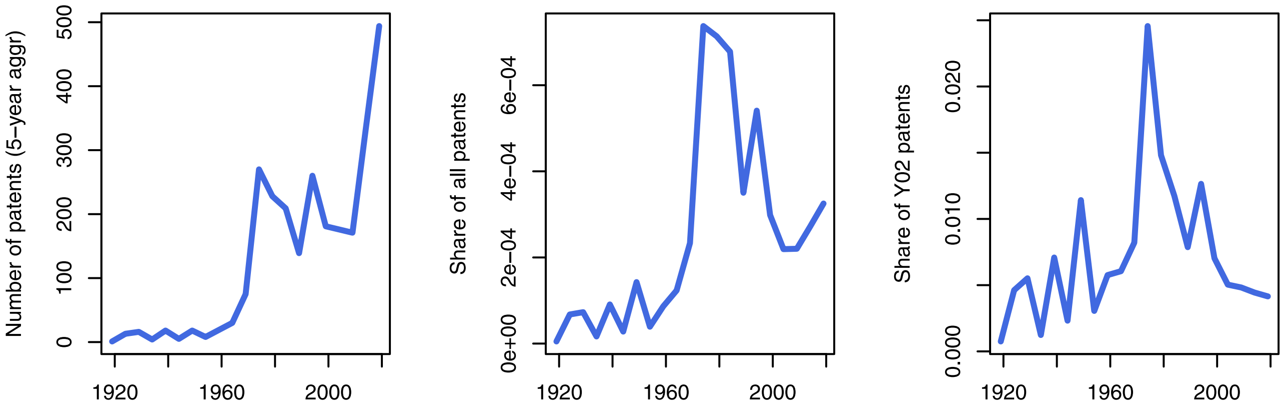
NOTE

This subclass covers technologies for adaptation to climate change, i.e. technologies that allow adapting to the adverse effects of climate change in human, industrial (including agriculture and livestock) and economic activities.

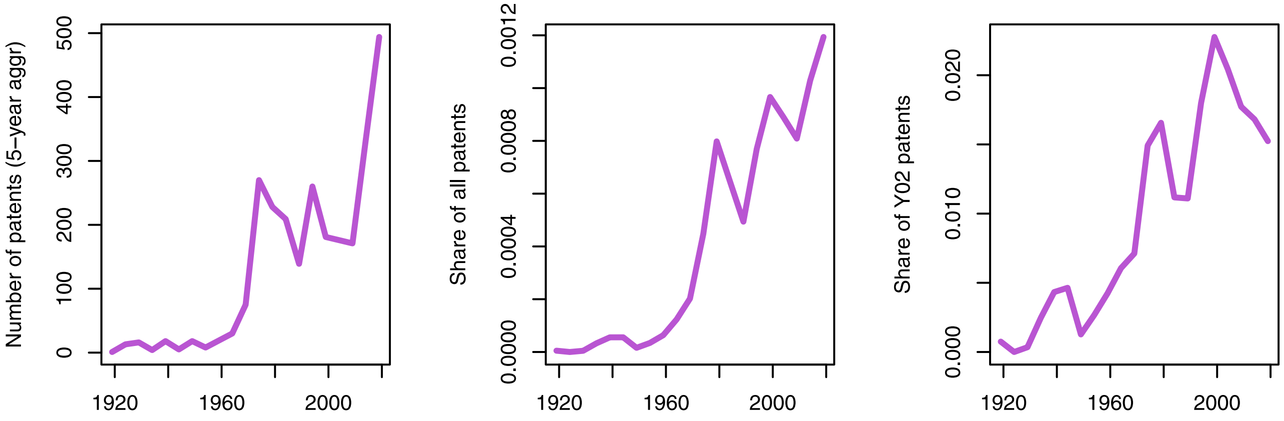
10/00	**at coastal zones; at river basins**
10/11	. Hard structures, e.g. dams, dykes or breakwaters
10/23	. Dune restoration or creation; Cliff stabilisation
10/26	. Artificial reefs or seaweed; Restoration or protection of coral reefs
10/30	. Flood prevention; Flood or storm water management, e.g. using flood barriers
10/40	. Controlling or monitoring, e.g. of flood or hurricane; Forecasting, e.g. risk assessment or mapping
20/00	**Water conservation; Efficient water supply; Efficient water use**
20/108	. Rainwater harvesting
20/124	. Water desalination
20/131	. . Reverse-osmosis
20/138	. . using renewable energy
20/141	. . . Wind power
20/142	. . . Solar thermal; Photovoltaics
20/144	. . . Wave energy
20/146	. using grey water
20/148	. . using household water from wash basins or showers
20/15	. Leakage reduction or detection in water storage or distribution
20/152	. Water filtration
20/20	. Controlling water pollution; Waste water treatment
20/204	. . Keeping clear the surface of open water from oil spills
20/208	. . Off-grid powered water treatment
20/211	. . . Solar-powered water purification
20/212	. . . Solar-powered wastewater sewage treatment, e.g. spray evaporation
20/30	. Relating to industrial water supply, e.g. used for cooling
20/40	. Protecting water resources
20/402	. . River restoration
20/404	. . Saltwater intrusion barriers
20/406	. . Aquifer recharge
20/411	. . Water saving techniques at user level
30/00	**Adapting or protecting infrastructure or their operation**
30/14	. Extreme weather resilient electric power supply systems, e.g. strengthening power lines or underground power cables
30/24	. Structural elements or technologies for improving thermal insulation
30/242	. . Slab shaped vacuum insulation
30/244	. . using natural or recycled building materials, e.g. straw, wool, clay or used tires
30/249	. . Glazing, e.g. vacuum glazing
30/254	. . Roof garden systems; Roof coverings with high solar reflectance
30/27	. Relating to heating, ventilation or air conditioning [HVAC] technologies
30/272	. . Solar heating or cooling
30/274	. . using waste energy, e.g. from internal combustion engine
30/30	. in transportation, e.g. on roads, waterways or railways
30/60	. Planning or developing urban green infrastructure
40/00	**Adaptation technologies in agriculture, forestry, livestock or agroalimentary production**
40/10	. in agriculture
40/13	. . Abiotic stress
40/132	. . . Plants tolerant to drought
40/135	. . . Plants tolerant to salinity
40/138	. . . Plants tolerant to heat
40/146	. . Genetically Modified [GMO] plants, e.g. transgenic plants
40/20	. . Fertilizers of biological origin, e.g. guano or fertilizers made from animal corpses
40/22	. . Improving land use; Improving water use or availability; Controlling erosion
40/25	. . Greenhouse technology, e.g. cooling systems therefor
40/28	. . specially adapted for farming
40/51	. . specially adapted for storing agricultural or horticultural products
40/58	. . . using renewable energies
40/60	. Ecological corridors or buffer zones

Y02A

40/70	. in livestock or poultry
40/76	. . using renewable energy
40/80	. in fisheries management
40/81	. . Aquaculture, e.g. of fish
40/818	. . . Alternative feeds for fish, e.g. in aquacultures
40/90	. in food processing or handling, e.g. food conservation
40/924	. . using renewable energies
40/926	. . . Cooking stoves or furnaces using solar heat
40/928	. . . Cooking stoves using biomass
40/963	. . Off-grid food refrigeration
40/966	. . . Powered by renewable energy sources
50/00	**in human health protection, e.g. against extreme weather**
50/20	. Air quality improvement or preservation, e.g. vehicle emission control or emission reduction by using catalytic converters
50/2351	. . Atmospheric particulate matter [PM], e.g. carbon smoke microparticles, smog, aerosol particles, dust
50/30	. Against vector-borne diseases, e.g. mosquito-borne, fly-borne, tick-borne or waterborne diseases whose impact is exacerbated by climate change
90/00	**Technologies having an indirect contribution to adaptation to climate change**
90/10	. Information and communication technologies [ICT] supporting adaptation to climate change, e.g. for weather forecasting or climate simulation
90/30	. Assessment of water resources
90/40	. Monitoring or fighting invasive species



(a) Pollution control technologies related to water



(b) Pollution control technologies related to health

Fig. A.1. Patenting trends in pollution control technologies.
Notes: These figures show the subset of pollution control technologies within the water and health adaptation patents. The first figure in each row shows the number of patents granted within 5-year time windows between 1915–2019 (x-axes). The second and the third figures in each row show this count as a share of all patents and all Y02 patents, respectively. Pollution control technologies in water are identified by the following CPC codes Y02A20/152, Y02A20/15, Y02A20/20, Y02A20/204, Y02A20/208, Y02A20/211, and Y02A20/212. To identify pollution control technologies related to health, we used the codes Y02A50/20 and Y02A50/2351. For an explanation of the codes, see A.1.

A.2. Additional results

A.2.1. Summary statistics of adaptation and mitigation patents

In Table A.1, we summarize the adaptation patents (at the DOCDB family level) granted over the full time horizon covered by our analysis. We have a relatively low number of patents in coastal adaptation (857) and the largest number of patents in health adaptation (16,363). We also report the number of patents that make at least one citation to science, the share of patents that cite to science, the number of scientific citations, average number of citations made by patents, average number of citations made by citing patent and the share of patents that are reliant on governmental support. Overall, we find that patents relying on public support tend to be more science intensive (i.e., exhibit a higher share of science reliant patents and make more citations to science than others).

Table A.2 summarizes all Y02-tagged technologies in our data differentiating between different types of mitigation and adaptation technologies. Fig. SI.1 shows a pie-chart illustrating the relative frequencies of different types of mitigation and adaptation technologies at the aggregate and disaggregate level.

A.2.2. Trends in pollution control innovation in water and health

The literature on environmental innovation has shown that environmental regulation can be a driver of innovation in pollution control technologies (see Popp (2019) for an overview). In Section 4.1.1, we have argued that the rise in water- and health-related adaptation technologies can be associated with major trends in pollution control policies, such as the Clean Air and Clean Water Act in the 1960s and 1970s.

In Fig. A.1, we show additional time series figures of the subset of patents with an explicit pollution control purpose. The first figure in each row shows the number of patents in pollution control technologies granted within 5-year windows between 1915–2019. The time series show a striking increase in the late 1960s/1970s. Between 1945–1964, the average number of patents granted within 5 years accounted for 18.75 for water and 13.25 for health. In 1965–1984, this number was strikingly higher with 195.5 for water and 170.75 for health.

This increase is also strikingly visible if we benchmark the increase against the number of all patents and all Y02 patents granted in the respective time window as shown in the second and third figure in each row, respectively. These figures show a similarly striking rise in the post 1960s.

Table A.1
Overview of adaptation technologies.

Technology	Total patents	Citing patents	Citing/total patents	Scientific citations	Citations per patents (all)	Citations per patents (citing)	Share Gov. support
Coastal	857	62	0.07	328	0.38	5.29	0.18
Water	4678	720	0.15	14173	3.03	19.68	0.22
Infrastructure	4671	421	0.09	3828	0.82	9.09	0.16
Agriculture	8089	2482	0.31	149341	18.46	60.17	0.23
Health	16363	9331	0.57	490310	29.96	52.55	0.39
Indirect	2978	1749	0.59	72759	24.43	41.60	0.58
All	37341	14681	0.30	730739	12.85	31.40	0.31
Gov. support (No)	21706	5717	0.26	158897	7.32	27.79	
Gov. support (Yes)	9853	6911	0.70	480611	48.78	69.54	

Notes: This table summarizes the characteristics of patents classified as climate change adaptation technologies. The categories are distinguished at the 6-digit CPC level. The column *Citing patents* shows the number of patents that rely on science, i.e. make at least one citation to the scientific literature. The row entry *All* corresponds to total numbers for columns *total patents*, *citing patents* and *scientific citations* and to averages for the other columns. We double-count patents that fall into multiple adaptation technology categories, i.e. totals in row *All* are smaller than the sum of totals by technology type. The rows *Gov. support: Yes* and *No* show statistics for the subset of patents that do and do not rely on public support, respectively. The data on government support is only available for the period 1928–2017, i.e. the patent counts do not sum up.

Table A.2
Overview of adaptation and mitigation technologies.

Technology	Total patents	Citing patents	Citing/total patents	Scientific citations	Citations per patents (all)	Citations per patents (citing)	Share Gov. support
Adaptation	37341	14681	0.39	672420	18.01	45.80	0.31
Buildings	43371	6243	0.14	39477	0.91	6.32	0.16
CCS	5111	2074	0.41	22261	4.36	10.73	0.34
Green ICT	32735	8281	0.25	55787	1.70	6.74	0.11
Energy	166061	40075	0.24	417128	2.51	10.41	0.32
Production	83967	27315	0.33	310779	3.70	11.38	0.21
Transport	109997	10457	0.10	70373	0.64	6.73	0.19
Waste	22368	4361	0.19	33671	1.51	7.72	0.19
All	445689	98084	0.26	1621896	4.17	13.23	0.23
Gov. support (No)	272606	46150	0.17	378647	1.39	8.20	
Gov. support (Yes)	81245	36919	0.45	1005000	12.37	27.22	

Notes: This table summarizes the characteristics of adaptation and mitigation technologies at the aggregate 4-digit CPC level. The column *Citing patents* shows the number of patents that rely on science, i.e. make at least one citation to the scientific literature. The row entry *All* corresponds to total numbers for columns *total patents*, *citing patents* and *scientific citations* and to averages for the other columns. We double-count patents that fall into multiple technology categories, i.e. totals in row *All* are smaller than the sum of totals by technology type. The rows *Gov. support: Yes* and *No* show statistics for the subset of patents that do and do not rely on public support, respectively.

However, our analysis does not provide any causal evidence but just reveals time series patterns that can be plausibly associated with trends in environmental regulation. Environmental regulation such as the Clean Water and Clean Air Act increased the commercial demand for technologies that help meet the standards (Andreen, 2003; Kemp et al., 2000; Popp, 2019). However, this does not mean that regulation is the only explanation for the patenting trends during this period.

A.2.3. The scientificness of adaptation and mitigation over time

Fig. A.2 (Fig. A.3) shows time series plots of counts of 6-digit adaptation (4-digit adaptation and mitigation) patents (blue line) and counts of patents that cite at least one scientific paper (orange line) at a logarithmic scale.

Among the adaptation technologies, adaptation in agriculture and health are the oldest technologies with first patents being granted in the mid 19th century. Indirect adaptation technologies emerged in the 1960s and exhibit a strong reliance on science. While agriculture, health and indirect exhibit exponential growth, the other three technologies rather stagnated for a long time. Post-2005, the number of annually granted patents was increasing.

Clean energy technologies show historically a relatively high number of patents, and also for adaptation, mitigation related to buildings, production and transport, patenting began already during the nineteenth century. Green ICT and CCS are the by far youngest technologies starting off in early to mid-twentieth century. For all technologies, we observe an increasing reliance on science starting off from the 1950s. The reliance on science has been increasing for all technologies, though we observe a strong heterogeneity across technology groups with adaptation, clean production, and CCS having the highest share of patents that make at least once citation to a scientific article (see also Table A.2).

In Fig. A.4 we show an alternative measure of the scientificness of patents given by the ratio of citations to science over the sum of citations to patents and science. This figure confirms the pattern observed before with adaptation showing the highest reliance on scientific rather than applied knowledge, but also CCS, clean production, energy, waste and green ICT to become increasingly scientific. However, as seen in Section 4.2, there is a high heterogeneity across subfields. For example, the high science intensity of adaptation is mainly driven by health technologies and previous research has shown that solar PV and biofuels are key drivers of the scientificness of clean energy technologies (Hötte et al., 2021b).

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.techfore.2022.121879.

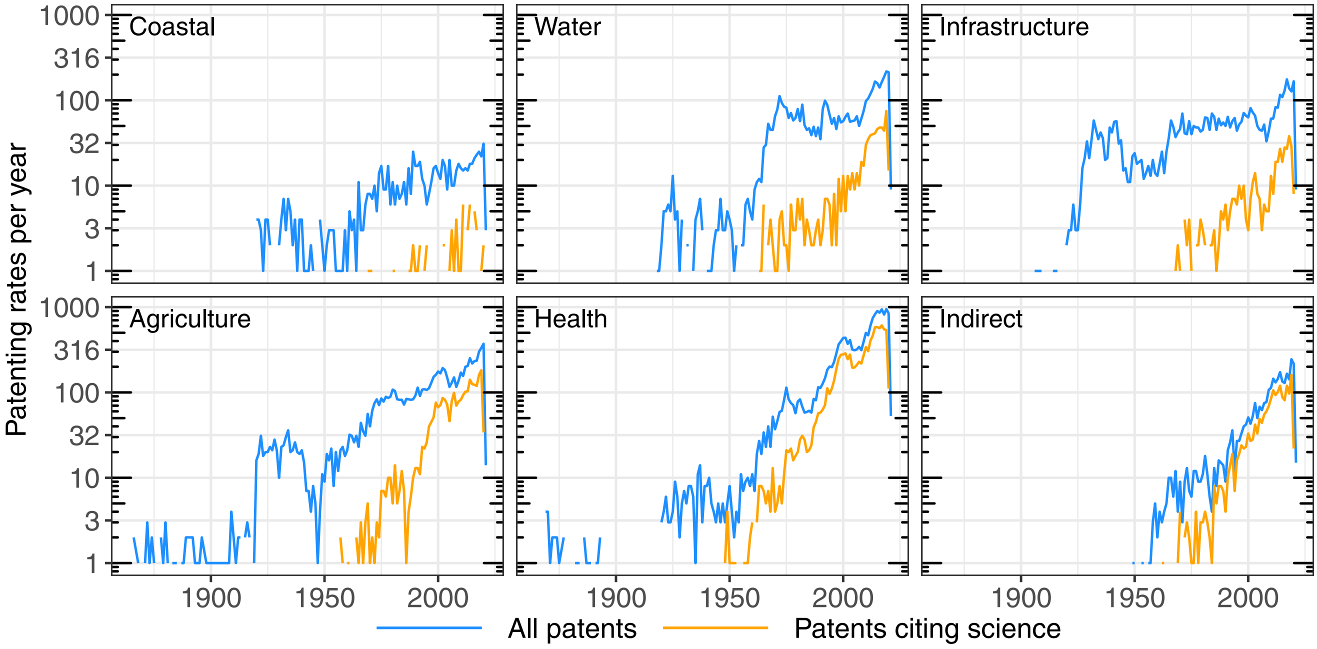


Fig. A.2. Adaptation patents and their science reliance.
Notes: Total number of patents by technology type and number of these patents that cite to science over time at a logarithmic scale.

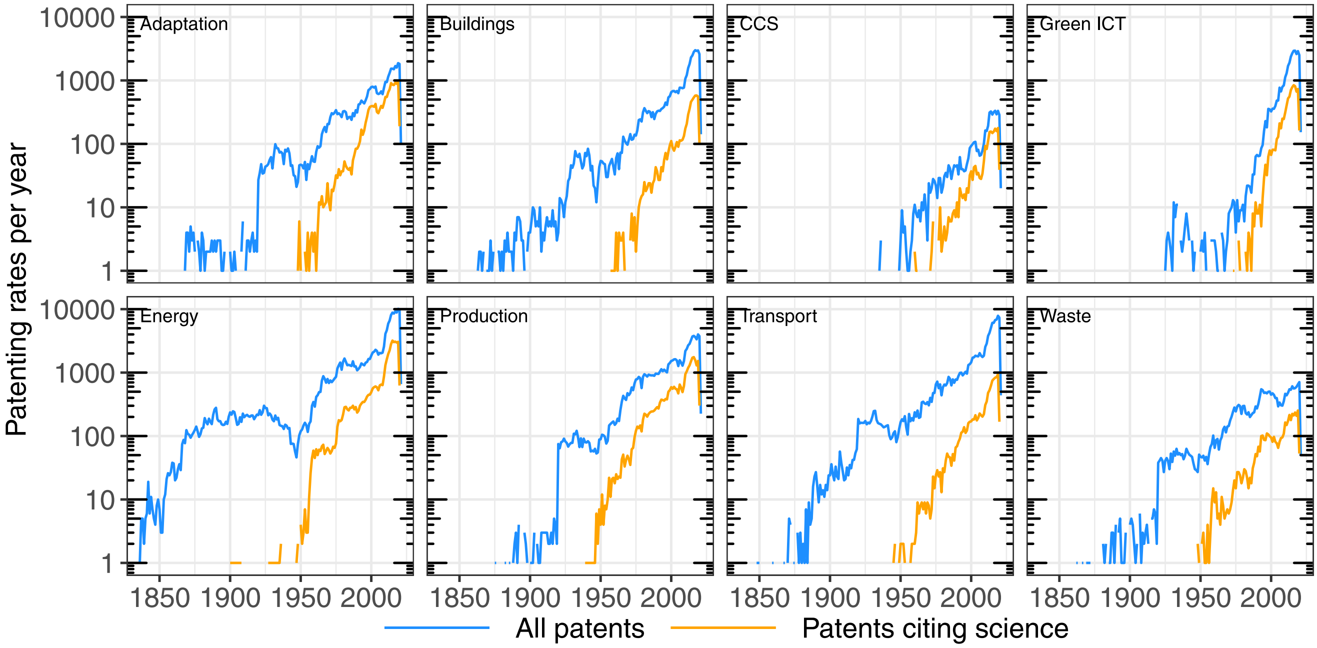


Fig. A.3. Adaptation and mitigation patents and their science reliance.
Notes: Total number of patents by technology type and number of these patents that cite to science over time at a logarithmic scale.

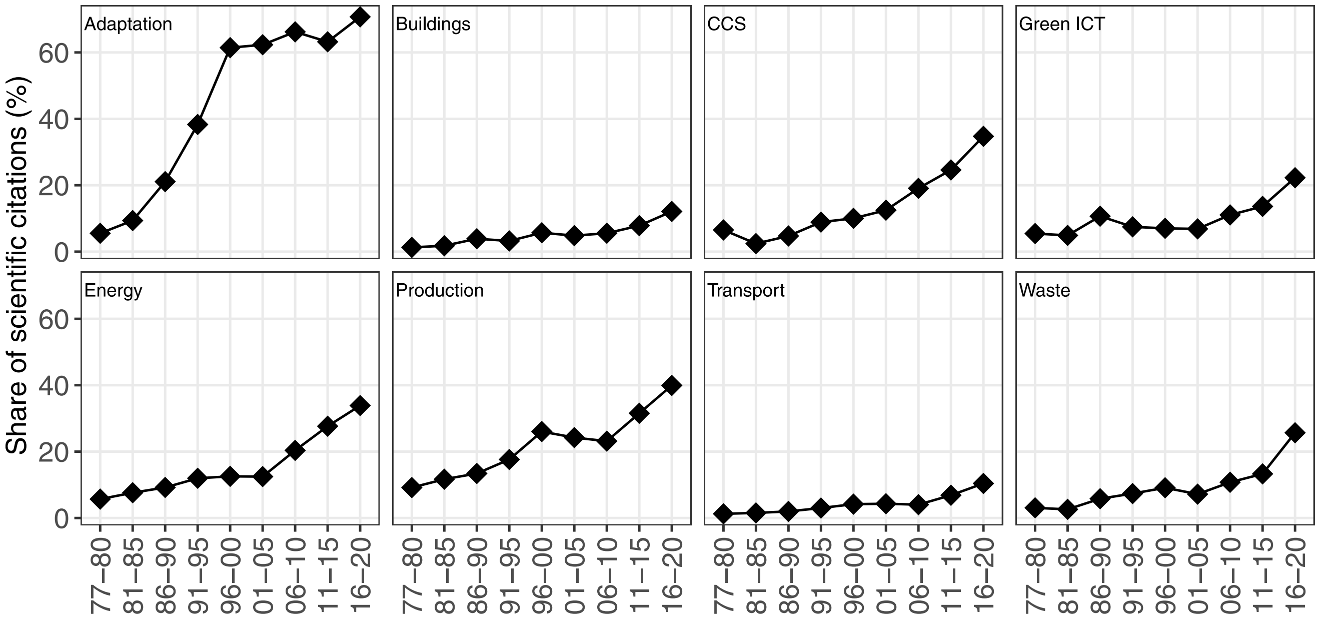


Fig. A.4. Science intensity of adaptation and mitigation.
Notes: Science-intensity of different 4-digit adaptation and mitigation patents measured by the share of citations to science in the number of total citations (sum of citations to other patents and scientific articles).

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