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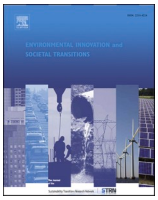

Technological trajectories in the circular economy: Evidence from patent networks and patent portfolios

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ABSTRACT

This paper investigates the dominant technological developments within the field of the Circular Economy (CE) and the potential drivers shaping these dynamics, which have received limited attention to date. To this end, we apply the *main path analysis* to a patent citation network to identify the key technological trajectories in CE. We then characterize these trajectories in terms of their technological, geographical, and business features, as well as the environmental policy frameworks potentially associated with them. Subsequently, through regression analysis, we examine the influence of two core attributes of the principal applicants' patent portfolios: total patent stock—used as a proxy for technological capability—and the share of patents in specific CE subfields—used as a proxy for technological specialization. Our results indicate that a firm's accumulated knowledge stock significantly enhances its ability to reach the CE technological frontier. Moreover, while specialization in a CE domain is positively associated with persistence at the frontier, excessive specialization appears to constrain adaptive capacity, thereby reversing this positive effect.

1. Introduction

In recent years, the circular economy (CE) has gained further importance due to the growing need to limit waste generation and the increasing unsustainability of the linear economic model, which is still mainly based on the "take, make, dispose" principle (Geissdoerfer et al., 2017; Suchek et al., 2021). The rapid proliferation of practices related to the circular economy has led to a vast literature spanning a wide range of fields, including the technological, economic, and strategic analysis of industries and competitors (for a review, see Suchek et al., 2021 and Sehnem et al., 2022). Besides its academic penetration, the CE has been stressed as an overall strategic framework by international organizations such as the United Nations and the European Union, as well as by entities such as the World Economic Forum and non-governmental entities such as the Ellen MacArthur Foundation (de Jesusa & Mendonça, 2018).

As CE practices and technologies spread and evolve over time and across geographies, adopting companies increasingly need to monitor and understand ongoing technological developments to define an effective R&D investment plan, predict future technological advancements, and position themselves in the market (Lai et al., 2023). According to Choi & Park (2009), possessing the technical ability to analyze and monitor the development of a technology can be regarded as one of the critical assets for gaining sustained competitive advantage and seizing significant opportunities. In this regard, a significant number of studies have investigated the

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evolution of a technological field over time and across different technologies, countries and applicants.

To identify the most relevant part of such technological evolution, which is effectively captured by the widely recognized concept of "technological trajectory" (Dosi, 1982; Nomaler & Verspagen, 2021)[1], the literature has often relied on patent citation networks and applied the powerful mathematical tool of the Main Path Analysis (MPA; Liu & Lu, 2012); MPA narrows down an initially large patent sample to a more focused set of patents that represent the most significant knowledge flow within the field under investigation. However, to succeed, firms not only need to understand the dominant developments within a given technological domain, but also to possess the resources and capabilities necessary to enter—and persist over time—at the frontier of that domain.

Although a broad strand of research has investigated the drivers of patenting concerning the broad sphere of the green economy, little is known about the determinants of circular economy patenting and, in particular, the factors that increase the probability for a patent/applicant to join and stay on the technological frontier of a specific technological area. Also, with the partial exception of the study by Gnekpe & Plantec (2023)[2], an extensive and fine-grained overview of the technological, geographical and business evolution of the circular economy based on the MPA applied to patent data has not yet been performed.

To fill this gap, in this paper we mainly aim to explore the dominant technological dynamics of the circular economy field and the potential drivers of such dynamics; in doing so, we focus on the role played by technological capability and technological specialisation, which are captured by two characteristics of the applicants' patent portfolios, namely, total patent stock and the share of patents referring to a certain CE sub-field, respectively. To this end, we implement a main path analysis on the patent citation network of the circular economy worldwide; the MPA allows us to identify the most relevant knowledge flows in the CE domain and to document the main technological, geographical and business dimensions of the identified technological trajectories. In addition, we link the identified trajectories to the geographical and temporal evolution of the main environmental regulations adopted by the leading countries: institutional factors, including regulations, are indeed recognized as important drivers of technological change along these trajectories (Dosi, 1982). Finally, we go beyond the detailed qualitative assessment of the CE main path and perform a regression analysis to assess the role of patent stock size and composition in a patent applicant's ability to enter and remain on the "main path" of the circular economy.

The qualitative overview of the technological trajectories suggests that there is a certain degree of heterogeneity in terms of technologies, central countries and main applicants, not only across sub- fields, but also within them, and provides various stylized facts. Importantly, the regression analysis reveals that technological capability, proxied by total patent stock, is positively associated with a patent/applicant's ability to enter the technological frontier (i.e., the larger the patent portfolio, the shorter the time to enter the technological trajectory). Furthermore, the degree of specialisation in a CE subfield (proxied by the share of corresponding patents) fosters persistence on the frontier, although over-specialisation can become a burden (thus reversing the initial positive effect).

This work adds to the economic literature on the patterns, drivers and implications of CE innovations and practices. Moreover, by investigating the determinants of firms and patents' performance on technological trajectories, this work relates to the broad line of research on the determinants of green patenting. Finally, since the two dependent variables of the regression analysis are based on the number of years needed for a (patented) technology to enter the main path and the duration of a technology's permanence ("leadership tenure") before being replaced by another technology, it also ties to the literature on technology cycle time (e.g., Park & Lee, 2006; Petralia et al., 2017)[3].

The balance of this work is organized as follows. Section 2 reviews the pertinent literature and derives the research questions. Section 3 introduces the data, the patent selection strategy and the MPA methodology. Section 4 provides a compact overview of the main CE technological trajectories and introduces some main path-based descriptive statistics. Section 5 presents the regression model and discusses the results of the regression analysis. Section 6 concludes. The main body of the paper is complemented by four Appendixes in which we offer a more detailed illustration of the MPA methodology (Appendix A), review the literature using the MPA to identify the technological trajectories in various domains (Appendix B), conduct a detailed overview of the CE main path (Appendix C) and include additional tables that contain robustness analysis (Appendix D).

2. Literature background and research questions

In our study, after identifying and illustrating the technological trajectories of the circular economy, we shed light on the role of technological knowledge/expertise and technological specialisation in a patent/firm's ability to enter and persist on the CE international frontier. Regarding firm's acquired knowledge and innovation ability, which is sometimes referred to as technological capability (e.g., Wu et al., 2020), it is often included among the determinants of environmental patenting performance. In particular,

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[1] A technological trajectory consists in a sequence of cumulative inventions influenced by the economic and social environment; such inventions form the major stream of technological change taking shape over time on the technological frontier (Dosi, 1982, Nomaler & Verspagen, 2021), which can be regarded as the highest level reached upon a technological path with respect to the relevant technological and economic dimensions (Dosi, 1982).

[2] Gnekpe & Plantec (2023) mainly aim to (qualitatively) explore the knowledge trajectories of CE-related inventions (classified into two main categories, namely, biological cycles and technical cycles) in the context of policymakers' regulatory efforts toward the CE paradigm. Hence, despite its valuable contribution, it focuses on the technological evolution of the CE field, of which it provides a mainly descriptive account.

[3] The Technology Cycle Time (TCT) measures how fast technologies change or become obsolete over time (Jaffe & Trajtenberg 2002) and has been incorporated by Park and Lee (2006) in the popular "technological regime" framework introduced by Nelson & Winter (1982). See Lee (2024) for a recent review of the literature on TLC and its role on the catching-up process of latecomers at the firm, sectoral, and national levels.

several studies proxy technological capability with firm-level R&D expenditures/intensity (e.g., Ayari et al., 2012; Marin, 2014; Kesidou & Wu, 2020; Wu et al., 2020; Zhang & Jin, 2021); other contributions, instead, measure it with the firm's patent stock, as patenting is a cumulative process that builds on a firm's established technological base (Arqué-Castells, 2012; Dong et al., 2021). As for corporate patent stock, some of these studies consider the total patent stock (e.g., Montobbio & Solito, 2018; He & Jiang, 2019; Dong et al., 2021), while others separately assess the impact of green patent stock and non-green patent stock (e.g., Aghion et al., 2016; Laurens et al., 2017; Corrocher & Solito, 2017; Aiello et al., 2021). All in all, these contributions indicate that environmental patenting performance is positively associated with the firm's overall knowledge base.

Accordingly, it seems that companies can also benefit from knowledge and expertise pertaining to different fields, including non-environmental ones. This is supported by various studies that split total stock into its green and non-green components and find a positive effect for non-green patent stock as well. Also, Barbieri et al. (2020) show that green patents, which, according to Petruzzelli et al. (2011), are characterized by higher levels of technological complexity and technological novelty than non-green patents, draw on significantly more diverse knowledge fields and combine a much larger number of technological components than non-green patents. Concerning the advantages of possessing technical knowledge and expertise in a variety of fields, a number of studies (e.g., Chen et al., 2012; Lin & Chang, 2015; Du et al., 2020; Li & Wang, 2021) have demonstrated that technological diversification, especially if "related"[4], has a positive effect on firm innovation performance.

Nonetheless, excessive diversification, particularly the "unrelated" type, can be detrimental to the company due to the dispersion of resources across a wide range of technologies. As a result, several contributions have identified an inverted U-shaped relationship between overall or unrelated technological diversification and firm economic and innovation performance (e.g., Pan et al., 2018; Pan et al., 2019; Corrocher & Ozman, 2020; Lee & Thi Le, 2021; Li & Wang, 2021; Zhao et al., 2024). On the other hand, a particularly strong degree of specialisation may become a constraint too: it may indeed be associated with limited competencies and know-how across different fields, which typically broadens the application range of an invention. Therefore, companies should aim to build a patent portfolio that balances diversification and specialisation to maximise the related benefits.

It should be noted that the aforementioned studies assessing the role of technological capability and technological specialisation/diversification on patenting performance refer to "green" or "environmental" patents, which either belong to the broad and composite field typically identified with the Cooperative Patent Classification (CPC) code "Y02" ("Climate change mitigation technologies"), or to one or more sub-categories of the Y02 domain. Hence, although some of these articles also account for patents that are classified by the CPC as CE patents (e.g., Ayari et al., 2012, who consider patents included in seven main renewable energy categories as identified by the previous work by Johnstone et al., 2010, also account for "waste patents"), it is not possible to assess whether and to what extent these findings hold for the circular economy field alone. In this respect, Portillo-Tarragona et al. (2024) and Valero-Gil & Scarpellini (2024) assert that, although eco-innovation and circular innovation have the common purpose of environmental improvement, the latter is more specifically aimed at closing the material flows and achieving the "Rs"(Reducing, Recovering and Recycling) transition; according to the authors, this fundamental difference makes it essential to perform a specific analysis of CE innovations and related patents. Also, Valero-Gil & Scarpellini (2024) claim that CE patents, which aim to pursue what is often recognized as a new frontier of innovation, namely, sustainability (Nidumolu et al., 2009; Cainelli et al., 2015), usually demand higher levels of originality, novelty and radicalness compared to non-green innovations and, in some cases, to (non-CE-related) green ones as well.

Nonetheless, a limited number of studies, such as the one conducted by Marin-Vinuesa et al. (2023) and Portillo-Tarragona et al. (2024)[5], have specifically investigated the drivers of CE patenting. Hence, and in light of the abovementioned considerations, it is difficult to tell whether the main findings on the role of technological capability and technological specialisation hold for CE patents too, especially when we look at firms that heavily resort to CE-related practices. In this respect, the quantitative analysis of Liu et al. (2024) reveals that companies significantly involved in "responsible innovation" (RI) related to the circular economy display a lower likelihood of patenting and lower patent productivity than non-RI firms, probably because of three mutually reinforcing factors known as the *hybrid organization effect*, the *disruptive technology effect* and the *institutional rigidity effect*[6].

Additionally, and importantly, the studies on the determinants of firms' green (or CE) patent intensity or patent performance mentioned in this section proxy the dependent variable with the number of green patents (in terms of granted patents or applications), the number of citations received by these patents, or a combination of these two indicators. However, the information used to build these variables does not allow us to understand whether the underpinning patents and applicants belong to the "best" knowledge flow of that field, and, if this is the case, how long they took to enter the technological frontier and, after that, how long they remained there.

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[4] Diversification across broad categories of technology is described as broad-field or unrelated technological diversification. Diversification across, and within, narrow categories of technology is labelled as core-field or related diversification (Kim et al., 2016).

[5] Marin-Vinuesa et al. (2023) and, in a companion study, Portillo-Tarragona et al. (2024), investigate the drivers of waste patents focusing on firms' intangible capabilities. To this end, they resort to partial least squares structural equation modelling to a sample of 2,216 Spanish firms that hold 120,406 patents. The analysis highlights the importance of the innovation capabilities of firms related to patenting, such as collaborative innovation, persistence in patenting or the capabilities to collaborate with research institutes, as drivers of the level of waste patents which also contribute to improve firm economic performance.

[6] First, related projects to "great causes" (GCs), such as those aimed to contrasting climate change, by definition have the potential for meaningful societal and economic impact, but they are also characterized by high levels of complexity, uncertainty and unpredictability that can undermine the innovation capacity of RI firms (*hybrid organization effect*). Second, because GCs by definition lack clear solutions and have expected outcomes of a disruptive nature, solving GCs may change production, consumption, and work paradigms; consequently, RI firms may lag behind non-RI firms in patenting when pursuing solutions to GCs (*disruptive technology effect*). Third, the strong influence of the rigid criteria and evaluation metrics imposed by public institutions often limits the independence of RI firms' research decision making (*institutional rigidity effect*).

In this regard, it is possible that a factor that fosters a patent/firm's access to the main path does not significantly matter for its subsequent endurance, or that a factor that does not play a relevant role in the entry process becomes relevant later, namely, for the persistence on the frontier.

In light of these considerations, we put forward the following research questions:

RQ1a: Does total patent stock matter for the patent/company's ability to enter the main path of the circular economy?
RQ1b: Does total patent stock matter for the patent/company's ability to stay in the main path of the circular economy?

And:

RQ2a: How is specialisation in CE knowledge areas related to a patent/company's ability to enter the main path of the circular economy?
RQ2b: How is specialisation in CE knowledge areas related to a patent/company's ability to endure on the main path of the circular economy?

In order to identify the patents and applicants along the main path, we first apply the main path analysis to the patent citation network of the circular economy worldwide. Specifically, we resort to a MPA procedure, known as key-route main path (KRMP) analysis (Liu & Lu, 2012), which allows us to identify both the so called top main path (TMP), i.e., the subset of the most relevant, "top" patents, and the key-route main path (KRMP), i.e., a larger subset which includes both the TMP and other important patents capturing the "second-best" knowledge flow. To account for within-sector heterogeneity and capture additional patterns of invention that would be neglected in the aggregate analysis of the technology field (Kalthaus, 2019), we do so not only for the whole CE, but also for its three sub-fields as identified by the patents' CPC codes[7].

3. Data and methodology

3.1. Data and patent selection strategy

Our data on CE patents comes from the PATSTAT dataset. We select all the patents labelled with Cooperative Patent Classification-CPC code "Y02W/Circular Economy" for all the years for which data were available (i.e., from 1920 to 2021)[8] and, for each of them, we retrieve information on the patent and patent family identifier, filing year, applicant (e.g., name and country of origin), eight-digit CPC codes, and patent citations, titles and abstracts. To perform the regression analysis, we also collect information on the entire patent portfolios of the applicants that appear at least once in the international technological frontier. Finally, to shed light on the applicants, we retrieve, from their official website, basic information on the major actors in each of the three subfields.

Our patent selection strategy, which exploits the CPC code "Y02W", was previously employed by other studies using patent data and focused on green technologies and the circular economy. In particular, we mainly draw upon the two recent and relevant contributions by Gnekpe & Plantec (2023) and Rainville et al. (2025), who shortly illustrate why this CPC code should be able to provide a satisfactory account of the vast and heterogeneous circular economy field without resorting to additional classifications (e.g., the OECD ENV-TECH classification for green technologies, which also accounts for IPC codes) and/or keywords. In this respect, Gnekpe & Plantec (2023) observe that "*Based on the definition of the CE model put forth by* Turecki (2016) *and used by* Duran-Romero et al. (2020)*, we believe that capitalizing on Y02W allows us to cover waste management and secondary raw materials, as well as processes to manage more eco-design products (e.g., biopackaging)*". They further stress this CPC code's ability to proper capture CE technologies by asserting that "(…) *such subclasses encompass the different fields expected when focusing on CE-related technologies, such as the recycling of fuel cells or batteries, and methane emission-related techniques*." The authors also summarize the main contents and provide some examples for the three main sub-classes of the Y02W class, and in the online Appendix disentangle each of these major CE sub-fields into their more fine-grained 8-digit subclasses (e.g., Y02W30/20).

A patent search strategy based on the CPC Y02W code is also employed by Rainville et al. (2025), who mainly aim to evaluate how well patent classifications can be used to measure innovation in green technologies at the global level and to indicate CE progress via these technologies at the European Union (EU) level. Interestingly, Rainville and co-authors include a figure (Fig. 6) that depicts the main technological contents of the Y02W code, showing how this CPC code provides a quite effective and reliable account of the broad and heterogeneous group of technologies related to the circular economy.

In light of these considerations, a patent selection based on the CPC code Y02W is supposed to capture not only mere recycling, but also recovering and reusing technologies, such as those associated with cement/concrete composition, plastic waste, lead-acid and lithium batteries and packaging (Rainville et al., 2025; p. 9). Importantly, it also allows us to capture circularity from an innovation

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[7] The Y02W CPC code ("Circular Economy") comprises the following six-digit codes: Y02W10 ("Technologies for wastewater treatment), Y02W30 ("Technologies for solid waste management") and Y02W90 "Enabling technologies or technologies with a potential or indirect contribution to greenhouse gas emissions mitigation").

[8] As a robustness check, we re-applied the MPA to the subsample of patents filed from 1970 onwards; we noticed that the patents forming the TMP and the KRMP from 1970 were the same ones observed in the main path obtained without applying this restriction and decided to use all the years available to provide a more exhaustive overview.

perspective at different points in the value chain, i.e., both upstream (e.g., design and production phase of products, including bio packaging – which represents an important part of the Y02W90 sub-field – and metals or minerals for cement or mortar production + eco-friendly concrete production technologies – emerging especially in the most recent part of the main path of the Y02W30 trajectory –) and downstream (e.g., the waste management phase aimed to increase the separate collection of targeted waste streams, thus supporting the development of the recycling sector and the market for recycled materials; Compagnoni, 2022).

3.2. Baseline descriptive statistics

Fig. 1 displays the number of CE patent families filed each year from 1970 to 2020 for both the whole circular economy (i.e., all the Y02W patent families, panel a) and for each of the three technological subfields (panel b). We observe that the overall number of patent families considerably increased over time (from 607 in 1970 to 23,337 in 2020). A positive trend is also observed across the three subfields, though they differ significantly in average level and growth rate. In particular, the Y02W30 subclass is the largest one, followed by Y02W10. More detailed information is provided in Table 1, which shows the distribution of patent families across subsequent periods for each subfield.

Fig. 2 depicts the distribution of patent families by applicant countries (i.e., the top 5 countries and the rest of the world). Interestingly, three of the five main players (i.e., China, Japan, and South Korea) are from Southeast Asia, suggesting that this dynamic and rapidly growing region is also making considerable efforts to reduce waste and strengthen environmental sustainability.

Table 2 reports the “top ten” applicants by the number of CE patent families and the corresponding countries. We can see that nine out of ten applicants are companies whose headquarters are located in Japan. Interestingly, the most active applicant is Chinese, and consists in a prominent research organization operating in the fields of high technology and natural sciences. Conversely, none of the principal applicants is located in Europe or in the US.

To sum up, these preliminary statistics reveal that the number of CE patents has risen considerably over the past 40 years. Also, the most representative technological subfield is solid waste treatment, while the subfield of technologies for mitigating greenhouse gas emissions is significantly smaller than the other two. Finally, a noticeable amount of CE patents has been filed by applicants located in three Southeast Asian countries (i.e., Japan, South Korea and China).

3.3. The main path analysis methodology

This section shortly illustrates the procedure followed to retrieve the main path of the CE, which is described in more detail in Appendix A. The implementation of our analysis begins with the construction of a patent citation network, i.e., a network in which nodes are patents and edges are patent citations. This patent citation network is directed –knowledge flows from the cited to the citing patent–, acyclic –a path starting from one node will never return to that node– and (initially) binary –all the citations are treated as equally important and then are given value one.

To identify the CE technological trajectories, drawing upon Hummon & Doreian (1989), we first transform the initial binary network into a weighted network to account for the fact that knowledge flows can be more or less relevant, depending on the number of nodes they connect (Martinelli, 2012). To this end, we employ a type of “traversal count”, known as Search Path Node Pair (SPNP), which measures the number of times a citation link has been traversed while going from a set of start-nodes to a set of end-nodes[9], and accounts not only for direct citations, but also for the indirect citations between .. patents (Liu et al., 2019), thus going beyond the assessment of innovation patterns based on citation counts only.

After that, we apply the quantitative method of the main path analysis (MPA), which, in recent years, has been used to detect technological trajectories across a large number of technological fields (see Appendix B for a review of this literature). A main path is identified through a “priority first search” algorithm, which, starting from a given start-node, follows consecutive citation links stepwise, choosing each time the next forward citation link with the highest SPNP value until hitting an end-node. In this study, we apply two search algorithms. The first one allows us to identify the top main path (TMP), which is the path with the most significant number of overall traversal counts and, by construction, connects the largest number of patents in the network; the TMP thus represents the critical backbone of knowledge flow in the network (Martinelli, 2012). The second search algorithm, i.e., the key-route main path analysis (Liu & Lu, 2012), allows us to obtain the key-route main path (KRMP), which always includes the TMP of a technological trajectory –i.e., the “first best” knowledge flow in the network of patent citations – and also the “second best” knowledge flow(s). In doing so, it also accounts for other relevant innovation patterns that the TMP would have discarded, thus providing a more accurate and exhaustive picture.

Using the software “Pajek”, we implement both the TMP and the KRMP analyses on the whole network (which comprises 143,638 nodes and 306,809 edges) and its sub-networks referring to the three subfields[10]. Since the use of individual patents presents some limitations mostly related to double counting issues (occurring, for instance, when a patent is filed in more than one jurisdiction), like other studies (e.g., Bekkers & Martinelli, 2012; Wang et al., 2020), we resort to patent families; hence, in our patent citation networks,

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[9] A start-node is a patent that is cited but does not cite any patents in the main path, while an end-node is a patent that cites other patents but that is not cited itself (in the main path). Accordingly, the start-nodes represent the origins of knowledge, while the end-nodes capture the final part of the knowledge dissemination process (Liu & Lu, 2012), thus defining the boundaries of the patent citations network.

[10] The Y02W10 sub-network contains 47,975 nodes and 109,468 edges, the Y02W30 sub-network includes 92,778 nodes and 193,276 edges, while the Y02W90 one comprises 2,885 nodes and 4,065 edges.

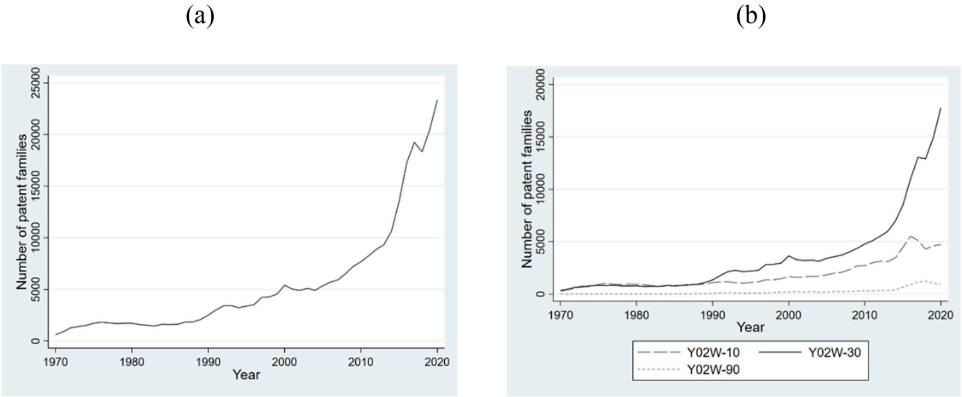

Fig. 1. Number of patent families per year for the whole circular economy (panel a) and its three technological subfields (panel b).
Source: authors' elaborations of PATSTAT data.

Table 1
Number of patent families by CPC code and time period.

Period	Y02W	Y02W10	Y02W30	Y02W90
≤ 1970	10805	2772	7941	105
1971 – 1980	15411	8017	7370	75
1981 – 1990	17590	8713	8746	190
1991 – 2000	38292	12494	24941	1189
2001 – 2010	58312	20197	36643	2268
2011 – 2020	149178	41314	101579	7208

Source: authors' elaboration of PATSTAT data.

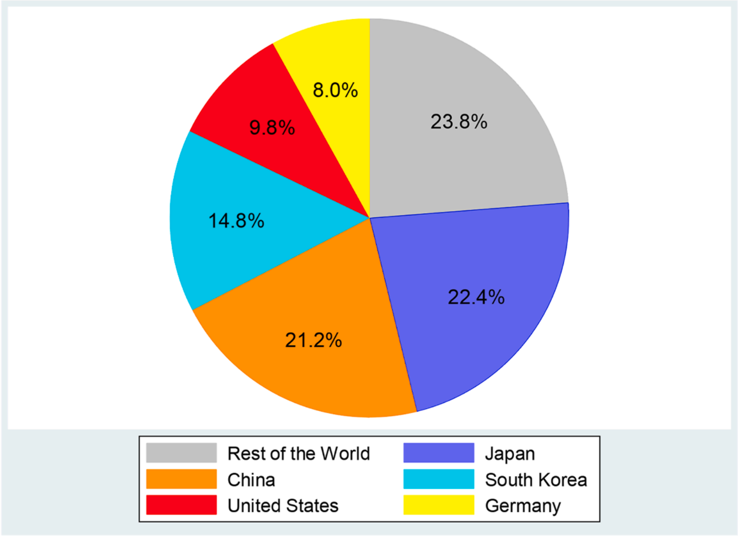

Fig. 2. Distribution of Y02W patent families by country (aggregate data).
Source: authors' elaboration of PATSTAT data.

the nodes are patent families, and the edges are the citations between patent families. Also, in order to obtain a more unbiased picture, we discard self-citations.

4. An overview of the technological trajectories of the circular economy

In this section, we provide a compact overview of the CE trajectories based on the analysis of the patents identified through the MPA. To this purpose, we analyse the title and abstract (and, if necessary, have a look at the main text too) of the documents of the

Table 2
Top 10 applicants in terms of total number of patent families in the technological field Y02W.

Applicant name	Applicant country of origin	Patent families
CHINESE ACADEMY OF SCIENCES	China	1140
TOSHIBA	Japan	1128
KUBOTA	Japan	1010
HITACHI	Japan	898
TAIHEIYO CEMENT	Japan	848
MITSUBISHI	Japan	822
KURITA	Japan	791
PANASONIC	Japan	749
NIPPON STEEL	Japan	708
NKK	Japan	542

Source: authors' elaboration of PATSTAT data.

selected patents; then, following Lai et al. (2023), identify different portions of the TMP corresponding to subsequent time intervals, as well as various ramifications of the second-best knowledge flow (KRMP). A detailed description of the technological trajectories, which briefly illustrates the various phases of the TMP and the different ramifications of the KRMP across the three sub-fields, is contained in Appendix C. In this section, for each of the three CE sub-fields[11]: (i) we summarise the "main highlights" concerning the technological, geographical and applicant profile along with an exploration of potential links to key institutional factors, i.e., environmental regulations that may have influenced the trajectory of technological change over time and across regions (Section 4.1); (ii) we provide a compact account of the CE domain as a whole (Section 4.2); we report some main path-related statistics (Section 4.3); (iii) we assess the patent quality of the CE main path (Section 4.4).

4.1. Main highlights

4.1.1. Highlights of sub-field Y02W10 – Technologies for wastewater treatment

This technological sub-class ranks second in terms of number total patents lying on the top main path, but is also the one with the smallest KRMP (see Fig. 3) Also, the patents belonging only to the KRMP do not form very clearly identifiable ramifications, are quite related to the top main path and fall within the subsequent phases identified for the main knowledge flow.

The inventions mostly concern wastewater treatment. Until the mid-1970s, patents described preliminary methods for sewage treatment and disposal, mainly aimed at removing suspended matter or minerals and focused on solving public health issues, with only indirect links to environmental concerns. The complexity of the processes increases over time, and from the 1980s onwards, patent documents mostly refer to biological treatment of water, which often includes the removal of nitrogen or phosphorus and/or involves both aerobic and anaerobic stages. Since the beginning of the nineties, most of the proposed methods employ a membrane filter and/or a (membrane) bioreactor[12], which enhances wastewater reuse. In the most recent period, a membrane biofilm reactor has also been used due to its lower energy consumption and operational costs compared to membrane bioreactors.

Regarding the applicants, some companies (e.g., Sharp Corporation and Air Products and Chemicals) have filed several patents in both the top main path and the KRMP. The phase characterized by the highest degree of applicant boundedness is the last one, whose patents are all attributable to the same player. All in all, this technological sub-class exhibits significant geographical boundedness, with a relatively small number of countries involved and a dominant role for the US. Japan ranks second in terms of patenting activity, while China (which, as shown in Fig. 2, is one of the main applicants worldwide) appears neither in the TMP nor in KRMP-only.

We also try to connect the technological trajectories of the Y02W10 sub-field with the geographical and temporal evolution of environmental regulations (see Table A1-a, Appendix D for a compact but detailed overview). The technological changes that occurred in this area are mainly driven by US "core" patents over the whole period under scrutiny. Specifically, during the 1980s, technological changes moved from sewage treatment and disposal technologies to (more sophisticated) biological treatment of water using a membrane filter or a membrane bioreactor. This technological shift from wastewater treatment technologies not designed for resource recovery (before the 1980s) to biological treatment technologies that align with circular water systems after the 1980s (e.g., closed-loop reuse of water for irrigation, industry and less discharge) may have been upheld by several federal laws enacted by the US and targeted explicitly to wastewater treatment. For instance, the Federal Water Pollution Control Act (FWPCA)[13] enacted in 1948 encouraged the construction of wastewater treatment plants; notably, the FWPCA was the first major US law to address water pollution, and anticipated the Clean Water Act (section 319),[14] which was adopted in 1987 (replacing the FWPCA) and expanded in 1990. The Clean Water Act incentivized energy efficiency, wastewater reuse and natural treatment systems, such as membrane bioreactors, anaerobic digesters and nutrient recovery units; the latter display a higher potential to achieve circularity goals than simple

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[11] As the main path of the Y02W as a whole significantly overlaps with that of the Y02W10 sub-sector, and since we want to account for within-sector heterogeneity, we directly illustrate the trajectories of the three CE sub-fields.

[12] A membrane bioreactor combines biological wastewater treatment with membrane filtration for highly efficient water purification (Mannina et al., 2020).

[13] https://www.epa.gov/sites/default/files/2017-08/documents/federal-water-pollution-control-act-508full.pdf

[14] https://www.epa.gov/nps/319-grant-program-states-and-territories

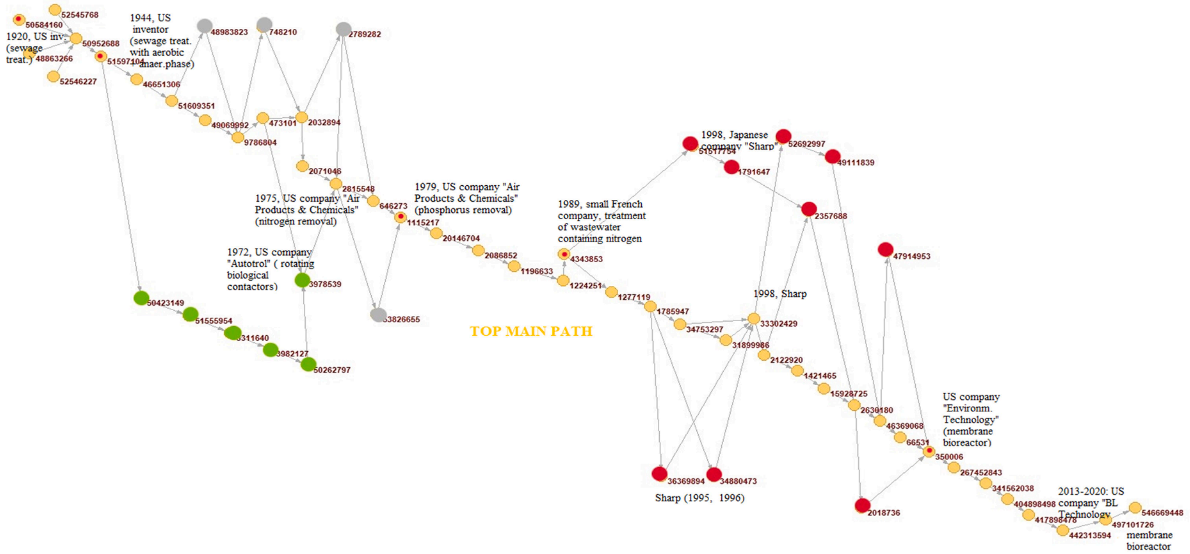


Fig. 3. Key-route main path of the subfield Y02W10 (technologies for wastewater treatment), 1920-2021.
Note: the circles/nodes represent the patent families that lie on the KRMP and the grey arrows represent the citation links among them. The numeric codes reported next to each node are the "inpadoc family identifiers" assigned by EPO-PATSTAT to each patent family. Different colors are used to identify various portions of the main knowledge flow. The starting nodes/"turning points" of the subsequent phases of the TMP (the nodes with a red dot in the center) and the various KRMP-only ramifications are identified on the basis of their incoming and/or outcoming links and their technological content. The same considerations hold for Figs. 4 and 5.
Source: authors' elaboration of PATSTAT data.

sewage treatments, which present limited potential in water reuse (Chen, 2019; Mannina et al., 2020).

4.1.2. Highlights of sub-field Y02W30 – Technologies for solid waste management

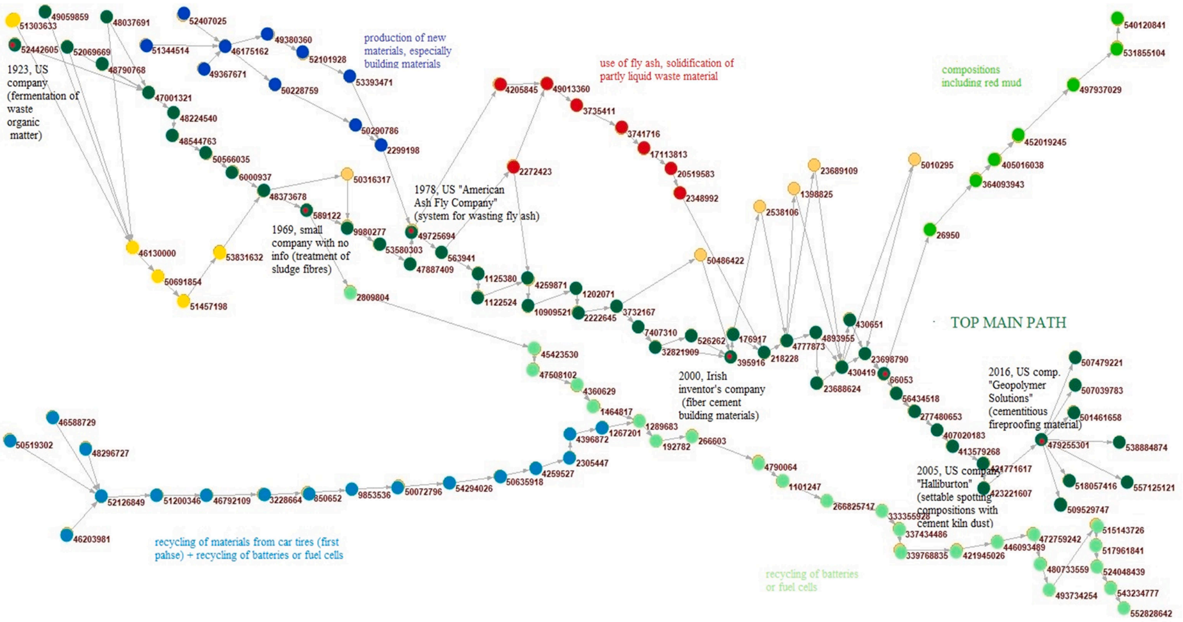
This technological sub-class is the largest one both in terms of overall number of patents and size of the main path (with 128 patents forming the key-route main path), and allows us to identify various subsequent phases of development of the main knowledge flow and a number of KR-only ramifications, i.e., patents that belong to the KRMP, but not to the TMP too (see Fig. 4).

The prevalent technological contents of two portions of the KR main path (highlighted in light blue and aqua green colours in Fig. 4) significantly differ from those of the top main path. At the same time, the remaining KR-only patents, some of which form well-defined blocks, are closely related to the TMP. Some KR-only blocks are entirely ascribable to the phases in which the main knowledge flow is split, while others unfold over two consequent phases.

The first phase of the TMP mainly concerns the treatment of organic material and consequent production of fertilizers; however, since the end of the sixties, the large majority of the top main path, as well as considerable portions of the (non-top) key-route main path, are dominated by patents describing the production of new building materials and objects based on the treatment of (often environmentally harmful) waste materials (by using cement and concrete by-products such as fly ash, slag and red mud) derived from various industrial processes, mainly employed in the construction and cement industries (see Table A1-b, Appendix D). The most recent of these materials have some specific properties, such as heating resistance, and/or are based on the use of geopolymer. Other relevant technologies that emerge from the KRMP only deal with the recovery and treatment of rubber and other materials derived from car tires (early-stage patents of the KR light blue portion), the recycling of plastics and resin materials from, for instance, bottles and other scrap articles (early-stage patents of the KR aqua green portion) and, in particular, the recycling of batteries (the latter referring in particular to methods for separating metals (such as lithium and cobalt) from lithium batteries aimed at the reuse of those metals; see the light blue portion and the aqua green portion of the KRMP).

The applicant boundedness varies over time and is significant especially in Phase 4. Notably, one of the two dominant applicants of this phase, i.e., Halliburton Energy Services, filed nine KR-only patents (which are grouped in either the red portion or the light green portion of the KRMP). Also, some phases, especially in recent years, are characterised by relatively high patent intensity. As for the countries represented in the overall main path, the US dominates the first part of the time horizon; the number of countries involved increases over time, and China starts to play a significant role in the most recent years, especially in the (KR-only) recycling of lithium batteries.

From our detailed overview (Appendix C), it emerges that technological changes related to the disposal of concrete waste, the use of slag waste for construction materials, and eco-friendly cement/concrete composition technologies occurred mainly from the 1970s, with the US being the major contributor to these technological changes across many phases of the KRMP. Also, the key-route MPA allows us to capture circularity over time at different stages of the value chain. Specifically, we identify a shift of innovation trajectories from downstream technologies – mainly related to concrete and slag waste management before 2000 – to upstream technologies –



1923, US company (fermentation of waste organic matter)

1969, small company with no info (treatment of sludge fibres)

1978, US "American Ash Fly Company" (system for wasting fly ash)

2000, Irish inventor's company (fiber cement building materials)

2005, US company "Halliburton" (settable spotting compositions with cement kiln dust)

2016, US comp. "Geopolymer Solutions" (cementitious fireproofing material)

Fig. 4. Key-route main path of the subfield Y02W30 (technologies for solid waste management), 1923-2021.
Source: authors' elaboration of PATSTAT data.

referring to eco-friendly concrete production, cement composition technologies and metals/minerals for construction materials' production – after 2000. This result might have been influenced by environmental regulations concerning the handling of hazardous waste components and efficient recycling processes. These regulations were mainly adopted by the US government and affected several industries, including construction and the cement industry (see Table A1-b, Appendix D). Examples of such regulations are the Resource Conservation and Recovery Act (RCRA), introduced in 1976, and the Hazardous and Solid Waste Amendments, in 1984 (Gnekpe & Plantec, 2023). These federal regulations, along with other federal rules and state-level laws adopted within the American States (listed in Table A1-b) may have spurred the production of eco-friendly patented technologies of this CE sub-field, even though the construction industry is still responsible for around one third of global waste (Cecere & Corrocher, 2016).

Beyond construction, the RCRA and its amendments may have also encouraged and improved the handling, sorting, recycling, and recovery of hazardous waste in other sectors, including plastics, tires, rubber, and lead-acid batteries – areas in which the US is a key contributor within specific branches of the KRMP – (see Fig. 4 and Table A1-b). Interestingly, the strong presence of Chinese patenting activities in recycling, recovery and, in the most recent period, the reuse of lithium batteries may have been encouraged by laws promoting circular economy goals adopted by the Chinese government over the last two decades (Priore et al., 2025). To give an example, the "Circular Economy Promotion Law of the People's Republic of China" (2008) established a legal and conceptual foundation for Extended Producer Responsibility (EPR)-like schemes. Ten years later, China revised that plan to achieve more ambitious goals for the transition toward a greener economy (Gnekpe & Plantec, 2023; Shao et al., 2018). Those policy strategies aim to strengthen China's circular economy framework, with particular attention to the recovery of Critical Raw Materials (CRMs) from lithium batteries, thereby reducing dependency on primary resource extraction. Accordingly, regulatory incentives turned out to be a key policy tool for fostering innovation to address environmental and resource challenges (Compagnoni et al., 2025).

4.1.3. Highlights of sub-field Y02W90 – Enabling technologies or technologies with a potential or indirect contribution to greenhouse gas emissions mitigation

This technological sub-class is the smallest one in terms of the number of both total patents and "top" patents; however, the key-route main path is much larger than the top main path (80 vs 17 patents; see Fig. 5). The TMP is quite linear and can be divided into two main subsequent phases, while the several KR-only patents form various ramifications – one of which, interestingly, is completely disconnected from the top main path – which differ in terms of size, time frame, dominant technology, degree of connection and similarity with the top main path. As expected, the prevalent technological contents of the disconnected block considerably differ from the ones that shape the top main path. Other portions of the KRMP are instead more related to the TMP.

This subclass concerns bio-packaging, and the related patents are all labelled with the 8-digit CPC code Y02W90/10; however, a certain degree of heterogeneity in the main technological content emerges both across different periods and across the top main path/key route (or various portions of the KRMP). The most relevant innovations regard containers/packages (or semi-finished products that can be used for creating shaped articles), several of which are starch-based and aimed to store food and sometimes beverages (Phase 1 of the TMP, early-stage patents of the KR blue portion and KR yellow portion of Fig. 5) with biodegradable or compostable features. More recently, packages or (parts of) containers (including capsules) present a well-defined shape and structure and are typically

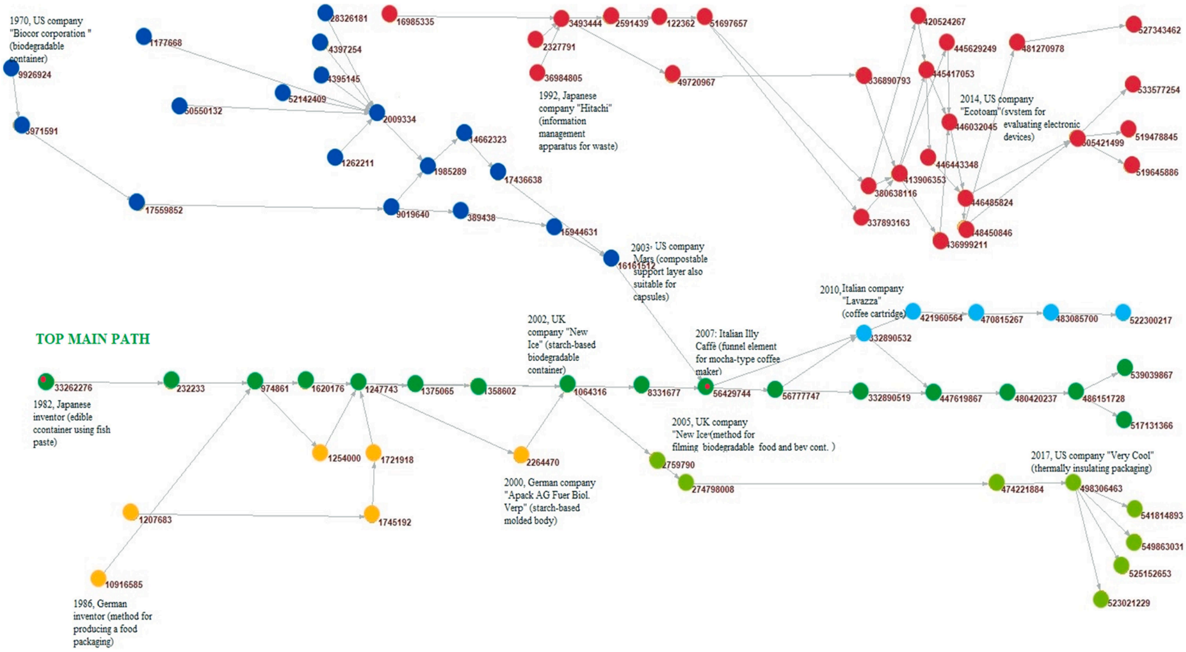


Fig. 5. Key-route main path of the subfield Y02W90 (technologies for greenhouse gas emissions mitigation), 1970-2020.
Source: authors' elaboration of PATSTAT data.

intended for preparing coffee or also other hot beverages (Phase 2 of the TMP, KR acid green portion, recent patents of the KR blue portion). Quite connected to the second phase of the main knowledge flow is the KR light green portion, which focuses more on certain physical properties linked to upstream value chain stages (eco-design) of the packages – e.g., heating resistance – than to their final destination associated with the downstream stage of the value chain, i.e., waste management. Finally, another significant knowledge stream, which, unlike the others, developed separately and in parallel with the main one (KR red portion), regards recycling systems, methods and programs, which, in recent years, mainly consist in the identification, evaluation and purchase of electrical and electronic equipment (EEE) and their related waste disposal. EEE production, despite some improvements, remains highly polluting and often fails to meet the principles of the circular economy (Juchneski & Antunes, 2022; Pèrez-Belis et al., 2015).

All in all, this technological sub-class presents low applicant boundedness (with the partial exception of the disconnected portion of KRMP) and higher geographical heterogeneity than the other two sub-classes. Interestingly, the US presence is relatively smaller than in the other two sub-fields, especially in the top main path. In recent years, China appears in key route main path-only, and four of its patents concern the identification, evaluation and purchase of EEE and their waste disposal.

Concerning the potential influence of environmental regulations (see Table A1-c, Appendix D), CE innovation trajectories in the Y02W90 sub-field seem to be mostly subject to EPR regulations, especially when it comes to technological changes in bio-packaging targeting the food & beverage industry. In Europe, EPR regulations were formally introduced in 1994 with Directive 94/62/EC[15]; its primary goal was to reduce the amount of waste generated and harmonize national measures for handling (plastic) packaging and packaging waste by imposing targets for recovery and recycling (Benedetti et al., 2025; Nicolli et al., 2012). The US, which plays a non-negligible role in shaping the Y02W90 trajectory, has no specific federal legislation on mandatory EPR regulations, but EPR actions are compulsory in many states within the US (Compagnoni, 2022). Regarding the US, it is worth mentioning also the RCRA in 1976 and the "Hazardous and Solid Waste Amendments" in 1984, which encouraged the recovery and recycling of plastic packaging along with other hazardous materials (Gnekpe & Plantec, 2023).

Two relevant US environmental regulations which are influenced by EPR principles are the US Department of Agriculture (USDA)'s BioPreferred program, expanded in The Farm Security and Rural Investment Act of 2002 (also known as the 2002 Farm Bill) with regular updates (Nicolli et al., 2012), and the "Federal Trade Commission's Green Guides" (first issued in 1992, updated in 2012) related to environmental marketing claims such as "biodegradable", "compostable" and "eco-friendly" (US Federal Trade Commission, 2012). In the context of technological changes related to bio-packaging, it is worth noting that such green innovations linked to eco-design are connected to upstream stages (especially, improvement of manufacturing methods) of the CE value chain (Cecere & Corrocher, 2016); this hints at the effectiveness of EPR regulations as CE enablers in upstream value-chain stages and their waste prevention objectives, going beyond their "traditional" influence on downstream stages related to waste management (Compagnoni et al., 2025; Zhao et al., 2021).

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[15] https://eur-lex.europa.eu/eli/dir/1994/62/oj/eng

The fact that the CE technological frontier of the Y02W90 sub-field is mostly shaped by bio-packaging technologies can be at least partly ascribable to the crucial CE goal of transitioning from fossil fuels to bio-based materials, such as bio-packaging. Traditional fossil-based plastics are derived from non-renewable resources and contribute significantly to greenhouse gas emissions and persistent pollution. Conversely, bio-based materials are obtained from renewable biomass sources, offering a more sustainable alternative (Duran-Romero et al., 2020). Some bio-based materials (such as those present in the KRMP of this CE technological sub-field; see Fig. 5 and Table A1-c) are designed to be biodegradable or industrially compostable, thereby fostering their potential for biological cycling and reducing landfill burden.

Meanwhile, some hazardous materials – whose recycling and recovery technologies are present in the Y02W90 trajectory after 2010 – that have been regulated after 2000 fall under the Electrical and Electronic Equipment (EEE) category. The US (69 %) and China (31 %) – the two countries contributing to these technological changes in the KRMP (more recent patents in the red portion) – introduced several laws based on EPR principles aimed at handling and preventing waste of EEE. Specifically, although there is no US federal legislation on this, 25 US States have passed EPR regulations on EEE, with the majority implemented in 2009 or later (Compagnoni, 2022). Concerning China, in 2006, it enacted measures to regulate pollution from electronic information products (China's "RoHS"). The technological changes identified through the key-route main path method in recycling and recovery of EEE appear to be driven by (the above) environmental regulations aimed at enhancing the mitigation of environmental and health risks (which arise especially when the separate collection of the complex mixture of materials contained in the EEE is not properly implemented). Another issue that these frontier technologies try to address is the limited downstream circularity in the EEE value chain, which results from inefficient waste collection and the use of recovery processes that do not meet the highest available technology standards. Notably, EEE waste is a significant source of precious metals and CRMs (Compagnoni, 2022; Pérez-Belis et al., 2015).

4.2. Baseline statistics of the CE main path

Table 3 presents some baseline statistics referring to the patent lying on the CE main path. We can see that the subfield Y02W30 has the greatest number of patents across the entire technological trajectory, but Y02W90 encompasses a larger fraction of patents placed on the KRMP-only ramifications. On the other hand, Y02W10 is characterised by patents that remain on the main path for a relatively long period of time; in particular, these patents stay on the technological trajectory (i.e., before being replaced by subsequent patents) for an average of 2.21 years, with 10 % of them remaining on the trajectory for 5 years or more.

Shifting the focus from the patent level to the applicant level, we note that the highest number of applicants is observed in the CE subclass Y02W30, which also displays the highest number of patents per applicant. Interestingly, these applicants hold, on average, a smaller patent stock (calculated as the total number of patents across both CE and non-CE technologies) than applicants in the other CE subclasses. At the same time, the Y02W10 subclass is the one with the most extensive average patent stock. With regard to the qualitative composition of these patent stocks, the CE subclass Y02W90 stands out in terms of the ratio of CE patents.

Additional heterogeneity across CE subclasses emerges when we examine the applicants' country. The US applicants dominate all the subclasses, but their share ranges from 44 % in Y02W90 to 69 % in Y02W10. Furthermore, among the leading countries in terms of

Table 3
Main quantitative highlights from the main path analysis.

Variable	Description	CE technological subclass			Total
		Y02W10	Y02W30	Y02W90	
Patent level					
No of KRMP patents	Number of patents in the KRMP	59	128	80	267
Share of only KRMP patents	Share of patents in the KRMP only	0.32	0.59	0.79	0.59
No of years on KRMP	Average number of years between two subsequent patents in the KRMP	2.21	1.38	1.38	1.56
Number of patents 5 years/more	Number of patents that stay in the KRMP for 5 years or more	0.10	0.02	0.01	0.03
Applicant level					
No of applicants	Number of applicants identified in the KRMP	39	98	65	201
No of patents by applicant	Average number of KRMP patents by applicant	2.25	2.97	2.18	2.57
Patent stock	Patent stock of the applicants	9150.6	2047.9	3090.6	3929.8
No of small applicants	Number of applicants with less than 5 patents	0.27	0.36	0.40	0.35
Share of CE patents	Share of CE patents on total patents	0.26	0.25	0.31	0.27
No of applicant countries	Number of applicant countries	10	16	14	21
Japan	Share of Japanese applicants	0.12	0.04	0.11	0.08
China	Share of Chinese applicants	0	0.13	0.06	0.08
South Korea	Share of South Korean applicants	0	0.02	0	0.01
US	Share of US applicants	0.69	0.52	0.44	0.53
DE	Share of German applicants	0.03	0.09	0.08	0.07
Rest of the World	Share of applicants from other countries	0.16	0.20	0.31	0.23
CE technological level					
Turbulence	Three-year moving average of the annual patent growth rates (whole period)	0.08	0.06	0.15	0.09
Turbulence before 1980	Three-year moving average of the annual patent growth rates (1920-1979)	0.14	0.07	-0.02	0.09
Turbulence from 1980 to 2000	Three-year moving average of the annual patent growth rates (1980-2000)	0.03	0.07	0.26	0.13
Turbulence after 2000	Three-year moving average of the annual patent growth rates (2001- 2021)	0.03	0.06	0.1	0.07

patent applications, we find that Chinese applicants have no patents lying on the technological trajectory of Y02W10. In contrast, South Korean applicants have no patents on the main path of either Y02W10 or Y02-W90. Finally, if we add up the shares of the five countries reported in the table, we see that the Y02W90 subarea shows the least concentration.

Finally, the bottom part of Table 3 provides information on the degree of "turbulence", proxied by the three-year moving average of the annual patent growth rates, experienced in the three CE subclasses. Considering the entire period, the highest turbulence is reported for Y02W90; however, a more heterogeneous picture emerges when we look at the subperiods. Specifically, Y02W90 displays the highest value of turbulence for the two most recent periods (i.e., after 1980), while Y02W10 exhibits more turbulence during the first phase (i.e., the time interval ending in 1980).

4.3. *Assessing the patent quality of the CE main path*

In this section, we provide additional descriptive statistics (with corresponding tables reported in Appendix D) that compare the key-route main path ("MP patents") patents and non-KRMP patents on indicators of patent quality. Specifically, in line with previous literature (e.g., Squicciarini et al., 2013; Priore et al., 2025), we constructed the following indexes: *Country coverage,* which indicates the number of patent offices that received a patent family application; *Number of backward NPL citations*, which captures the number of backward citations to non-patent literature; *Number of inventors,* which reports the number of inventors involved; *Number of forward citations*, which measures the number of forward citations received within five years from the priority date. To compute the latter, in order to address the truncation citation problem, we consider only citations received within five years of the priority date.

The average values of the four indicators for KRMP and non-KRMP patents are shown in Table A2 for the three technological subfields (Y02W10, Y02W30, and Y02W90) as well as for the Y02W technology as a whole. As expected, on average, KRMP patents exhibit higher values across all the selected indicators, suggesting higher quality.

Second, we compare the Top Main Path (TMP) patents and the KRMP-only patents for the previously identified time periods and ramifications (in cases of overlap between periods or a low number of patents, we merged different KRMP branches). The average values of the four previously introduced patent quality indicators for the Y02W10, Y02W30 and Y02W90 technological subfields are displayed in Tables A3, A4 and A5 (Appendix D), respectively. All in all, from these tables, it emerges that KRMP-only patents are similar to TMP patents in terms of quality, confirming that KRMP analysis can identify valuable innovation trends that the top main path would miss.

Finally, we examine how these patent quality indicators vary across the applicant countries along the main path of the CE trajectory (Table A6). We notice that, although China is the world leader in terms of number of CE patents, Chinese KRMP patents present a relatively low patent quality – in line with existent literature examining the quality of Chinese patents (see e.g., Alessandri, 2023; Priore et al., 2025) – in terms of country coverage and number of NPL (non-patent literature) backward citations. Despite that, China has played a relevant role in recent years, especially in the recycling of lithium batteries. In general, no clear correlation between the quality and quantity of CE patents emerges, especially when we consider other top countries such as the US and Germany. This interesting stylized fact may deserve further investigation by future research.

5. Regression analysis

The analysis of the CE main path, illustrated in Section 4 and Appendix C, provides useful information on the technological, geographical, and applicant dimensions of the CE trajectories. Also, it provides us with some stylised facts which, although they require further investigation, seem to give some hints for our research questions: we notice that those that manage to stay longer on the international technological frontier have often patented a significant number of innovations concerning various technological domains; moreover, we observe that various companies that are mainly involved in CE-related activities, especially in wastewater treatment (e.g., the American Zimpro Environmental, the Canadian Zenon Environmental, the Japanese Kurita Water, and the US Siemens Water Technologies) either closed or, more often, merged or have been absorbed by other firms. We delve into these issues by performing a regression analysis aimed mainly at investigating the roles of the size and composition of the "best" applicants' patent portfolios.

5.1. *Regression model*

The patents identified through the MPA (i.e., all the patents included in the KRMP of the three CE subfields), which allowed us to provide an accurate qualitative overview of the CE trajectories, also constitute the sample of the regression analysis, which aims to answer the research questions defined at the end of Section 2. To build our two alternative dependent variables, we compute the number of years between two subsequent patents in the main path: specifically, the first dependent variable –*Entry Time*– in which the time lag is computed from the perspective of the most recent ("successor") patent, captures the time employed by a patent to enter the frontier; the second dependent variable –*Leadership Tenure*– in which the time interval is measured from the perspective of the oldest ("predecessor") patent, measures how long a patent persists in the main path before being replaced by another patent. Given the count data nature of the two dependent variables, we perform a set of Poisson regressions to estimate the following empirical model:

$$\begin{aligned} NUMyears_{ikt} = exp\ \Big[\alpha + \beta\ Share\ of\ CE\ patents_{ikt} + \ \gamma\ Squared\ Share\ of\ CE\ patents_{ikt}{}^{2} + \\ + \ \upsilon\ (log) Total\ patent\ stock_{it} + \ \pi\ Technological\ turbulence\ _{kt} + \theta_k \ + \ \varphi_i \ \Big]\ \varepsilon\ _{ikt} \end{aligned} \tag{1}$$

$NUMyears_{ikt}$ is the absolute value of the number of years between a patent *i* observed in the main path of the CE subfield *k* at time *t*

and its temporal predecessor/subsequent patent. In particular, in the first case, this variable is interpreted as *Entry Time*, while, in the second case, it is interpreted as *Leadership Tenure.*

Our key regressors, *Total Patent stock*$_{it}$ and *Share of CE patents*$_{ikt}$, which proxy for the total amount of knowledge embedded in the company's patent portfolio and the degree of specialisation in CE innovations, respectively, are constructed using data on the entire patent portfolios of these applicants. In particular, *Total patent stock*$_{it}$ considers all the patents (CE and non-CE patents) filed by the applicant of patent *i* until year *t* and is calculated using the perpetual inventory method (Hall, 1990; Kaiser, 2009) with a discount rate of 10 %; *Share of CE patents*$_{ikt}$, instead, captures the degree of specialisation in a CE technology of the applicant holding patent *i*, and is calculated as the ratio between the cumulative number of patents referring to the CE subfield *k* at time *t* (computed using the perpetual inventory method) and the cumulative total number of patents (i.e., *Total patent stock*$_{it}$).[16] We also include the square of this variable (*Squared share of CE patents*$_{ikt}$) to account for potential non-linear effects.

To avoid the influence of specific technological time windows, we control for periods of "technological turbulence", i.e., periods that exhibit a relatively high patenting intensity attributable to increased patenting efforts by incumbent applicants and/or the emergence of new players in the focal technological field. We expect that the temporal lag (number of years) between two subsequent patents is lower during turbulent periods, and vice versa in mostly stable periods; hence, we enter the variable *Technological turbulence*, which is computed as the three-year moving average of the annual patent growth rates in each of the *k* (three) CE subfields. We then extend Equation [1], i.e., the baseline specification, by adding patent- and applicant-level controls that may influence entry to or persistence on the main path, namely patent novelty, patent quality and the role of environmental regulations.

Specifically, following Verhoeven et al. (2016), we construct a measure of patent novelty in recombination by examining each patent's pairs of CPC 4-digit codes (*Patent novelty*). A patent is classified as novel if at least one pair of its CPC groups has not previously appeared in any of the circular patents. The novelty indicator equals one when such a new pairwise combination exists, and zero otherwise. Then, to measure patent quality, we calculate a composite *Patent Quality Index*: in line with other studies (e.g., Lanjouw & Schankerman, 2004), we compute this indicator by applying a factor analysis on the four indicators of patent quality presented in Section 4.3, namely, country coverage, the number of inventors, the number of backward citations to non-patent literature and the number of forward citations. The obtained patent quality index is positively correlated with all the components used in its construction. Additionally, to account for environmental regulation, we use the internationally comparable OECD Environmental Policy Stringency (EPS) Index (Bettarelli et al., 2025; Kruse et al., 2022), which captures the stringency of climate change and air pollution mitigation policies closely aligned with circularity objectives; in particular, higher values correspond to more stringent environmental regulations. Because the *EPS index* is available only from 1990 onward, we impute missing values using the growth rates observed during the available period. Specifically, for each country, we calculate the average annual growth rate and use it to fill in missing observations until 1989. We also rescale the index to a 0–1 range using the min–max normalization. Finally, we include two sets of dummies to control for technological subfields' specificities (θ_k) and applicants' country fixed effects (φ_i), the latter capturing unobservable country-specific heterogeneity (including geographical variation in environmental regulation).

Table 4 reports the baseline descriptive statistics and the correlation matrix for the main variables.

5.2. *Results of the regression analysis*

Table 5 presents the results of the Poisson regressions. We observe that, when the dependent variable is *Entry Time* (Models 1-3), the overall patent stock is negative and significant. This suggests that applicants with a larger stock of technological knowledge may be better able to develop new technologies that quickly replace (in the trajectory) the incumbent ones. This result also holds after controlling for the applicant's specialisation in CE technologies (whose two related variables, *Share of CE patents*$_{ikt}$ and *Squared Share of CE patents*$_{ikt}$, are not significant); in other words, the patent stock is positively associated with the entry processes regardless of the patent portfolio's composition in terms of CE or non-CE patents. The positive and significant relationship supports the view that a firm's accumulated technological capabilities enhance its absorptive capacity (Montobbio & Solito, 2018; Wu et al., 2020) and strengthen the problem-solving skills required to enter new technological paths (Dosi, 1982). A larger patent stock, which is indicative of greater technological sophistication, enables companies to more effectively identify, assimilate and apply external knowledge, thereby shortening the time required to reach the technological frontier. Accumulated patents thus serve as repositories of both tacit and codified knowledge, thus reinforcing firms' ability to recombine external inputs. This interpretation aligns with prior studies emphasizing the role of cumulative knowledge and internal capability building in fostering earlier and higher-quality innovation outcomes (Fabrizio, 2009) and in accelerating technological convergence (Park & Lee, 2006). Accordingly, companies endowed with substantial technological capabilities, which can leverage absorptive capacity and complementary assets to adapt to emerging technological paths, are likely to enter the CE trajectory earlier.

Interestingly, a quite different picture emerges when we examine the drivers of *Leadership Tenure* (Models 4-6). In particular, patent stock is not significant, whereas both the variables Share of CE patents and Squared Share of CE patents are significant and indicate an inverted U-shaped relationship between the share of CE patents and leadership tenure. Hence, it seems that a certain level of specialisation in CE technologies fosters relevant inventions that manage to stay longer on the international technological frontier; nonetheless, as suggested by the change in the sign of this link once a certain value is exceeded, over-specialisation turns out to be penalizing. The persistence of patents (applicants) on the technological frontier is likely influenced by firm-level recombination

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[16] The estimation results are robust to alternative discount rates (i.e., 5% and 15%). The results of these additional estimates are available from the authors upon request.

Table 4
Baseline descriptive statistics and pairwise correlations of our main variables.

	Variable	Mean	SD	Min	Max	1	2	3	4	5	6
1	Entry time	1.54	1.24	1	10						
2	Leadership tenure	1.56	1.29	1	10	0.42					
3	Total patent stock	1331.31	4908.39	1	39551.90	-0.07	0.02				
4	Share of CE patents	0.27	0.39	0.00	1	0.12	0.06	-0.24			
5	EPS index	0.54	0.22	0.05	1	-0.18	-0.23	-0.18	0.11		
6	Patent novelty	0.11	0.32	0	1	-0.01	0.09	0.00	-0.06	0.01	
7	Patent Quality Index	0.00	0.79	-0.69	6.72	-0.20	-0.11	-0.28	0.15	0.05	0.16

Source: authors' elaborations of PATSTAT data.

Table 5
Results of the Poisson regressions.

		Entry time		Leadership tenure		
VARIABLES	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Share of CE patents	0.050	-0.187	-0.417	0.179	1.305**	1.423***
	(0.143)	(0.547)	(0.507)	(0.130)	(0.520)	(0.484)
Squared share of CE patents		0.232	0.331		-1.100**	-1.242***
		(0.563)	(0.510)		(0.539)	(0.480)
Total patent stock (in log.)	-0.067***	-0.068***	-0.055***	-0.001	0.008	0.027
	(0.021)	(0.021)	(0.021)	(0.024)	(0.025)	(0.022)
Technological turbulence	-1.329**	-1.346**	-1.268**	-1.121***	-1.151***	-1.064***
	(0.606)	(0.598)	(0.600)	(0.417)	(0.418)	(0.327)
Patent Quality Index			-0.198***			-0.043
			(0.058)			(0.060)
Patent novelty			0.125			0.291**
			(0.120)			(0.148)
EPS index			-0.988**			-2.044***
			(0.442)			(0.417)
Constant	1.096***	1.127***	1.504***	0.869***	0.727***	1.428***
	(0.174)	(0.175)	(0.228)	(0.178)	(0.170)	(0.229)
Subfield fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	264	264	264	262	262	262
Log likelihood	-353.9	-353.8	-345.3	-362.5	-360.8	-345.9

Notes: Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source: authors' elaborations of PATSTAT data.

capabilities, i.e., the ability to integrate diverse technological and organizational knowledge bases across projects. A firm's ability to manage and exploit diverse sources of knowledge – without excessive focus on any single domain – can translate into inventions with broader technological scope and longer technological life. This interpretation is consistent with the rationale of general-purpose technologies (Bresnahan & Trajtenberg, 1995), which typically arise from firms that successfully orchestrate diverse knowledge domains. The observed inverted U-shaped relationship between specialisation and leadership tenure aligns with prior evidence that moderate specialisation fosters innovation efficiency and depth, while excessive focus constrains cross-domain learning and adaptability (Corrocher & Ozman, 2020; Lee & Thi Le, 2021). Therefore, long-term persistence on the CE technological trajectories should reflect a balance between exploration and exploitation—where sustained leadership requires a concentrated yet flexible specialisation strategy. In a similar vein, Corrocher & Özman (2020) show that European ICT firms exhibit an inverted U-shaped relationship between technological diversification and the likelihood of developing green patents. Moderate diversification facilitates the recombination of heterogeneous knowledge domains, whereas excessive dispersion reduces innovation efficiency due to coordination and integration costs. This mechanism parallels our results for circular economy technologies: firms benefit from maintaining a balanced technological focus, combining depth in core competencies with selective exploration of adjacent fields, avoiding the pitfalls of both over-specialisation and excessive diversification.

Table 5 also shows that, as expected, technological turbulence reduces the time required to replace an existing patent (Model 3) and the permanence of a patent on the international technological frontier (Model 6). In line with the expectations, the patent quality index has a positive and significant relationship with *Entry time* (Model 3), suggesting that higher-quality patents quickly replace (on the main path of the technological trajectory) incumbent patents. Moreover, patent novelty is positively and significantly associated with *Leadership Tenure* (Model 6). Specifically, the greater the novelty of a patent—defined as the extent to which the combination of components and principles employed to fulfill its function differs from those embodied in prior technologies—, the longer the patent's endurance on the CE technological frontier. This relationship may emerge because higher patent novelty increases the likelihood of achieving radical breakthrough performance (Verhoeven, 2016). Additionally, the EPS index – a proxy for environmental regulations – exhibits a negative and significant relationship with both *Entry time* (Model 3) and *Leadership tenure* (Model 6). Consistent with the

“Porter Hypothesis” (Porter & Van der Linde, 1995), greater environmental regulation stringency may initially promote innovation in resource-efficient and loop-closing technologies, facilitating industrial modernization and accelerating firms’ entry into circular economy trajectories. Nonetheless, sustained increases in regulatory stringency may eventually reduce the persistence of CE patents on the technological frontier (*Leadership tenure*), as higher compliance costs and input prices can constrain firms’ investment capacity in circular innovation[17] (Zhao et al., 2022).

Concerning the Y02W subclasses, we notice that the Y02W10 subfield (which is used as the reference category) exhibits a longer entry time but also longer permanence on the frontier – hence, it is more “stable” and with a lower turnover rate – compared to the other two CE subfields. Interestingly, the Y02W10 domain is the one with the smaller KRMP, but also the one that dominates the main path of the overall circular economy; additionally, as illustrated in Section 4 and Appendix C, in recent years these technologies have become increasingly sophisticated and oriented towards “eco-friendly” strategies like water reuse, while technologies for solid waste and GHG mitigation, despite some progress (e.g., through bio-packaging), still heavily rely on less environmentally friendly practices, especially recycling.

Finally, in this regression we have also included country-level fixed effects, with the US used as the reference category, of which we report the single coefficients in the extended version of Table 5 (Table A7) in Appendix D. In this respect, we note that most of the KRMP applicant countries take less time to enter the technological frontier but, after that, are more quickly replaced compared to patents filed by US applicants (which account for 53 % of the whole stock of KRMP patents under scrutiny).

To sum up, from the regression analysis, it emerges that the accumulated stock of knowledge and expertise across various patenting fields is a critical asset in the entry phase. Once a patent/an applicant has entered the main path, the specialisation in a CE domain becomes a relevant determinant of leadership tenure (while the role of patent stock shrinks); however, excessive specialisation reverses this positive relationship.

5.3. Robustness checks

To assess the robustness of our main results, we perform two additional robustness checks. First, we tackle the issue of co-patenting/collaborative patents, which involve the co-presence of two or more applicants. The regressors based on patent count are built by considering the applicant with the highest number of patents. Since we acknowledge the subjectivity of this choice, we run several additional regressions: first, we include a dummy variable (*Co-applicants*) which is set equal to 1 for patents showing the co-presence of two or more applicants (Table 6 - Models 7 and 9); second, we perform estimates on the subsample of KRMP patents obtained by excluding patents assigned to two or more applicants (Table 6 - Models 8 and 10). The results of these estimates are consistent with the main findings.

Second, we account for the (limited) presence of some subsequent patents on the KRMP referring to the same applicant and assess whether this fact may bias the results. Specifically, we run a set of regressions including a dummy variable (*Same applicant*) which is set equal to 1 when subsequent patents are developed by the same applicant (Table 7 - Models 11 and 13), and another set of regressions in which the sample is a subsample of KRMP patents obtained by excluding subsequent patents with the same applicant (Table 7 - Models 12 and 14). The results of these estimates, reported in Table 7, are consistent with our main findings, suggesting that the presence of some subsequent KRMP patents filed by the same applicant does not represent a significant issue.

6. Conclusions

The most recent years have been characterised by a pervasive and unprecedented wave of technological progress, which has affected a wide range of technological fields, has given rise to new technological domains and has significantly boosted some already existing ones, including the broad field of CE. As CE practices and technologies spread and evolve over time and across different geographical areas, adopting companies increasingly need to monitor and understand ongoing technological developments, as well as to acquire or strengthen the required resources and competencies, in order to maintain competitive advantage and possibly join the frontier of their technological domain. However, little is known about the drivers of the patenting efforts specifically devoted to CE practices, and in particular about the determinants of a patent/applicant’s ability to enter and stay on the CE technological frontier. In this study, we aim to fill this gap; to this end, we first identify and describe the main technological changes in the CE and then delve into some possible determinants, focusing on the role played by technological capability and technological specialisation.

From the detailed appraisal of the technological trajectories of the CE subfields, several stylised facts emerge. Overall, we detect significant technological heterogeneity not only across different CE subfields but also within subfields, both over time and across various ramifications of the trajectories; this confirms the importance of conducting a fine-grained investigation (based on a KRMP analysis, rather than a more limited TMP analysis) of the aggregate CE. Importantly, the KRMP analysis also allows us to capture circularity along different points in the CE value chain, i.e., both upstream and downstream. For instance, we identify a shift in innovation trajectories in the Y02W30 subfield from downstream technologies – mainly related to concrete and slag waste management before 2000 – to upstream technologies – referring to eco-friendly concrete production, cement composition technologies and metals/minerals for construction materials’ production – after 2000. Additionally, CE innovation trajectories can be linked to the

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[17] In a robustness check (available upon request), we also controlled for patent complexity (proxied by the number of distinct CPC 4-digit codes associated with a patent) and the Herfindahl–Hirschman Index-HHI (which captures the technological specialization or variety of applicants’ patent portfolios). Their inclusion does not affect the main regression results but the corresponding coefficients are not statistically significant.

Table 6

Results of the Poisson regressions – Robustness check for the presence of co-applicants.

	Entry time		Leadership tenure	
VARIABLES	Model 7	Model 8	Model 9	Model 10
Share of CE patents	-0.410	-0.553	1.423***	1.145**
	(0.509)	(0.559)	(0.485)	(0.500)
Squared share of CE patents	0.327	0.440	-1.242***	-1.034**
	(0.512)	(0.545)	(0.480)	(0.492)
Total patent stock (in log.)	-0.055**	-0.060**	0.027	0.025
	(0.022)	(0.026)	(0.022)	(0.025)
Technological turbulence	-1.263**	-1.192*	-1.063***	-1.065***
	(0.606)	(0.623)	(0.328)	(0.336)
Patent Quality Index	-0.200***	-0.187***	-0.043	-0.036
	(0.058)	(0.056)	(0.060)	(0.059)
Patent novelty	0.126	0.117	0.291**	0.205
	(0.120)	(0.127)	(0.148)	(0.148)
EPS index	-1.001**	-1.327***	-2.048***	-2.372***
	(0.442)	(0.417)	(0.408)	(0.405)
Co-applicants	0.049		0.013	
	(0.130)		(0.150)	
Constant	1.502***	1.650***	1.428***	1.604***
	(0.229)	(0.227)	(0.230)	(0.224)
Subfield fixed effects	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes
Observations	264	242	262	240
Log likelihood	-345.3	-315.2	-345.9	-316.5

Notes: Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source: authors' elaborations of PATSTAT data.

Table 7

Poisson regressions – Robustness check for subsequent patents developed by the same applicant.

	Entry time		Leadership tenure	
VARIABLES	Model 11	Model 12	Model 13	Model 14
Share of CE patents	-0.400	-0.484	1.443***	1.505***
	(0.512)	(0.540)	(0.483)	(0.487)
Squared share of CE patents	0.319	0.426	-1.252***	-1.302***
	(0.511)	(0.538)	(0.477)	(0.481)
Total patent stock (in log.)	-0.054**	-0.056***	0.030	0.032
	(0.022)	(0.022)	(0.024)	(0.024)
Technological turbulence	-1.266**	-1.345**	-1.063***	-1.150***
	(0.600)	(0.588)	(0.323)	(0.371)
Patent Quality Index	-0.195***	-0.226***	-0.039	-0.044
	(0.061)	(0.079)	(0.061)	(0.066)
Patent novelty	0.124	0.118	0.284*	0.290**
	(0.119)	(0.128)	(0.146)	(0.142)
EPS index	-0.995**	-0.956**	-2.054***	-1.761***
	(0.443)	(0.441)	(0.417)	(0.415)
Same applicant (subsequent patents)	-0.036		-0.053	
	(0.112)		(0.151)	
Constant	1.506***	1.477***	1.432***	1.305***
	(0.228)	(0.244)	(0.228)	(0.236)
Subfield fixed effects	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes
Observations	264	227	262	225
Log likelihood	-345.3	-299.9	-345.9	-296.4

Notes: Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source: authors' elaborations of PATSTAT data.

geographical and temporal evolution of environmental regulations adopted by leading countries lying on the frontier. In this respect, it appears that EPR regulations – introduced in China, the European Union and in many US states starting from the 1990s – may have influenced technological changes mostly in downstream stages of the value chain related to waste management for lithium batteries, tires and EEE, but also in upstream stages (e.g., eco-design) of the CE value chain in the case of bio-packaging mainly concerning food & beverages.

Overall, the results show that – on the international technological frontier - recycling technologies often prevail over other more efficient and eco-friendlier strategies, such as reuse, when it comes to solid waste, with the partial exception of eco-design innovation strategies adopted in the case of bio-packaging, and lithium batteries in the most recent period. A different narrative emerges in the case of wastewater treatment technologies, which have become more sophisticated and directed to water reuse over time. Specifically, especially since the 1990s, advanced biological treatment technologies have prevailed on the frontier and align with circular water systems, such as closed-loop reuse of water for irrigation, industry and less discharge. However, the development of such cutting-edge wastewater treatment technologies is restricted to a limited geographical area, i.e., the US.

From the regression analysis conducted on the patents located along the KRMP, evidence indicates a negative relationship between the total patent stock and the time required for a new patent to replace its predecessor on the main path—that is, the larger the patent stock, the shorter the time needed to reach the technological frontier. Moreover, the results reveal an inverted U-shaped relationship between the degree of specialization in a CE subfield and the duration of a patent's presence on the main path. These findings suggest that different resources and capabilities play distinct roles depending on the phase of technological development to which a patent or applicant belongs within a given period.

Our comprehensive analysis of the CE trajectories and the results of the regression model can assist companies in the CE sector in identifying key technological trends, the most dynamic geographic regions, and leading market actors—potentially representing both competitors and strategic partners. In particular, collaborations between highly specialized small enterprises and larger, more diversified firms may mitigate the respective drawbacks of over-specialization and limited expertise or resources dedicated to CE initiatives. This study may also support policymakers interested in promoting CE practices by highlighting both the most established and the most promising technological advancements on the frontier, and by shedding light on companies that have introduced significant innovations but may need financial support. For instance, policymakers should put greater effort into designing regulations to push companies toward innovation strategies (e.g., eco-design) that target reusing or prolonging products' lifecycles rather than mere recycling, since the latter is a less efficient loop to pursue circularity goals (Gnekpe & Plantec, 2023). Moreover, balancing specialisation and diversification in technological portfolios is crucial: firms should reinforce core technological capabilities while retaining flexibility to explore adjacent circular economy domains, as excessive specialisation may impede adaptability over time.

This work presents some limitations. First, given the nature of our dataset, the relationships among the variables under scrutiny should be viewed more as correlations than causal links. Also, we are not able to predict to what extent the regression analysis results can be extended to domains outside the circular economy. Future research could examine other technological fields or further investigate the CE domain using complementary patent search strategies, such as those based on the OECD ENV-TECH classification for green technologies and/or keyword-based approaches.

[Note: the citations marked with an asterisk are mentioned in the Appendix only]

CRediT authorship contribution statement

Enrico Alessandri: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Conceptualization. **Riccardo Cappelli:** Writing – review & editing, Validation, Investigation, Formal analysis, Data curation. **Marco Cucculelli:** Writing – review & editing, Supervision, Resources, Conceptualization. **Jasmine Mondolo:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Formal analysis.

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.

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APPENDIX A. The Main Path Analysis methodology

This Appendix provides a more detailed description of the MPA methodology shortly illustrated in Section 3.

The implementation of our analysis starts from the construction of a patent citation network, i.e., a network in which the nodes are patents, and the edges are patent citations. Patent citations are widely used in the literature to trace the linkages between patents (Jaffe & Trajtenberg, 2002; Jaffe & de Rassenfosse, 2017) and suggest that the knowledge contained in a particular patent was crucial in the innovative processes of later patents. This patent citation network is directed –knowledge flows from the cited to the citing patent–, acyclic –a path starting from one node will never return to that node– and (initially) binary –all the citations are treated as equally important and then are given value one.

To identify the CE technological trajectories, we go through the following procedure. First, drawing upon Hummon & Doreian (1989), we transform the initial binary network into a weighted network to account for the fact that knowledge flows can be more or less relevant, depending on the number of nodes they connect (Martinelli, 2012). To this end, we employ a type of "traversal count", known as Search Path Node Pair (SPNP), which measures the number of times a citation link has been traversed while going from a set of start-nodes to a set of end-nodes, and accounts not only for direct citations, but also for the indirect citations between .. patents (Liu et al., 2019); in doing so, it goes beyond the assessment of innovation patterns based on citation counts only. A start-node is a patent that is cited but does not cite any patents in the main path, while an end-node is a patent that cites other patents but that is not cited itself (in the main path). Accordingly, the start-nodes represent the origins of knowledge, while the end-nodes capture the final part of the knowledge dissemination process (Liu & Lu, 2012), thus defining the boundaries of the patent citations network.

In order to obtain a SPNP value for the citation of patent X in patent Y, we first count all the patents in the network for which a path to X exists (including X itself), and then count all the patents that can be reached from patent Y (including Y itself). The SPNP value associated with the citation of patent X in patent Y is thus the result of the multiplication of these two counts and measures the number of pairs that can be formed by the "upstream" patent and the "downstream" patent of a citation (Nomaler & Verspagen, 2016).

After that, we apply the quantitative method of the main path analysis (MPA). A main path is identified through a "priority first search" algorithm, which, starting from a given start-node, follows consecutive citation links stepwise, choosing each time the next forward citation link with the highest SPNP value until hitting an end-node. In this study, we apply two search algorithms. The first one allows us to identify the top main path (TMP), which is the path with the largest number of overall traversal counts and, by construction, connects the largest number of patents in the network; the TMP thus represents the critical backbone of knowledge flow in the network (Martinelli, 2012).

Despite its widely recognized effectiveness, the TMP analysis presents some limitations; in particular, it can be too selective –for instance, it may include only a few dozens of patents out of a sample of thousands of patents (nodes) or more–, and often lacks the necessary degree of granularity (Bekkers & Martinelli, 2012). Accordingly, we resort to a second search algorithm, i.e., the key-route main path analysis (Liu & Lu, 2012), whose outcome, the key-route main path (KRMP), always includes the TMP of a technological trajectory –i.e., the "first best" knowledge flow in the network of patent citations – and also the "second best" knowledge flow(s). Specifically, in the KRMP analysis, the main path is viewed as an extension of the most significant link, and a search, known as key-route search, starts from both ends of the key-route –i.e., the link that has the highest traversal count– rather than from the sources; in this way, the key-route is always included in the main path. The key-route search procedure consists of the following phases: 1) select the key-route, i.e., the link that has the highest traversal count. 2) search forward from the end node of the key-route until a sink is hit; 3) search backward from the start node of the key-route until a source is hit. It is also possible to select the number of key-routes and execute this procedure multiple times –each time selecting the link with the next-highest traversal count– to obtain a more detailed key-route main path (Lu & Liu, 2016). In our analysis, after some attempts, we select 50 as the number of key-routes (i.e., we consider the top 50 significant routes), as this value provides an extensive overview of the important technological advancement on the technological frontier and, at the same time, excludes ramifications and nodes (patents) that do not significantly enrich the historical narrative. In doing so, it also accounts for other relevant innovation patterns that the TMP would have discarded, thus providing a more accurate and exhaustive picture.

APPENDIX B. The main path analysis as a tool to identify technological trajectories: a compact review of the literature

In recent years, several studies have resorted to the main path analysis to identify and explore the trajectories of a broad and heterogeneous array of technologies including: electrical steel (You & Park, 2018); green technologies (Nomaler & Verspagen, 2019 and 2021); mobile telecommunications (Bekkers & Martinelli, 2012); mobile payment technologies (Kumar et al., 2021 and Lai et al., 2023); fuel cells (Ho & al., 2014); 3D printing (Wang et al., 2020); blockchain applications (Yu & Pan, 2021; Bhatt et al., 2023; Tseng et al., 2023); Artificial Intelligence (Iori et al., 2021); Augmented Reality (Su et al., 2021); biochips (Kuan et al., 2021); semiconductors (Filippin, 2021); autonomous vehicles (Cho et al, 2021; Oh et al., 2023); electric vehicles (Liu et al., 2024), thin-film solar photovoltaic/cells (Lai et al., 2021a; Lai et al., 2021b); internal combustion engines (Weiss & Scherer, 2022);mining technologies (Alessandri, 2023); biomass power generation (Li & Xu, 2023); low Earth orbit (LEO) satellite (Chen & Cho, 2024).

While this strand of literature rapidly evolves, an increasing number of works devote relevant attention also to the identity of the main applicants and countries involved and resort to the key-route main path, rather to the much more selective top main path. Also, whereas some studies mainly aim to identify and illustrate the main ramifications, over time and sometimes across different geographical areas and/or subfields of the technology under scrutiny, other contributions also exploit the results of the main path analysis to provide additional insights concerning the patents and firms' position in the main knowledge flow. To give some examples, Bekkers & Martinelli (2012) classify patents into three groups based on their relationship with the main path (i.e., lying on the main path; feeding the main path; not related to the main path) and then aggregate these indicators in a firm-level index. Kuan et al. 2021 extend and refine Bekkels & Martinelli's approach and identify five specific assignee' roles/positions in a technological trajectory based on the share of patents belonging to the main path ("mainstream patents") and of the share of different types of non-mainstream patents. Alessandri et al. (2023) disentangles the technological trajectory of the mining sector in its sub-trajectories to account for within-sector heterogeneity and explore to what extent such trajectories are "technology bounded", "applicant bounded" and/or "geographically bounded". Tseng et al. (2023) shed light on their key-route network of blockchain technologies by applying text analysis and cluster analysis, which allow the authors to identify twelve major subfields.

The aforementioned works provide useful but mostly qualitative insights into the results of the main path analysis; meanwhile, a few studies have delved into the preliminary evidence provided by the MPA using regression techniques. Specifically, Ho et al. (2014) shed light on the patent characteristics which particularly matter for patent diffusion, and show that the patent applicant's location (with Japan and South Korea among the most relevant countries) and the brokerage characteristics of a patent (e.g., coordinating domestically or liaising among three or more countries) play a vital role in the process of knowledge diffusion. Furthermore, Qu et al. (2023) and Qu et al. (2024) use information retrieved from a sample of USPTO patents in the electric communication industry to investigate the effect of firms' technological search strategies and firm's "technological niche" (i.e., the distance between a company's knowledge base and the technological main path of the company's industry) on firms' "breakthrough" or "disruptive" innovations.

APPENDIX C. A detailed account of the main knowledge flows of the circular economy

In this section, we present a compact overview of the technological trajectories that emerge from the main path analysis of the three CE subfields. We do not show and comment the network visualization referring to the whole Y02W field because it almost completely overlaps with the subfield Y02W10. This finding is consistent with those of a recent OECD study (Leflaive et al., 2020), which stresses how wastewater treatment technologies are particularly relevant in the CE.

For each CE subfield, we analyze the basic contents of the related patent documents[18] and, following Lai et al. (2023), identify different portions of the TMP corresponding to subsequent time intervals, as well as various ramifications of the second-best knowledge flow ("KRMP only"); for each block, we thus provide a short description of its main technological advancements, applicants and countries. For the sake of simplicity, from now on we mostly use the term "patent", rather than "patent family". The complete list of TMP and KRMP-only patents, coupled with information on their applicants, abstracts, CPC codes and so on, is very large and available upon request.

A3.1. Technologies for wastewater treatment (Y02W10)

This technological subfield, which encompasses wastewater treatment technologies, ranks second in terms of number of total patents lying on the TMP, but is also the one with the smallest overall key-route main path. Also, the patents capturing the "second-best knowledge flow" do not form very clearly identifiable ramifications and are quite related to the TMP. The KRMP of this subfield is shown in Fig. 3 in the main body of the paper.

Top main path-Phase 1 (1920-1942)

This preliminary phase begins about 100 years ago and can be interpreted as what Lai et al. (2023) define "Technology embryonic phase". It consists of five patents referring to preliminary methods for sewage treatment and disposal, some of which mention clarification (i.e., the removal of suspended matter and minerals). The three applicants, one inventor and two companies, come from the US.

Top main path-Phase 2 (1944-1976)

Phase 2, which can be regarded as what Lai et al. (2023) define "First technology-explosion phase", is more dynamic and complex than Phase 1, and the corresponding time interval also embraces two KRMP-only ramifications. The so-called focal patent (i.e., the one that starts this phase, which is filed by a US inventor) proposes a sewage treating process which includes both an anaerobic and an anaerobic stage, a feature that will be frequently stressed in the patent abstracts of much more recent patents. The ten patents under scrutiny often mention an aeration process and, since the beginning of the Seventies, often deal with the removal of nitrogen or phosphorus. In this period, the term "wastewater" starts to become common, while the term "sewage" is gradually discarded. The applicants consist in two different inventors and five distinct companies (e.g., Air Products and Chemicals, a large provider of industrial gases, and Union Carbide Corporation, a chemical corporation which, since 2001, has been wholly owned by Dow Chemical Company). All the applicants come from the US, except for The South African Inventions Development Corporation (which, based on the name, could be a sort of network of South-African inventors, but for which no information was available).

Top Main Path-Phase 3 (1979-1989)

The quite dynamic Phase 2 is followed by a more stable Phase 3 ("First stabilization phase"), which consists in a linear chain of five patents describing wastewater treatments that often mention aeration, the removal of nitrogen or phosphorus and/or a two-step process (e.g., aerobic and anaerobic). The four applicants are all companies; one of them, the American Air Products and

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[18] To conduct this descriptive analysis, we proxy each patent family with the earliest patent included for which we retrieve and analyze the information stored in the abstract of the patent document (sometimes also checking the main text), coupled with data on the year, the 8-digit CPC code, the patent office and the applicant. Finally, we also recover basic information (e.g., about its core business, age and current state –still active; not available; closed; absorbed/merged with another company–) on all the applicants that are companies and organizations lying on the TMP.

Chemicals, also appears in Phase 2, and two of them are headquartered in a country different from the US (i.e., Japan and Australia).

Top Main Path-Phase 4 (1989-2006)

The patents of Phase 4 (which can be ascribed to a second "Technology explosion phase") describe more and more sophisticated methods for treating wastewater, which often encompass both an aerobic and an anaerobic (/anoxic) phase/zone, and increasingly refer to a membrane filter and/or a (membrane) bioreactor –which may be the antecedent of the biofilm reactor emerging from Phase 5–. Instead, the term "sewage" is mostly discarded. Strengthening the trend of Phase 3, the applicants are all companies, both small (e.g., the German Protec Partner Fuer Umwelttech) and large (e.g., the Japanese Sharp Corporation); some of them, in the meantime, have been acquired by other companies – for instance, Zenon Environmental, which filed one patent in the TMP and three in the KRMP only, was a water treatment Canadian company which, in 2006, was acquired by GE Water & Process Technologies–. All in all, this phase shows a certain variety of applicants, among which Sharp Corporation stands out.

Top Main Path-Phase 5 (2007-2020)

The quite intense and diversified Phase 4 is followed by a period characterized by more stabilization ("Second stabilization Phase"), in which the TMP and the KRMP coincide and are represented by a linear chain of eight patents. In line with the most recent developments of the previous stage, several patents (including the focal one) resort to a membrane bioreactor, present both an aerobic and an anaerobic stage/tank and refer to nitrogen and/or nitritation. Notably, the latest part of this phase is dominated by a technology consisting in a membrane biofilm reactor –which, accordingly, is likely to have played a relevant role in the latest stage of development of this technological subfield–, and by one applicant, the US company BL Technology. Hence, we can posit that, in recent years, the Y02W10 technological subfield has been characterized by strong applicant and technological boundedness.

Key-route main path only (gray and light green portions, 1953-1977)

This ramification, which spans over a time horizon that is a subset of the one corresponding to Phase 2 of the TMP, comprises ten patents that refer to technologies that seem quite similar to those observed in the TMP. A partial exception may be the rotating biological contactor described in two patents of the US company Autotrol Corporation (whose core business is seemingly quite distant, at least in recent years, from the wastewater sector), which does not appear in any other title, abstract or set of keywords of the whole Y02W10 KRMP. However, the most recent of Autotrol's patents contributed to the well-linked "top" patent filed by Air Products and Chemicals in 1975.

Key-route main path only (red portion, 1995-2005)

Significantly related to (Phase 4 of) the TMP are nine "key-route only" patents, which either form a very short chain that is linked on both sides to the TMP, or are linked only to a top patent both through an incoming and an outgoing edge. All in all, it seems that, also during this period, the knowledge flow captured in the KRMP only does not significantly diverge, in terms of technological content –and in part also in terms of applicants– from the "first-best" one captured by the TMP.

A3.2. Technologies for solid waste treatment (Y02W30)

This technological subfield is the largest one both in terms of overall number of patents and size of the main path (with 128 patents forming the KRMP) and allows us to split both the TMP and the KRMP-only in various phases and ramifications, respectively. The KRMP-only portions vary in terms of degree of similarity with the TMP technologies; also, some of these blocks are entirely ascribable to the phases in which the main knowledge flow is split, while others unfold over more than one phase. The key-route main path of this subfield is shown in Fig. 4 in the main body of the paper.

Top main path-Phase 1 (1923-1962)

The "top" patents filed between 1923 and 1962[19] mainly refer to processes of decomposition and transformation of organic waste material, often aimed to obtaining organic fertilizers. All the applicants but one (a Danish inventor) come from the US, including a company, A.O. Smith Corporation, which is currently one of the world's leading providers of water heating and water treatment solutions. There is relevant applicant heterogeneity, and only one applicant (the American inventor Eric W. Eweson, who later founded his corporation) has filed more than one patent.

Top main path-Phase 2 (1969-1978)

At the end of the Sixties, the main technological content of this subfield starts to shift towards the use of waste materials for the production of other materials or formed objects, such as particulate materials, decorative and structural products mainly based on coal fly ash and a mixed polymeric resin. Unlike those of Phase 1, most of these patents refer to technologies using waste materials as fillers for mortars or concrete, which will dominate the subsequent stages. Regarding the applicants, all those for which information was available come from the US; an exception may be represented by the earliest patent's applicant, who, judging from the surname of the inventor/head of the small organization and the patent office, may come from Germany or Austria.

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[19] During the same period, there are also six patents which belong only to the KRMP; since this small block is linked to this section of the TMP and presents similar contents, we do not analyse them as a separate block.

Top main path-Phase 3 (1978-2000)

Phase 3 embraces patents that mostly concern the treatment and disposal of environmentally harmful waste generated through industrial processes, such as fly ash derived from coal-burning power generating stations, waste sludge, gases evolved during steel preparation, filter dusts resulting from incineration plants, municipal solid waste incinerator ash etc. While some early-stage patents refer to processes aimed to safely discard this waste (e.g., through landfilling), from the end of the Eighties, an increasing number of innovations refer to processes that, starting from waste, lead to new materials –especially building materials– and products. In this phase, geographical heterogeneity is significantly higher compared to the previous two. Several applicants are companies providing cements and ceramic products; notably, the latest three patents are attributable to a company which was founded by the inventor himself (James Hardie), and which is currently one of the worldwide main producers and marketers of fiber cement and fiber gypsum building solutions. Finally, it should be noted that the starting patent and the second patent of this portion of the TMP give rise to an alternative knowledge flow (highlighted in red) which reconnects to the TMP by giving knowledge to the James Hardie's patent filed in 2001.

Top main path-Phase 4 (2000-2005)

This phase corresponds to a short time span which, however, displays significant patent intensity. It encompasses nine TMP patents[20] which mostly refer to increasingly sophisticated cement compositions with specific and appreciable properties (e.g., lightness and low density) or based on a particular component, such as flexible and compressible beads, microsphere suspensions and cement kiln dust. The focus is on the final product, and the term "waste", which often appears in abstracts of older patents, is never used. Moreover, this phase exhibits high applicant boundedness, as all the patents are attributable either to James Hardie's corporations or to Halliburton Energy Services.

Top main path-Phase 5 (2005-2013)

In this phase, which is more stable than the previous one, the TMP consists in a linear stream of seven patents attributable to four applicants, two of which, Halliburton and James Hardie Technology/Finance, are the ones that led Phase 4. In line with the previous stage, these inventions concern sophisticated cement-based compositions which comprise a variety of substances (e.g., gypsum) and which, in some cases, possess thermal insulating/fire resistant properties. It should be noticed that the starting node, i.e., a Halliburton's patent describing "settable spotting compositions comprising cement kiln dust", also gave rise to an alternative knowledge flow (highlighted in light green colour in Fig. 5) made up of seven patents.

Top main path-Phase 6 (2016-2020)

The most recent phase comprises a starting node, i.e., a patent filed in 2005 by Geopolymer Solutions (a US firm specialized in the production of concrete, including "green" geopolymer concrete) and seven subsequent patents, each of which is linked only to the starting patent. The underlying inventions mostly concern geopolymer compositions/concrete, which is regarded as a more innovative and eco-friendly construction material than the ordinary Portland cement concrete. Interestingly, among the applicants of the aforementioned seven patents, we observe a Korean company (Heungkuk Ind. Company, which mostly deals with the manufacturing of heating equipment) and a Chinese company (Sinohydro Bureau 7 Company, which provides infrastructure construction services); hence, two new countries (China and South Korea) have entered the TMP in the most recent years.

Key-route main path only, light blue portion (1920-1997)

This portion of the KRMP, which is linked, through its latest patent, to another KRMP portion and is not directly connected to any TMP patent, embraces a quite long-time horizon, which approximately encompasses the first three phases of the TMP. Based on its main technological content, we can divide this alternative knowledge stream into two main groups: the first one, which refers to the earliest decades, include patents mainly dealing with the recovery and treatment of rubber and other materials derived from car tires, while the second group comprises more recently filed patents addressing the recycling of batteries or fuel cells. Hence, both these parts of this KRMP ramification significantly differ from the main innovations of the TMP, which, since the Sixties, has been dominated by technologies making use of waste materials as fillers for mortars or concrete. Finally, none of the applicants also appears in the TMP, thus suggesting that the KRMP analysis has been useful for identifying additional applicants on the international technological frontier.

Key-route main path only, blue portion (1928-1970)

This portion of the KRMP, which spans over a considerably long-time horizon, feeds the starting node of Phase 3 of the TMP. These inventions concern the production of new materials, especially building materials, starting from fly ash and other waste products of various industrial processes, which are the main object of the TMP patents filed from 1978 onwards. Hence, we can say that, even though the first phase of the TMP was driven by inventions concerning the treatment of organic waste material and the production of fertilizers, during the same decades, an alternative knowledge flow that represents the antecedent of the TMP knowledge stream of the subsequent decades emerged. Finally, we can see that, as in the previously described ramification, none of the applicants enters the TMP too.

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[20] Four of these nine patents are linked to four KRMP-only patents (represented by dark yellow circles in Figure 5) that are not directly connected to each other and to any other patent, and that turn out to be strictly related to this portion of the TMP both in terms of content and applicant.

Key-route main path only, aqua green portion (1974 to 2021)

This portion departs from the focal patent of Phase 2 of the TMP. The earliest patents mainly refer to the recycling of plastics and resin materials derived from bottles and other scrap articles; starting from the patent filed in 1991 by the US company NL Industries, and especially from the subsequent Japanese patent (which receives knowledge from the last patent of the KRMP light blue block), this KRMP ramification has focused on the recycling of batteries and fuel cells. Concerning the applicants, which also include some research institutions, we can notice that all the patents filed from 2009 onwards are attributable to Chinese applicants with only one exception, which, anyway, comes from another dynamic South-Eastern Asian country (South Korea). This confirms the increasing importance of this geographical area in this subfield of the circular economy.

Key-route main path only, red portion (1983-1997)

In line with those belonging to Phase 3 of the TMP, the eight patents of this ramification mainly concern the production of materials based on waste treatment, which often includes the use of fly ash. We can notice that most of these inventions refer to the solidification of partly liquid waste material, resulting, for instance, from the drilling of an oil and gas well, and this may represent a specific characteristic that differentiate these patents from those belonging to the TMP-Phase 3. Interestingly, four patents, including the one feeding a TMP patent, are attributable to the US company Halliburton Energy Services, which is considered one of the world’s largest providers of products and services to the energy industry.

Key-route main path only, light green portion (2005-2020)

This linear KRMP portion spans over a 15-year period and is made up of six patents. The earliest one, which is linked to the “top” Halliburton’s patent starting Phase 5, is another Halliburton’s patent whose abstract highlights an element of the cement contribution under scrutiny (i.e., a fluid loss control additive comprising a graft copolymer) that does not appear in any patent abstract of the TMP; hence, it may represent a partly different technological advancement which, however, significantly contributed to the development of this technological subfield. Also, three patents mention the presence of red mud. As for the applicants, Halliburton stands out; however, as in the last phase of the TMP, the three latest patents are attributable to Chinese applicants.

A3.3. Enabling technologies or technologies with a potential or indirect contribution to greenhouse gas emissions mitigation (Y02W90)

This technological subfield is the smallest one in terms of TMP but presents a KRMP which is much larger than the TMP (80 vs 17 patents). The TMP is quite linear and can be divided into two main subsequent phases, while the several KRMP patents form various ramifications which differ in terms of size, time frame, dominant technology, degree of connection and similarity with the TMP. Interestingly, one of them is completely disconnected from the TMP and, not surprisingly, concern significantly different technological contents, confirming the usefulness of the KRMP analysis in detecting other relevant technological advances on the frontier. The KRMP of Y02W90 is shown in Figure 5 in the main body of the paper.

Top Main Path-Phase 1 (1982-2004)

The nine inventions concerning Phase 1, which may embrace both the embryonic and stabilization phases defined by Lai et al. (2023), consist in containers/packages and, to a lesser extent, semi-finished products that can be used for creating shaped articles. Most of these items are biodegradable (and even edible) and are mainly aimed to store food and beverages. The patent abstracts focus more on the materials involved –among which starch stands out– rather than on the structure of the item. Regarding the applicants, which also include some inventors, we see that they have filed one patent each and come from six different countries (i.e., Japan, Germany, Austria, Canada, the US and Great Britain); hence, there are no dominant countries or applicants.

Top Main Path-Phase 2 (2007-2019)

The most recent patents, which may be ascribable to the “explosion phase”, refer to packages or (parts of) containers with a well-defined shape and structure, and which are typically intended for preparing hot beverages (especially coffee, but also tea or chocolate). Compared to the first stage, more attention is devoted, in the abstract of the patent documents, to the illustration of the various elements forming the object, while information on the types of materials involved (e.g., polysaccharide and cellulose) is often limited; in this regard, it should be mentioned that, unlike Phase 1, none of the titles and/or the abstracts of the patents under scrutiny mention starch.

Concerning the applicants, three of them (i.e., the Italian companies Illycaffè and Lavazza, and the German BBC Bremer Bagasse Company) operate in the coffee business. As earlier, there is significant geographical heterogeneity and, interestingly, the US never appear in this phase. Hence, we can assert that both the stages of the Y02W90 TMP display limited geographical and applicant boundedness.

Key-route main path only, blue portion (1970-2003)

This portion consists in the knowledge flow feeding the Illycaffè’s patent, which can be regarded as the “turning point” of the TMP.

Most of the inventions under scrutiny make use of biodegradable materials, such as paper, cellulose, dunnage and biodegradable polymers. Similarly to what happens in the first segment of the TMP, several patents refer to containers, while others concern semi-finished products, such as layers, laminates and blends, which in turn can be used to produce packages. Regarding the main stored object, the patents filed until 1991 do not mention food and beverages (at least in the abstract). Notably, two well-connected patents, i.e., the one filed in 1992 by the German Buck Werke & Compan, and the patent filed in 1995 by the Finnish Upm-Kymmene Corporation, describe a packaging material mainly intended for packaging foodstuffs. From that moment on, the knowledge flow of this portion of the KRMP increasingly focuses on semi-final products or well-defined containers aimed to store food and beverages; in particular, the text of the most recent patent, which is the one linking this block to the TMP by giving knowledge to the Illycaffè's patent, mentions compostable capsules as well. Finally, we can notice that none of the applicants, which are quite heterogeneous in terms of country of origin, appears in the TMP as well. Interestingly, other patents of one of the applicants, i.e., the US company Union Carbide Corporation, enter both the KRMP and the TMP of the technological subclass Y02W10.

Key-route main path only-orange portion (1986-2000)

This portion contains six patents linked to the first part of the TMP through both direct and indirect (outcoming and incoming) links. The inventions mainly refer to biodegradable products and packages which, like those in the TMP-Phase 1, are often starch-based. Only the abstract of one of these patents mentions foodstuff (i.e., the one which was filed in 1986 by a German inventor and which gives knowledge to a TMP patent), while the abstract of the patent filed in 1992 by the Japanese company Nissei concerns moulded articles "which can be used in a variety of fields". Hence, this knowledge stream is quite integrated with that of the first part of the TMP, but seems to be much less centred on food storage. Regarding the applicants, they come from four distinct countries, and none of them also enters the TMP of this technological subfield.

Key-route main path only, red portion (1992-2020)

This sizeable component of the KR main path comprises 26 patents and is completely disconnected from the TMP of the technological subclass Y02W90. The main underlying technologies, which, as expected, considerably differ from the ones that drive the TMP, are centred on recycling systems, methods and programmes. Specifically, the earliest patents (from Hitachi's patent filed in 1992 to Remag's patent filed in 2010) refer to methods and systems aimed at the disposal and recycling of waste, including "household products", recyclable containers and periodicals. The four subsequent patents (filed between 2011 and 2013) still concern recycling but, rather than directly dealing with waste disposal, illustrate methods and systems mainly aimed to monitor, collect information and, especially, promote recycling activities among consumers. Then, from 2014 onwards, patents refer to systems and methods, some of which involve "kiosks", aimed at the recycling of electronic devices, such as mobile phones, computers and laptops. Regarding the applicants, the US dominate this KRMP portion, which comprises only two additional countries (i.e., China and Japan). Also, this block is characterised by relevant applicant boundedness, as two applicants appear twice and another applicant (the US company Ecoatm) appears nine times between 2014 and 2020, suggesting that this company plays a significant role in the most recent phase focused on electronic devices.

Key-route main path only (light green portion, 2005-2020)

This relatively recent portion of the KRMP departs from the TMP patent (concerning a biodegradable food container) filed in 2002 by the British company New Ice and does not have additional links with the TMP. The earliest patent is filed by New Ice too, and, similarly to the related "top" patent, mainly concerns "biodegradable or compostable containers that can hold hot beverages and foods". However, from the third patent (filed in 2016 by the US company Vericool, which filed three patents of this block) onwards, the knowledge flow starts focusing on packages that are resistant to water and, especially, heat. A patent which presents various outcoming links is the one filed in 2017 by Vericool, which describes a "thermally insulating packaging to hold an item" and contributed to the development of four more recent inventions. Finally, most of the applicants come from the US or the UK.

Key-route main path only (light blue portion, 2010-2019)

This small KRMP portion originates from the two first TMP patents of Phase 2 (the one filed by Illycaffè in 2007 and the one filed by a Swiss inventor in 2009), and through its first patent, attributable to Lavazza, fuels the TMP by giving knowledge to another Lavazza's patent. All the inventions considered refer to a cartridge or a capsule for storing coffee or other hot beverages, of which the patent abstracts generally illustrate the materials and the main components. Hence, it seems that this portion of the KRMP significantly resembles the knowledge flow shaping the TMP from 2007 onwards. Finally, the applicants come from three different countries.

APPENDIX D. Additional tables

Table A1

Technological and geographical evolution over time of CE innovation trajectories and main regulations.

a) Subfield Y02W10 – Technologies for wastewater treatment

Phase of the KRMP		Number of patents	Main type of technology	Applicant country (% of total patents in a specific phase)	Main regulations	Main sources
TMP	**KRMP-only**					
Phase 1 (1920-1942)		5	Sewage treatment and disposal (e.g. removal of suspended matter and minerals)	**100 % United States**	Public health service programs suggested sewage treatment goals with no central concern about nutrient removal such as nitrogen or phosphorus (United States, 1912-1968)	US federal government, available at: https://www.archives.gov/research/guide-fed-records/groups/090.html
Phase 2 (1944-1976)		17	Sewage treatment and disposal (removal of nitrogen or phosphorus from 1970s)	**88 % United States;** 6 % Great Britain; 6 % South Africa	Federal water pollution control act (FWPCA) encouraging construction of wastewater treatment plants (United States, 1948)	US federal government, available at: https://www.epa.gov/sites/default/files/2017-08/documents/federal-water-pollution-control-act-508full.pdf
Phase 3 (1979-1989)		5	Biological treatment of water (removal of nitrogen/phosphorus and/or two-step process, e.g. aerobic and anaerobic)	**80 % United States;** 20 % Japan		
Phase 4 (1989-2006)		13	Biological treatment of water (two-step process, e.g. aerobic and anaerobic with use of membrane filter and/or membrane bioreactor)	**31 % United States; 31 % Japan;** 15 % Canada; 8 % France; 8 % Germany	Sewerage law no. 79 promoting the use of membrane bioreactors and advanced biological systems in sewerage and wastewater treatment facilities (Japan; 1958, amended in 2001) Clean water act section 319 – nonpoint source management program encouraging wastewater reuse and natural treatment systems (United States; 1987, expanded in 1990s)	Tamaki (1980) US EPA, available at: https://www.epa.gov/nps/319-grant-program-states-and-territories
Phase 5 (2007-2020)		8	Biological treatment of water (use of a membrane filter and of a membrane biofilm reactor, in the latter period)	**88 % United States;** 12 % Canada	EPA's 1999 combined sewer overflow (CSO) control policy Total maximum daily load (TMDL) program (expanded in 1990s) on the identification of impaired waters and development of pollution limits (TMDLs) (United States,	US EPA (1999b) US EPA, available at: https://www.epa.gov/tmdl/tmdl-support-documents

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Table A1 (*continued*)

a) Subfield Y02W10 – Technologies for wastewater treatment

Phase of the KRMP		Number of patents	Main type of technology	Applicant country (% of total patents in a specific phase)	Main regulations	Main sources
	Gray and light green portions (1953-1977)	10	Sewage treatment and disposal	**90 % United States**; 10 % Great Britain	FWPCA (United States, 1948)	US federal government, available at: https://www.epa.gov/sites/default/files/2017-08/documents/federal-water-pollution-control-act-508full.pdf
	Red portion (1995-2005)	9	Biological treatment of water (two-step process, e.g. aerobic and anaerobic with use of membrane filter and/or membrane bioreactor)	**56 % United States**; 22 % Canada; 22 % Japan	Clean water act section 319 ((United States; 1987, expanded in 1990s)	US EPA, available at: https://www.epa.gov/nps/319-grant-program-states-and-territories

b) Subfield Y02W30 – Technologies for solid waste management

Phase of KRMP		Number of patents	Type of technology	Applicant country (% of total patents in a specific phase)	Main regulations	Main sources
TMP	**KRMP-only**					
Phase 1 (1923-1962)		14	Production of fertilizer from organic products	**83 % United States**; 13 % Denmark	Agricultural marketing acts (1920s-30 s) indirectly promoting quality standards for organic fertilizers (United States, 1920s-1930s); Soil conservation policy on promoted use of organic matter (United States, 1930s-60 s); Federal insecticide, fungicide, and rodenticide act (FIFRA) – (United States, 1947)	National Archives: Records of the Bureau of Plant Industry, Soils, and Agricultural Engineering (BPISAE). Available at: https://www.archives.gov/research/guide-fed-records/groups/054.html

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Table A1 (*continued*)

b) Subfield Y02W30 – Technologies for solid waste management

Phase of KRMP		**Number of patents**	**Type of technology**	**Applicant country (% of total patents in a specific phase)**	**Main regulations**	**Main sources**
Phase 2 (1969-1978)		5	Concrete waste	**83 % United States**; 13 % Liechtenstein	Solid waste disposal act (SWDA) - (United States, 1965)	Rodgers (1973)
Phase 3 (1978-2000)		15	Slag waste for construction materials	**33 % United States**; 27 % Germany; 13 % Japan; 7 % Australia; 7 % Great Britain; 7 % Ireland; 7 % The Netherlands	Resource conservation and recovery act (RCRA) (United States, 1976)	Gnekpe and Plantec (2023; p. 3)
Phase 4 (2000-2005)		12	Sophisticated cement composition technologies	**67 % United States**; 17 % Australia; 17 % The Netherlands	Clean air act – National Emission standards for hazardous air pollutants (NESHAP) for cement kilns (United States; 1999, 2002, 2010, 2015).	US EPA regulations available at: https://www.federalregister.gov/documents/2002/02/13/02-3346/neshap-interim-standards-for-hazardous-air-pollutants-for-hazardous-waste-combustors-interim
Phase 5 (2005-2013)		7	Metals or minerals for cement or mortar production	**43 % The Netherlands**; 29 % United States; 14 % France; 14 % Ireland		Directive 2010/75/EU available at: https://eur-lex.europa.eu/eli/dir/2010/75/oj/eng
Phase 6 (2016-2020)		8	Eco-friendly concrete production technologies	**63 % United States**; 25 % China; 13 % Republic of Korea	Dutch environmental permitting act (The Netherlands, 2010), which transposes the EU industrial emissions directive (IED) 2010/75/EU to control emissions of heavy metals, particulates, and other hazardous materials related to the cement industry	
	Blue portion (1928-1970)	10	Slag waste for construction materials	**83 % United States**; 17 % Germany	Resource conservation and recovery act (United States, 1976)	Gnekpe and Plantec (2023; p. 3)
	Red portion (1983-1997)	8	Slag waste for construction materials	**88 % United States**; 13 % Canada	EPA special waste reports	EPA (1999a)
	Light green portion (2005-2020)	7	Metals or minerals for cement or mortar production	**57 % United States**; 43 % China	EPA's sustainable materials policy – comprehensive	US EPA website at: https://www.epa.gov/smm/comprehensive-procurement-guidelines-construction-products Chinese Ministry of Ecology and Environment

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Table A1 (*continued*)

b) Subfield Y02W30 – Technologies for solid waste management

Phase of KRMP	Number of patents	Type of technology	Applicant country (% of total patents in a specific phase)	Main regulations	Main sources
				procurement guidelines for construction products (United States) GB 30485-2013 and technical spec HJ 662-2013 focused on co-processing of industrial solid waste, including fly ash, slag, and metal-containing residues (China, 2013)	website at: https://www.gov.cn/gzdt/2013-12/30/content_2556871.htm
Light blue portion (1920-1971)	10	Tire and rubber waste	**75 % United States**; 25 % Germany	State or municipal waste laws within the United States enacted mainly for economic and wartime reasons - e.g. retreading - with indirect benefits on the environment (United States, before 1970s)	Takallou and Takallou (1991)
Light blue portion (1973-1997)	7	Lead-acid battery (Recycling and recovery)	**43 % United States**; 29 % Italy; 14 % Germany; 14 % Switzerland	Resource conservation and recovery act (RCRA) (United States, 1976); Hazardous and solid waste amendments (United States, 1984)	Gnekpe and Plantec (2023; p. 3)
Aqua green portion (1974-1989)	5	Plastic waste (Recycling and recovery)	**80 % United States**; 20 % Germany		
Aqua green portion (1991-2021)	18	Lithium battery (Recycling, recovery and reuse of economically valuable materials)	**61 % China**; 17 % Japan; 11 % United States; 6 % France; 6 % Switzerland	Circular Economy Promotion Law of the People’s Republic of China (China, 2008); China revised plan for CE promotion (China, 2018)	Priore et al. (2025); Gnekpe and Plantec (2023); Shao et al. (2018)

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Table A1 (*continued*)

b) Subfield Y02W30 – Technologies for solid waste management

Phase of KRMP	Number of patents	Type of technology	Applicant country (% of total patents in a specific phase)	Main regulations	Main sources
				Law for the promotion of utilization of recyclables resources (Japan, Act No. 48, April 26th 1991)	Kasutani (1992)

c) Sub-field Y02W90 – Enabling technologies or technologies with a potential or indirect contribution to greenhouse gas emissions mitigation

Phase of KRMP		Number of patents	Type of technology	Applicant country (% of total patents in a specific phase)	Main regulations	Main sources
TMP	**KRMP-only**					
Phase 1 (1982-2004)		9	Bio-packaging in the food industry (starch-based and biodegradable for many types of food & beverages)	**22 % United States; 22 % Japan; 22 % Great Britain;** 11 % Germany; 11 % Austria; 11 % Canada	Resource conservation and recovery act (RCRA) (United States, 1976); Hazardous and solid waste amendments (United States, 1984)	Gnekpe and Plantec (2023; p. 3)
					Environmental protection act (part II) on waste disposal and recycling facilities, with duty of care for waste producers (Great Britain, 1990)	UK Parliament (1990)
					Waste management and public cleansing law (1970, revised 1991) (Japan, 1970; 1991)	Japanese Ministry of Environment, available at: https://www.env.go.jp/en/recycle/basel_conv/files/Waste_Management_and_Public_Cleansing.pdf
Phase 2 (2007-2019)		8	Bio-packaging in the food industry (hot beverages, focus on coffee cartridges)	**38 % Italy;** 25 % Germany; 25 % Great Britain; 13 % Switzerland	Directive 85/339/EEC on the disposal of liquid beverage containers (European Union, 1985)	Nicolli et al. (2012; p. 278)
					Directive 94/62/EC (mandatory EPR schemes) on harmonising national measures for managing packaging and packaging waste (European Union, 1994)	

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Table A1 (*continued*)

c) Sub-field Y02W90 – Enabling technologies or technologies with a potential or indirect contribution to greenhouse gas emissions mitigation

Phase of KRMP	Number of patents	Type of technology	Applicant country (% of total patents in a specific phase)	Main regulations	Main sources
Blue portion (1970-1991)	11	Bio-packaging not related to foodstuff (biodegradable paper containers)	**56 % United States;** 11 % Canada; 11 % France; 11 % Spain; 11 % Sweden	RCRA (United States, 1976); Hazardous and solid waste amendments (United States, 1984)	Gnekpe and Plantec (2023; p. 3)
Blue portion (1992-2007)	9	Bio-packaging in the food industry (biodegradable, focus on coffee cartridges in the latter period)	**33 % Finland;** 22 % United States; 11 % Germany; 11 % Italy; 11 % Japan; 11 % Switzerland	EU Directive 94/62/EC Waste act (1072/1993) including producer responsibility rules for packaging formally implemented from 1997 onwards (Finland, 1993)	Nicolli et al. (2012; p. 279) Finnish Ministry of the Environment, available at: https://www.finlex.fi/en/legislation/collection/1993/1072
Yellow portion (1986-2000)	6	Bio-packaging (mostly starch-based with wide applicability besides foodstuff)	**33 % United States; 33 % Germany;** 17 % The Netherlands; 17 % Japan	U.S. Department of Agriculture (USDA) BioPreferred Program, expanded in 2002 Farm Bill and updated regularly (United States, from 2000 onwards)	USDA BioPreferred Program available at: https://www.biopreferred.gov/BioPreferred/ Nicolli et al. (2012; p. 279)
Red portion (1992-2010)	10	Recycling methods and systems (household products such as containers, periodicals)	**70 % United States;** 30 % Japan	State-level laws (in 22 states) on EPR actions within the United States (United States, 1990s-2000s)	
Red portion (2011-2013)	3	Garbage bin classification process	**100 % United States**		
Red portion (2014-2020)	13	Recycling and recovery of Electrical and Electronic Equipment (EEE)	**69 % United States;** 31 % China	No federal legislation in the United States. 25 states passed EPR regulations on EEE, the majority of which implemented in 2009 or after. First regulation: “Electronic waste recycling act” in California, 2003 (United States, from 2000s onwards) Measures for administration of the pollution control caused by electronic information products (“China	Compagnoni (2022) Compagnoni (2022); Pérez-Belis et al. (2015)

(*continued on next page*)

Table A1 (*continued*)

c) Sub-field Y02W90 – Enabling technologies or technologies with a potential or indirect contribution to greenhouse gas emissions mitigation

Phase of KRMP	**Number of patents**	**Type of technology**	**Applicant country (% of total patents in a specific phase)**	**Main regulations**	**Main sources**
				RoHS") (China, 2006)	
				Ordinance on the administration of the recovery and disposal of waste electrical and electronic products ("China WEEE Directive") (China, 2009)	Compagnoni (2022)
Light green portion (2005-2020)	8	Bio-packaging in the food industry (biodegradable or compostable containers, with water- and heat-resistant properties)	**62.5 % United States;** 25 % Great Britain; 12.5 % China	Federal trade commission's green guides related to environmental marketing claims such as "biodegradable", "compostable" and "eco-friendly", based on EPR principles (United States; first issued 1992, updated 2012)	Federal Trade Commssion (2012)
Light blue portion (2010-2019)	5	Bio-packaging in the food industry (hot beverages and coffee cartridges)	**40 % Italy; 40 % Great Britain;** 20 % United States	National waste framework law (D.Lgs. 22/1997), transposing EU Directive 94/62/EC on mandatory EPR schemes, establishing a consortium (CONAI) for the management of packaging and packaging waste (Italy, 1997)	Nicolli et al. (2012; p. 279)
				Producer responsibility obligations (packaging waste) Regulations 1997, implementing EU Directive 94/62/EC that firstly introduced EPR schemes for packaging (United Kingdom, 1997)	UK Government (1997)

Notes: the KRMP phases are based on Fig. 3 (Y02W10) and the detailed account of the main knowledge flows of the CE (Appendix C); the reported CE regulations mainly refer to countries (highlighted in bold) giving a major contribution to technological changes on the frontier for each KRMP phase.
Notes: the KRMP phases are based on Fig. 4 (Y02W30) and the detailed account of the main knowledge flows of the CE (Appendix C); the reported CE regulations mainly refer to countries (highlighted in bold) giving a major contribution to technological changes on the frontier for each KRMP phase.
Notes: the KRMP phases are based on Fig. 5 (Y02W90) and the detailed account of the main knowledge flows of the CE (Appendix C); the reported CE regulations mainly refer to countries (highlighted in bold) giving a major contribution to technological changes on the frontier for each KRMP phase.

Table A2
Patent quality indicators – Average values for KRMP and non-KRMP patents.

	Non-KRMP patents				KRMP patents			
Variable	Y02W	Y02W10	Y02W30	Y02W90	Y02W	Y02W10	Y02W30	Y02W90
Country coverage	1.43	1.44	1.41	1.44	4.93	5.85	4.37	5.14
Number of inventors	1.26	1.26	1.27	1.25	2.67	2.47	2.85	2.54
Number of backward NPL citations	0.85	0.91	0.84	0.54	4.88	1.93	7.25	3.28
Number of forward citations (5 years)	0.44	0.43	0.46	0.21	5.67	8.42	5.93	3.23

Source: authors' elaborations of PATSTAT data.

Table A3
Patent quality indicators for the Y02W10 technological field – Average values by TMP and KRMP only.

Variable	KRMP-only Gray and light green portions	TMP Period: 1953-1977	KRMP-only Red portion	TMP Period: 1995- 2025
Country coverage	6.71	8.91	4.25	3.67
Number of inventors	1.57	1.73	2.88	3.01
Number of backward NPL citations	1.57	1.55	3.5	3.89
Number of forward citations (5 years)	5.57	11.01	11.88	12.11

Source: authors' elaborations of PATSTAT data.

Table A4
Patent quality indicators for the Y02W30 technological field – Average values by TMP and KRMP only.

Variable	KRMP only Blue and light blue portions	TMP Period: 1920-1971	KRMP only Aqua green and light blue portions	TMP Period: 1973 - 1990	KRMP only Light green and acqua green portions	TMP Period: 1991-2021
Country coverage	1.42	2.51	4.78	4.92	4.76	7.43
Number of inventors	1.73	1.08	2.43	2.38	4.22	3.39
Number of backward NPL citations	0.04	0.33	2.13	1.38	5.95	23.93
Number of forward citations (5 years)	1.08	1.51	9.48	3.31	7.24	9.32

Source: authors' elaborations of PATSTAT data.

Table A5
Patent quality indicators for the Y02W90 technological field – Average values by TMP and KRMP only.

Variable	KRMP only Blue and yellow portions	TMP Period: 1970-2000	KRMP only Red, light blue and light green portions	TMP Period: 2005 - 2020
Country coverage	5.56	7.01	3.51	4.61
Number of inventors	1.78	2.51	3.04	2.81
Number of backward NPL citations	1.44	9.14	4.65	0.00
Number of forward citations (5 years)	3.28	2.49	3.11	3.85

Source: authors' elaborations of PATSTAT data.

Table A6
Patent quality indicators – Average values by country.

Applicant Country	Country coverage	Number of inventors	Number of NPL backward citations	Number of forward citations (within 5 years)	Number of KRMP patents
Austria	12.00	3.00	2.00	7.00	1
Australia	15.80	2.60	19.40	15.60	5
Canada	3.13	2.75	4.63	14.50	8
Switzerland	6.67	2.67	1.00	1.67	3
Cina	1.14	4.27	0.00	4.41	22
Germany	5.58	2.42	0.53	4.68	19
Finland	4.25	2.25	0.75	2.75	4
France	7.83	2.50	2.00	6.00	6
United Kingdom	4.25	1.75	0.17	1.33	12

(*continued on next page*)

Table A6 (*continued*)

Applicant Country	Country coverage	Number of inventors	Number of NPL backward citations	Number of forward citations (within 5 years)	Number of KRMP patents
Ireland	4.00	4.00	0.00	6.00	1
India	8.00	5.00	0.00	3.00	1
Italy	7.71	2.29	0.29	4.57	7
Japan	4.52	2.95	1.38	4.48	21
South Korea	4.50	3.50	0.00	8.00	2
Liechtenstein	15.00	1.00	1.00	7.00	1
Netherlands	8.86	3.14	19.43	8.86	7
Poland	2.00	3.00	0.00	7.00	1
Sweden	6.00	2.00	0.00	0.00	2
United States	4.65	2.50	6.78	5.70	143
South Africa	7.00	1.00	0.00	17.00	1
Total	4.93	2.67	4.88	5.67	267

Source: authors' elaborations of PATSTAT data.

Table A7

Extended version of Table 5 showing also the coefficients of the country-level fixed effects.

	Entry time			Leadership tenure		
VARIABLES	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Share of CE patents	0.050	-0.187	-0.417	0.179	1.305**	1.423***
	(0.143)	(0.547)	(0.507)	(0.130)	(0.520)	(0.484)
Squared share of CE patents		0.232	0.331		-1.100**	-1.242***
		(0.563)	(0.510)		(0.539)	(0.480)
Total patent stock (in log.)	-0.067***	-0.068***	-0.055***	-0.001	0.008	0.027
	(0.021)	(0.021)	(0.021)	(0.024)	(0.025)	(0.022)
Technological Field: Y02W30	-0.496***	-0.507***	-0.533***	-0.475***	-0.427***	-0.485***
	(0.123)	(0.122)	(0.111)	(0.129)	(0.128)	(0.108)
Technological Field: Y02W90	-0.445***	-0.458***	-0.350***	-0.414**	-0.346*	-0.187
	(0.153)	(0.152)	(0.132)	(0.179)	(0.181)	(0.141)
Technological turbulence	-1.329**	-1.346**	-1.268**	-1.121***	-1.151***	-1.064***
	(0.606)	(0.598)	(0.600)	(0.417)	(0.418)	(0.327)
Patent Quality Index			-0.198***			-0.043
			(0.058)			(0.060)
Patent novelty			0.125			0.291**
			(0.120)			(0.148)
EPS index			-0.988**			-2.044***
			(0.442)			(0.417)
Austria	-0.321***	-0.332***	0.148	-0.341***	-0.275**	0.380*
	(0.107)	(0.109)	(0.212)	(0.114)	(0.111)	(0.216)
Australia	-0.174	-0.153	-0.014	-0.260	-0.364*	-0.686***
	(0.217)	(0.226)	(0.186)	(0.190)	(0.191)	(0.191)
Canada	-0.203	-0.185	-0.206	-0.615***	-0.687***	-0.783***
	(0.181)	(0.185)	(0.233)	(0.151)	(0.163)	(0.246)
Switzerland	-0.455***	-0.466***	-0.012	-0.413***	-0.367***	0.605***
	(0.095)	(0.099)	(0.244)	(0.096)	(0.100)	(0.183)
Cina	-0.223***	-0.215***	-0.182**	-0.303***	-0.345***	-0.042
	(0.074)	(0.075)	(0.091)	(0.097)	(0.103)	(0.109)
Germany	0.064	0.069	0.446**	0.135	0.110	0.948***
	(0.131)	(0.134)	(0.207)	(0.159)	(0.153)	(0.228)
Finland	0.080	0.076	0.383	-0.179	-0.168	0.696**
	(0.243)	(0.240)	(0.325)	(0.241)	(0.237)	(0.296)
France	-0.094	-0.077	0.353	0.126	0.042	0.811***
	(0.325)	(0.324)	(0.293)	(0.160)	(0.170)	(0.178)
United Kingdom	-0.429***	-0.433***	-0.359**	-0.220	-0.200	0.053
	(0.134)	(0.137)	(0.142)	(0.148)	(0.140)	(0.131)
Ireland	-0.287***	-0.252**	-0.031	-0.365***	-0.529***	-0.057
	(0.072)	(0.115)	(0.113)	(0.066)	(0.111)	(0.116)
India	-0.156	-0.169	-0.235	0.110	0.188	0.155
	(0.261)	(0.256)	(0.263)	(0.120)	(0.120)	(0.191)
Italy	-0.305**	-0.294*	0.182	-0.332***	-0.395***	0.627***
	(0.152)	(0.159)	(0.286)	(0.090)	(0.096)	(0.199)
Japan	0.181	0.182	0.554**	-0.119	-0.140	0.730***
	(0.252)	(0.250)	(0.247)	(0.193)	(0.193)	(0.215)
South Korea	-0.199	-0.208	0.010	-0.504**	-0.452**	0.168
	(0.182)	(0.185)	(0.206)	(0.211)	(0.189)	(0.201)
Liechtenstein	0.939***	0.921***	1.379***	-0.148	-0.059	0.591**
	(0.166)	(0.166)	(0.257)	(0.164)	(0.165)	(0.247)

(*continued on next page*)

Table A7 (*continued*)

	Entry time			Leadership tenure		
VARIABLES	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Netherlands	-0.387***	-0.356***	0.234	-0.310**	-0.442***	0.340
	(0.084)	(0.107)	(0.169)	(0.126)	(0.140)	(0.217)
Poland	-0.611***	-0.592***	-0.291	-0.563***	-0.663***	-0.094
	(0.132)	(0.132)	(0.186)	(0.125)	(0.134)	(0.124)
Sweden	0.566	0.584	0.633	0.105	0.010	0.295
	(0.501)	(0.489)	(0.469)	(0.329)	(0.403)	(0.325)
South Africa	0.120	0.118	0.227	-0.827***	-0.808***	-0.475***
	(0.167)	(0.165)	(0.139)	(0.134)	(0.129)	(0.094)
Constant	1.096***	1.127***	1.504***	0.869***	0.727***	1.428***
	(0.174)	(0.175)	(0.228)	(0.178)	(0.170)	(0.229)
Subfield fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	264	264	264	262	262	262
Log likelihood	-353.9	-353.8	-345.3	-362.5	-360.8	-345.9
Notes: Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$						

Notes: robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; the reference category for the set of dummies capturing the Y02W subclasses is Y02W10; the reference category for the set of dummies capturing the countries is the United States.
Source: authors' elaborations of PATSTAT data.

Data availability

Data will be made available on request.

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