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# Technological Innovations in Decarbonisation Strategies: A Text-Mining Approach to Technological Readiness and Potential

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**Abstract:** This study presents a novel, multifaceted approach to evaluating decarbonisation technologies by integrating advanced text-mining tools with comprehensive data analysis. The analysis of scientific documents (2011–2021) and mapping 368 technologies from the IEA's Energy Technology Perspectives identified 41 technology domains, including 20 with the highest relevance and occurrence. Domain readiness was assessed using mean Technology Readiness Levels (TRLs) and linked to six decarbonisation pathways. The "Electrification of uses" pathway ranked highest, demonstrating significant $CO_2$ mitigation potential and high readiness (mean TRL 7.4, with two-thirds of technologies scoring over 7) despite challenges in hard-to-electrify sectors. The findings provide actionable insights for policymakers, highlighting the need for pathway-specific strategies, a deeper understanding of synergies between pathways, and balancing innovation with deployment to accelerate decarbonisation.

**Keywords:** decarbonisation; decarbonisation pathways; text mining; technological innovations



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## 1. Introduction

Global warming poses a critical threat to humanity and is driven primarily by escalating carbon dioxide ($CO_2$) emissions from modern activities like energy generation [1]. Reliance on fossil fuels to fulfil global energy needs intensifies greenhouse gas release [2]. The pressure to decarbonise surged after the Paris Agreement, which set the target to halve $CO_2$ emissions by 2030 and achieve "net-zero" emissions by 2050 to limit global warming to 1.5 °C. Despite these efforts, recent scientific evidence suggests that observed global warming exceeds expectations, raising concerns about the pace of implementation of decarbonisation targets [1]. Technological innovation is essential for accelerating carbon mitigation [1]. Additionally, there is an urgent need to identify and compare strategies (or pathways) for accelerating the reduction of $CO_2$ emissions, particularly the combination of technological innovations associated with each pathway.

The effectiveness of a decarbonisation strategy depends on its capacity to mitigate $CO_2$ emissions, which in turn greatly depends on the availability, readiness, and potential of supporting technologies. Recent years have seen a surge in research on technology innovation and decarbonisation strategies, evidenced by numerous publications on the former (e.g., [3–12]) and technologies (e.g., [13–19]). This abundance of research poses challenges in navigating the various options.

Text-mining tools offer a promising solution to navigate this complexity. Several studies have utilised these tools to explore the landscape of decarbonisation, focusing on specific technologies and sectors, as shown in Table 1.

**Table 1.** A non-exhaustive survey of bibliometric analyses of decarbonisation technologies.

| Study | Focus (Technology or Sector) | Period | Software | Number of Publications | Description |
|---|---|---|---|---|---|
| [20] | Energy Efficiency Technologies | 2008–2018 | Web of Science (WoS) | N.a. | Assesses the impact of energy efficiency technologies on decarbonisation in European residential buildings, revealing asymmetrical research activity across member states and the need for more research to quantify and monetise impacts. |
| [21] | Carbon Capture, Storage, and Use (CCSU) | 2002–2019 | Citespace | 1202 | Utilises Citespace software to analyse CCSU research in China, highlighting the influence of government policies on research trends. |
| [22] | Biomass and Organic Waste | N.a. | N.a. | N.a. | Characterises biomass and organic waste potentials for implementing circular bioeconomy platforms through bibliometric analysis. |
| [23] | Green Hydrogen (H2) | 2016–2021 | VOSviewer | N.a. | Analyses trends in green hydrogen research, highlighting the number of articles published, productive organisations, countries, and relevant research items using VOSviewer. |
| [24] | Energy Storage | 2011–2021 | Scopus | N.a. | Examines the importance of energy storage in decarbonising the electricity sector, emphasising its integration into grids. |
| [25] | Maritime Decarbonisation Policies | 2009–2021 | Web of Science (WoS) | 75 | Conducts a quantitative literature review on policies toward maritime decarbonisation, highlighting the evolution of policies, regulations, design details, impacts, and methods of quantifying the effects of environmental policies. Contributes to a better understanding of the field's evolution, trends, and emerging research themes. |
| [26] | Carbon Neutrality Research | N.a. | Vosviewer, BibliometrixWoS | 909 | Concludes that carbon neutrality publications have increased dramatically, with focus areas including practical, technical, policy, and economic aspects. Identifies hotspots in renewable energy sources, carbon conversion technologies, and carbon capture and storage technologies. Outlines future research opportunities, including integration with artificial intelligence and the metaverse. |
| [27] | Low-Carbon Energy Generation | 1983–2021 | CiteSpace | 1419 | Utilises CiteSpace software to analyse developments in low-carbon energy generation, concluding that renewable energy resources and storage are crucial for decarbonisation. |
| [28] | Climate Change Mitigation Concepts | N.a. | Scopus | N.a. | Presents a literature revision on key concepts related to climate change mitigation, exploring geographic and sectoral focuses and interrelationships between concepts using data mining software. |
| [29] | Global Decarbonisation of Electricity System | N.a. | Science Citation Index (SCI) | N.a. | Performs a bibliometric analysis of the titles, abstracts, and literature keywords from the Science Citation Index Expanded and Social Sciences Citation Index databases. It concludes that the search for cleaner alternatives was driven by coal and nuclear fuel dependence in the 1990s and the focus on energy efficiency will continue. |

For instance, the authors of [24] highlight the importance of energy storage in decarbonising the electricity sector, while the authors of [20] examine the impact of energy efficiency technologies on European residential buildings. Other studies delve into topics such as carbon capture, biomass, green hydrogen, and low-carbon energy generation [21–23,27]. However, the existing literature tends to concentrate on individual technologies, as well as on single text-mining techniques and sources like publications, overlooking comprehensive assessments and the integration of diverse sources like patents and research projects.

This work addresses this gap by developing a novel methodology that combines multiple text-mining tools and considers various types of documents, such as research papers and patents, to assess technology readiness, risks, and potentials across different decarbonisation pathways. Technology readiness is assessed using data from 368 innovative technologies available in the International Energy Agency's (IEA) Energy Technology Perspectives (ETP) 2020 database. Risk levels are evaluated based on both the Technology Readiness Levels (TRL) and the relevance–occurrence ratios derived from the bibliographic analysis. Technology potential is estimated using the carbon mitigation data collected from the IPCC for individual technologies. The methodology significantly advances existing approaches by further evaluating the readiness, risk, and potential of groups of technologies that frequently co-occur in identified strategies for decarbonisation or decarbonisation pathways (see [30]). The process begins by identifying the main technology domains involved in decarbonisation according to the literature. These domains are then intersected with six decarbonisation pathways derived from an extensive review of over one million scientific papers [30], evaluating the carbon mitigation potential of these pathways and the associated risks. This approach enables a comprehensive comparison of the capacity of the strategies or pathways to accelerate decarbonisation through the analysis of the maturity, risk, and potential of the underlying technology innovations.

The remainder of the paper is organised as follows. The next section outlines the methodology developed to identify the domains of technology innovations for decarbonisation that have received more attention from the scientific community in recent years. Section 3 evaluates the readiness and impact of the combined innovations within the decarbonisation strategies. The final section presents the main conclusions and suggests new research avenues.

## 2. Methodology

### *2.1. Approach*

The capacity to mitigate $CO_2$ emissions relies largely on technological innovations' availability, readiness, and potential. This capacity determines the effectiveness of the decarbonisation pathways they support. Therefore, identifying technological innovations associated with decarbonisation is a crucial step in characterising the main pathways to decarbonisation that have been proposed over the years. However, the vast amount of recent scientific work has made comparing the diverse technological options for supporting decarbonisation challenging.

Figure 1 summarises the methodology used in this work to identify domains of innovative decarbonisation-related technologies. This identification is based on documents available in scientific publications, projects, and patent databases. The proposed methodology is divided into three fundamental steps: (i) obtaining a set of raw terms from appropriate scientific documents available on suitable databases; (ii) normalising, filtering, and aggregating the extracted terms; and (iii) identifying from these terms the main technology domains.

The initial two steps of the methodology involve extracting terms from scientific publications, projects, and patents related to decarbonisation technologies and processes. It is worthwhile noting that information on the occurrence and relevance of the identified terms, obtained through text-mining tools, is also gathered and treated during these steps. Subsequently, the collected terms serve as the basis for defining technology domains, which occurs in the third step of the methodology, as shown in the schematic representation of the workflow. The results of the technology domains are then analysed based on the combinations of domains that compose the diverse decarbonisation pathways, allowing for a comparison of the readiness and potential of these pathways (in Section 3.3).

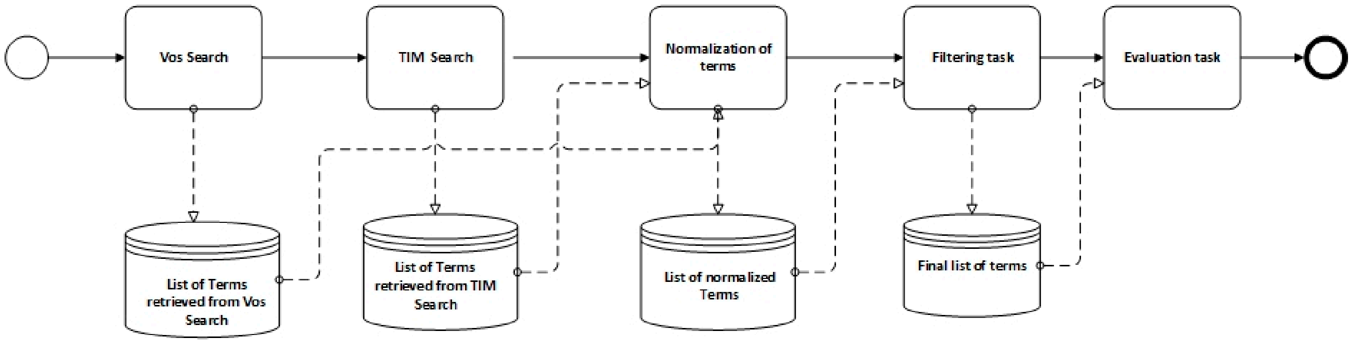


**Figure 1.** Summary of the methodology.

### 2.2. Obtention of Raw Terms: Software and Sources

In the first step of the methodology, two readily available text-mining tools were deployed to obtain a set of raw terms from scientific publications and patents related to decarbonisation. Concretely, the European Commission's TIM ("Tools for Innovation Monitoring") [31] and VOSviewer (from Leiden University) [32] software were used to identify trends concerning decarbonising technologies in databases of scientific papers (WoS and Scopus), projects (Cordis), and patents (Patsat).

VOSviewer [32] is a software program that performs different types of bibliometric analysis, allowing the exploration of co-authorship, co-occurrence, citation, bibliographic coupling, and co-citation links in one of three possible representations: network, overlay, or density visualisation [33]. This analysis focused on documents obtained from the WoS database through the dedicated search engine. The dataset of documents was used as VOSviewer's input to obtain the author keywords of the documents and their "occurrence". Note that "occurrence" refers to the number of documents in which a given keyword or term appears.

TIM [31] software tracks established and emerging technologies by retrieving bibliometric data directly from various databases, namely SCOPUS, CORDIS, and PATSTAT [34]. Thus, it does not impose a previous dataset extraction. The search can be carried out in different fields associated with the entries (papers, projects, patents). In this work, the search was carried out on the documents' titles, abstracts, and keywords included in the source databases. After obtaining the dataset, TIM classifies the keywords according to different algorithms. In this work, the" Relevant Keywords" algorithm was chosen. This algorithm ranks the keywords by a "relevance" value defined by a modified version of the classic Inverse Document Frequency (TF-IDF). TF-IDF assigns different weights to keywords according to location: 1 whenever the keywords are in the document's title; 0.5 in the abstract; or 2 in the keyword field [33]. Therefore, the meaning of "relevance" obtained using the TIM tool should not be directly compared to the "occurrence" obtained through VOSviewer.

The search in both WoS and TIM implies the definition of a suitable Boolean string. The search string used in this work was designed based on a previous literature review about decarbonisation technologies, allowing for defining decarbonisation-related terms. The search string reconciled the WoS and TIM search engines' particularities (e.g., plural or singular words are automatically considered in TIM but not in WoS). The adopted search string was:

> *(("transformation pathway*" OR "$CO_2$ emission*" OR "carbon dioxide" OR "greenhouse gas emission*" OR "technological innovation*" OR "2050" OR "system transformation*" OR "2030" OR "global warming" OR "climate solution*" OR "climate*

*target*" OR "climate policy" OR "displace fossil fuels "OR "1.5°" OR "ghg emission*" OR "greenhouse gas" OR "paris agreement" OR "transition in electricity" OR "energy transition" OR "clean energy" OR "sustainable energy" OR "new energy" OR "carbon emission*" OR "climate change" OR "mitigation" OR "technology" OR "disruptive") AND ("decarbonisation" OR "carbon reduction" OR "low carbon" OR "emission* reduction" OR "zero carbon" OR "carbon neutral" OR "carbon neutrality" OR "net-zero" OR "decarbonised"))*

The search string has two parts linked through a logical AND, which forces each document in the retrieved datasets to contain at least one of the terms of each part of the string. Therefore, the string was designed to capture the most relevant domains of technologies to decarbonise while minimising the retrieval of irrelevant data and avoiding exceeding the limit of 10,000 documents that the TIM software can handle—although this limit did not affect the maximum output number of the search results.

The evaluation of the literature on technology innovations was carried out annually to track the temporal progression. Thus, the search string was employed with the WoS and TIM search engines for each year between 2011 and 2021. Figure 2 shows the results, revealing 87,212 documents retrieved from the databases, with 59,411 originating from TIM and 27,801 from WoS. It is worth noting that there is a consistent upward trend in the number of documents retrieved each year, particularly in scientific papers, indicating an evident growth in the literature.

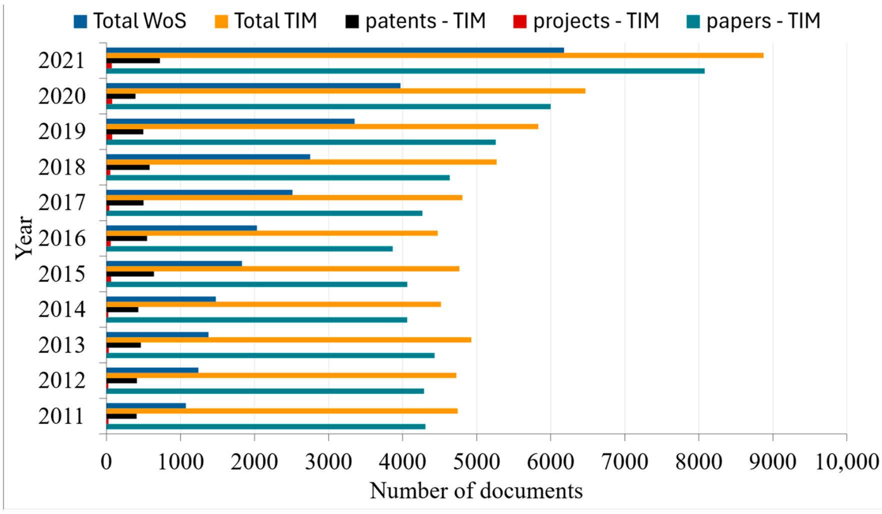


**Figure 2.** Number of retrieved documents from the databases.

The bibliometric analysis was conducted using TIM and VOSviewer software (version 1.6.19) to find the technology domains. The analysis retrieved 11 sets of "Relevant Keywords" with their corresponding "relevance" (from TIM) and 11 sets of "Author Keywords" with their respective "occurrence" (from VOSviewer). In total, 793,700 terms were obtained, with 689,075 from TIM and 104,625 from VOSviewer. As many terms were repeated across multiple annual sets within the same software program, duplicates were eliminated. As a result, 196,129 keywords/terms were obtained (155,778 from TIM and 40,351 from VOSviewer). However, the total number of non-repeated keywords is 176,029, as there were also terms repeated by both TIM and VOSviewer, which were subsequently eliminated.

### 2.3. Obtention of Final Terms: Semantic Dictionary and Filtering

The list of raw terms obtained through the procedure described in the previous section included many keywords and terms irrelevant to this study. In addition, various terms with the same meaning appear in the list (e.g., PV system, photovoltaic, photovoltaics, solar PV, etc.). Therefore, it was necessary to process the list of raw terms to clean up the list. A filtering process based on a customised semantic dictionary eliminated the irrelevant terms and aggregated the ones with the same meaning.

Before applying the filtering procedure, it was necessary to use a text normalisation procedure [35] to consolidate the retrieved list of raw terms. Therefore, a Python code was implemented for text normalisation, which included converting plural nouns to singular, reducing verbs to their stems, converting comparative adjectives to their base forms, and removing connectors and stop words. The normalisation procedure also addressed the acronyms and abbreviations, eliminating redundancies and keeping the terms that could not be removed (e.g., the H2 in the term "H2 storage").

Following the normalisation process, a program developed in Phyton filtered the data, isolating the raw terms relevant to this study. Irrelevant terms were discarded, while relevant terms had their relevance/occurrence values aggregated under the corresponding technology items.

The filtering procedure relied on a semantic dictionary. The construction of this dictionary started with the definition of an initial set of 102 keywords/terms obtained through a preliminary bibliographical review, considering the authors' knowledge in the area. Subsequently, a semi-automatic approach [36], depicted in Figure 3, was employed to augment and refine the semantic dictionary. This comprehensive process improved the dictionary's accuracy and completeness, enhancing confidence in the overall filtering procedure.

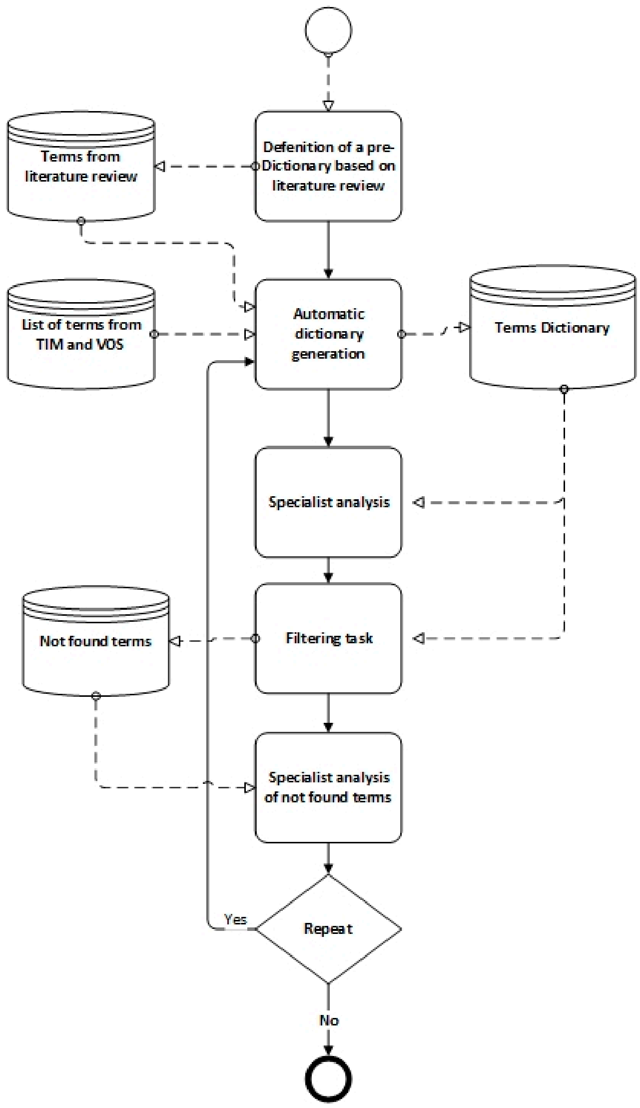


**Figure 3.** Iterative procedure followed to create the semantic dictionary.

A Python code was developed to implement the automatic part of the procedure, which is based on the Levenshtein approach [35]. This approach measures the differences between two text strings. This part generated new terms for each dictionary entry by considering the existing terms in the current dictionary (a pre-dictionary was required). An expert then evaluated the automatic suggestions and determined which should be included in a revised dictionary version. The updated dictionary was subsequently employed in the previously described filtering procedure with the retrieved lists of terms (the filtered list), resulting in a compilation of terms that were not found. Then, the specialist could add new terms from the list of not-found terms to the current dictionary.

The construction of the dictionary involved several iterations to ensure the inclusion of a comprehensive set of terms in the final version. The procedure was repeated, starting with the automatic part of the algorithm. The evolution of the number of keywords/terms included in the dictionary is shown in Figure 4. Only the terms found in the years 2020 and 2021 were used in the seven initial iterations, as most of the publications occurred in the last two years of the sample (Figure 2). The first Levenshtein ratio was equal to 0.75, which was increased along the iterative procedure until the maximum value of 0.9 (i.e., larger distance between the terms). The following five iterations were performed considering all the keywords/terms returned for the 11-year study period (176,029 keywords/terms). This fact justifies the variation from the seventh to the eighth iteration. The Levenshtein ratio was redefined in the eighth iteration as equal to 0.8 and increased by 0.05 on each subsequent iteration until it reached 0.9. The iterative process was stopped when the list of not-found terms resulting from the filtering process did not contain new keywords/terms to be added to the dictionary with an occurrence of greater than three or a relevance of greater than 5.

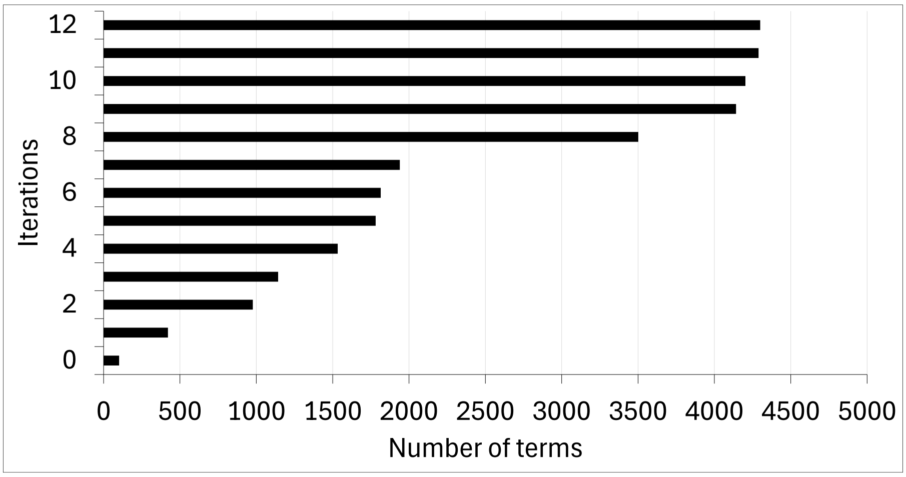


**Figure 4.** Evolution of the number of terms in the semantic dictionary.

The obtained final dictionary had 4300 keywords/terms divided into 426 sets with similar semantic meanings. An extract of the 426 sets is presented in Table 2.

**Table 2.** Extract of the 426 sets of terms with similar meaning.

| # | Terms With Similar Semantic Meaning | | | |
|---|---|---|---|---|
| 1 | renewable energy system | renewable energy | hybrid renewable energy system | ... |
| 4 | photovoltaic | photovoltaic energy | photovoltaic panel | ... |
| 13 | perovskite solar cell | perovskite silicon tandem solar cell | perovskite | ... |
| 16 | solar chimney power plant | solar chimney | hybrid solar chimney power plant | ... |
| 22 | photovoltaic thermal | building photovoltaic thermal | photovoltaic thermal collector | ... |
| 28 | building integration solar based technology | solar thermal integration | solar energy integration | ... |
| 38 | ocean energy system | ocean energy | ocean renewable energy | ... |
| 55 | biomethane | biochemical methane potential | biomethanation | ... |

**Table 2.** *Cont.*

| # | Terms With Similar Semantic Meaning | | | |
|---|---|---|---|---|
| 69 | biomass | crop production | wood production | ... |
| 104 | nuclear fission | fission power system | fission energy | ... |
| 115 | renewable hydrogen production | sustainable hydrogen production | biohydrogen | ... |
| 139 | hydrogen turbine | hydrogen engine | hydrogen internal combustion engine | ... |
| 162 | electricity transmission | inter-regional power transmission | interprovincial electricity transmission | ... |
| 175 | air source heat pump | air heat pump | air water heat pump | ... |
| 202 | microgeneration | micro generation | micro generator | ... |
| 207 | micro combined heat power | micro combined heat | micro turbine generator | ... |
| 219 | envelop design | building envelope | modular construction | ... |
| 232 | hybrid vehicle | hybrid electric vehicle | parallel hybrid vehicle | ... |
| 255 | blast furnace | ironmaking blast furnace | blast furnace ironmaking | ... |
| 282 | low carbon agriculture | climate smart agriculture | agriculture emission | ... |
| 303 | demand response | demand response function | energy demand response | ... |
| 320 | magnesium battery | magnesium ion battery | magnesium air battery | ... |
| 321 | air redox battery | redox flow battery | air battery | ... |
| 322 | li battery | lithium battery | ion battery | ... |
| 338 | power to x storage | power ga storage | power gas storage | ... |
| 341 | flywheel | flywheel energy storage | flywheel energy storage system | ... |
| 345 | ice storage | ice thermal energy storage | ice thermal storage | ... |
| 361 | carbon capture utilization sequestration | carbon capture utilization technology | carbon dioxide capture utilization | ... |
| 368 | carbon capture power plant | carbon capture storage power plant | capture power plant | ... |
| 370 | direct air capture | direct air carbon capture | direct air carbon capture storage | ... |
| 378 | smart city | smart green city | smart city system | ... |
| 388 | digital energy system | digital energy | digital power | ... |
| 406 | carbon abatement policy | carbon emission policy | carbon pilot policy | ... |

## 3. Technology Assessment of Decarbonisation Pathways

### *3.1. Technology Domains*

This section presents the technology domains that were identified in the bibliometric analysis. Following the procedure explained in the last paragraph of Section 2.3, 426 sets of similar terms were aggregated into 41 domains, shown in Table 3.

**Table 3.** Technology domains.

| # | Domain | # | Domain |
|---|---|---|---|
| 1 | not specified renewable | 22 | energy transmission infrastructure |
| 2 | photovoltaic | 23 | transportation infrastructure |
| 3 | solar power/steam generation | 24 | electrification |
| 4 | wind energy | 25 | heat pump |
| 5 | geothermal energy | 26 | HVAC |
| 6 | marine energy | 27 | microgeneration/self-consumption |
| 7 | hydro power | 28 | building construction/isolation |
| 8 | solar thermal energy | 29 | low carbon and autonomous transportation |
| 9 | combined photovoltaic/thermal generation | 30 | generic industry furnace/heating |
| 10 | not specified distributed generation | 31 | cement industry |
| 11 | hybrid generation system | 32 | stell, iron, and aluminium industry |
| 12 | other generation | 33 | other heavy industry |
| 13 | biofuel | 34 | agricultural sector |
| 14 | synthetic fuel | 35 | energy efficiency and management |
| 15 | not specified alternative fuel | 36 | energy community |
| 16 | nuclear power | 37 | energy storage |
| 17 | clean coal/natural gas power plant | 38 | carbon capture, storage, and use |
| 18 | natural gas power generation | 39 | natural carbon capture and storage |
| 19 | shale natural gas | 40 | digitalisation and smart systems |
| 20 | combined heat/cool/power generation | 41 | policy and circular measures |
| 21 | hydrogen | | |

Two of the defined domains do not fit into the logic of conventional technology domains ("policy and circular measures" and "natural carbon capture and storage"). Therefore, they were not included in the assessment of technology domains.

Moreover, the importance of each technology domain according to its appearance in the publications was also evaluated, as not all domains have received the same attention.

The bibliometric analysis described in Section 2 provides the occurrence (VOSviewer) and the relevance (TIM) values, which measure the attention received by each technology domain from the scientific community. The "occurrence" value enables the comparison of domains by quantifying associated scientific works, reflecting extensive research. Conversely, the "relevance" parameter emphasises the relative importance of technology domains in scientific documents, with a high value signifying sustained interest and focus within the scientific community.

Figures 5 and 6 illustrate the cumulative "relevance" and "occurrence" values per year for the top 20 technology domains during the analysis period (2011–2021). Note that the analysis of the "relevance" and "occurrence" metrics for the technology domains indicates that the "policy and circular measures" domain has the highest accumulated value of "relevance" (6146.5) and the second highest accumulated value of "occurrence" (3297). However, as mentioned earlier, it is worth noting that the "policy and circular measures" and "natural carbon capture and storage" domains are not aligned with the logic of technology domains. Consequently, they have been excluded from the subsequent analysis. It is important to note that 19 out of the 20 top domains coincide. However, the most occurrent domains are not necessarily the most relevant. Additionally, the combined relevance and occurrence values of these top 20 domains account for 87% and 93% of the total accumulated relevance and occurrence values, respectively. The ten most relevant domains represent almost two-thirds of the total accumulated relevance, whereas the ten most occurrent domains represent three-quarters of the accumulated occurrence.

Furthermore, eight of the top ten most relevant domains also rank among the top ten most occurrent, representing 58% of the total accumulated relevance and 61% of the total accumulated occurrence. The "energy transmission infrastructure" and "buildings—passive measures" domains are among the top ten in relevance but not in occurrence. Conversely, the "biofuel" and "wind energy" domains are among the top ten most occurrent but not among the top ten most relevant.

Figures 7 and 8 show the normalised relevance and occurrence values for each year of the study period, encompassing the 20 technology domains previously mentioned. The normalisation process was conducted yearly, dividing the individual accumulated values of each technology domain by the sum of the accumulated values of all 41 defined domains. This procedure aids in comprehending the evolution of the share of each domain over the years.

As for relevance, the domains of "energy efficiency and management", "carbon capture, storage, and use", "not specified renewable", and "hydrogen" presented the highest values of relative relevance during the 2011–2021 period. However, the shares of the first two domains have been decreasing significantly, while there is a rapid increase in the case of the "hydrogen" domain. The "energy storage", "low carbon and autonomous transportation", "energy transmission infrastructure", "energy community", and "electrification" domains have increased their relative relevance values. The "biofuel" and "nuclear power" domains present a decreasing value of relative relevance, along with, surprisingly, "buildings—passive measures". Concerning the occurrence, the "energy efficiency and management", "biofuel", and "not specified renewable" domains appear to present higher values of relative occurrence. However, the two first domains show a decrease in relative occurrence values. The same tendency may be perceived for the "carbon capture, storage and use", "nuclear power", and "energy community" domains. After a decrease, the relative occurrence for the "hydrogen" domain began increasing. The relative occurrence is also increasing for the "low carbon and autonomous transportation", "energy storage", and "photovoltaic" domains.

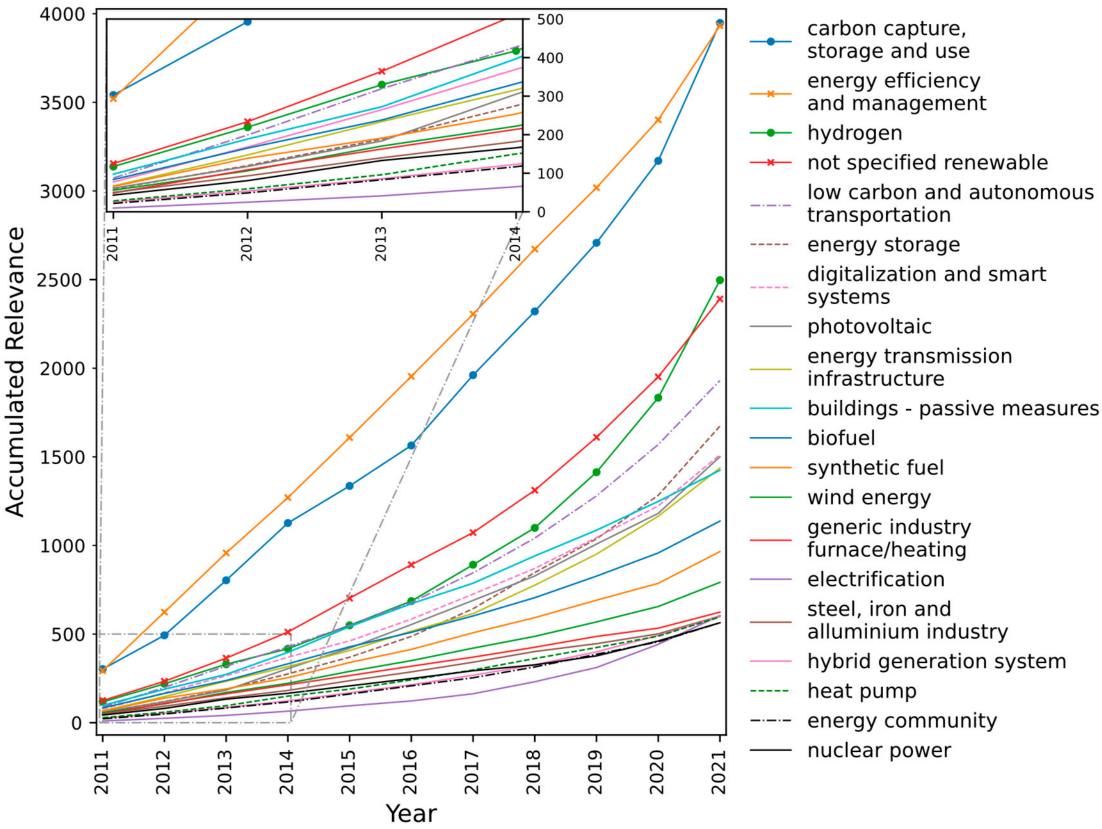


**Figure 5.** Per-year accumulated relevance for the top 20 domains.

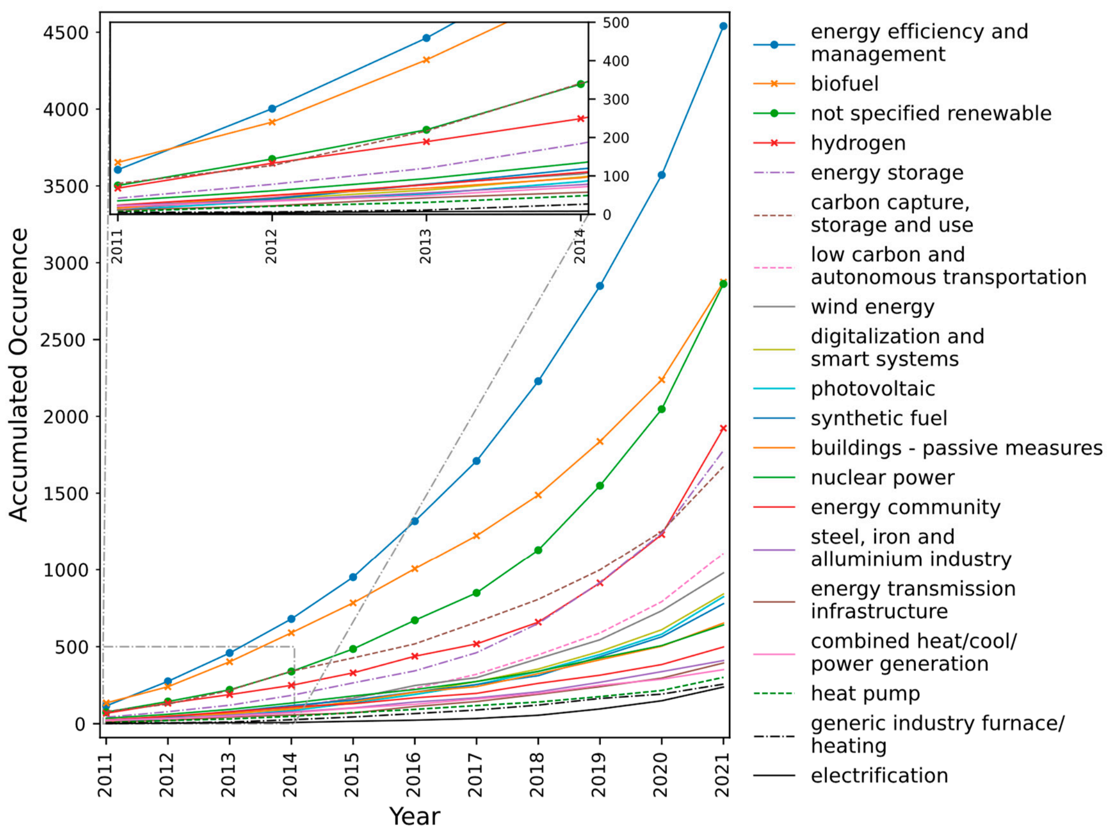


**Figure 6.** Per-year accumulated occurrence for the top 20 domains.

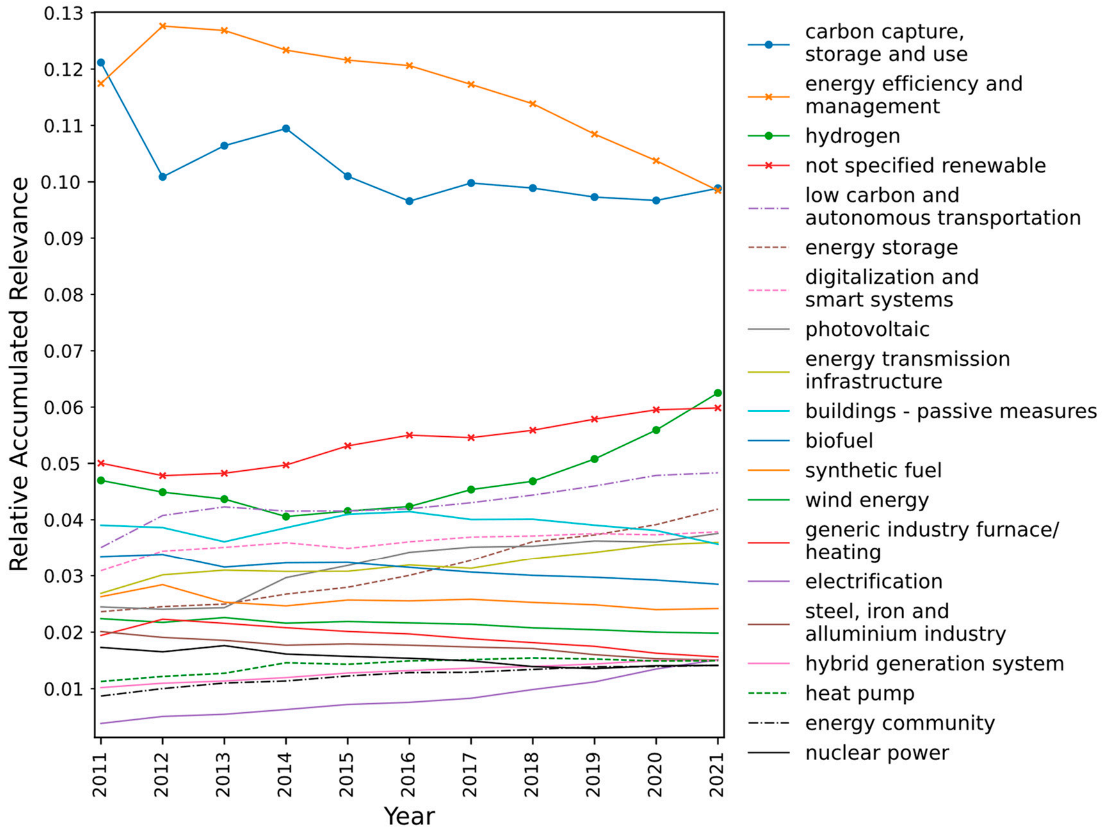


**Figure 7.** Per-year normalised accumulated relevance for the top 20 domains.

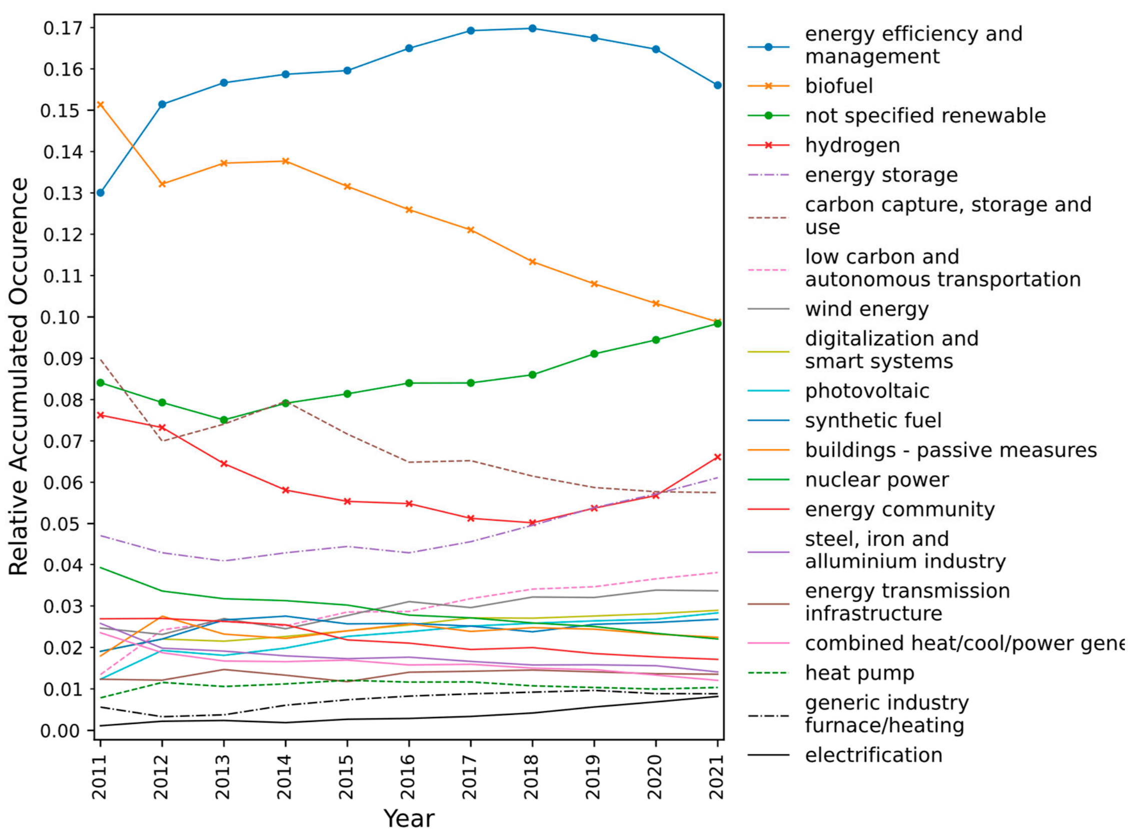


**Figure 8.** Per-year normalised accumulated occurrence for the top 20 domains.

The readiness of the technology domains (Section 3.2) is further evaluated before assessing the decarbonisation strategies (Section 3.3), which combine multiple technology domains in terms of their readiness and potential for mitigating $CO_2$ emissions.

### *3.2. Readiness of Technology Domains*

Assessing the readiness of technology domains is crucial in determining their potential contribution to decarbonisation in the short term. Domains with higher readiness levels are more likely to contribute to expedited decarbonisation. This issue is of utmost importance to successfully meet the climate goals for 2030 and ultimately achieve net-zero emissions by 2050.

The Technology Readiness Level (TRL) metric was utilised to evaluate the readiness of the technology domains outlined in Section 3.1. The metric utilised adheres to IEA's scale, using a TRL score from 1 to 11 (see Figure 9). Moreover, for the analysis in this study, the 11 readiness levels have been further consolidated into two distinct groups: technologies in the pre-commercial stage and those in the market introduction stage or the formative phase (cf. [37]).

| | | |
|---|---|---|
| **1** | **Initial idea**<br>Basic principles have been defined | **Pre-commercial** |
| **2** | **Application formulated**<br>Concept and application of solution have been formulated | |
| **3** | **Concept needs validation**<br>Solution needs to be prototyped and applied | |
| **4** | **Early prototype**<br>Prototype proven in test conditions | |
| **5** | **Large prototype**<br>Components proven in conditions to be deployed | |
| **6** | **Full prototype at scale**<br>Prototype proven at scale in conditions to be deployed | |
| **7** | **Pre-commercial demonstration**<br>Prototype working in expected conditions | |
| **8** | **First of a kind commercial**<br>Commercial demonstration, full scale deployment in final conditions | **Market Introduction (formative phase)** |
| **9** | **Commercial operation in relevant environment**<br>Solution is commercially available, needs evolutionary improvement to stay competitive | |
| **10** | **Integration needed at scale**<br>Solution is commercial and competitive but needs further integration efforts | |
| **11** | **Proof of stability reached**<br>Predictable growth | |

**Figure 9.** TRL score.

The information regarding the innovative technologies considered in each domain was obtained from a database linked to the IEA's Energy Technology Perspectives 2020 [38]. This comprehensive database encompasses 368 distinct technology designs and components spanning the entire energy system, all contributing to the objective of achieving net-zero emissions. Each technology entry in the database includes details on its maturity level (TRL value), development and deployment plans, cost and performance improvement targets, and key players in the field.

The technologies within the database were assigned to specific technology domains based on their unique characteristics. It is worth noting that certain technologies were associated with multiple domains, reflecting their diverse applications. For example, Floating hybrid energy platforms were categorised under both the "wind energy" and "hybrid generation system" domains and "building integrated photovoltaic" (BIPV) was included in both the "photovoltaic" and "microgeneration/self-consumption" domains. Moreover, the 368 individual technologies were associated with 35 of the identified domains. Indeed, no technologies were associated with the "policy and circular measures", "natural carbon capture and storage", "shale natural gas", "natural gas power generation", "agricultural sector", and "not specified distributed generation" domains.

The readiness of each domain was then obtained by calculating the average TRL for the specific set of innovative technologies associated with that domain. By averaging the TRL values, it is possible to gain valuable insights into the overall readiness of a domain.

Figure 10 compares the readiness of the technology domains after allocating the technologies to domains. Besides the average TRL of the domains, the figure displays the number of technologies included in each domain as well as the share of technologies in the "pre-commercial" and "commercial/market formation" stages (marked in green or red if they are below or above TRL 7, respectively).

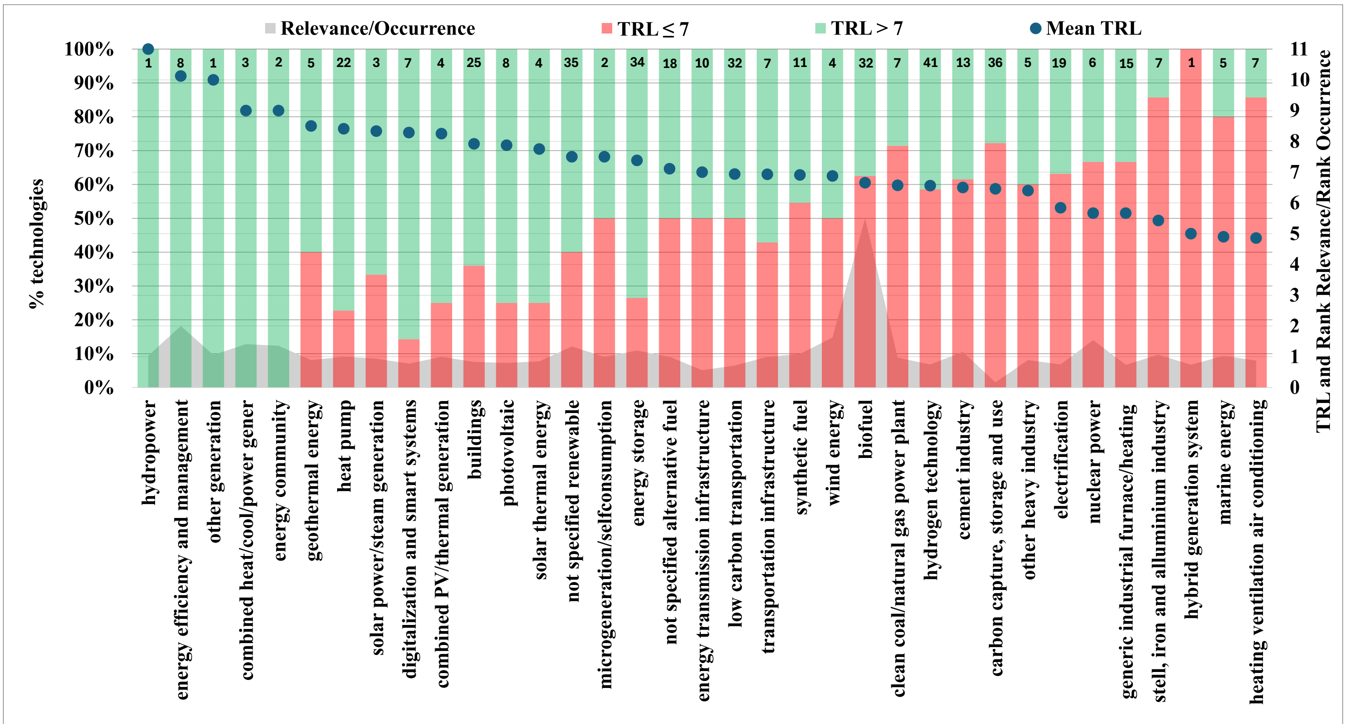


**Figure 10.** Readiness and relevance/occurrence ratio for technology domains (technologies are sorted in the decreasing order of the mean TRL).

One-third of the technology domains remain in the pre-commercial (development) stage. Approximately half (51%) of the domains have an average TRL greater than 7, and four additional domains (11%) have an average TRL close to 7 (greater than 6.9), i.e., are approaching the market introduction. Domains with more associated technologies may still have a high percentage in the commercial stage; for instance, "energy storage" has over 70% and "not specified renewables" has 60% in this stage. Conversely, "hydrogen technology" has over 60% of its technologies in the non-commercial stage and domains like "nuclear power" and "marine energy" have low average TRL values due to many pre-commercial innovations.

Figure 10 displays the ratio between relevance and occurrence ranks, which measures the relative attention received by the technology domain in the scientific community. The relevance of a specific domain is dominant (meaning high attention) when the mentioned ratio is lower than 1, and the occurrence is prevalent (i.e., more diffused presence) otherwise. Apart from "Biofuels" and "Wind energy", which present a very high relative relevance, mature technology domains like "Energy efficiency" and "Power generation" present a slightly higher relative relevance than emerging "Hybrid generation" or "Heating ventilation (HVAC)".

Figure 11 compares the maturity of the technologies considered in the study based on whether those technologies predominantly apply to energy supply or demand. The importance of granular demand-side energy technologies for more rapid system transformation has been argued in the literature (e.g., [39]). It is worth noting that infrastructure-related technologies were included in the supply side. Additionally, some technologies, such as photovoltaics, were categorised in supply and demand, depending on their nature. The demand side set included 202 technologies, while the supply side set included 238.

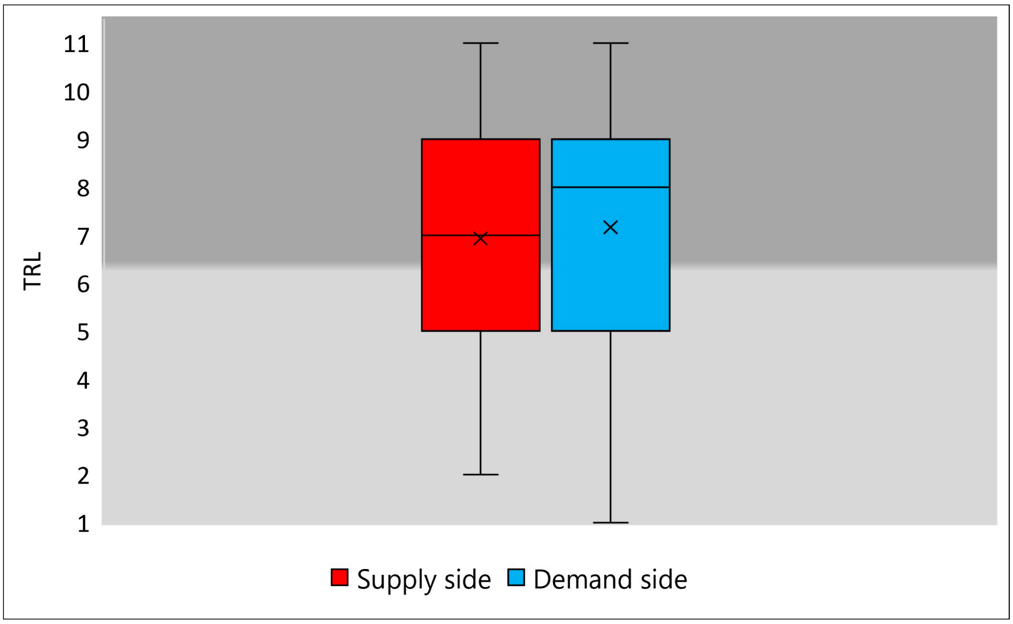


**Figure 11.** Maturity of technologies according to the prevalence of supply-side or demand-side. The boxplot shows the mean (cross), the median (horizontal line), the interquartile interval (box) where 50% of the domains are found, and the minimum and maximum TRLs of each group.

Demand-side and supply-side technologies show similar average values of TRL (TRL = 7), falling in the frontier between the pre-commercial and commercial stages. However, the median TRL is higher for demand-side technologies (TRL = 8) than supply-side technologies (TRL = 7), indicating a slightly higher level of readiness for demand-side technologies.

### *3.3. Technology Readiness and Impact of Decarbonisation Strategies*

The third section examines the risks and potential of the diverse decarbonisation strategies or pathways proposed in the literature by analysing the combination of the specific technology domains that compose them. The primary objective is to gain insights into the effectiveness of these pathways in reducing carbon emissions and facilitating the transition to net-zero emissions.

#### 3.3.1. Technology Domains in Decarbonisation Strategies

The decarbonisation pathways identified in [30], where the authors conducted an extensive literature review of over a million scientific papers and analysed the 100,000 most relevant ones in detail, are used in this work. The referred to study identified six distinct archetypical decarbonisation pathways, which are summarised in Table 4. To our knowledge, this is the largest and most comprehensive systematic review available in the literature.

**Table 4.** Description of the typology of decarbonisation pathways (cf. [30]).

| Strategy | Description |
|---|---|
| Integrated systems | This integrative approach involves macroeconomic assessments, often considering the commitments and synergies of multisectoral transformations in the energy system. |
| Technological breakthrough | This approach focuses on developing and implementing radical and incremental technological innovations to enable deep decarbonisation. |
| Demand reduction and co-benefits | This pathway considers the role of multisectoral energy demand and the potential co-benefits of decarbonisation. |
| Decarbonisation of electricity | This strategy centres on decarbonising the electricity sector through increased use of renewable energy sources and reducing fossil fuel-based generation. |
| Electrification of uses | This approach involves electrifying various end uses by replacing fossil fuel-based energy sources. |
| Land use and circularity | This combined pathway considers the role of land use in emission reduction and prioritises resource efficiency through circular economy principles. |

The technology domains were associated with the six decarbonisation pathways. This process involved cross-referencing the scientific papers' titles, abstracts, and keywords with the previously mentioned semantic dictionary terms. This approach established associations between each scientific paper, the terms within the semantic dictionary, and the 41 defined technology domains. Consequently, each technology domain was linked to one or more decarbonisation pathways. Table 5 shows the top five technology domains associated with each decarbonisation pathway.

**Table 5.** Five most significant technology domains associated with decarbonisation pathways.

| Strategy | Domains of Technologies |
|---|---|
| Integrated systems | Energy efficiency and management; Not specified renewable; Policy and circular measures; Biofuel; Energy transmission infrastructures. |
| Technological breakthrough | Biofuel; Hydrogen technology; Energy efficiency and management; Energy storage; Synthetic fuel. |
| Demand reduction and co-benefits | Energy efficiency and management; Policy and circular measures; Not specified renewable; Biofuel; Energy transmission infrastructures. |
| Decarbonisation of electricity | Energy storage; Energy efficiency and management; Hydrogen technology; Wind energy; Low carbon transportation. |
| Electrification of uses | Energy efficiency and management; Energy storage; Not specified renewable; Wind energy; Heating, ventilation and air conditioning. |
| Land use and circularity | Biofuel; Energy efficiency and management; Not specified renewable; Carbon capture, storage and use; Hydrogen technology. |

Only 12 of the 41 identified technology domains are among the five most relevant for each decarbonisation pathway. Additionally, only 11 of these fit the concept of technology domains, as the "policy and circular measures" domain is associated with some decarbonisation strategies. Nonetheless, these are more than half of the 20 domains with the highest accumulated relevance and occurrence values (see Section 3.1)—only the "energy transmission infrastructure" domain is not part of this top 20.

#### 3.3.2. Readiness Assessment

Decarbonisation pathways' readiness can now be compared based on the distribution and maturity of the associated technologies. Figure 12 presents the number of innovative technologies linked to each decarbonisation pathway, the average TRL of those technologies, and the percentage of the technologies in either commercial or pre-commercial stages. The figure derives information from the innovative technologies in the five most relevant technology domains associated with each decarbonisation pathway (from the previous sub-section).

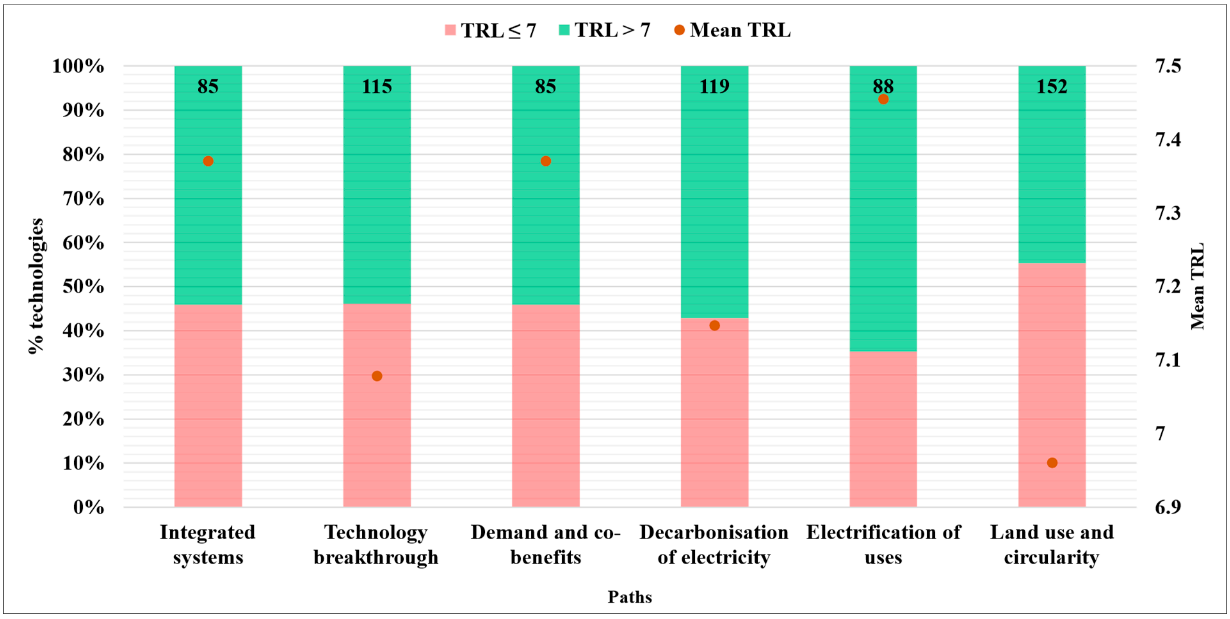


**Figure 12.** Characterisation of pathways' readiness.

The "Electrification of uses" pathway exhibits the highest average TRL value and percentage of technologies in the commercial stage (the largest green part of the bar). In contrast, the "Land use and circularity" pathway is characterised by having the lowest average TRL value and share of technologies in the commercial stage. However, "Electrification of uses" encompasses a relatively smaller number of associated technologies (88), especially when compared to "Land use and circularity" (152), "Decarbonisation of electricity" (119), or "Technology breakthrough" (115).

The pathways "Technology breakthrough" and "Decarbonisation of electricity" present similar shares regarding the number and percentage of associated technologies in pre-commercial status. However, the "Decarbonisation of electricity" has a slightly higher average TRL value. The "Integrated systems" and "Demand and co-benefits" pathways have similar shares of technologies in the pre-commercial stage to the other two pathways but with much higher average TRL values.

#### 3.3.3. Risk Assessment

The analysis of reported TRL values is enhanced by incorporating the dynamics of scientific knowledge production. This procedure helps better understand the technology risk associated with the different decarbonisation pathways.

The ratio between the relevance and occurrence rankings is a valuable indicator for evaluating technology domains in decarbonisation. In this regard, we assume emerging technologies receive more focused attention in a few research papers. Consequently, terms associated with these technologies tend to have higher relevance values, as they are more likely to appear in the keyword field and title of the documents. On the other hand, technologies that have already made progress are often cited in research papers without necessarily receiving significant attention.

It is important to note that the ranking metric is counter-intuitive: the higher the ranking, the lower the number (with the extreme being equal to unity). A higher relevance value (lower ranking) indicates greater attention from the scientific community, while higher occurrence signifies broader coverage (although not necessarily being the main focus of these studies). By combining these aspects through the ratio of relevance and occurrence rankings, we can evaluate the readiness of technologies and domains for short-term diffusion. Domains with lower ratios (relevance is dominant) are still developing, as they have received more attention in fewer studies. Conversely, domains with higher ratios (occurrence dominant) have been studied more extensively.

Crossing this ratio with the average TRLs enables us to evaluate the domains' greater (lesser) suitability to support decarbonisation in the short term (Figure 13). Domains in zone A are more consolidated as their occurrence is dominant, and the average TRL is greater than seven (commercial stage). Conversely, domains in zone C are riskier as they present a non-commercial TRL and lower relative ranking occurrence. Zones B and D correspond to intermediate cases with mixed risk situations according to average their TRL or relevance/occurrence ranking ratio.

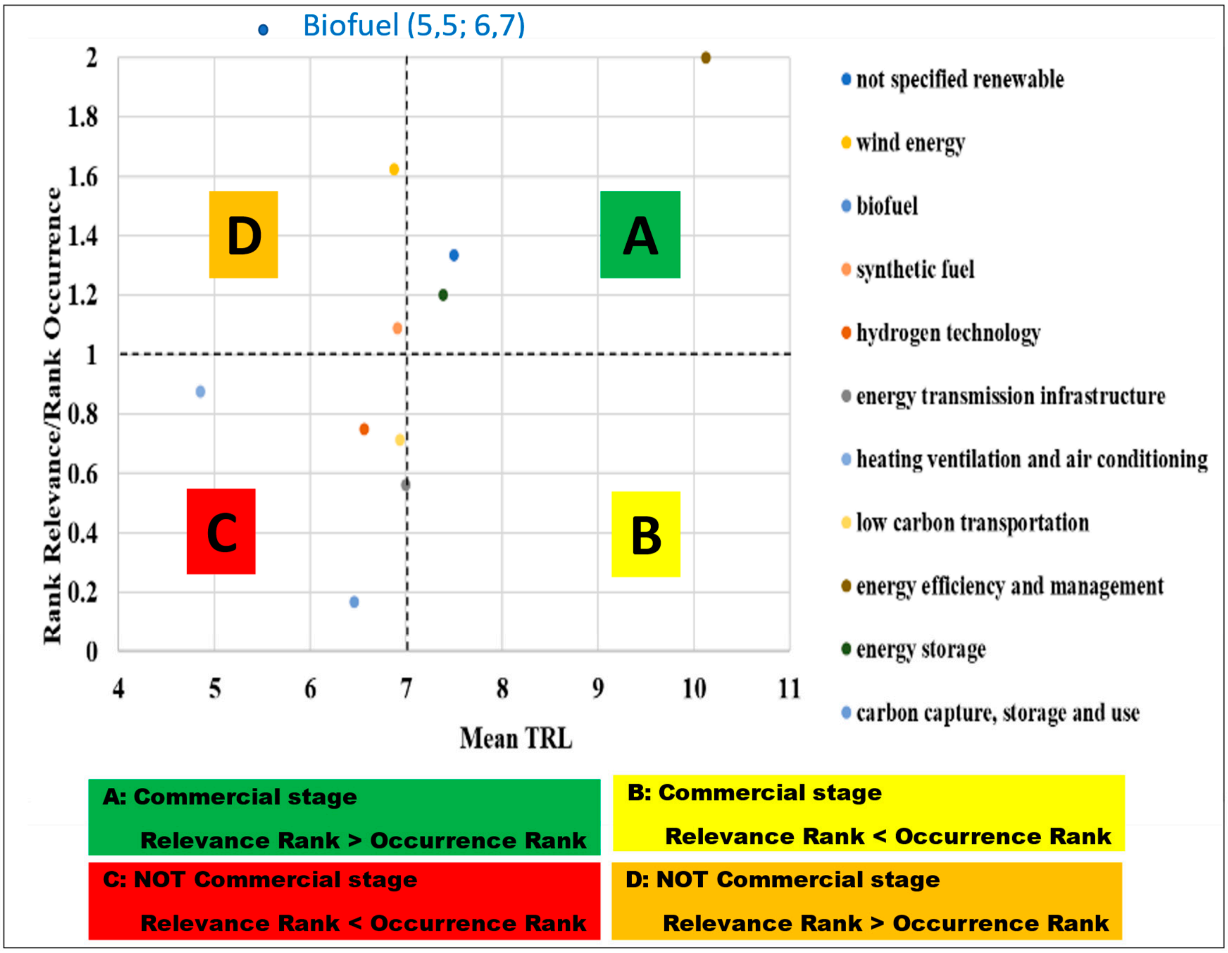


**Figure 13.** Suitability of domains to support decarbonisation.

A numerical scale was implemented to evaluate each domain according to its placement in zones A to D in Figure 13, allowing some conclusions about the risk of the different decarbonisation pathways to be extracted. This approach facilitates a comprehensive assessment of the risk associated with decarbonisation pathways. Hence, domains falling within zone A were assigned a value of $\gamma = 1$, indicating a lower level of risk. Conversely, domains located in zone C were assigned a value of $\gamma = -1$, indicating a higher level of risk. Domains in zones B and D were assigned a value $\Gamma = 0$, representing an intermediate level of risk. The risk level associated with each decarbonisation pathway was then calculated by summing up the assigned risk values for each domain associated with the pathway and dividing it by the number of associated domains ($N_i$). Table 6 synthesises this procedure.

According to this approach, the "Electrification of uses" is less risky, while the "Decarbonisation of electricity" and "Land use and circularity" pathways involve relatively more immature technology domains.

**Table 6.** Technological risk associated with each decarbonisation pathway.

| Domains | Decarbonisation Pathways | | | | | |
|---|---|---|---|---|---|---|
| | Integrated Systems | Technology Breakthrough | Demand and Co-Benefits | Decarbonization of Electricity | Electrification of Uses | Land Use and Circularity |
| Energy efficiency and management | A | A | A | A | A | A |
| Not specified renewable | A | | A | | A | A |
| Biofuel | D | D | D | | | D |
| Energy transmission infrastructure | C | | C | | | |
| Hydrogen technology | | C | | C | | C |
| Energy storage | | A | | A | A | |
| Synthetic fuel | | D | | | | |
| Wind energy | | | | D | D | |
| Low carbon transportation | | | | C | | |
| Heating, ventilation and air conditioning | | | | | C | |
| Carbon capture and storage use | | | | | | C |
| $R = \frac{\sum \gamma_i}{N_i}$ | 0.25 | 0.2 | 0.25 | 0 | 0.4 | 0 |
| Risk | - - | - - - | - - | - - - - | - | - - - - |

The letters and background colours in the table correspond to those shown in Figure 13.

### 3.3.4. Potential Assessment

Evaluating the environmental performance of a decarbonisation pathway involves assessing the potential of various technology domains associated with that pathway to mitigate $CO_2$ emissions (see Section 3.3.1). This mitigation potential depends on the capabilities of the innovative technologies within these domains. Therefore, evaluating a specific pathway's mitigation potential requires an initial assessment of the emission reduction capabilities of the individual technologies integrated within the relevant domains.

The literature provides extensive information regarding the potential impact of various individual innovative technologies on emissions reduction. The potential of a specific technology is influenced by factors such as implementation variations, efficiency, scale of deployment, operational conditions, and resource availability (e.g., [39]).

This study utilised data from the IPCC [40], which outlines the emissions mitigation potential of various individual technologies. These technologies were considered in the relevant technology domains based on their unique attributes, focusing on the top five domains associated with each pathway (see Section 3.3.1). Each technology's average emission reduction potential was used to characterise the corresponding domain. The mitigation potential of each domain was calculated as the average of these values for the technologies within that domain. Finally, the emission mitigation potential of each pathway was determined by averaging the mitigation potential of the domains integrated within that pathway.

Figure 14 illustrates the potential of each pathway to reduce net $CO_2$ emissions by 2030. The "Electrification of uses" stands out with the highest average potential for $CO_2$ emissions reduction, followed closely by the "Integrated systems" and "Demand reduction" approaches." Conversely, the "Technology breakthrough" and "Decarbonisation of electricity" pathways show the lowest potential for $CO_2$ mitigation.

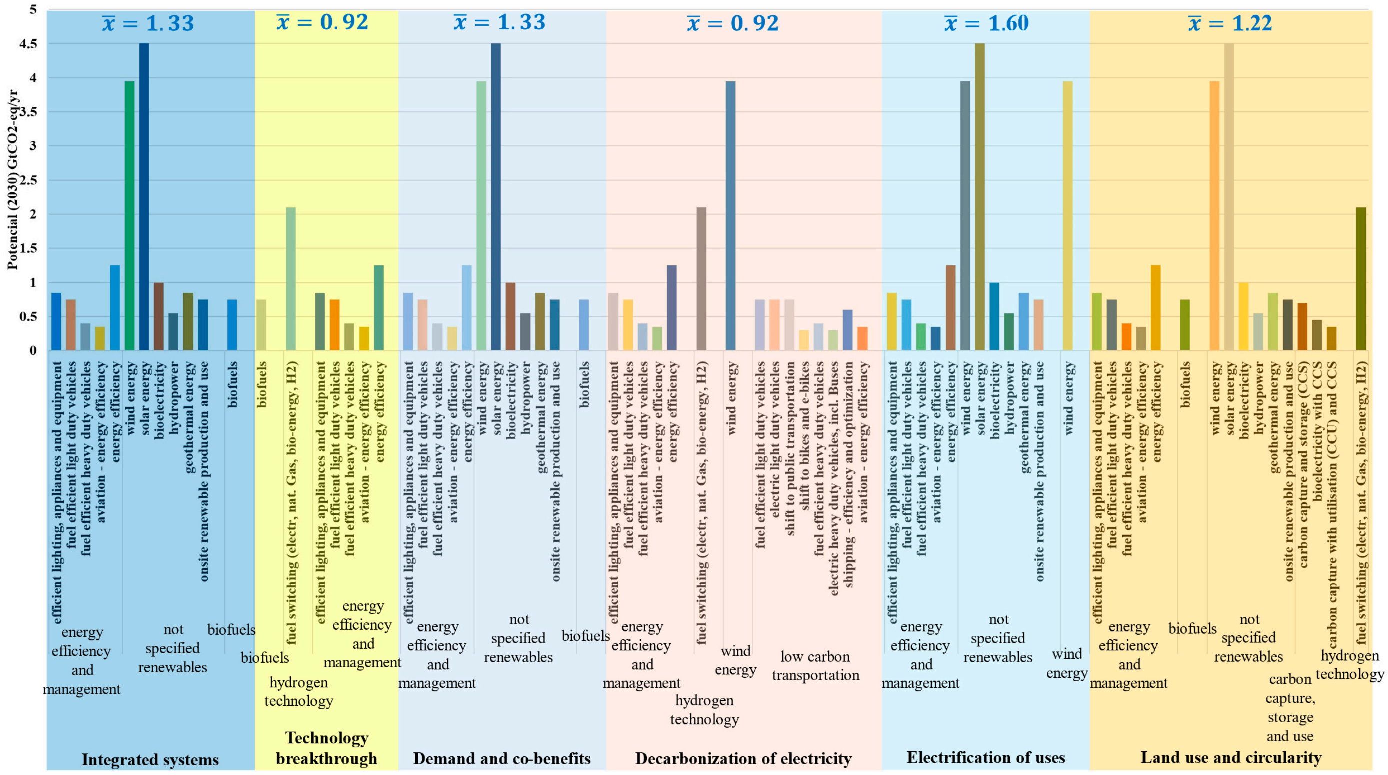


**Figure 14.** Potential to reduce net $CO_2$ emissions of each decarbonisation pathway. Source: created by the authors based on IPCC (2023).

### 3.3.5. Global Assessment

The global performance of each decarbonisation pathway may be assessed based on the previous results. Table 7 presents a summary ranking analysis of the pathway's readiness, potential, and risk. The risk assessment does not include the overall score to avoid double counting.

**Table 7.** Ranking scores of each decarbonisation pathway (the lower the number, the better the result. Similarly, for "risk level", the fewer the traces the better).

| | Decarbonisation Pathways | | | | | |
|---|---|---|---|---|---|---|
| | **Integrated Systems** | **Technology Breakthrough** | **Demand and Co-Benefits** | **Decarbonization of Electricity** | **Electrification of Uses** | **Land Use and Circularity** |
| Readiness (average TRL) | 2 | 5 | 2 | 4 | 1 | 6 |
| Potential | 2 | 5 | 2 | 5 | 1 | 4 |
| Sum | 4 | 10 | 4 | 9 | 2 | 10 |
| Rank | 2 | 5 | 2 | 4 | 1 | 5 |
| Risk level | - - | - - - | - - | - - - - | - | - - - - |

The technology assessment indicates that the "Electrification of uses" pathway is the most promising decarbonisation strategy to reduce greenhouse gas emissions in transport, buildings, and industry. However, sectors reliant on hard-to-electrify processes, like manufacturing and heavy-duty transportation, may require substantial infrastructure updates. It is worth noting that the second place is occupied by the "Integrated systems" approach and "Demand (reduction) and co-benefits", both showing low but slightly higher risks than the "Electrification of uses." In contrast, "Technology breakthrough" and "Land use and circularity" were the worst pathways in this technology assessment, performing consistently poorly in the three dimensions of readiness, potential, and risk. Therefore, policymakers willing to promote these two pathways should select policies that fit their status and minimise the technological risks.

The analysis compares the pathways individually, but they might interact in practice. For example, the "electrification of uses" pathway depends on the "decarbonisation of electricity" for advancing decarbonisation. Likewise, "Electrification of uses" may only achieve strong effects when combined with energy efficiency improvements from the "Demand reduction and co-benefits." Despite the limitation of this study of not considering the interactions between pathways, the insights are still helpful, as countries tend to focus on a few pathways (when not just a single one) for decarbonisation (cf. [30]).

Additionally, the focus on emerging technologies might partially explain the low performance of the "Decarbonisation of electricity" pathway regarding readiness, potential, and risk. Over the past decades, we saw significant advancements in renewable energy technologies that have increased the availability of established options, shifting the locus of the investment from innovation to deployment. The "Demand and co-benefits" pathway is also penalised by this focus on emerging technologies (disregarding existing technologies, such as energy efficiency and management), despite the higher number of emergent technology innovations associated with this pathway.

## 4. Conclusions and Policy Implications

A multifaceted method was devised to identify and evaluate promising innovative technologies for decarbonisation. These technologies are frequently combined in decarbonisation pathways outlined in the literature. The study assesses the readiness, risk, and potential of various decarbonisation pathways based on these technological innovations to address urgent decarbonisation needs. That is, the analysis includes technologies under development, such as nuclear fusion and small modular reactors, but excludes established fission technologies currently in operation, for the nuclear power case.

The proposed novel methodology integrates text-mining tools with various data sources, including scientific papers, patents, and research projects, to assess innovative decarbonisation technologies' readiness, risk, and $CO_2$ mitigation potential across six pathways. By mapping 368 technologies to 41 domains and linking them to pathways, the study provides a comprehensive framework for assessing decarbonisation strategies. Additionally, incorporating occurrence and relevance metrics from text-mining tools enabled us to evaluate pathway risks, offering significant methodological advances over prior studies reliant on single techniques and unique datasets (e.g., [21,23]).

Despite challenges in electrifying hard-to-transition sectors, the "Electrification of uses" pathway emerged as the most promising, demonstrating the highest readiness and mitigation potential for reducing emissions in transport, buildings, and industry. "Integrated systems" and "Demand reduction and co-benefits" followed closely, offering additional mitigation opportunities. Pathways like "Technology breakthrough" and "Land use and circularity" showed lower readiness and higher risks, requiring tailored policy interventions to mitigate these challenges.

This analysis underscores the importance of targeted investment in high-readiness pathways while recognizing the need to account for interdependencies, such as the reliance on "Electrification of uses" and "Decarbonisation of electricity."

Future research should focus on pathway interactions, refining metrics to track evolving innovations, and examining how investment strategies influence readiness and diversity in technology development.

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**Data Availability Statement:** Dataset available on request from the authors.

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