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EMERGING INNOVATIVE TECHNOLOGIES FOR ENVIRONMENTAL REVOLUTION: A TECHNOLOGICAL FORECASTING PERSPECTIVE

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Bilal Kargi: Conceptualization, Methodology, Software,Validation, Formal analysis, Resources, Revision and editing, Viewing, Funding acquisition. **Mario Coccia:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing –original draft, Project administration, Funding acquisition.

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Abstract

Objective of the Study: This study aims to identify emerging technologies with transformative potential to achieve environmental protection and foster a sustainable future.
Methodology/Approach: Utilizing technological forecasting models, the study explores and evaluates various advanced technologies, including clean steel production techniques, green hydrogen, cellular agriculture, and blockchain technology, to assess their capacity for environmental impact reduction.
Originality/Relevance*:* The study presents an interdisciplinary approach that bridges technological forecasting, environmental science, and policy analysis. It highlights the significance of these technologies in mitigating environmental degradation and promoting sustainability, offering practical insights for stakeholders and policymakers.
Main Results: The research identifies several promising technologies, such as offshore wind turbines, carbon capture and storage, clean steel production techniques, green hydrogen, cellular agriculture, and blockchain technology, that have the potential to significantly reduce environmental impact and support sustainable development.
Theoretical/Methodological Contributions: This study contributes to the literature on sustainability and innovation by offering a comprehensive evaluation of emerging technologies. It provides a methodological framework for integrating technological advancements into environmental protection strategies.
Social/Management Contributions: The findings equip policymakers with a roadmap of technological advancements, facilitating informed decision-making aimed at creating a future characterized by minimal environmental degradation. The study addresses the urgent need for innovative solutions to environmental challenges and guides the transition towards a more sustainable society.

Keywords: emerging technologies, innovative technologies, environmental revolution, sustainability, technological forecasting.

Emergindo tecnologias inovadoras para uma revolução ambiental: uma perspectiva de previsão tecnológica

Resumo

Objetivo do Estudo: Este estudo visa identificar tecnologias emergentes com potencial transformador para alcançar a proteção ambiental e fomentar um futuro sustentável.
Metodologia/Abordagem: Utilizando modelos de previsão tecnológica, o estudo explora e avalia várias tecnologias avançadas, incluindo técnicas de produção de aço limpo, hidrogênio verde, agricultura celular e tecnologia blockchain, para avaliar sua capacidade de redução de impacto ambiental.
Originalidade/Relevância: O estudo apresenta uma abordagem interdisciplinar que conecta previsão tecnológica, ciência ambiental e análise de políticas. Destaca a importância dessas tecnologias na mitigação da degradação ambiental e na promoção da sustentabilidade, oferecendo insights práticos para stakeholders e formuladores de políticas.
Principais Resultados*:* A pesquisa identifica várias tecnologias promissoras, como turbinas eólicas offshore, captura e armazenamento de carbono, técnicas de produção de aço limpo,

hidrogênio verde, agricultura celular e tecnologia blockchain, que têm o potencial de reduzir significativamente o impacto ambiental e apoiar o desenvolvimento sustentável.
Contribuições Teóricas/Metodológicas: Este estudo contribui para a literatura sobre sustentabilidade e inovação, oferecendo uma avaliação abrangente de tecnologias emergentes. Ele fornece uma estrutura metodológica para integrar os avanços tecnológicos nas estratégias de proteção ambiental.
Contribuições Sociais/Gerenciais: Os resultados fornecem aos formuladores de políticas um roteiro de avanços tecnológicos, facilitando uma tomada de decisão informada voltada para a criação de um futuro caracterizado por mínima degradação ambiental. O estudo aborda a necessidade urgente de soluções inovadoras para os desafios ambientais e orienta a transição para uma sociedade mais sustentável.

Palavras-chave: tecnologias emergentes, tecnologias inovadoras, revolução ambiental, sustentabilidade, previsão tecnológica.

Tecnologías innovadoras emergentes para la revolución ambiental: una perspectiva de previsión tecnológica

Resumen

Objetivo del Estudio: Este estudio tiene como objetivo identificar tecnologías emergentes con potencial transformador para lograr la protección ambiental y fomentar un futuro sostenible.
Metodología/Enfoque: Utilizando modelos de previsión tecnológica, el estudio explora y evalúa diversas tecnologías avanzadas, incluyendo técnicas de producción de acero limpio, hidrógeno verde, agricultura celular y tecnología blockchain, para evaluar su capacidad de reducción del impacto ambiental.
Originalidad/Relevancia: El estudio presenta un enfoque interdisciplinario que une la previsión tecnológica, la ciencia ambiental y el análisis de políticas. Destaca la importancia de estas tecnologías en la mitigación de la degradación ambiental y en la promoción de la sostenibilidad, ofreciendo conocimientos prácticos para las partes interesadas y los responsables de la formulación de políticas.
Principales Resultados: La investigación identifica varias tecnologías prometedoras, como turbinas eólicas marinas, captura y almacenamiento de carbono, técnicas de producción de acero limpio, hidrógeno verde, agricultura celular y tecnología blockchain, que tienen el potencial de reducir significativamente el impacto ambiental y apoyar el desarrollo sostenible.
Contribuciones Teóricas/Metodológicas: Este estudio contribuye a la literatura sobre sostenibilidad e innovación al ofrecer una evaluación integral de las tecnologías emergentes. Proporciona un marco metodológico para integrar los avances tecnológicos en las estrategias de protección ambiental.
Contribuciones Sociales/De Gestión: Los hallazgos dotan a los responsables de políticas de una hoja de ruta de los avances tecnológicos, facilitando la toma de decisiones informadas con el objetivo de crear un futuro caracterizado por una mínima degradación ambiental. El estudio aborda la urgente necesidad de soluciones innovadoras a los desafíos ambientales y guía la transición hacia una sociedad más sostenible.

Palabras clave: tecnologías emergentes, tecnologías innovadoras, revolución ambiental, sostenibilidad, previsión tecnológica.

Introduction

The 1860s marked a turning point. Following the social, economic, and technological advancements of the Industrial Revolutions, scientific inquiry into human impact on the environment began to blossom (Marsh, 1864; Fowler et al., 2020). However, this progress was a double-edged sword. The burgeoning industries relied heavily on fossil fuels like coal, natural gas, and petroleum to power key sectors like heavy organic chemicals, synthetic materials, and textiles, leading to a significant increase in pollution and environmental degradation (Ayres, 1990, 1990a; Campbell, 2002; Coccia, 2008, 2014). While some argue this era ushered in novel technologies that fostered economic growth (Ayres, 1998; Sterner et al., 1998; Coccia, 2015), research suggests it also fueled a rapid rise in the global population, energy consumption, and atmospheric CO2 levels, fundamentally altering the course of human history (Fowler et al., 2020).

Industrialization, urbanization, and the relentless march of human activity have undeniably intensified our influence on the biosphere. Widespread fossil fuel dependence has triggered a chain reaction. Population growth and economic expansion have resulted in a society characterized by high consumption, resource depletion, vast amounts of solid waste, and significant environmental changes (Chin et al., 2013; Coccia, 2021; Kaza et al., 2018). The economic prosperity brought about by industrialization in developed and developing nations has, unfortunately, come at a heavy price – environmental degradation, fossil fuel pollution, and detrimental health effects for populations worldwide (Adam, 2021; Ali et al., 2021; Belpomme et al., 2007; Coccia, 2017, 2018, 2019, 2020).

This undeniable correlation between human activity and its environmental consequences has led to the concept of the Anthropocene – a new geological epoch defined by the profound impact of humans on Earth's systems (Crutzen & Stoermer, 2000; Zalasiewicz et al., 2011). The exact starting point of the Anthropocene is still a topic of debate. Some, like Ruddiman (2003), propose it began with the rise in CO2 levels 6,000 years ago, while others argue for the industrial era's pivotal role in environmental pollution marking its inception (Crutzen & Stoermer, 2000; Steffen et al., 2007). Regardless of the exact date, the significant contribution of greenhouse gas emissions to environmental deterioration is undeniable (Hausfather & Peters, 2020; Moss et al., 2010; Tollefson, 2020). These emissions are projected to cause a global temperature rise of up to

5°C by 2100, alongside the thawing of permafrost – a major environmental threat with cascading effects (Hausfather & Peters, 2020; Tollefson, 2020).

The good news is that achieving carbon neutrality – a state where CO2 emissions are balanced by removal – can mitigate this dangerous climate change scenario (Chapman et al., 2022). Research suggests that new technologies focused on green hydrogen production, clean manufacturing processes, solar thermal energy storage, and carbon capture can pave the way towards this goal (Chapman et al., 2022; National Academies of Sciences, 2022; NIST, 2022). As Linstone (2010) aptly states, "the global future will strongly depend on our willingness to take near-term action for a sustainable long-term future" (p.147).

Therefore, a critical aspect of addressing this challenge lies in exploring novel technological and ecological innovation pathways. These innovations should not only facilitate an energy transition towards sustainable socio-economic systems but also simultaneously safeguard the atmosphere, lithosphere, hydrosphere, and the entire biosphere – the very foundation of life on Planet Earth (Sanni & Verdolini, 2022). The following section delves into the methodologies for investigating these crucial areas at the intersection of science and society.

In this context, a main research question that this study endeavors to clarify is:

What are the principal directions of technological trajectories and eco-innovations that can support the ecological transition (the gradual shift from fossil fuels to renewable and sustainable energy sources) in modern socioeconomic systems to support sustainable development?

The sections after the theoretical framework, delves into the methodologies for investigating these crucial areas of research at the intersection of environment and society in a perspective of sustainability. The study uses Scopus (2022), a multidisciplinary database covering journal articles, conference proceedings, and books to collect and analyze data of articles and patents for sustainable technologies. A regression analysis based on a log-linear model of time series and log-log model of technological evolution including relative growth of Y (patents) in relation to scientific production X of technologies under study suggests promising technological technologies directed to sustainability. Analysis of findings and an in-depth discussion explain the results of statistical analyses and visualize trends to provide main implications to support innovation policies for ecological transition directed to sustainability.

Theoretical background and framework

Ayres (1998) points out that fossil fuels and breakthrough technologies have been key to human development throughout history (Sterner et al., 1998, p. 254). The post-World War II industrial boom relied heavily on coal, natural gas, and petroleum-based materials (Campbell, 2002). These fuels drove economic growth and innovation, particularly in industries like heavy chemicals, synthetic materials, and petrochemicals (Ayres, 1990a, 1990b; Coccia, 2008). However, this industrialization and technological progress also contributed to urbanization, population growth, and serious environmental pollution, leading to significant human and social changes (Belpomme et al., 2007). In 1972, Meadows et al. warned that the Earth's natural resources and ecosystems might not be able to support unchecked economic and population growth beyond 2100, even with technological advances. Their prediction highlighted several critical factors, such as population growth, declining agricultural output, depletion of non-renewable resources, and increased industrial production and pollution. Still, the Club of Rome's report (Meadows et al., 1972) suggested that humanity could sustain itself indefinitely if limits were placed on resource use and production, and a shift toward recycling and sustainable development was embraced to meet current needs without harming the environment for future generations.

Adam (2021) refers to the United Nations' projection that the global population will hit around 11 billion by 2100. However, a 2014 report from the International Institute for Applied Systems Analysis in Austria estimates the population peaking at 9.4 billion by the 2070s, before falling to 9 billion by the 2090s. Similarly, researchers at the University of Washington predict a peak of 9.7 billion around 2060, followed by a decline to roughly 8.8 billion by 2100. These varying estimates are due to uncertainties in fertility rates and unforeseen events, such as pandemics (e.g., COVID-19), conflicts, and natural disasters. High population growth raises several socioeconomic issues (Global Change, 2022), such as increased extraction and consumption of natural resources (fossil fuels, minerals, water), greater urbanization, higher production and consumption of goods, waste generation, pollution, and environmental degradation (La Scalia et al., 2022). These are some of the main drivers of climate change and global warming (Coccia, 2024). In response, many countries continue to depend on cheap fossil fuels to boost their economies, especially after crises like the COVID-19 pandemic or wars. Unfortunately, this reliance on fossil fuels is predicted to drive a global temperature increase of +5°C by the end of the century, along with permafrost thawing (Hausfather & Peters, 2020; Moss et al., 2010; Tollefson, 2020).

The long-term effects of climate change on human society are significant (IPCC, 2007; 2013; NASA Global Climate Change, 2022). These include longer frost-free seasons, changes in precipitation patterns, more intense droughts and heat waves, stronger hurricanes, and a rise in global sea levels—potentially by as much as 1 to 10 feet by 2100 due to melting ice. The current global economy, still heavily reliant on cheap fossil fuels and nuclear power, continues to cause pollution, while renewable energy remains expensive and insufficient to meet the energy needs of most countries. Scholars argue that societies need to be more resilient and shift toward ecological transitions to address the extreme environmental and social challenges ahead (Campbell, 2002).

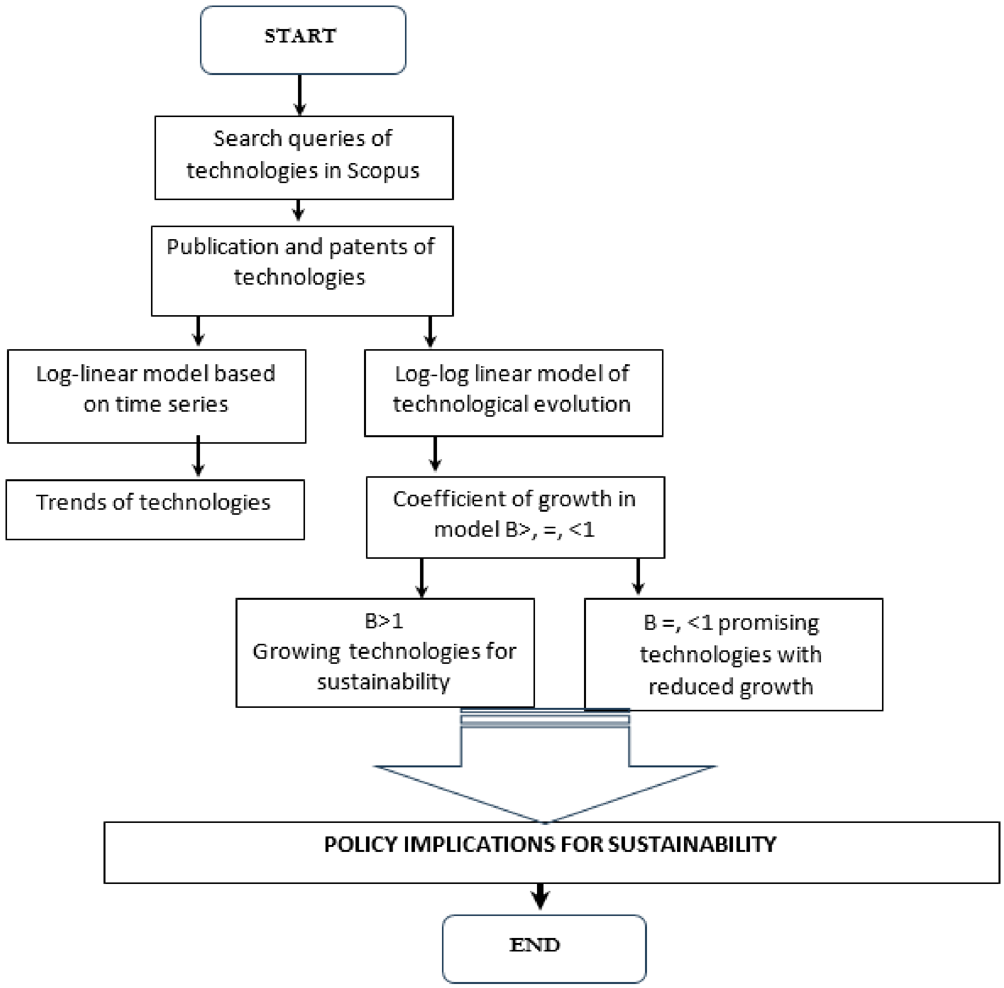
Ali et al. (2021) show that in developed countries, natural resource depletion is closely linked to environmental degradation, while renewable energy sources positively impact the environment. Human activities have been the main contributors to environmental damage and the decline of atmospheric oxygen. As a result, societies now need to take urgent action to reduce environmental risks by adopting sustainable technologies and pursuing ecological transitions to improve both the environment and human well-being. The following section outlines the methods for identifying sustainable technologies that could help mitigate environmental challenges and conserve natural resources for a sustainable future.

Study Design

The following figure 1 shows the sequential flow chart of the study design here.

Figure 1

Sequential flow chart of the research methodology here to detect evolution of sustainable technologies



Sources and data collection

The research hinges on a powerful tool: Scopus (2022). This comprehensive database acts as a digital library, encompassing not just academic journals and books, but also conference proceedings and even patent records from intellectual property offices worldwide (Gonzalo et al., 2022; Li et al., 2022; Wang et al., 2022). This rich resource empowers researchers to identify cutting-edge advancements in promising technologies that hold the key to ecological transition and a sustainable future (e.g., Gonzalo et al., 2022; Balaji & Rabiei, 2022).

Within Scopus, the "Search documents" function serves as the cornerstone of this investigative process. By leveraging keywords (outlined in Table 1, not shown here) meticulously chosen to correspond to these transformative technologies, researchers can cast a wide net. The search encompasses article titles, abstracts, and keywords within the database, allowing researchers to pinpoint relevant scientific papers and patents (specific search terms can be found in Table 1). The references included here (e.g., Gonzalo et al., 2022; Balaji & Rabiei, 2022) offer a glimpse into the kind of valuable studies this approach can unearth.

The data collection for this study spanned from March 30, 2022 (initial download) to November 15, 2022 (data integration). Information from 2022 was deliberately excluded due to its ongoing nature and the ever-evolving scientific and technological ecosystem. As Coccia et al. (2022) aptly point out, scientific publications (articles, conference papers, etc.) and patents serve as the bedrock for scientific and technological analyses. Technologies under study are selected according to current literature in environmental and sustainability sciences (Gonzalo et al., 2022; Li et al., 2022; Wang et al., 2022; Balaji & Rabiei, 2022; Elavarasan et al., 2022; Chapman et al., 2022; Gadikota, 2021; Bapat et al., 2022; Moritz et al., 2022; Esmaeilzadeh, 2022; Strepparava et al., 2022).

Here, the goal is to identify novel technological pathways that can not only combat environmental degradation but also foster ecological transition and sustainability within socio-economic systems.

To achieve this ambitious goal, the retrieved information is meticulously categorized into four distinct technological groups based on their primary applications and potential contributions to a sustainable future:

- Renewable energy technologies: This group encompasses technologies focused on harnessing the power of renewable energy sources, such as wind turbines that generate electricity.

- Renewable energy and storage technologies: This category delves into technologies that go beyond mere generation of renewable energy. It encompasses solutions for storing this clean energy for later use, like thermal energy storage systems.

- Sustainable products and clean manufacturing processes: This group zooms in on technologies that promote the development and production of sustainable products through clean manufacturing processes. Clean steel production exemplifies this category. Additionally, technologies aimed at CO2 capture and utilization, such as catalytic conversion and CO2 copolymerization, also fall under this umbrella.

a) Measures

For evaluation purposes, the study employs two key metrics: Number of scientific products: The total number of articles and scientific products retrieved using the search queries (from Table 1) serves as a proxy for the scientific progress related to technological advancement. Data from 2022 is excluded due to its incompleteness.

Patent analysis: By analyzing the number of patents retrieved using the search terms (excluding data from 2022), the research can identify potential innovations that can contribute to sustainable development. This methodology provides a systematic framework for identifying and analyzing promising technologies for ecological transition and sustainability. By focusing on scientific publications and patents, the research aims to uncover new technological advancements that can address environmental challenges and promote sustainable socio-economic systems.

Beyond the identified technological groups, further research could explore other promising areas like biomimicry, which draws inspiration from nature's design principles for sustainable solutions. Additionally, social and economic factors that can influence the adoption and implementation of these technologies warrant investigation.

Table 1

Queries and data analyzed

Inquiries about publications and patents pertaining to sustainable technologies	Data analyzed until 2021*	
Renewable Energy Sources	**Documents/ Articles**	**Patents**
Wave energy systems harness the power of ocean waves.	78	341
Offshore wind turbines generate clean electricity from wind at sea.	6978	3791
Floating solar panels capture sunlight on water bodies.	76	43
Green hydrogen is a clean fuel produced from renewable energy sources.	1000	172
Blue hydrogen is a clean fuel produced from natural gas with carbon capture.	77	198
Geothermal energy utilizes heat from the Earth's core to generate electricity.	317	182
Concentrated solar power (CSP) focuses sunlight to create high temperatures for electricity generation.	1841	2451
Renewable Energy Storage and Carbon Capture		
Heat storage systems store excess thermal energy for later use.	15,573	8888
Carbon capture and storage (CCS) captures carbon emissions from power plants and stores them underground.	7544	1365
Post-combustion CCS captures carbon from flue gas after combustion.	631	286
Pre-combustion CCS captures carbon from fuel before combustion.	90	70
Oxy-fuel combustion burns fuel in pure oxygen, making it easier to capture carbon dioxide.	89	227
Carbon-negative technologies remove more carbon from the atmosphere than they emit.	34	10
CO2 Capture and Utilization		
Electrochemical conversion uses electricity to transform CO2 into useful products.	510	376
Photocatalytic conversion uses sunlight and catalysts to convert CO2 into valuable chemicals.	424	32
Photothermal catalytic conversion combines sunlight and heat with catalysts to utilize CO2.	4	0
Solar energy conversion uses sunlight to convert CO2 into fuels or chemicals.	300	194
Catalytic conversion uses catalysts to transform CO2 into new materials.	776	2433
Bioconversion uses microorganisms to convert CO2 into biofuels or other products.	896	1060
Copolymerization incorporates CO2 into polymers for various applications.	1215	4283
Mineral carbonation converts CO2 into stable carbonate minerals.	769	168
Sustainable Products and Processes		
Aluminum batteries offer a potentially sustainable alternative to lithium batteries.	228	1033
Clean steel production minimizes environmental impact compared to traditional methods.	92	28
Sustainable ammonia production focuses on environmentally friendly ways to produce ammonia.	1058	3370
Cellular agriculture grows meat products directly from cells, reducing environmental impact.	81	21
Blockchain technology can be used to promote sustainability practices in supply chains.	259	60

Note: * the year 2022 is not considered because data were ongoing when the analysis is performed; this aspect does not affect the detection and trend of on-going trajectories of technologies.

Table 2 shows the main research string used in this study, inserted in the window of search documents in Scopus (2022). The words indicated in table 2 are used within quotation marks to identify with accuracy the technologies under study and in some cases they are combined with the Boolean operator AND in order to examine the technologies related to our study.

Table 2

Main research strings used to collect data

wave power systems
offshore wind turbine
floating photovoltaic systems
green hydrogen
blue hydrogen
geothermal technology
thermal technology
thermal energy storage
carbon capture and storage
carbon capture and storage (CCS) post-combustion
carbon capture and storage pre-combustion
carbon capture and storage oxy-fuel combustion
carbon-negative technologies
electrochemical conversion AND CO_2
photocatalytic conversion AND CO_2
photothermal catalytic conversion AND CO_2
solar energy conversion AND CO_2
catalytic conversion AND CO_2
bioconversion AND CO_2
copolymerization AND CO_2
mineral carbonation AND CO_2
aluminium battery
clean steel production
ammonia AND sustainability
cellular agriculture
blockchain technology AND sustainability

Source: Coccia, 2017a; Kargı et al., 2023.

b) *Models of technological progress and data analysis*

This study discusses two steps in a scientific analysis process. First, it highlights the importance of logarithmic transformation to achieve a normal distribution of variables, likely for statistical tests requiring this assumption (reference not provided). This ensures reliable results from the chosen parametric analysis method.

The second step describes data collection. The authors plan to use the "Search documents" feature in Scopus (2022) to obtain time series data on publications and patents related to a specific technology (technology i). The details of the analysis model used to examine these trends will be explained in the following part of this paper.

$$\log y_{i,t} = a + b\ time + u_{i,t} \quad (1)$$

–$y_{i,\,t}$ is scientific products *or* patents of technology *i* at the *time t*

–*a* is a constant; *b* is the coefficient of regression; $u_{\,i,t}$ = error term of technology *i* at the *time t*

–*log* is logarithmic with base *e*= 2.7182818

The text continues to explain the analysis method used to examine trends in technology development. The Ordinary Least-Squares (OLS) method is employed to estimate the relationship between two variables (parameters *a* and *b*) in the model (1).

Thirdly, using a model of technical development in which the number of patents (Y) is a function of the amount of scientific production (X) over time, the potential expansion of sustainable technologies is examined (cf., Sahal, 1981). This method gives the relative rate of technological progress, which illustrates how the accumulation of scientific publications drives the evolution of technological units (patents) over time. To put it briefly, the model [2] examines how technology has evolved *i*, assessing how the increase of patents, Y*i*, is impacted by the development and accumulation of scientific information (based on publications X*i*) (cf. Sahal, 1981):

$$\log Yi = \log A + B \quad \log Xi \quad (2)$$

- *A*=constant
- *B* = the relative growth coefficient that gauges how patents, or Y, have changed in relation to technology *i*'s (X) scientific output.

Specifically, the model [2]'s coefficient *B* value shows several patterns of technical growth as indicated by:

- $B < 1$, over time, the evolution of patents in technology has slowed down in comparison to the growth in scientific productivity.
- $B = 1$, as publications and patents increase proportionately, technology advances.
- $B > 1$, faster technical progress over time, with disproportionate improvements in technology as measured by patents Y compared to publications.

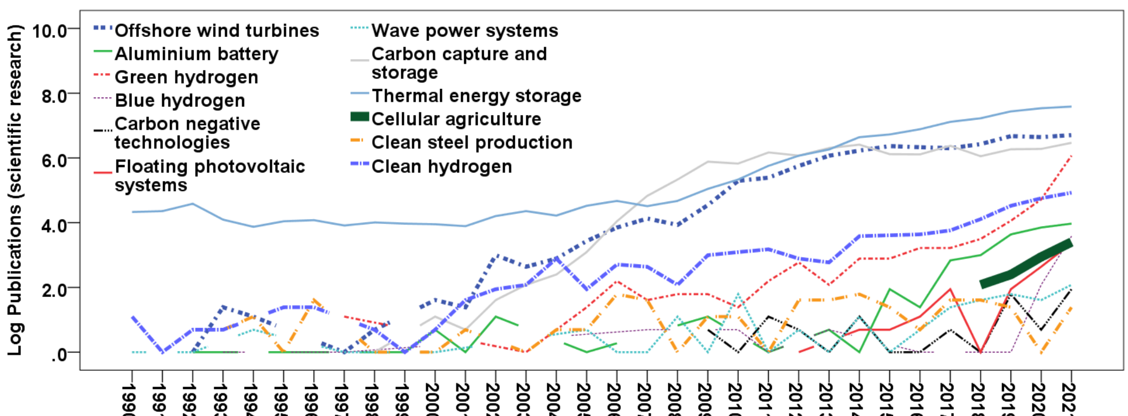
The Ordinary Least-Squares (OLS) approach is also used to estimate the linear parameters of this *log-log model* [2]. IBM SPSS Statistics 26® is the program used for statistical analysis.

Empirical Results

Model [1] is a tool used to visualize patterns in patents and publications pertaining to sustainable technology. Specifically, figure 2 illustrates how various technologies have evolved in light of knowledge expansion as indicated by published papers, while figure 2 illustrates how technologies have evolved in light of patents.

Figure 2

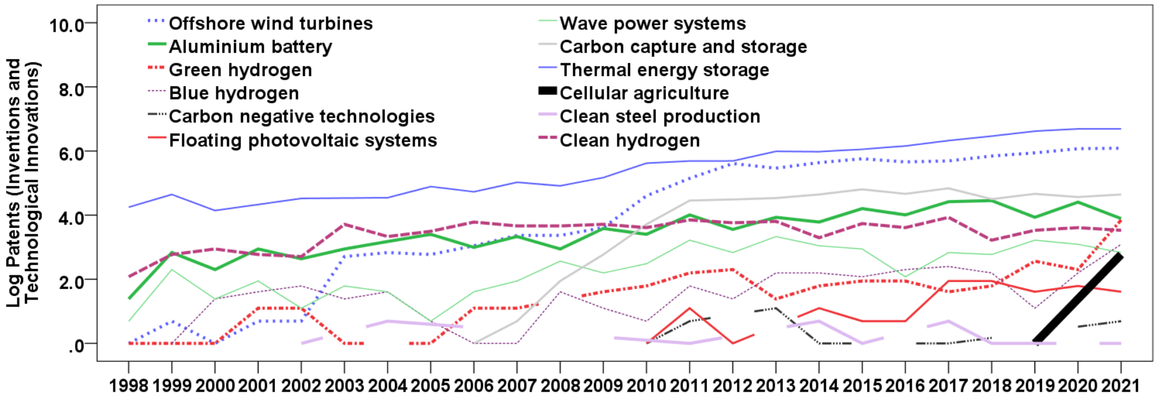
Trends in publishing related to sustainable technologies.



Note: The timeframe begins in 1990 in order to better illustrate the changes.

Figure 3

Paths taken by technologies that use patents to achieve sustainability.



Note: the time frame begins in 1998 to better illustrate the tendencies

The relative rate of expansion of various technologies throughout time is evaluated by combining and analyzing the trends of figures 2 and 3, along with the underlying data, using model [2].

Table 3

Relationships between patents on scientific research that produces innovations aimed at sustainability in the future that are estimated

Renewable Energy Sources	**Coefficient *B***	**Constant A**	***F-test***	**R^2**
Wave energy systems harness the power of ocean waves.	.840**	1.160***	7.68**	0.22
Offshore wind turbines generate clean electricity from wind at sea.	**1.062*** **	–0.968**	391.65***	0.95
Floating solar panels capture sunlight on water bodies.	0.309	0.840*	2.75	0.28
Green hydrogen is a clean fuel produced from renewable energy sources.	0.584***	0.101	45.84***	0.74
Blue hydrogen is a clean fuel produced from natural gas with carbon capture.	0.542*	.956***	6.33*	0.30
Geothermal energy utilizes heat from the Earth's core to generate electricity.	0.840***	–0.240***	32.95***	0.54
Concentrated solar power (CSP) focuses sunlight to create high temperatures for electricity generation.	0.980***	0.330	104.73***	0.71
Renewable Energy Storage and Carbon Capture	**Coefficient *B***	**Constant A**	***F-test***	**R^2**
Heat storage systems store excess thermal energy for later use.	0.935**	0.036	319.33***	0.87
Carbon capture and storage (CCS) captures carbon emissions from power plants and stores them underground.	**2.270*** **	–9.690***	169.81***	0.91
Post-combustion CCS captures carbon from flue gas after combustion.	1.000***	–0.840	32.24***	0.69
Pre-combustion CCS captures carbon from fuel before combustion.	0.270	1.010*	1.14	0.01
Oxy-fuel combustion burns fuel in pure oxygen, making it easier to capture carbon dioxide.	0.660***	1.270***	16.14***	0.44
Carbon-negative technologies remove more carbon from the atmosphere than they emit.	0.039	0.383	0.02	.004
CO2 Capture and Utilization	**Coefficient *B***	**Constant A**	***F-test***	**R^2**
Electrochemical conversion uses electricity to transform CO2 into useful products.	**1.740*** **	–2.172**	52.82***	0.72
Photocatalytic conversion uses sunlight and catalysts to convert CO2 into valuable chemicals.	.384**	–.364	10.83**	0.45
Photothermal catalytic conversion combines sunlight and heat with catalysts to utilize CO2.	--	--	--	--
Solar energy conversion uses sunlight to convert CO2 into fuels or chemicals.	0.590***	.560*	29.50***	0.59
Catalytic conversion uses catalysts to transform CO2 into new materials.	0.440***	2.800***	70.28***	0.63
Bioconversion uses microorganisms to convert CO2 into biofuels or other products.	**1.040*** **	–.250	180.43***	0.81
Copolymerization incorporates CO2 into polymers for various applications.	0.570***	2.720***	63.52***	0.63
Mineral carbonation converts CO2 into stable carbonate minerals.	0.640***	–.340	19.47***	0.49
Sustainable Products and Processes	**Coefficient *B***	**Constant A**	***F-test***	**R^2**
Aluminum batteries offer a potentially sustainable alternative to lithium batteries.	.600***	2.295***	19.71***	0.461
Clean steel production minimizes environmental impact compared to traditional methods.	–0.063	0.379	0.046	.005

Sustainable ammonia production focuses on environmentally friendly ways to produce ammonia.	**1.890*****	0.81***	284.72***	0.91
Cellular agriculture grows meat products directly from cells, reducing environmental impact.	**2.760***	–6.65*	374.61*	.99
Blockchain technology can be used to promote sustainability practices in supply chains.	0.810	–0.04	48.73	0.96

Note: *log-log* framework. Technology-related patents are the dependent variable. Technology publications *i* are the explanatory variable; they are *** significant at 1‰, ** significant at 1%, and * significant at 5%. *F* is the ratio of the variance that the model can explain to the variation that cannot be explained. The coefficient of determination is known as R^2. Technologies with a B>1 outlook on technological growth are bolded.

Table 3's coefficient of technical evolution, *B*>1, indicates that some technologies have grown disproportionately (and more quickly) over time, which could have an impact on future sustainable social and economic transformation. In contrast, several technologies in Table 3 have B<1, indicating a slower growth. This is probably due to the fact that these technologies are still in the early stages of technological evolution, meaning that even if they have patents, they are not yet developed enough to be fully used in markets. Lastly, some technologies are not taken into consideration since they do not have a substantial coefficient *B*.

Technology for Constructing Sustainability is Discussed

A key takeaway from Table 3's regression coefficients is the identification of technologies with a B value greater than 1. These technologies, including offshore wind turbines, represent faster pathways for technological evolution towards a sustainable future. Offshore wind turbines exemplify market-accepted technological innovation, while others like Carbon Capture Storage (CCS) are still under research and development (R&D). Similarly, CO2 electrochemical conversion, bioconversion of CO2, sustainable ammonia production, and cellular agriculture are all in the R&D stage.

Exploring the potential uses of these technologies can provide valuable insights into fostering a positive energy transition. Discussions surrounding these advancements can help define crucial aspects for constructing sustainable socioeconomic systems. It's important to recognize the different development stages. While offshore wind turbines are driving market progress, technologies like CCS remain immature for widespread adoption in the current market. This distinction highlights the need for continued advancements to facilitate a smooth ecological transition and ensure a sustainable future for our global society.

The text concludes by hinting at the potential of a specific modern technology, likely with a B>1 value, that is commercially available due to its rapid scientific and technological progress. However, the specific technology isn't mentioned.

- Wind power can be harnessed from either land (onshore) or sea (offshore) locations, with offshore farms offering several benefits. Studies by Gonzalo et al. (2022) suggest that offshore wind farms can be larger, more powerful, and have a lower environmental impact. Wind technology, particularly newer turbine generations, is considered a significant and cost-effective source of renewable energy (Nemet, 2006; Pérez & Ponce, 2015). Technological advancements are continuously driving down costs by over 30% through improvements in labor productivity (e.g., faster installation) and material selection (e.g., using lighter, stronger fiberglass) (Elia et al., 2020). Research by Elia et al. (2020) and Oh (2020) highlights "learning by deployment" as a major factor in reducing wind turbine technology costs between 2005 and 2017. This signifies that as more turbines are deployed, the industry gains experience and optimizes production processes. Wang et al. (2021) documented significant advancements in wind power technology between 2005 and 2019, with global installed wind capacity exceeding 651 GW by 2019, reflecting an 1100% increase. A key driver of this growth is the shift towards offshore wind farms. Stronger, more consistent winds and the ability to install larger turbines (up to 17 MW compared to the current 6 MW onshore limit) make offshore locations highly attractive (Li et al., 2022). Research by Li et al. (2022) even suggests that combining offshore wind with tidal stream energy systems can further reduce energy costs for coastal communities. Examples of countries leading the offshore wind revolution include South Korea (over 10,000 MW), China (current capacity exceeding 43,300 MW), and the United Kingdom (boasting one of the world's largest offshore wind farms) (Chen et al., 2023).

In addition to offshore wind turbines, this study highlights several innovative energy-transition technologies that are still in the early stages of development and have not yet been widely released or adopted in the market, but are focused on producing renewable energy and capturing and storing CO_2:

- Carbon Capture Storage (CCS) and Carbon Capture, Utilization, and Storage (CCUS) are emerging technologies with the potential to significantly reduce our carbon footprint. As highlighted by Balaji & Rabiei (2022), these technologies can tackle CO_2 emissions from major industrial sectors like steel, cement, and petrochemicals. Furthermore, CCUS offers the possibility of converting captured CO_2 into valuable products like fuels, chemicals, and even agricultural materials (Ghiat & Al-Ansari, 2021; Peplow, 2022). This shift from a reliance on fossil fuels to a low-carbon economy is crucial for a sustainable future. While many CCS and CCUS technologies are still under development with ongoing market trials (National Academies of Sciences, 2022), their potential is undeniable. CCS, when integrated with existing power plants, can dramatically reduce CO_2 emissions by 80-90% compared to uncaptured emissions (IEA, 2022). Existing CCUS facilities are already capturing a significant amount of CO_2 globally, reaching nearly 45 Mt according to Gadikota (2021). Importantly, these novel chemical processes can also decrease the overall carbon footprint of various industrial processes by optimizing energy and resource conversion. Despite initial delays in implementation, CCUS is gaining momentum with over 300 projects currently in various development stages (CTCN, 2022). By 2030, projections estimate roughly 200 operational capture plants with a combined annual capture capacity exceeding 220 million tons of CO_2 (IEA, 2022; Resources Magazine, 2022). Elavarasan et al. (2022) emphasize the need for strategic decarbonization plans, particularly in Europe, that leverage CCS and CCUS technologies for hard-to-decarbonize sectors like industry (Chapman et al., 2022; NIST, 2022). These advancements offer a promising path towards achieving climate neutrality.

- CO_2 capture and utilization using electrochemical conversion (CCU). The electrochemical conversion of CO_2 into products, such as syngas, methane, methanol, or dimethylether with the addition of renewable energy, is one of the technologies with expanding prospects for CCU. The Sunfire company, which generated high-quality diesel fuel in 2015, and ETOGAS, which created a technique that uses alkaline pressure electrolysis of H_2O to make H_2, which then combines with CO_2 to yield CH_4 (Methane), are the two main examples of this technology. Although the Sunfire and ETOGAS processes can now produce tiny amounts of industrial output, more research and development as well as learning from the use of these processes in this technology can lead to larger-scale applications (Zhu, 2019).
- CO_2 capture and utilization (CCU) bioconversion. The bioconversion of CO_2 is a technology that has the potential to be more sustainable, however it is currently in the

research and development stage with first applications in industrial operations. For example, the company LanzaTech has created a biological gas-fermentation method that turns industrial exhaust gases into chemicals and fuels. The method converts CO-rich waste gases and residues into compounds by growing bacteria on gases. This company, which is connected to the Japanese company Sekisui Chemical, developed an industrial plant in 2014 that gasifies unsorted, non-recycled, non-compostable municipal solid waste. The syngas that is produced is then burned to produce electricity. Alternatively, the US company Joule Unlimited Technologies has created artificial microorganisms, including genetically altered cyanobacteria, that use solar energy to continuously convert CO2 and H2O into ethanol or hydrocarbon fuels (Zhu, 2019).

- Sustainable methods for producing ammonia. Table 2's results further demonstrate the strong technological progress of ammonia (NH_3). The industry that produces nitrogen (N) fertilizers is based on ammonia. One of the most intriguing areas of chemical study to promote sustainability is the generation of ammonia from molecular dinitrogen (N2) in mild circumstances (Ampelli, 2020; Cui et al., 2018). Actually, there is a lot of room for sustainable, low-energy NH3 synthesis through the electrochemical reduction of N2. According to Soloveichik (2019), the Haber-Bosch process is a key technology; however, electrochemical pathways, which emphasize electrocatalysts, electrolytes, and innovative cell design, can lower energy consumption and sustain a sustainable production of ammonia. According to Lv et al. (2020), the energy-intensive Haber-Bosch process may be replaced by an emerging technique called ammonia (NH3) electrosynthesis from atmospheric nitrogen (N2) and water; however, process bottlenecks and technological issues may prevent the method's broad industrial adoption. According to Tavella et al. (2022), the increasing industrial demand for ammonia can be met by direct electrocatalytic generation of ammonia (NH3) from N2 and H2O under ambient circumstances. Furthermore, current research and development in this field is focused on developing gas diffusion electrodes, designing cell configurations, and adopting three-dimensional nanoarchitecture for the electrode surface. Additionally, more effective lithium-mediated techniques in non-aqueous solvents are being studied, such as flooding of the gas diffusion electrodes. sustainability of the proton-shuttle system).

- Research suggests that cellular agriculture, also known as cell-based farming, holds promise for a more sustainable future (Table 2). This technology has the potential to address some of the environmental challenges associated with conventional agriculture. Livestock farming, particularly cattle rearing, is a major contributor to greenhouse gas emissions, accounting for roughly 38% of methane emissions globally (Cho, 2022). Traditional agricultural practices also contribute to CO2 emissions, though to a lesser extent, at around 1%. Cellular agriculture presents an opportunity to reduce these emissions by offering a more environmentally friendly approach to food production. This method, along with other sustainable practices like agroecology and regenerative agriculture, can contribute to lower CO2 emissions and improved soil health (Pronti & Coccia, 2020, 2021; Kargı et al., 2023, 2023a; Uçkaç et al., 2023, 2023a). These advancements are crucial as the global population is projected to reach 11 billion by 2100, necessitating adaptations in our current food production systems (Willett et al., 2019; Global Change, 2022). To meet this growing demand for food, particularly protein-rich options, while minimizing environmental impact, new and sustainable agricultural models are needed (Edeme et al., 2020; Pronti & Coccia, 2021, 2021b, 2021c, 2022). Cellular agriculture could be a key component of a future-proof agricultural system that prioritizes sustainability and supports resilient food production networks (Bapat et al., 2021; Campbell, 2002). This technology leverages advancements in cell cultivation to create animal products without the environmental footprint associated with traditional livestock production. While some, like Moritz et al. (2022), acknowledge the potential hurdles and necessary adaptations for widespread commercial adoption, cellular agriculture represents a methodical shift towards a more sustainable future for food production. Large-scale industrial production based on this technology may not be achievable in the immediate future, but ongoing research and development hold significant promise.

c) Additional exciting solutions for a sustainable socioeconomic future that are in the R&D stage or have just entered the market

Wave control frameworks are one of the advances beneath examination that are accessible on the advertise, but concurring to Table 2's information, have experienced less logical and innovative progression. The essential employments of this innovation incorporate wave ranches built in Portugal in 2008 utilizing wavering water column and surface-following attenuator innovation, Israel in 2009 utilizing swaying wave surge converter innovation, Spain and the UK within the 2000s and 2010s utilizing swaying water column innovation, etc (Kaldellis & Chrysikos, 2019).

Numerous of the innovations beneath examination here, though having a tall potential for feasible arrangements and the capacity to produce licenses, are not however mechanical propels that ought to be connected to markets for wide dispersal. For illustration, there are various new businesses within the early stages of the advertise dispatch of warm vitality capacity technology. Highview Control, financed within the UK and established in 2005, creates a liquid-air vitality capacity arrangement for framework applications; MALTA, financed over 2018 in Cambridge, USA; and Antora Vitality, supported in 2017 (USA) that stores vitality as warm in cheap crude materials and changes over that warm back to power with an proficient thermophotovoltaic warm motor, etc. (Tracxn, 2022).

A novel innovation with imperative components for supportability is green hydrogen. As of now within the inquire about and improvement arrange, the Iberdrola group—a worldwide pioneer in energy—has put into benefit the biggest green hydrogen generation plant in Spain, which is based totally on renewable assets for mechanical utilize. It is comprised of a 100 MW photovoltaic sun powered plant, a 20 MWh lithium-ion battery framework, and one of the biggest electrolytic hydrogen generation frameworks within the world (20 MW; see, Iberdrola, 2022). Siemens has begun building one of the biggest sun powered and wind-powered green hydrogen fabricating offices in Germany (CNBC, 2022). By June 2023, Sinopec (China Petroleum & Chemical Enterprise) intends to develop the biggest hydrogen fabricating office within the world utilizing renewable vitality, driven by a 300 MW photovoltaic plant. The objective is to deliver 20,000 tons of green hydrogen yearly, which is evaluated to result in a 485,000-ton yearly diminish in CO2 emanations (Balkan Green Vitality News, 2022).

In spite of the fact that the presentation of clean steel fabricating to the showcase is still in its test stage, it could be a handle advancement with critical potential to diminish discuss contamination and improve supportability (Coccia, 2014). In arrange to diminish press ore and dispose of the necessity for carbon within the steelmaking handle, Arcelor (2022) is investigating new clean fabricating strategies, such as hydrogen or electrolysis, which is able decrease CO2 outflows. H2 Hamburg (Germany) is an captivating explore that employments hydrogen to create steel and diminishes press mineral straightforwardly amid the steel-making prepare. The long-term objective is to grow this innovation on an mechanical scale, and the Hamburg extend ought to utilize green hydrogen determined from renewable sources.

Finally, although it is still in its earliest stages in these spaces of think about and innovation, blockchain innovation may be a general-purpose apparatus that can too offer assistance guarantee a clean and maintainable future for all individuals (Howson, 2019; Hughes et al., 2019; Esmaeilzadeh, 2022; Coccia, 2017a, 2017b, 2017c). To approve exchanges and protect the system's information judgment, blockchain stages make utilize of a decentralized arrange of scattered hubs (Centobelli et al., 2021). One way to cut nursery gas outflows by 2050 is for nations to coordinated more disseminated renewable vitality sources into their vitality supply frameworks. This implies moving absent from conventional top-down power conveyance, which relies on huge control plants to meet all request, and toward a decentralized framework where vitality is delivered and put away at the end-user level (Javid et al., 2021). The foundation of this mechanical and advertise change must be a neighborhood vitality advertise (LEM), wherein vitality producers and consumers are connected to one another in arrange to execute vitality on a stage backed by decentralized advertise plans and blockchain innovation. This inventive innovation has the potential to invigorate a advertise move that comes about in sensible vitality utilization hones and expanded framework effectiveness (Strepparava et al., 2022).

Concluding Remarks and Pledges to Fulfill at Least one of the Sustainable Development Goals

The key findings, based on the estimated regression coefficients, show that technologies with B>1—indicating they are on accelerated paths of technological advancement to support sustainable futures—include the following:

- Offshore wind turbines, which have already been adopted in markets
- Carbon Capture Storage, currently in the development phase and not yet widely implemented
- Electrochemical conversion of CO_2, still in the research and development stage
- Bioconversion of CO_2, also in the research and development phase
- Sustainable processes for ammonia production, in the research and development phase
- Cellular agriculture, which is likewise in the research and development stage.

This study is bizarre in that it employments a show based on distributions (logical information, informative variable) and licenses (a intermediary for specialized advancement, reaction variable) to investigate the advancement of unused innovation directions pointed at vitality move. The discoveries point to advances that are developing more rapidly and have the potential to assist future economical financial frameworks. In differentiate to past entries, this think about presents a number of imaginative and possibly economical advances, counting seaward wind turbines, carbon capture and capacity, electrochemical and bioconversion of CO2, maintainable alkali fabricating procedures, and cellular farming. The comes about too illustrate that a few of these technologies—such as the electrochemical and bioconversion of CO2 forms, which have 376 and more than 1,000 licenses, respectively—are not creating innovative enhancements for wide advertise applications, in spite of holding a sizable number of licenses. A few vitality companies and prestigious colleges are right now inquiring about and creating these innovations, which have the potential to decrease nursery emanations by utilizing renewable assets. For case, Equinor (2022) is working on a extend to securely and forever store carbon beneath the seabed in arrange to avoid worldwide warming at whatever point conceivable. Modern activities at George Washington College (USA) are making low-voltage, low-cost terminals made of steel and nickel to change over CO2 into carbon nanofibers and carbon nanotubes. These carbon composites are basic to industry since they can be utilized in batteries and as lightweight substitutes for metal in flying machine, extravagance sports cars, and sports gear (Zhu, 2019). The bioconversion of CO2 capture and utilization could be a promising innovation that has driven to captivating activities utilizing proteins and microbes that have been created. For illustration, analysts in Scotland are working on a strategy that would permit the bacteria Escherichia coli to operate as a really viable carbon-capture gadget, changing over CO2 into formic corrosive (Roger et al., 2018). Or maybe, a unused protein being developed by US analysts is able of changing over formaldehyde into dihydroxyacetone, which can at that point be utilized to convert CO2 into fills like ethanol. Unused roads for CO2-conversion based on microbial biotechnology are being opened by this creating innovation.

Implications for policy to lessen the negative effects of polluting economic and social development on the environment

Nations must empower the fast advancement of specialized advances pointed at environmental move and supportability in financial frameworks in light of worldwide vitality and natural contamination issues (Calza et al., 2020; Nti et al., 2022; Khan et al., 2022; Sterner & Coria, 2012). This consider illustrates how modern innovative approaches are being created to decrease CO2 emanations through the utilize of renewable assets (like seaward wind turbines) and to capture and utilize CO2 for the generation of maintainable vitality (like green hydrogen created by wind and photovoltaic sun powered plants that are as of now experiencing inquire about and improvement). The interaction of different advances pointed at an environmental move that produces quickened co-evolution pathways for maintainability is another vital finding here. For illustration, the mechanical interaction between green hydrogen created from renewable assets and clean steel generation maintains a strategic distance from carbon within the steelmaking prepare, in this manner diminishing CO2 emanations (cf., Coccia, 2017c, 2018a, 2019a). In order to advance maintainability and reduce environmental issues related to the shortage or exhaustion of normal assets, these modern technological directions must be progressively taken after (Knolls et al., 1972; Sulston, 2012). Subsequently, in arrange to guarantee that human society may proceed for a economical future, financial frameworks ought to back the innovations that are the subject of this investigation and have the capacity to viably minimize natural debasement and ensure the biosphere (Magdoff, 2013; Magdoff & Cultivate, 2011; Saeli et al., 2022). The progression of science and innovation, as well as its commercialization in markets, can be quickened by money related assets, as policymakers, directors, and scholastics are mindful of (Roshani et al., 2021,a, 2022; Mosleh et al., 2022). In arrange to advance economical advancement for a great affect on industry and society, policymakers ought to utilize the pivotal data given by this consider to target their R&D speculations toward promising disciplines and innovations related to vitality move (Coccia, 2021a; Kargı, & Coccia, 2024). These R&D speculation procedures can be connected to vitality and financial arrangements that advance an harmony between the environment, common assets, and human society inside cities and expansive urban agglomerations: in other words, an eco-socialism framework built on on institutions and individuals working together to protecting the environment and financial sustainability in technologies (Aidnik, 2022; Adaman & Devine, 2022).

In common, countries ought to create and actualize long-term, systemic methodologies pointed at lessening their dependence on coal and petroleum-based economies. A few advances that have been distinguished here have promising applications within the zones of clean energy generation, recyclable merchandise, renewable energies, directed to large circular economy, which coordinates the ecosystem for future generations' well-being and maintainable financial development (cf., Aresta & Dibenedetto, 2020; Pronti & Coccia, 2021).

Limitations

Conclusions here are, of course, tentative. This study provides some interesting but preliminary results in these complex fields of the scientific and technological evolution in sustainable technologies. Whereas this ponder yields a few captivating, if preliminary comes about, it encompasses a number of inadequacies that require be tended to in ensuing considers utilizing new data and techniques to bolster the conclusions drawn here. Some limitations are that: 1) scientific outputs and research topics can only detect certain aspects of the ongoing dynamics of sustainable technology; 2) statistical analyses consider results and implications based on specific technological fields in sustainability; 3) proposed framework analyzes specific scientific and research fields, but discarding interesting insights from other research and technological fields for ecological transition: 4) Beyond the identified technological groups, further research could explore other promising areas like biomimicry, which draws inspiration from nature's design principles for sustainable solutions. Additionally, social and economic factors can influence the adoption and implementation of these technologies warrant investigation.

Despite these limitations, the results here clearly illustrate dynamics of main technologies that can drive ecological transition and sustainability in socioeconomic systems.

Ideas for future research

There is need for much more detailed research into the investigation of the emerging evolutionary patterns of scientific and technological fields directed to ecological transition and sustainability. More precise areas for further investigation are:

a) Complementary analyses to provide a more comprehensive view of the scientific and innovative ecosystem, evolutionary pathways revealing not only scientific advancements but also innovation and practical applications directed to sustainability in science and society.

b) Consider in future analyses confounding factors, such as level of public and private R&D investments, international collaboration in specific sustainable technologies, etc. These factors can explain other aspects of emerging research fields and technologies.

c) Statistical analyses consider specific scientific and technological fields but next studies have to be improved with more data based on a lot of research fields in different scientific and technological domains, from life sciences, chemical to environmental sciences for an overall ecological transition.

To conclude, these findings here can encourage further theoretical exploration in the *terra incognita* of the technologies directed to sustainability. This ponder extends the state-of-the art in scientific and technological information directed to support ecological transition and sustainability by promising technologies. In conclusion, an intensive and progressing investigation is required to upgrade the sustainable expectations about new technology that nations must design to moderate environmental contamination and degradation. However, a comprehensive explanation of the evolution of science and technology directed to sustainability is a difficult topic for manifold complex and inter-related factors associated with economic, social, political and institutional factors as well as in the presence of changing and turbulent environment, such that Wright (1997, p.1562) properly claims that: “In the world of technological change, bounded rationality is the rule.”

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