Publication date: September 28, 2023
DOI: 10.52270/26585561_2023_19_21_100

SIMULTANEOUS ENCOURAGING EFFECTS OF NEW TECHNOLOGIES FOR SOCIOECONOMIC AND ENVIRONMENTAL SUSTAINABILITY

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Abstract

This research delves into the progression of technologies designed to facilitate the shift toward sustainable energy and eco-friendliness, assessing their potential influence on both ecological and economic systems. By examining data from sources like Scopus and patent records, it pinpoints promising technologies, such as offshore wind turbines, carbon capture storage, electrochemical CO2 conversion, bioconversion of CO2, sustainable ammonia production, and cellular agriculture. While certain of these technologies are already making significant progress in the market, others are still undergoing research and development. The study underscores the significance of these technologies in curbing CO2 emissions and environmental harm, providing valuable insights for policymakers and investors. It stresses the necessity for nations to transition from fossil fuel-dependent economies and instead adopt principles of a circular economy, renewable energy sources, and environmentally friendly production practices. Despite its limitations, this research illuminates essential technological avenues for sustainable development and ecological transformation.

Keywords: fossil-based energy; Environmental pollution; Environmental degradation; Sustainability science; Sustainable technologies; Environmental technologies; Green technology; Sustainable development.

JEL: O30; Q01; Q50; Q53.

I. INTRODUCTION

Research into the impact of human activities on the environment traces its origins back to the 1860s, as noted by Marsh in 1864. This scientific interest is closely linked to the industrial revolutions that began in the 1760s. While these revolutions have driven technological, economic, and social progress, they have also resulted in significant pollution from fossil fuels and environmental degradation, as discussed by Fowler and colleagues in 2020. The industrialization that began in the 1760s heavily relied on coal, natural gas, and petroleum-based materials, which have been integral to sectors such as textiles, automotive, heavy organic chemicals, synthetic materials, and petrochemicals globally (as observed by Ayres in 1990 and 1990a).

Ayres (1998) highlighted that this industrial shift ushered in new manufacturing processes fueled by fossil fuels, leading to radical technological innovations that supported economic growth and human development, as corroborated by Sterner et al. in 1998 and Coccia in 2010.

Furthermore, Foley et al. (2013) pointed out that these industrial revolutions, technological advancements, and economic transformations spurred the rapid growth of the human population, increased energy consumption, and raised atmospheric CO2 levels. The impact of human activities on the biosphere, as asserted by Chin et al. (2013), is attributable to various factors, including industrialization and urbanization, all of which contribute to fossil-fuel pollution.

This chain of events begins with industrialization, economic development, and population growth, leading to heightened consumption of goods, depletion of resources, the accumulation of billions of tons of solid waste, and, consequently, pollution and environmental changes, as discussed by Coccia in 2021 and Kaza et al. in 2018. In practice, industrialization in Europe, North America, and emerging nations has indeed driven economic growth. However, it has also been accompanied by fossil-fuel pollution, environmental degradation, and public health concerns, as noted by various scholars (Adam in 2021, Ali et al. in 2021, Belpomme et al. in 2007, Coccia in 2017, 2018, 2019, 2020, Constant et al. in 2014, IPCC in 2007 and 2013, Global Change in 2022, La Scalia et al. in 2022, NASA Global Climate Change in 2022, Steingraber in 1997, and Thomson & Stanberry in 2022). Some scholars have introduced the concept of the "Anthropocene" to describe these temporal and spatial phenomena, marking a new geological epoch characterized by the profound impact of human activities on the atmosphere, lithosphere, hydrosphere, and biosphere (as proposed by Crutzen & Stoermer in 2000 and Zalasiewicz et al. in 2011). Ruddiman (2003) suggests that the onset of the Anthropocene can be traced back 6,000 years due to CO2 increases, while Crutzen & Stoermer (2000) and Steffen et al. (2007) argue that it commenced with the industrial age in the 18th century, which also contributed to environmental pollution (as discussed in Bowman et al. in 2011, Glikson in 2013, and Steffen et al. in 2007). One significant consequence of this environmental degradation is the rise in greenhouse gas emissions and global temperatures, which could result in a 5°C temperature increase by 2100, along with permafrost thawing, as highlighted by Hausfather & Peters in 2020, Moss et al. in 2010, and Tollefson in 2020. Chapman et al. (2022) argue that mitigating this climate change risk requires achieving a state of net-zero CO2 emissions and carbon neutrality, in line with recommendations from the National Academies of Sciences in 2022 and Wang et al. in 2021. The pursuit of this objective can also be accomplished through innovative technologies focused on carbon capture, storage, and utilization, green hydrogen, sustainable production, solar thermal energy and storage, among others (referenced in Chapman et al., 2022; National Academies of Sciences, 2022; NIST, 2022). In fact, as Linstone (2010) aptly points out, "the global future will strongly depend on our willingness to take near-term action for a sustainable long-term future." In this context, one of the central challenges is the examination of emerging technological directions and eco-innovations that can facilitate the transition to sustainable socioeconomic systems while preserving the integrity of the atmosphere, lithosphere, hydrosphere, and overall biosphere (as explored by Sanni & Verdolini, 2022). The primary objective of this study is to identify and assess novel technological pathways capable of reducing atmospheric CO2 emissions and environmental pollution, thereby guiding society toward ecological transitions, including energy, industrial, and agri-food transformations, in pursuit of a sustainable future.The following section outlines the research methods employed to investigate these critical aspects in the realm of science and society.

II. STUDY DESIGN

This study relies on data from Scopus (2022), a comprehensive database encompassing journal articles, conference proceedings, books, and even patent records from various global patent offices. To identify scientific documents and patents relevant to promising technologies for ecological transition and sustainability, as delineated in Table 1 and in accordance with current environmental science literature (as indicated by 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), the "Search documents" feature within the Scopus (2022) database is utilized. Initial data retrieval occurred on

March 30, 2022, with subsequent updates performed on November 15, 2022. Scientific outputs, including articles, conference papers, book chapters, letters, etc., as well as patents, serve as the fundamental units for scientific and technological analyses (as detailed in Coccia et al., 2022). These analyses aim to identify emerging technological trajectories capable of mitigating environmental pollution and aligning with sustainability objectives in socioeconomic systems.

Furthermore, the data is organized into four distinct technological categories, each reflecting primary applications and usages, to elucidate diverse avenues supporting sustainable futures:

- Technologies focused on renewable energy, such as wind turbines.
- Technologies centered on renewable energy and storage, including thermal energy storage.
- Technologies geared toward CO2 capture and utilization, encompassing catalytic conversion and CO2 copolymerization, among others.
- Technologies oriented toward sustainable products and clean production processes, such as environmentally-friendly steel production.

Evaluation Criteria The study assesses the advancement of technologies through the following evaluation criteria:

- The quantity of articles and various scientific outputs obtained from the search criteria detailed in Table 1, aimed at identifying the cumulative body of scientific knowledge underpinning technological advancements. The year 2022 is not considered in this analysis as it is still in progress.

Additionally, this research scrutinizes patents as indicators of inventive ideas and potential innovations that contribute to the progression of technological trajectories addressing sustainability challenges. The evaluation criteria for patents is as follows:

- The count of patents retrieved using the search criteria outlined in Table 1, with the exclusion of the year 2022 due to its ongoing status at the time of the study's development.

Table 1. *Queries and data analyzed*

Queries of articles and patents of technologies oriented to sustainability	Data analyzed until 2021*	
• *Technologies oriented to renewable energy*	Documents/ Articles	Patents
wave power systems	78	341
offshore wind turbine	6978	3791
floating photovoltaic systems	76	43
green hydrogen	1000	172
blue hydrogen	77	198
geothermal technology	317	182
thermal technology	1841	2451
• *Technologies oriented to renewable energy and storage*		
thermal energy storage	15,573	8888
carbon capture and storage	7544	1365
carbon capture and storage (CCS) post-combustion	631	286
carbon capture and storage pre-combustion	90	70
carbon capture and storage oxy-fuel combustion	89	227
carbon-negative technologies	34	10
• *Technologies oriented to CO_2 Capture and Utilization*		
electrochemical conversion AND CO_2	510	376
photocatalytic conversion AND CO_2	424	32
photothermal catalytic conversion AND CO_2	4	0
solar energy conversion AND CO_2	300	194
catalytic conversion AND CO_2	776	2433
bioconversion AND CO_2	896	1060
copolymerization AND CO_2	1215	4283
mineral carbonation AND CO_2	769	168

• *Technologies oriented to sustainable products and clean production process*		
aluminium battery	228	1033
clean steel production	92	28
ammonia AND sustainability	1058	3370
cellular agriculture	81	21
blockchain technology AND sustainability	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.

Data Analysis and Models of Technological Progress

To begin, a logarithmic transformation is applied to the data. This transformation aims to normalize the distribution of variables, facilitating the use of appropriate parametric analyses and ensuring the generation of robust results.

Next, the Scopus (2022) "Search documents" tool is employed to obtain a time series of articles and patents related to technology "i" at time "t," based on the terms outlined in Table 1. These data are subjected to analysis employing the following model to discern trends:

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

- $y_{i,t}$ 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 parameters *a* and *b* of model [1] are estimated with the Ordinary Least-Squares (OLS) Method.

The parameters "a" and "b" in Model [1] are estimated using the Ordinary Least-Squares (OLS) Method.

Moving on, the potential growth of technologies geared toward sustainability is examined using a model of technological development. In this model, the number of patents (Y) is considered a function of the volume of scientific output (X) over time. This approach is based on the work of Sahal (1981) and aims to determine the relative rate of technological advancement, illustrating how technological units (patents) evolve over time in response to the accumulation of scientific knowledge through articles. In essence, Model [2] investigates the evolution of technology "i" by quantifying the influence of the accumulation and progression of scientific knowledge (represented by publications Xi) on the growth of patents, Yi, as proposed by Sahal (1981).

- *A*=constant (2)
- B =the coefficient of relative growth that measures the evolution of *Y* (patents) in relation to scientific production *X* of technology *i*.

In particular, the value of coefficient in the model [2] indicates different patterns of technological evolution given by:

- $B < 1$, technology has a *slowing down evolution* of patents compared to the growth of scientific production over the course of time
- $B = 1$, technology evolves with a *proportional growth* of publications and patents
- $B > 1$, technology has a disproportionate advances of patents *Y* compared to publications (*accelerated technological evolution* over time).

The log-log Model [2] employs linear parameters that are also estimated using the Ordinary Least-Squares (OLS) method. Statistical analyses are conducted using IBM SPSS Statistics 26® software.

III. EMPIRICAL RESULTS

Model [1] is utilized to depict trends in the publication and patenting of technologies focused on sustainability. Specifically, Figure 1 illustrates the progression of various technologies in relation to the growth of knowledge, as measured by published research papers. Meanwhile, Figure 2 showcases the evolution of these technologies based on patenting activities.

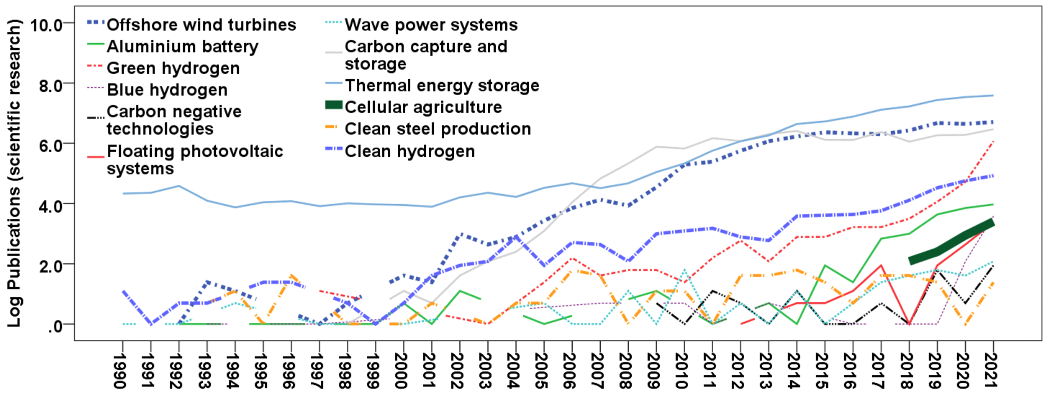

Figure 1. *Trends of publications for technologies directed to sustainability.*

Note: to show better the trends, the period starts from 1990

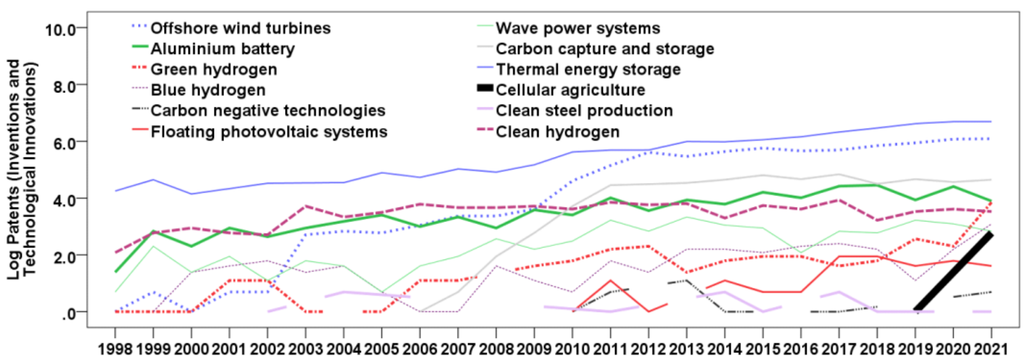

Figure 2. *Trajectories of technologies directed to sustainability using patents*.

Note: the period starts from 1998 to show better the trends.

Trends of figures 1 and 2, and underlying data, are combined and analyzed with model [2] to assess the relative rate of growth of these technologies over time.

Table 2. *Estimated relationships of patents on scientific production of technologies directed to future sustainability*

• *Technologies oriented to renewable energy*	Coefficient *B*	Constant A	*F-test*	R^2
Wave power systems	.840**	1.160***	7.68**	0.22
Offshore wind turbines	**1.062*** **	0.968**	391.65***	0.95
Floating photovoltaic systems	0.309	0.840*	2.75	0.28
Green hydrogen	0.584***	0.101	45.84***	0.74

Blue hydrogen	0.542*	.956***	6.33*	0.30
Geothermal technology	0.840***	0.240***	32.95***	0.54
Thermal technology	0.980***	0.330	104.73***	0.71
• *Technologies oriented to renewable energy and storage*	Coefficient *B*	Constant A	*F-test*	R^2
Thermal energy storage	0.935**	0.036	319.33***	0.87
Carbon Capture storage	**2.270*** **	9.690***	169.81***	0.91
"carbon capture and storage" CCS post-combustion	1.000***	0.840	32.24***	0.69
"carbon capture and storage" CCS pre-combustion	0.270	1.010*	1.14	0.01
"carbon capture and storage" CCS oxy-fuel combustion	0.660***	1.270***	16.14***	0.44
Carbon negative technologies	0.039	0.383	0.02	.004
• *Technologies oriented to CO_2 Capture and Utilization*	Coefficient *B*	Constant A	*F-test*	R^2
Electrochemical conversion of CO_2	**1.740*** **	2.172**	52.82***	0.72
Photocatalytic catalytic conversion of CO_2	.384**	.364	10.83**	0.45
Photothermal catalytic conversion of CO_2	--	--	--	--
Solar energy conversion of CO_2	0.590***	.560*	29.50***	0.59
Catalytic conversion of CO_2	0.440***	2.800***	70.28***	0.63
Bioconversion of CO_2	**1.040*** **	.250	180.43***	0.81
Copolymerization of CO_2	0.570***	2.720***	63.52***	0.63
Mineral carbonation	0.640***	.340	19.47***	0.49
• *Technologies oriented to sustainable products and clean production process*	Coefficient *B*	Constant A	*F-test*	R^2
Aluminum battery	.600***	2.295***	19.71***	0.461
Clean steel production	0.063	0.379	0.046	.005
Ammonia (sustainable production)	**1.890*** **	0.81***	284.72***	0.91
Cellular agriculture	**2.760***	6.65*	374.61*	.99
Blockchain technology in environmental sciences	0.810	0.04	48.73	0.96

Note: *log-log* model. Dependent variable: Patents of technology *i*; Explanatory variable: Publications of technology *i*; *** significant at 1‰; ** significant at 1%; * significant at 5%. *F* is the ratio of the variance explained by the model to the unexplained variance. R^2 is the coefficient of determination. In bold, technologies with B>1 having a high perspective of technological growth.

The coefficient of technological evolution *B*>1 in table 2 suggests a disproportionate (accelerated) growth of some technologies over time: they may affect a sustainable economic and social change in future. Instead, other technologies have *B*<1 in table 2, i.e. a reduced growth also likely because of their initial phase of technological evolution such that although these technologies have patents, they are not still mature to be fully implemented in markets. Finally, some technologies do not have a significant coefficient *B*, and as a consequence, they are not considered.

IV. DISCUSSION OF TECHNOLOGIES FOR BUILDING SUSTAINABILITY

Results, using the estimated coefficients of regression in table 2, reveal that technologies having *B*>1, i.e., accelerated pathways of technological evolution to support sustainable futures, are:

- Technologies and Their Stages of Development

- Several technologies with varying stages of development play a pivotal role in shaping sustainable socioeconomic systems. These technologies encompass a range of innovation and market adoption:

- Offshore Wind Turbines (Technological Innovation in Markets): Offshore wind turbines represent a mature technology that has made its mark in the market.

They offer advantages such as the potential for larger-scale operations, increased power generation, and reduced environmental impact when compared to onshore wind farms (as highlighted by Gonzalo et al., 2022). This technology, with its new generation of turbines, stands as a significant contributor to renewable energy with cost-effectiveness (Nemet, 2006; Pérez & Ponce, 2015).

- Continuous technological advancements have led to cost reductions, including materials costs (e.g., through the use of fiberglass) and improved labor productivity, achieving over a 30% reduction (Elia et al., 2020). Studies indicate that the learning-by-deployment approach has been a key driver behind cost reductions in wind turbine technology from 2005 to 2017 (Elia et al., 2020; Oh, 2020). Wind power technology has experienced remarkable growth, with a more than 1100% increase in global cumulative installed wind capacity from 2005 to 2019, reaching approximately 651GW by the end of 2019 (Wang et al., 2022). The industry is gravitating toward offshore wind farms due to the steadier and stronger wind speeds at sea, along with the ample space available for installing high-capacity wind turbines, some capable of generating up to 17MW, compared to land-based turbines with a maximum capacity of around 6MW. Coastal communities can benefit from energy savings through hybrid offshore wind and tidal stream energy systems, as demonstrated by Li et al. (2022). Notable offshore wind farms are operational in countries like the United Kingdom, China (with a capacity of 43,300MW), South Korea (with over 10,000MW), and more (Chen et al., 2023).

- These technologies are at various stages of development, with some already contributing to markets and sustainability, while others are still in the research and technological development phase, holding potential for future contributions to ecological transitions in global society.

Apart from offshore wind turbines, the study highlights other promising technologies in the phase of technological development that aim to contribute to renewable energy production and carbon capture-storage. These technologies have not yet been widely introduced or adopted in markets:

- Carbon Capture Storage (CCS): According to Balaji & Rabiei (2022), Carbon Capture, Storage (CCS), and Utilization (CCUS) are pivotal technologies for reducing CO2 emissions in energy-intensive sectors like cement, metallurgy, petrochemicals, steel, and more. They can also support the conversion of CO2 into fuels, chemicals, polymers, and other products, facilitating a shift from traditional to low-carbon economies (as noted by Ghiat & Al-Ansari, 2021, and Peplow, 2022). Many CCS and CCUS technologies are in the research and development (R&D) phase with initial applications emerging in the market (National Academies of Sciences, 2022). When applied to conventional power plants, CCS technologies can reduce CO2 emissions into the atmosphere by approximately 80–90% compared to plants without CCS (IEA, 2022). CCUS facilities currently capture nearly 45 million tons of CO2 globally. Gadikota (2021) suggests that new chemical processes within this technology can decrease the carbon intensity of energy and resource conversion processes. While CCUS deployment has not met earlier expectations, the outlook is improving, with more than 300 projects in various stages of technological development in 2022. The goal is to have over 200 operational capture facilities by 2030, capable of capturing more than 220 million tons of CO2 per year (CTCN, 2022; IEA, 2022; Resources Magazine, 2022). Elavarasan et al. (2022) emphasize that various decarbonization policies should focus on carbon capture, storage, and utilization technologies, as they can play a vital role in achieving climate neutrality, especially in sectors that are challenging to decarbonize (as discussed by Chapman et al., 2022, and NIST, 2022).

- Electrochemical Conversion of CO2 Capture and Utilization (CCU): One of the technologies showing growing promise for CCU is the electrochemical conversion of CO2 into products like syngas, methane, methanol, or dimethylether, often incorporating renewable energy. Notable examples include Sunfire, which successfully produced high-quality diesel fuel in 2015, and ETOGAS, which developed a process using alkaline pressurized electrolysis of H2O to produce H2, subsequently reacting with CO2 to form CH4 (methane). Although Sunfire and ETOGAS processes currently operate at a small industrial scale, ongoing research and learning through Pr ocess refinement are expected to foster larger-scale applications (Zhu, 2019).

- Bioconversion of CO2 Capture and Utilization (CCU): Another technology showing promise for sustainability is the bioconversion of CO2, although it is still in the research and development phase with initial applications in industrial processes. For example, the company LanzaTech has developed a biological gas-fermentation process that utilizes exhaust gases from industries to produce fuels and chemicals. This process relies on microbes that grow on gases to transform CO-rich waste gases and residues into valuable chemicals. In 2014, LanzaTech, in collaboration with Japanese Sekisui Chemical, applied this technology to produce ethanol from municipal solid waste, establishing an industrial plant that gasifies unsorted, non-recycled, non-compostable municipal solid waste, with the resultant syngas being burned to generate electricity. Meanwhile, the U.S. firm Joule Unlimited Technologies has engineered microbes, including genetically modified cyanobacteria, which harness solar energy to convert CO2 and H2O into ethanol or hydrocarbon fuels through a continuous process (Zhu, 2019).

- Sustainable Processes for Ammonia Production: Table 2 reveals significant technological growth in ammonia (NH_3) production. Ammonia serves as the cornerstone of the nitrogen (N) fertilizer industry. The sustainable production of ammonia from molecular dinitrogen (N2) under mild conditions represents a compelling research area within chemistry aimed at promoting sustainability (as highlighted by Ampelli, 2020, and Cui et al., 2018). Electrochemical reduction of N2 presents substantial potential for sustainable NH3 production with lower energy consumption. Soloveichik (2019) notes that while the Haber–Bosch process is a predominant technology, electrochemical pathways for ammonia synthesis can reduce energy consumption and foster sustainable production, focusing on electrocatalysts, electrolytes, and novel cell designs. Lv et al. (2020) propose that ammonia (NH3) electrosynthesis from atmospheric nitrogen (N2) and water is an emerging technology as an alternative to the energy-intensive Haber–Bosch process, although technical challenges may impede full-scale industrial application. Tavella et al. (2022) suggest that the direct electrocatalytic production of ammonia (NH3) from N2 and H2O under ambient conditions can meet the increasing industrial demand for ammonia. Current research and development in this field are exploring three-dimensional nanoarchitecture of electrode surfaces, cell configuration design (including gas diffusion electrodes), and more efficient lithium-mediated techniques in non-aqueous solvents (such as improving the proton-shuttle system's sustainability).

- Cellular Agriculture: The results indicate that cellular agriculture is experiencing rapid growth and has the potential to contribute significantly to future sustainability (Table 2). Agricultural activities currently contribute 1% of CO2 emissions and 38% of methane emissions, primarily from livestock production. More sustainable farming practices, including regenerative agriculture, which enhances soil carbon storage and preserves biodiversity, along with agroecological systems and cellular agriculture, can help reduce CO2 emissions (as noted by Cho, 2022, and Pronti & Coccia, 2020, 2021). Furthermore, global population growth is projected to reach approximately 11 billion by 2100 (Willett et al., 2019; Global Change, 2022). In light of this demographic trend and the increased demand for protein-rich food, society requires new and sustainable models for agricultural and livestock production to meet nutritional needs while mitigating deforestation, CO2 emissions, environmental pollution, emerging diseases, and other challenges (Edeme et al., 2020; Pronti & Coccia, 2021). Cellular agriculture offers a fundamental component of a novel agricultural system aimed at sustainability, supporting resilient organizations to address the growing global food demand and enhance the planet's life support systems (as proposed by Bapat et al., 2021, and Campbell, 2002). Transitioning from conventional agricultural systems to cellular agriculture hinges on new cell-cultivation technologies for producing animal products while reducing pollution associated with livestock production. Moritz et al. (2022) underscore that policymakers and stakeholders recognize the changes and challenges required for the adoption of cellular agriculture technology in the market, acknowledging that large-scale industrial production based on cellular agriculture may not be a feasible system in the near term. Wave Power Systems: Among the technologies examined in this study, wave power systems have made their way into the market but are experiencing limited scientific and technological growth, as indicated in Table 2. These systems involve the construction of wave farms and have been deployed in various countries, including Portugal, Israel, Spain, and the UK.

- Different technologies like surface-following attenuators and oscillating water column technology have been used for these wave farms (Kaldellis & Chrysikos, 2019). Thermal Energy Storage Technology: Thermal energy storage technology is in its early stages of market introduction and has seen the emergence of numerous startups. Examples include Antora Energy, founded in 2017 in the USA, which stores energy as heat in cost-effective materials and converts it back to electricity using efficient thermophotovoltaic heat engines. Highview Power, established in the UK in 2005, is developing a liquid-air energy storage solution for grid applications. MALTA, founded in Cambridge, USA in 2018, is also exploring innovative approaches to energy storage (Tracxn, 2022).

Green Hydrogen: Green hydrogen, a technology critical for sustainability, is currently in the research and development phase. Notable projects include Iberdrola's endeavor in Spain, where the company has commissioned the world's largest plant for green hydrogen production using renewable resources. Siemens in Germany is constructing one of the largest green hydrogen production plants powered by wind and solar energy. China Petroleum & Chemical Corporation (Sinopec) plans to build the world's largest renewable-based hydrogen production facility, aiming to generate substantial amounts of green hydrogen and reduce CO2 emissions significantly (Balkan Green Energy News, 2022).

Clean Steel Production: Clean steel production, a process innovation with substantial potential for reducing air pollution and promoting sustainability, is currently in the experimental phase. Companies like ArcelorMittal are exploring new technologies for cleaner steel production, including the use of hydrogen or electrolysis to reduce iron ore and eliminate the need for carbon in the steelmaking process, resulting in reduced CO2 emissions. The H2 Hamburg project in Germany aims to produce steel using hydrogen and direct iron ore reduction, with plans to scale up this technology for industrial use (ArcelorMittal, 2022).

Blockchain Technology: Blockchain technology, a versatile technology with the potential to contribute to a clean and sustainable future, is still in the early stages of research and innovation within these fields. Blockchain platforms leverage decentralized networks of distributed nodes to validate transactions and maintain data integrity. One promising application involves integrating an increasing number of distributed renewable energy sources into a country's energy supply system, transitioning from a centralized to a decentralized model. This shift enables energy trading between consumers and producers in a local energy market (LEM) through blockchain technology and the Internet of Things (IoT), fostering decentralized market architectures and promoting efficient energy consumption and overall system efficiency (Strepparava et al., 2022).

V. CONCLUSIONS AND PROMISING FOR ACHIEVING ONE OR MORE OF THE SUSTAINABLE DEVELOPMENT GOALS

The unique aspect of this study lies in its exploration of the evolution of emerging technology trajectories geared towards energy transition. This exploration is conducted through a model utilizing patents as a proxy for technological innovation (the response variable) and scientific publications as an explanatory variable for scientific knowledge. The results shed light on technologies exhibiting rapid growth potential, which could play a pivotal role in supporting sustainable socioeconomic systems in the future. Noteworthy technologies highlighted in this study include offshore wind turbines, carbon capture storage, electrochemical conversion of CO2, bioconversion of CO2, sustainable processes for ammonia production, and cellular agriculture. The study also reveals that while many of these technologies have amassed a considerable number of patents, they are still in the early stages of development and have not yet translated into widespread technological innovations for market applications. For instance, technologies like electrochemical and bioconversion of CO2, boasting 376 and over 1,000 patents, respectively, remain in the research and development phase within certain energy firms and prominent universities. For instance, Equinor (2022) is working on a project to safely and permanently store carbon beneath the seabed to combat global warming.

Additionally, researchers at the George Washington University (USA) are exploring a technology to convert CO2 into carbon nanofibers and nanotubes using cost-effective materials and low voltage, with applications in batteries and lightweight alternatives to metals, including aircraft and sports cars. Bioconversion of CO2 also presents promising projects utilizing engineered bacteria and enzymes. Scholars in Scotland are developing a process using the Escherichia coli bacterium to efficiently capture and convert CO2 into formic acid. Meanwhile, some U.S. scientists are enhancing an innovative enzyme capable of transforming formaldehyde into dihydroxyacetone, which can then be converted into fuels like ethanol. These developments in microbial biotechnology offer new avenues for CO2 conversion. Policy Implications for Environmental Impact Reduction in Economic and Social Development: In light of global environmental pollution and energy challenges, nations must actively promote the rapid development of specific technologies aimed at ecological transition and sustainability within socioeconomic systems (Calza *et al.,* 2020; Nti *et al.,* 2022; Khan *et al.,* 2022; Sterner & Coria, 2012). This study underscores the emergence of technologies geared towards reducing CO2 emissions by harnessing renewable resources, such as offshore wind turbines, as well as technologies focused on CO2 capture and utilization, such as green hydrogen production via wind and photovoltaic solar plants, which are currently in the research and development phase. A key finding is the interplay between various technologies geared towards ecological transition, which fosters accelerated co-evolution pathways towards sustainability. An illustrative example is the technological synergy between clean steel production and green hydrogen production from renewable resources. This synergy eliminates carbon from the steelmaking process, resulting in reduced CO2 emissions (cf., Coccia, 2017, 2018, 2019). These new technological directions should be actively pursued to support sustainability efforts and mitigate environmental challenges stemming from the depletion of natural resources (Meadows *et al.,* 1972; Sulston, 2012). Therefore, economic systems should prioritize investment in these technologies, which have the potential to effectively address environmental degradation and preserve the biosphere for a sustainable future of human society (Magdoff, 2013; Magdoff & Bellamy Foster, 2011; Saeli *et al.,* 2022). Policymakers, industry leaders, and scholars recognize the pivotal role of financial resources in advancing science and technology and facilitating their commercialization (Roshani *et al.,* 2021; Mosleh *et al.,* 2022). This study provides valuable insights to guide R&D investments by policymakers towards promising research fields and technologies in the realm of energy transition, thereby fostering sustainable development and generating positive industrial and societal impacts (cf., Coccia, 2021). These strategies for R&D investments can align with energy and economic policies that promote equilibrium between the environment, natural resources, and human society within cities and urban centers. This approach, often characterized as an eco-socialism system, emphasizes collaboration among individuals and institutions to address resource constraints while simultaneously safeguarding the environment and economic aspects (Aidnik, 2022; Adaman & Devine, 2022). In conclusion, this study underscores the importance of proactive investments in emerging technologies to drive sustainable development, mitigate environmental challenges, and propel society towards a more equitable and environmentally conscious future (cf., Aresta & Dibenedetto, 2020; Pronti & Coccia, 2021). The study's recommendations and insights provide a valuable roadmap for countries seeking to transition away from coal and petroleum-based economies toward sustainable, renewable energy sources and clean production practices. Embracing these technologies and fostering a circular economy is essential for long-term economic growth and the well-being of future generations.

While the study offers significant contributions, it's important to acknowledge its limitations, as you rightly pointed out:

1. Data Source Limitations: The study relies on data from Scopus and patents to capture the dynamics of technological innovation. These sources may not provide a comprehensive view of all ongoing technology developments. Future research could explore additional data sources or methodologies to address this limitation.

2. Confounding Factors: Various factors beyond the scope of this study can influence technology evolution. These include government policies, intellectual property rights, international collaboration, and economic conditions. Investigating these confounding factors in future research could offer a more holistic understanding of technological trajectories.

3. Time Period: The study focuses on a specific time period. Expanding the analysis to cover a longer period could reveal longer.

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ОДНОВРЕМЕННОЕ СТИМУЛИРУЮЩЕЕ ВОЗДЕЙСТВИЕ НОВЫХ ТЕХНОЛОГИЙ НА СОЦИАЛЬНО-ЭКОНОМИЧЕСКУЮ И ЭКОЛОГИЧЕСКУЮ УСТОЙЧИВОСТЬ

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Аннотация

В данном исследовании рассматривается развитие технологий, призванных способствовать переходу к устойчивой энергетике и экологичности, оценивается их потенциальное влияние как на экологическую, так и на экономическую системы. На основе анализа данных из таких источников, как Scopus и патентные документы, выделены такие перспективные технологии, как морские ветряные турбины, хранение углерода, электрохимическая конверсия CO2, биоконверсия CO2, устойчивое производство аммиака и клеточное сельское хозяйство. Некоторые из этих технологий уже достигли значительных успехов на рынке, другие все еще находятся в стадии исследований и разработок. В исследовании подчеркивается значение этих технологий для сокращения выбросов CO2 и снижения вреда, наносимого окружающей среде, а также приводятся ценные сведения для политиков и инвесторов. Подчеркивается необходимость перехода стран от экономики, зависящей от ископаемого топлива, к принципам циркулярной экономики, возобновляемым источникам энергии и экологически безопасным методам производства. Несмотря на имеющиеся недостатки, данное исследование открывает важные технологические пути для устойчивого развития и экологических преобразований.

Ключевые слова: энергия на основе ископаемого топлива; загрязнение окружающей среды; деградация окружающей среды; наука об устойчивом развитии; устойчивые технологии; экологические технологии; "зеленые" технологии; устойчивое развитие.

JEL: O30; Q01; Q50; Q53.

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