Article

Sustainable Technologies for Ecological Societies Directed to Energy Transition

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Sustainable Technologies for Ecological Societies Directed to Energy Transition

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Abstract: Ecological Society is based on socioeconomic systems directed to the equilibrium of inter-relationships between environment, climate, production systems, technologies and human communities to promote the overall well-being of people and the Earth planet. It has a main goal for supporting sustainable development and equitable societies and achieving optimal health outcomes recognizing the interconnection between people, technologies, animals, plants, and their shared environment for the one health. Using data of scientific publications and patents until the year 2024, this study shows new technologies that can support the energy transition with the shift from fossil fuels to renewable energy sources in an effort to reduce CO_2 emissions for an ecological society having, whenever possible, zero-carbon economies to reduce environmental pollution and climate change and foster health and wellbeing of people. Results reveal that sustainable technologies supporting the transformation of the energy sector, economies and societies, and having a rapid growth, are blue hydrogen, floating photovoltaic systems, carbon capture and utilization, green hydrogen and liquid metal batteries. These findings can guide decisions of policymakers and stakeholders towards fruitful investments driving the transition from fossil-based to zero-carbon socioeconomic systems to have a long-run sustainable development of overall world system that has to direct towards an ecological society associated with one health.

Keywords: ecological society; sustainable future; fossil-fuel pollution; climate change; sustainable technologies; energy transition; zero-carbon; environmental impact; sustainable society; equal society; renewable energy; sustainable development

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1. Introduction

Evolution of modern societies with industrial acceleration, high population growth, different conflicts is generating changes in environment, climate, land use and biodiversity with deterioration of many ecosystems (Foley et al., 2013). Intensive industrialization of advanced and developing economies and land clearing are increasing carbon emissions associated with a rise in atmospheric greenhouse gases and emerging contaminants (Marsh, 1864; Fowler et al., 2020; Núñez-Delgado et al., 2024, 2024a, 2023). The intensity of human interactions with the total environment (atmosphere, lithosphere, hydrosphere, biosphere, and anthroposphere) has accelerated in recent decades (Chin and Fu, 2013). Many changes are due to transformations in physical, biological, and chemical processes in soils and waters for manifold human activities, urban development, industrialization, intensive agriculture and mining, construction and removal of dams and levees (Adam, 2021; Ali et al., 2021; Belpomme et al., 2007; Coccia, 2017, 2018, 2019, 2020; Constant et al., 2014; IPCC, 2007; 2013). Human societies are also inducing warming climate and further alterations in Earth processes and systems (Global change, 2022, La Scalia et al., 2022; NASA Global climate change, 2022; Steingraber, 1997; Thomson and Stanberry, 2022). The human interactions are changing Earth's surface, oceans, cryosphere, ecosystems, and climate such that scholars suggest a new geological epoch called Anthropocene (Crutzen and Stoermer, 2000; cf., Ayres, 1990, 1990a; Bowman et al., 2011; Glikson, 2013; Campbell, 2002; Chin et al., 2013; Coccia, 2009, 2010; 2021; Kaza et al., 2018; Ruddiman, 2003; Steffen et al., 2007; Sterner et al., 1998; Zalasiewicz et al., 2011). In this context, all places on Earth

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are affected by human activity and this tendency is increasing with the growing human population that may exceed 10.5 billion inhabitants later this century (United Nations, 2010). van Dijk et al. (2021) argue that total global food demand may increase from 35% to 56% by 2050, while population at risk of hunger is expected to change from −91% to +8%. The factor of climate change can increase the upper limit of these ranges to +62% for total food demand and to +30% for population at risk of hunger. Human-induced degradation on Earth system is increasing environmental pollution, emerging contaminants, greenhouse gas emissions and global temperature that may be more than + 3.5 °C of warming by 2100s (Hausfather and Peters, 2020; Moss et al., 2010; Tollefson, 2020; Chapman et al., 2022; National Academies of Sciences, 2022; Wang et al., 2021). Linstone (2010, p. 1417, original emphasis) states that: "the global future will strongly depend on our willingness to take near-term action for a sustainable long-term future". The recovery of environmental degradation can be achieved with sustainable technologies directed to renewable energy for societies based on ecological society that foster an equilibrium between atmosphere, lithosphere, hydrosphere, and overall biosphere (Sanni and Verdolini, 2022; Chapman et al., 2022; National Academies of Sciences, 2022; NIST, 2022).

The investigation goal here is to show new sustainable technologies that guide the socioeconomic pathway of economies toward transformation of the energy sector from fossil-based to zero-carbon systems for supporting an ecological society that reduces environmental pollution and fosters ecological transition (energy-industrial and agri-food transformations) in human societies.

2. Study design

Data collection

The study uses data of Scopus (2024), a multidisciplinary on-line database of journal articles and patents by the academic publisher Elsevier. Table 1 shows some critical sustainable technologies for supporting energy transition according to literature of environmental and sustainable sciences (EPO, 2022; Gonzalo et al., 2022; Li et al., 2022; Wang et al., 2022; Balaji and 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). Data are downloaded on 18th June 2024. Articles and patents are basic units for scientific and technology analyses (Coccia et al., 2022) to detect new sustainable technologies oriented to renewable energy, carbon capture and utilization and clean production processes.

Variables

The scientific development of sustainable technologies for the transformation of the energy sector directed to carbon neutrality in a perspective of ecological society is investigated considering articles collected from the search queries described in table 1 until June 2024. Technological directions also consider total number of patents in current technological cycle of these technologies: patents indicate inventions and potential innovations supporting the evolution of sustainable technologies by using the search queries described in Table 1[1].

Table 1. Queries for detecting directions of sustainable technologies. Source: Scopus 2024.

Queries of articles and patents of sustainable technologies	Data analyzed until June 2024		
	Articles	Patents	
	Total number	Patent period	Total number

[1] See also Coccia, 2022; Coccia et al., 2022.

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Offshore wind turbine (1976-2024)	10074	(1998-2024)	5541
Floating photovoltaic systems (2012-2024)	192	(2010-2024)	77
Grey hydrogen (2007-2024)	146	(2001-2024)	259
Green hydrogen (1997-2024)	5352	(1991-2024)	1033
Blue hydrogen (2016-2024)	265	(1979-2024)	358
Carbon capture utilization and storage (2010-2024)	1535	(2013-2024)	207
Smart grids of electricity networks (2006-2024)	480	(2010-2024)	313
Redox-flow batteries (1979-2024)	5932	(1983-2024)	7792
Liquid metal batteries (2009-2024)	259	(1981-2024)	226

Modelling and data analysis procedure

Firstly, logarithmic transformation of data is applied to have normality in distribution of variables and perform appropriate parametric analysis for producing robust results.

Secondly, statistical descriptives are used to visualize trends of scientific development of these sustainable technologies over time.

Thirdly, the tool "Search documents" in Scopus (2024) of terms indicated in table 1 provides a time series of articles for technology *i* at *t*. These data are analyzed with the following log-linear model to show trends:

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

- $y_{i,t}$ is scientific products 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.

Statistical analyses are performed with the software IBM SPSS Statistics 26 ®.

3. New technologies for sustainable economies

Figure 1 shows trends of publications of some sustainable technologies for the shift from fossil fuels to renewable energy sources in an effort to reduce CO_2 emissions for ecological transition and sustainable development. The growing trajectories are mainly offshore wind turbines, green hydrogen, carbon capture and utilization, blue hydrogen, and floating photovoltaic systems.

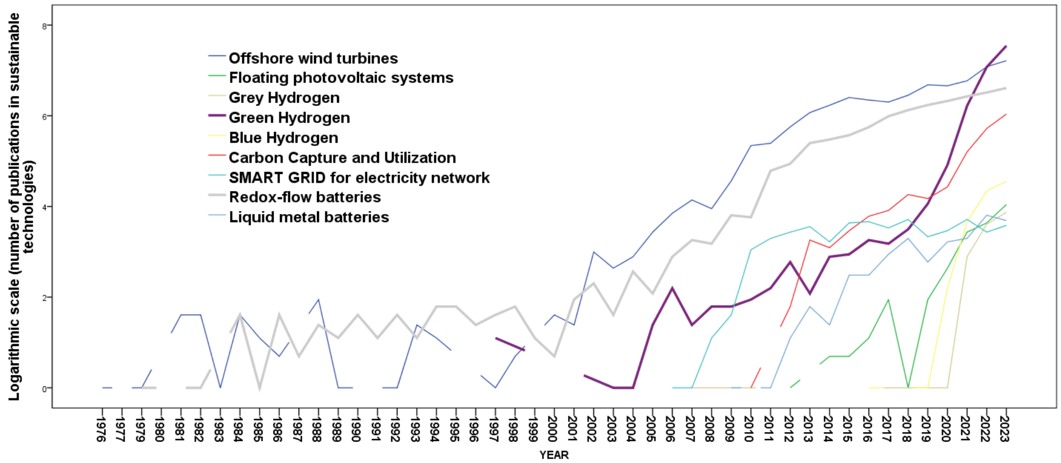

Figure 1. Trends of publications of sustainable technologies.

Figure 2 confirms that the amount of scientific publications and patents in sustainable technologies is higher in offshore wind turbines, redox flow batteries and green hydrogen (cf., Table 1).

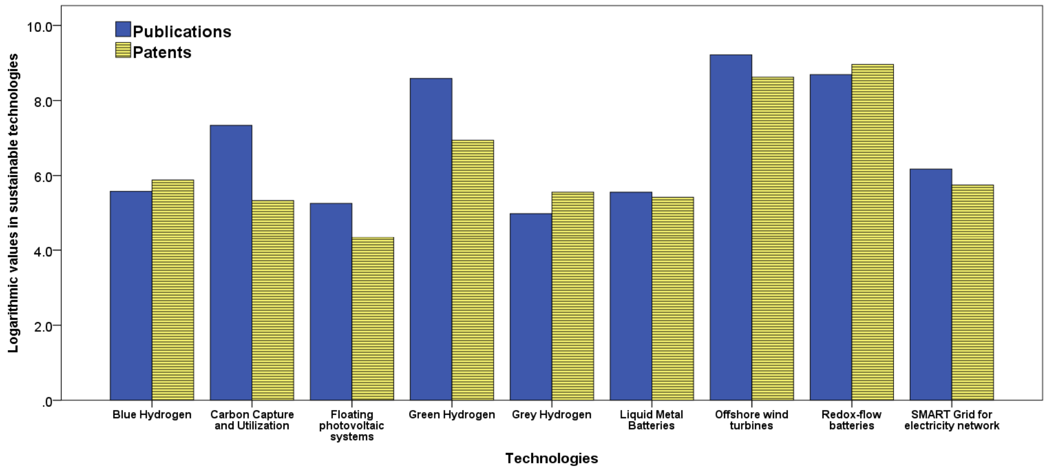

Figure 2. Comparison of patents and publications of sustainable technologies.

Table 2 shows the estimated relationships based on log-linear model [1]. The higher coefficient of regression is in blue hydrogen b=0.64 (p-value=0.01); it indicates that 1 -unit change in X (time) corresponds to approximately and expected increase in Y of $e^{0.64}$= 1.90, 90%. Other emerging technologies having a rapid temporal growth are Floating photovoltaic systems and Carbon Capture and Utilization b=0.35 (p-value=0.001), as a consequence $e^{0.35}$= 1.42: 1 -unit change in X (time) corresponds to approximately and expected increase in Y of 42%. Other promising sustainable technologies having an acceleration of scientific knowledge and advances are Green Hydrogen b=0.27 (p-value=0.001), every year this technology increases by 31% and Liquid Metal Batteries b=0.25 (p-value=0.001), every year this sustainable technology increases by 28%

Table 2. Estimated relationships of scientific production on time in technologies directed to future sustainability.

	Coefficient *B, time*	Constant	*F-test*	R^2
Offshore wind turbines	0.17***	–332.74***	218.32***	0.85
Floating photovoltaic systems	0.35***	–697.83***	38.94***	0.80
Grey Hydrogen	0.22	–443.71	5.16	0.56
Green Hydrogen	0.27***	–541.44***	89.76***	0.81
Blue Hydrogen	0.64**	–1292.24**	17.24**	0.78
Carbon Capture and Utilization	0.35***	–699.62***	88.60***	0.88
Smart Grid for Electricity Network	0.15**	–289.52**	13.62**	0.45
Redox-flow batteries	0.16***	–316.80***	307.08***	0.88
Liquid Metal Batteries	0.25***	–491.67***	62.74***	0.83

Note: Dependent variable: Log publications of technology *i*; Explanatory variable: time, year; *** 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 the log-linear model, the literal interpretation of the estimated coefficient b is that a one-unit increase in *X* will produce an expected increase in log *Y* of b units. In terms of *Y* itself, this means that the expected value of *Y* is multiplied by e^b.

4. Discussion

Results, using the estimated coefficients of regression in Table 2, reveal, unlike figure 1 that sustainable technologies having a rapid growth are blue hydrogen, floating photovoltaic systems, carbon capture and utilization, green hydrogen and liquid metal batteries. Considering the relevance of these technologies, they are described to show their potentiality:

- Hydrogen (H2) is considered a sustainable energy driver, especially when generated using renewable energy sources such as solar, wind and hydropower. A distinction is between "grey" hydrogen, "blue" hydrogen and "green" hydrogen:
  - "Grey" hydrogen is produced using natural gas by a "steam reforming" process that also generates CO_2.
  - "Blue" hydrogen is produced the same way, but more than 80% of the CO2 emissions are captured and stored rather than being released into the atmosphere.
  - Finally, "Green hydrogen" is produced using renewable energy sources. This process can be done by means of the electrolysis of water using solar, wind or hydropower as the electricity source.
- Carbon capture utilization and storage (CCU) enables the capture of carbon dioxide (CO_2) generated by combustion or industrial processes. This CO_2 can be used as a resource in manufacturing industries for products or to be stored, instead of being emitted into the atmosphere. Storage locations are underground geological formations, such as depleted oil or gas wells, or salt caverns. CCU is a general purpose technology for achieving net-zero emissions and carbon neutrality in economies (Coccia, 2015a, 2017a). Main advantages of CCU are that capturing CO_2 directly at source prevents its emission into the atmosphere. The use of CCU is useful for hydrogen production processes that use fossil fuels ("blue" hydrogen). Moreover, CCU may support the goal of "negative emissions". In short, re-using CO_2 can be an ingredient for new products such as a fuel, a chemical or a building material.

Captured CO_2 that cannot be re-used, have to be stored in locations such as depleted oil or gas wells.

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- Photovoltaic installations have been located in places where the climate was conducive to a good number of hours of sunshine. Technology of floating photovoltaics uses the surface of important bodies of water to install floating photovoltaic panels. The World Bank argues that floating solar power could double the existing installed capacity of solar power using square kilometers of artificial water reservoirs, i.e., swamps, reservoirs and so on. Singapore in Asia inaugurated a 60 MW plant in 2021 and has requested a study for increasing to 140 MW. In Europe, the Netherlands has several floating photovoltaic plants and Spain has a lot of infrastructures of this new technology in reservoirs, dams, etc. (Iberdrola, 2024).
- Finally, an alternative to recycling batteries is re-using them in second-life applications. Technology of liquid metal batteries is able to retain 99% of their original capacity over 5 000 charging cycles because they do not suffer the structural damage that conventional batteries experience as charged atoms flow through them. This technology can reduce the economic cost of storing solar and wind power on the electricity grid, leading to a larger overall proportion of clean power being consumed during peak load time.

Other promising sustainable technologies in the emerging phase of evolution are:

- Technology of redox-flow batteries have mainly aqueous-based systems, enable very flexible scalability and large-scale storage. Redox-flow batteries are a cost-effective technology of stationary storage, particularly when it comes to long discharges, long storage times and high cyclability. This technology is appropriate for integration into a renewable energy systems based on production and energy storage solutions.
- Complex technology of smart grids for electricity delivery is based on smart metering infrastructure, smart distribution boards, renewable energy sources and energy storage systems. These elements are interconnected and monitored using fiber broadband paired with a wireless backup system in order to achieve the goal of "cost-efficiently integrate the behaviour and actions of all users connected to it - generators, consumers to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety”. Their advantages are networks that can handle bidirectional energy flow; network users can supply energy to the grid (for instance, generated by rooftop photovoltaic panels); moreover, smart grid technologies can support demand-side management, real-time adjustments in energy distribution lines and lower energy prices. In this context, blockchain platforms use a decentralized network of distributed nodes to validate transactions and maintain the smart grid data integrity (Centobelli et al., 2021). Smart grids are the basis for local energy markets such that energy customers are inter-related with producers to trade energy on a market platform by using blockchain technology and internet of things that can support decentralized market architectures (Strepparava et al., 2022).

5. Conclusions and energy policy implications for ecological society

As the future is coming fast, societies will be dealing with a vastly different climate and energy landscape soon. The study here examines the evolution of new trajectories of technologies directed to energy transition. Results suggest technologies having an accelerated growth that can positively support sustainable socioeconomic systems in future. In particular, this study shows that new directions of technologies directed to carbon neutrality are mainly based on CO_2 capture and utilization, blue hydrogen, photovoltaic solar plants etc. A main finding here is also the interaction between these different technologies directed to ecological transition is generating accelerated co-evolution pathways for sustainability, such as the technological interaction between CO_2 capture and utilization and blue hydrogen more and more basic for clean production (cf., Coccia, 2017c, 2018a, 2019a). Results show that energy transition for ecological society is by no means a linear process and it is associated with scientific advances, described here, in sustainable technologies and changing conditions of total environments. In fact, renewable energy sources often are intermittent: such as a limited number of hours of sunlight per day and inevitable down time at night, variability of wind speed, such that supply and demand can generate continuous disequilibrium. Sustainable technologies discussed here can support renewable electricity for a large share of energy consumption in the industrialized countries by 2055, but not all of it. Hydrogen has the potential to help bridge the gap, including as a vector for renewable energy storage, alongside batteries. Renewables-based hydrogen can also be used as feedstock for the chemical sector and as fuel. It can provide a medium-term solution for certain industrial sectors that may otherwise be hard to decarbonize.

These new directions have to be more and more pursued to support sustainability and reduce environmental issues associated with shortage or depletion of natural resources (Meadows et al., 1972; Sulston, 2012). Hence, economic systems should support some technologies, analyzed here, that have potential aspects to effectively reduce environmental degradation and preserve biosphere for a sustainable future of human society with 'one health' (Magdoff, 2013; Magdoff and Bellamy Foster, 2011; Saeli et al., 2022).

This study provides critical information to guide R&D investments and energy policies of policymakers towards promising research fields and technologies directed to energy transition to foster sustainable development for a positive industrial and societal impact (cf., Roshani et al., 2021; Mosleh et al., 2022; Coccia, 2021a).

In general, countries should design and implement systemic and long-run strategies and energy policies directed to reduce their coal and petroleum-based economies by developing and implementing some sustainable technologies, detected here, which have fruitful perspectives towards renewable energies, clean productions, recyclable goods, etc. in a context of overall circular economy that guides the ecological transition for a sustainable economic growth and well-being of future generations (cf., Aresta and Dibenedetto, 2020; Pronti and Coccia, 2021). Hence, economic systems should support some technologies, analyzed here, that have potential aspects to effectively reduce environmental degradation and preserve total environment for a sustainable future of human society (Magdoff, 2013; Magdoff and Bellamy Foster, 2011; Saeli et al., 2022). In addition to sustainable technologies, energy and sustainable polices have to support within megalopolis and large urban agglomerations an equilibrium between environment, natural resources and human society: i.e., an eco-socialism system based on a cooperation among people, institutions, firms and other actors to cope with resource limits and preserve. In addition, environmental, social and economic policies have to support the equilibrium in human society with the goal of achieving optimal health outcomes recognizing the interconnection between people, animals, plants, and their shared environment for one health in a perspective of equal ecological society (Aidnik, 2022; Adaman and Devine, 2022).

To conclude countries should design and implement systemic and long-run environmental, energy and industrial polices to reduce their coal and petroleum-based economies by developing and implementing some sustainable technologies directed to carbon neutrality based on renewable energies, clean productions, in a context of circular economy that guides the ecological transition for a sustainable economic growth and well-being of future generations (cf., Aresta and Dibenedetto, 2020; Pronti and Coccia, 2021).

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