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The Political Economy of Green Transition: The Need for a Two-Pronged Approach to Address Climate Change and the Necessity of "Science Citizens"

Antonios Angelakis [1], Manolis Manioudis [2,*] and Anthi Koskina [3]

[1] Department of Political Science, School of Social Sciences, Gallos Campus, University of Crete, 74150 Rethymno, Greece; angelakis@uoc.gr
[2] Department of Economics, University of Patras, Laboratory of Economics of Strategy, Innovation and Sustainability—LENS, University Campus, 26504 Patras, Greece
[3] National Observatory of Athens, 11810 Athens, Greece; akoskina@noa.gr
* Correspondence: mmanioudis@upatras.gr

Abstract: Given the need to strengthen responses to the growing challenges posed by climate change, the purpose of this paper is to explore innovative approaches and interdisciplinary perspectives for tackling these issues, focusing on the role of the institutional framework, emerging technologies, and the necessity to also encourage the involvement of small-scale actors (such as citizens). The main approaches of this paper involve, first, the technological developments spurred by the necessity to effectively address climate change problems, emphasizing macro-level dimensions in terms of the political economy of green transition and the technological components of climate solutions. Parallel to that, it provides results and presents key elements of the legal context that promoted the sustainable transition, such as the establishment of a science-based policymaking process, the development of scientific data and tools, and efforts to encourage the participation of all relevant actors in sustainable economic development. Against this background, this paper puts forward the idea that a combined approach is required to address climate change issues, integrating top-down, e.g., macro-policy approaches with bottom-up strategies (with the latter allowing for a more dynamic participation of citizens and individuals), in order to complement current institutional, legal, policy, and technological measures. The result of the analysis is that this paper provides evidence for the introduction of guidelines strengthening macro-economic approaches in addition to the concept of a "science citizen" as a major component of new problem-focused solutions. The principal results and findings offer interpretations and insights while encouraging further discussion on transitioning to a sustainable science society. In this context, the analysis results elucidate that there is evidence for an increased policy emphasis on technology development (economy-based approaches) rather than on technology diffusion and assessment, and/or the integration of key small-scale actors, such as citizens. Thus, this paper provides evidence for the need to incorporate "science citizens" as a key parameter into the technology and innovation chain (e.g., data provision) and the public policy domain. Overall, this paper outlines a holistic analysis of the international economic, technological, institutional, legal, and policy environment regarding innovation, sustainability, and the climate crisis.

Keywords: climate change; sustainability; green transition; science citizen

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1. Introduction

The unprecedented nature of the climate crisis makes it clear that humanity will have to face unrivaled challenges of an inconceivable magnitude. In this context, policymakers should find innovative ways of strengthening and maximizing communities' resilience, taking into account the crucial economic, technological, and legal aspects of the sustainable transition as dictated by the current and dominant international political economy configurations and policy trends. Therefore, following on from that, a key research question that arises is how feasible the implementation of new policy approaches would be—to efficiently complement the existing technological as well as institutional, legal, and policy frameworks—and what key features it should incorporate. In other words, would a solution be to strengthen the existing frameworks and efforts by trying to establish a foundation that facilitates the engagement of all stakeholders concerned by climate change, including by putting the focus on allowing (and encouraging) the participation of the base of the society, i.e., citizens, as well?

In trying to address this challenge, this article puts forward the idea that specific measures should be adopted to allow for citizens' dynamic participation, to complement the dominant current macro-approaches aiming to address climate change. Hence, it focuses on discussing and examining the feasibility of such a new policy approach, as follows.

Building upon the introduction in Section 1, Section 2 presents the main methods of the paper, which involve a holistic analysis of the international economic, technological, institutional, and policy environments regarding innovation, sustainability, and the climate crisis. Setting the broader context from the view of political economy in Section 3, Section 4 of this paper will shed some light on the major trends in the international technology landscape with a major emphasis on technology growth and innovation as related to climate change effects. In Section 5 of this paper, the major existing gaps of the legal and institutional environment regarding green transition are presented, namely, a plethora of technological and policy tools (such as are the establishment of a science-based policymaking process, the development of scientific data and tools, and efforts toward encouraging the participation of all actors concerned), which are all characterized by the absence of citizen participation. Section 6 further discusses and explains the concept and multifold role of the "science citizen" under legal and technological points of view. In this respect, this paper examines, in Section 7, the "science citizen" concept as a major constituent of new problem-focused approaches and flagship bottom-up interventions, in the context of cross-boundary initiatives to address climate crisis. In the final section, Section 8, this paper summarizes the main findings, analyzing the main conclusions and interpretations along with core foresight considerations, and further issues related to an open discussion for a transition to a sustainable science society.

2. Materials and Methods

The methodology adopted in this study involves a holistic and interdisciplinary analysis of the international economic, technological, institutional, and policy environment, with the aim to examine the approach adopted for utilizing technology in order to tackle climate change problems. This study integrates multiple dimensions to provide a comprehensive understanding of the issue and to provide an in-depth multidisciplinary scientific novelty. In particular, this study examines, first, the global political economy dynamics, with an emphasis on examining the literature with respect to hyperindustrialization; this part shows that hyperindustrialization has resulted in environmental degradation but has also created tools allowing us to measure and address such negative impacts on the environment. Following on from that (second), this study examines the policies adopted on technological advancement and use, showing that said policies are mainly focused on key players in this field (e.g., companies operating in the fields of cleantech and greentech). Thus, this paper presents a review of global patenting activity to illustrate priorities adopted regarding the role of technologies in addressing climate issues. In that respect, the patent analysis in this paper uses valid results provided from relevant studies/sources, such as the European Patent Office and World Intellectual Property Organisation. Finally (third), this paper presents the international legal obligations as well as the institutional arrangements promoting the development and application of scientific and technological approaches to address climate change, and gaps and opportunities in these frameworks, particularly concerning non-key players, such as through bottom-up (i.e., citizen) engagement. Overall, this paper assesses green policies and strategies, in conjunction to international legislation adopted in this field, as implemented in key economies. It focuses on their macro-level impact and alignment with sustainability goals; at the same time, it brings to light the need for an enhanced public policy contribution and role, despite the increasing accessibility and widespread adoption of new technologies. Building on these findings, this paper proposes a dual strategy, combining top-down macro-policy interventions with bottom-up, citizen-centered initiatives and participation, that should, in any case, be effectively integrated into official policymaking processes by the relevant authorities.

3. The Global Political Economy and Industrialization's Impact on Climate Change

The wider international political economy context sets the stage for understanding the deep environmental challenges linked to escalating industrialization and globalization. However, although it is undisputed that, on the one hand, economic integration has strongly contributed to environmental decline (Section 3.1), it is, at the same time, true that industrialization has also provided precision tools enabling scientists and decisionmakers to measure and address the environmental impacts of hyperglobalization (Section 3.2).

3.1. Economic Integration and Environmental Decline

Globalization, as the most critical economic phenomenon of the 20th century, is associated with an unprecedented growth of international trade and Foreign Direct Investments (FDIs). In addition, the era of globalization is marked by financialization, a process where financial markets, financial institutions, and financial elites gain power over economic policy (Palley, 2007). In this sense, globalization is implied to further intensify economic activity as capitalism, according to Marx and Engels, "creates a world after his own image" (Marx & Engels, 1848/1888) globalization has been developing in recent decades and has been associated with the need of many states to expand their economic activities to improve the social welfare of society (Omifade et al., 2021). In this sense, globalization was "upgraded" to hyperglobalization. However, hyperglobalization is in crisis.

The signs of this crisis are numerous. The most critical issues are the recent trade war between the United States of America and China (Jeong & Lee, 2021), the Ukraine war, and the recent war in the Middle East. This reality is associated with a transition from the increasing global economic integration to geoeconomic fragmentation (GEF), which is transformed into a critical mega-threat of the international economy.[1] Furthermore, GEF is intermingled with various mega-trends. A crucial trend among them is ever-growing global income inequalities that are at their peak as the wealth of the top 1% has increased drastically after the COVID-19 pandemic. According to Ghosh (2022), the global share of the poorest half of the world's population is around half of what it was during the first decades of the nineteenth century. Concentrating capital in a few multinational corporations is a major force leading to inequality among states. The inequality is intensified through the de-regulation of markets imposed through financialization, leading to the decline in public wealth across the globe. In addition, the COVID-19 pandemic led to stagnation and recession and caused a reversal of the effects of globalization, known as de-globalization (Sutkowski, 2020).

This intensification, which is associated with what is now called hyperglobalization (Rodrik, 2018), has important implications for the natural environment (Clapp, 2014). Many studies link globalization with pollution (Rafidandi & Usman, 2019; Acheampong et al., 2019). The growth of industrial activity and conventional energy consumption led to greenhouse gas emissions, transforming climate change into a climate crisis. The climate crisis and environmental degradation are significant mega-threats to the international economy. Climate crisis is associated with the "triple trap" of global warming, biodiversity crisis, and pollution. More specifically, 14 of the 15 warmest years recorded have occurred during the first 24 years of the 21st century. Moreover, the seven hottest days of the past 170 years were experienced in July 2024, and one million species are at immediate risk of extinction. Lastly, pollution levels from chemicals and hazardous waste threaten health, environmental protection, and natural resource management. The "triple trap" of the climate, biodiversity, and pollution crises illustrates the immediate need to go beyond economic growth and prepare the ground toward a green transition (Aranitou et al., 2024). Increasing environmental degradation and the environmental impact of economic activities exacerbate the need to reduce environmental impact and resource use to allow future generations to meet their own needs. Thus, the transition of economic policies from the traditional target of economic growth (mainly GDP growth) to sustainable development is a remarkable shift in development studies and will direct the policy's future policy implications.

Against this background, technology, developed in the context of hyperglobalization, has evidently driven economic development, while also being used in activities harmful to the environment. Importantly though, technology (i.e., as developed in this specific context) also provides revolutionary tools to address such climate challenges.

3.2. A "Hyperglobalized" Technology Also Enables Climate Challenge Measurement

Based on climate change science, the challenges that societies are facing in terms of long-term changes in temperatures and weather patterns are radical and devastating. According to Noam Chomsky, humans are facing major problems today that are really different to any that have arisen before in human history (Chomsky et al., 2020), as extreme weather events create unhabitable conditions in vast areas of the Earth (ibid.).

Indeed, new technological advances and earth-orbiting satellites assist scientists to collect and analyze data on dramatic climate change. According to the Intergovernmental Panel on Climate Change available data (IPCC, 2023), global greenhouse gas emissions have increased with ongoing contributions arising from unsustainable energy use, land use, lifestyles and patterns of consumption, and production across regions, countries, and among individuals. Overall, human activities, mainly through emissions of greenhouse gases, have caused global warming, with the global surface temperature reaching 1.1 °C above 1850–1900 in 2011–2020 (ibid.).

Similarly, based on NASA data[2] (NASA, 2024), the current warming is taking place at a fast rate not seen in the past 10,000 years, while the rate of change since the mid-20th century is unprecedented[3]. For example, the planet's average surface temperature has risen about 2 degrees Fahrenheit (1 degrees Celsius) since the late 19th century, and this is mainly driven by increased carbon dioxide emissions into the atmosphere. Additionally, the global sea level rose about 8 inches in the last century, and glaciers are retreating at a global level. Human-caused climate change is affecting many weather and climate extremes in every region across the globe (IPCC, 2023). This is causing widespread impacts and damages to nature, societies, and people. Responding to emerging challenges, scientists, governments, international organizations, communities, and citizens are developing initiatives, solutions, and ideas to cope with climate challenges. Aggregate technological progress provides new tools with which to collect and analyze various sources of information about the planet and its climate, illustrating shifting patterns of climate change. Similarly technological development unfolds new technological solutions focused on environmental sustainability and energy transition (cleantech and green tech).

Therefore, it is clear that the technological advancements at our disposal enable the precise measurement and analysis of environmental impacts, based on reliable series of data (unstructured and structured). Be that as it may, the critical question that arises is whether such scientific and technological tools are being utilized in an efficient manner to address and mitigate the underlying causes of climate change.

4. Utilizing Technology to Tackle the Issue? Emphasizing the Green Transition

Reality shows that, against the background of the pressing need to address climate issues and utilize technology to tackle the environmental challenges, governments have mainly put the emphasis on the green transition (Section 4.1), as demonstrated by the various policy frameworks adopted to promote sustainable development. A key example of this is related to the supportive green policies, the relevant policy frameworks, and the technology trends revealed by the patenting activity that plays a key role in encouraging cleantech innovation and supporting the adoption of green technologies, inter alia (Section 4.2).

4.1. Policies Focused on Enhancing Green Transition

Over the past few years, key developed economies have pursued policy schemes to enhance green energy, green technologies, and industrial sectors, with emphasis on cleantech. Energy policies and sustainability programs are usually combined with several policy initiatives within the frame of interlinked public policies such as technology and innovation policies, industrial policies, and transport policies. The direction of green policies both through large-scale green technology plans but also within interlinked policies, are increasingly characterized by macro-policy mechanisms that compile the major building blocks of green transition policies, inter alia, as follows: legal frameworks and new institutions, infrastructures and investments, technological development and innovation, business framework and funding, skill empowerment, demand-oriented incentives and measures, tax incentives, and international collaboration. Nevertheless, an integral part of green policies is increasingly involving targeted and topic-focused measures and initiatives, advanced technological tools (e.g., geophysical observatories, software systems based on Artificial Intelligence for analyzing satellite data, atmosphere monitoring tools, advanced algorithms), and new legal frameworks and institutions (e.g., legal frameworks for the use of open data).

A large part of the green policies during the last years has been focused on green economy and sustainable development along with the improvement of resource efficiency. Moreover, circular economy constitutes a major part of policy priorities for a wide range of green policy strategies, especially regarding sustainability and resource management development. On top of that, new innovative models for green entrepreneurship have emerged, while several initiatives at the national and international level are emphasizing sustainable economic growth (Han & Gao, 2024). Overall, large-scale green technology plans set the framework and provide tools in innumerable ways. For example, the European Climate Law[4] (July 2021) and the European Green Deal[5] constitute fundamental institutional and policy initiatives to accelerate green transition in the dominant practices at the level of infrastructure, production, consumption, and energy resources. The European Union has set climate neutrality as a target by 2050 through targeted strategies for enhancing emissions cutting (reducing net greenhouse gas emissions by at least 55% for EU countries by 2030), supporting technology development in green solutions and protecting the natural environment[6]. Similarly, the Green Deal Industrial Plan[7] aims to revitalize the competitiveness of Europe's net-zero industry and to accelerate the transition to climate neutrality through the support of manufacturing for net-zero technologies.

In the USA, the Inflation Reduction Act[8] (IRA) comes into law in August 2022. The United States of America invests nearly USD 400 billion (federal funding) for clean energy through the IRA with the aim of net-zero emissions and limiting carbon emissions by 2030. In tandem, a considerable part of the investments is directed to the support of the country's innovation capacity, economic competitiveness, domestic manufacturing capacity, and R&D support in key sectors, such as carbon capture and storage and clean hydrogen (McKinsey & Company, 2022). The IRA is part of a set of investment bills that have been deployed over the past few years, exceeding USD 2 trillion, since 2021 (together with the Bipartisan Infrastructure Law and the CHIPS and Science Act)[9].

People's Republic of China also exhibits increasing technology and production capacities in cleantech innovation activity. A wide set of investments, policies, programs, and tools (e.g., Green Bond Principles, industrial clusters, pilot demonstrations) have been designed and implemented to pursue research and development, energy transition, and carbon neutrality. In 2022, China[10] released its 14th Five-Year-Plan on Renewable Energy Development (2021–2025) (World Economic Forum, 2023), which involves a 50% increase in renewable energy generation (from 2.2 trillion kWh in 2020 to 3.3 trillion kWh in 2025) and promotes a renewable electricity consumption share of 33% up to 2025 along with a target of deriving 50% of the country's incremental electricity and energy consumption from renewables during 2021–2025. Several fields of technology development also involve large-scale renewable energy bases, distributed wind and photovoltaic infrastructures, integrated systems of water and solar bases, and the development of offshore windmills in several areas (ibid.).

Besides the large-scale strategies and green policies, green transition requires wider socio-economic transformations with shifts in several legal, institutional, and social parameters (e.g., social diffusion, citizens' engagement, open data exploitation). According to Schot and Kanger (2018), interconnected social, economic, and ecological challenges necessitate fundamental changes in a wide range of socio-technical systems (e.g., energy, mobility, water, food). For example, the debate about redesigning the direction of modern industrial policies has already been enriched with insights, proposals, measures, and initiatives for deliberately sustainable, welfare-oriented, innovation-oriented, and holistic policy mechanisms based on the cooperation between government agencies and private and third-party sectors (Mazzucato & Rodrik, 2023). Moreover, the availability and the coalescence of multiple and complementary technological tools co-evolves with legal change and leaves room for new forms of social and citizen participation into the science and technology domains. As long as the large-scale green policies are crucial for developing the core technological and innovation framework as well as the legal environment, the topic-focused acceleration mechanisms aiming to enhance social diffusion and citizens' engagement also constitute a prerequisite for social embeddedness for green technologies and green transition.

Nonetheless, policy initiatives and institutional arrangements unfold potential frameworks of action to manage climate change. In his work to analyze global trade and world economy, Dani Rodrik (2018) states that market-supporting institutions are not unique and there is not a limited range of plausible variation in institutions that might differ significantly across countries. Taken further, this evidence-based argument indicates that institutional setups might be re-configured and recombined to tackle several issues and challenges of social inequality, social insecurity and justice, or climate change. In a nutshell, institutional design, institutional setups, and organizational changes are major complements for efficiently deploying technological progress and tackling social challenges. Moreover, according to Mazzucato (2018b), innovation has a rate and a direction. As a result, innovation policy design should be inextricably interlinked to the increasing need to cope with emerging challenges such as climate change. In this respect, mission-oriented policies are defined as systemic public policies that draw on frontier knowledge to achieve specific goals and to confront social challenges (Mazzucato, 2018a, 2021).

Overall, the legal and institutional arrangements as well the direction of technological change and innovation constitute crucial parameters to create unique and adjusted technology-enabled approaches to tackle social challenges and, more specifically, to cope with the dramatic climate crisis.

4.2. Technological Change and Patents: A Key Aspect of the Policies Adopted

Regarding technological change, global patenting activity, and emerging patent trends illustrate an overall picture on technological progress in the fields of sustainable technologies, cleantech, and greentech. Cleantech and green technologies involve a wide array of technological applications such as low-carbon electricity production, low-carbon transportation, energy efficiency in the buildings sector and the manufacturing sector, air pollution control technologies, and waste management (OECD, 2019).

It should be mentioned that there are different methodologies available to identify green patents based on the code classification (ENV-TECH developed by OECD, IPC Green Inventory by WIPO, and Y02/Y04S Tagging scheme by EPO) (Favot et al., 2023). As a result, in several cases, the methodologies should be used in combination in order to obtain a complete and precise picture of general trends. According to Favot et al. (2023), for instance, ENV-TECH and IPC Green Inventory should be used in combination to identify more green patents, with the inclusion of the “CPC” ENV-TECH green codes (when applicable) while the mutual integration of the three methodologies is recommended.

For example, a study by Rivera León et al. (2023) based on the IPC Green Inventory of the World Intellectual Property Organization (WIPO), examined four broad categories of green energy technologies, including alternative energy production technologies, energy conservation technologies, and green transportation in the period 2005–2017. The findings revealed that energy innovation-related patenting activity first expanded exponentially up until 2013, both in total number of patent families and PCT (Patent Cooperation Treaty[11]) international patent applications in green energy technologies (ibid.).

Most of the green energy technologies have seen a downward trend in the annual number of patents published since 2012 (e.g., nuclear power generation technologies and renewable energy technologies, such as solar and wind energy, and fuel cells). On the other side, according to Rivera León et al. (2023), the number of patents in energy conservation technologies and green transportation technologies has continued to grow, although at a slower rate.

According to a joint study[12] published by the European Patent Office (EPO) and the International Energy Agency (IEA) (EPO & IEA, 2021), the number of patents related to low-carbon energy technologies around the world grew by an average rate of 3.3% per year in the 2017–2019 period. Since 2017, there is increasing innovation activity in low-carbon energy (LCE) regarding crosscutting technology areas such as batteries, hydrogen, and smart grids as well as carbon capture, utilization, and storage (CCUS) (ibid.).

More recently, according to the recent joint report[13] by the European Investment Bank (EIB) and European Patent Office (EPO) (EIB & EPO, 2024), there has been an increase in patents related to technologies focused on environmental sustainability and energy transition. Based on the European Patent Office classification, cleantech patents involve six categories: low-carbon energy[14]; climate change mitigation technologies (CCMTs) related to transport and buildings, in manufacturing and ICT; climate change adaptation solutions; smart grids; waste and wastewater treatment technologies; and CO_2 capture and storage solutions (ibid.).

Overall, over 750,000 international patent families (IPFs) in clean and sustainable technologies have been filed worldwide, which represent nearly 12% of all IPFs (EIB & EPO, 2024). Low-carbon energy technologies, encompassing renewable energy generation and energy storage solutions like batteries, constitute the predominant cleantech sector. According to the EIB and EPO (2024) report data, followed by a decline up to 2012, this sector accounted for over 78,000 IPFs, representing 32.1% of all IPFs in cleantech from 2017 to 2021[15] (ibid.).

Based on the WIPO's Green Technology Book (2023), there is a wide range of climate change mitigation solutions based on mature and emerging innovation technologies available. According to WIPO data (2023), inventions in climate change mitigation technologies increased fivefold between 1995 and 2011, while the period 2014–2017 was characterized by a slowdown (due to factors related to fossil fuel prices and technological maturity of climate mitigation technologies, among others). Since then, there is an observable upward trend (WIPO, 2023). In terms of technology areas, indicatively, patenting activity increased between 2017 and 2020 in low-carbon energy technologies as a result of the activity in the fuel switching, energy efficiency, and crosscutting technologies, such as hydrogen and batteries for transport.

Consequently, it seems that the increasing rate of investments on green technologies is correlated with the increasing patenting rates of the international patent families (IPFs) in clean and sustainable technologies worldwide. Part of this increase is tightly interlinked with the green policies being implemented in recent years in key developed economies and the institutional arrangements pursuing the deployment of these technologies by paving the way through new governance schemes and by eliminating technological and commercialization uncertainty.

All of the above developments stem from economic and developmental dynamics, while also reflecting the increasing global awareness of climate change challenges. However, in reality, states have, in light of this awareness, also undertaken significant commitments under international law to use all the available scientific and technological resources to address climate change effectively, and agreed on duties that extend well beyond the mere promotion of technologies for a green transition.

5. International Law: Optimizing the Use of Science—Enabling Citizen Engagement

States adopted the policies presented above, also grounded in their agreement at the international level to use science to tackle climate change. Indeed, the creation and use of green technology and climate-related scientific knowledge was actively promoted by the international community following the adoption of binding law instruments aimed at adapting to climate change issues by increasing the resilience of societies. Such developments were encouraged in two ways, namely via the establishment of (first) a clear obligation of states to use scientific data within the context of policymaking and (second) the setting up of dedicated bodies empowered to promote the creation and utilization of scientific information; said frameworks are, however, characterized by the limited role and opportunities for participation afforded to small-scale actors, like citizens (Section 5.1). Be that as it may, they undoubtedly facilitated the development of technologies empowering citizen participation in climate monitoring and data collection (Section 5.2).

5.1. The Basic Orientations Established in International Environmental Law

Concerning, first, the obligation of states to utilize scientific data within policymaking processes, one may note that already in the early 90s, the UN Framework convention on Climate Change (1992, UNFCCC)[16] first mentioned scientific knowledge by highlighting that "lack of full scientific certainty should not be used as a reason for postponing" measures to address climate change (Art. 3.3). In this sense, a twofold duty of states was created to, on the one hand, address climate change in an effective manner and avoid any recourse to (easy) excuses and, on the other hand, develop and use science in the best possible way. Following on from that, the Kyoto Protocol (adopted in 1997, entered into force in 2005)[17], inter alia, was built upon science to define and clarify states' obligations to reduce emissions (Annex A of the Protocol). However, a few years later, this objective was still not reached, and the IPCC admitted in 2007 that the warming of the climate system is "unequivocal" (IPCC, 2007). As a response, the obligation to make maximum use of the possibilities offered by the best available science was strengthened in the Paris Agreement (2015), laying down that in adopting related policies, states must consider, as well as share and develop, scientific knowledge on and understanding of climate change (e.g., Art. 7.5 and 14.1)[18].

Importantly though and parallel to that (second), dedicated bodies were also created right from the outset to facilitate and encourage the collection and use of scientific data. By way of illustration, in 1988, the United Nations Environmental Program (UNEP), which had been launched at the 1972 Stockholm conference, and the World Meteorological Organization (WMO) agreed upon the creation of the International Panel on Climate Change (IPCC) to assess the available climate-related information[19] and formulate response strategies (Art. 1). The IPCC was maintained under the UNFCCC (Art. 21), and its role was strengthened further. At the same time, the UNFCCC also established the Subsidiary Body for Scientific and Technological Advice (SBSTA) to assist the decision-making organ (Conference of the Parties/COP) in using scientific knowledge, such as by providing it with relevant advice and information, opinions on climate-related technologies, etc. (see, e.g., Art. 9.2.a and Art. 9.2.b). Finally, the Paris Agreement created teams of experts entitled to review the consistency of scientific (climate-related) information submitted by state parties (Art. 13.11). In this context, it is noteworthy that the latter treaty additionally laid down the rule that states should strengthen "institutional arrangements, including those under the Convention ..." (Art. 7.7.b). Thus, in an indirect though clear manner, the duty was established to also create national bodies and tools that would be competent to support the work conducted by the international specialized authorities mentioned above, in a scientific and sustainable way.

Following on from that, one may observe that emphasis was put on developing specialized tools and authorities that would allow for the participation of all actors involved to assist policymakers; in reality though, the idea mostly applied to global initiatives (e.g., campaigns, structured partnerships), city alliances or networks, regional initiatives, etc. (UNEP, 2023). In other words, the individual, namely the citizen per se, appears to be absent from being actively involved in this framework, although it was clearly established from the outset that "Man has the fundamental right to ... adequate conditions of life, in an environment of a quality ... and he bears *a solemn responsibility to protect and improve the environment* for present and future generations" (Stockholm Declaration Principle 1; emphasis added)[20]. In truth, legal tools to achieve this objective were soon adopted, such as the procedural right of access to (climate-related) information or the right to public participation, as it is presented in the 2019 UNEP Frist Report on the Environmental Rule of Law[21]. However, human rights organizations denounce the fact that citizens (individually) have been denied the right of access to climate-related information or have even reported cases of "climate science censorship" (ARTICLE 19, 2009). Consequently, the prevailing impression is that individuals remain largely excluded from active participation within the existing system.

At the same time, given the proliferation of new scientific tools (such as open data platforms utilizing mobile applications and the Internet of Things, as explained below), one may argue that there is significant potential to enhance citizen involvement by leveraging, e.g., the accessibility, continuity, quality, and affordability of scientific means. The only question that remains to be answered is what form citizens' interaction and participation in climate-change decision-making could take, especially taking into account that the issue of citizens' coproduction in fields of public policy, lato sensu, has already raised concerns as to its precise implementation (e.g., in the context of health, see Koch et al., 2024).

Therefore, in addressing this challenge, it is worth considering that scientific and technological advancements have also considerably facilitated the development of open data platforms and climate data store APIs (application programming interfaces), enabled the aggregation of climate information, and enhanced predictive capabilities and the monitoring of climate trends in specific regions, while fostering opportunities for citizen involvement.

5.2. Technological Advances: Enabling Citizen Participation in Climate Monirtoring

The international legal framework described above has allowed states to first understand the potential of science in tackling climate change and adapting/mitigating its impacts, and also to encourage the development and use of green devices and infrastructure. Hence, based on the idea that the development and use of technology is an international priority—and of vital importance for tackling climate change, such as in the case of clean energy devices (UNFCCC 2016)[22]—states have tried to also make the most of space systems and Earth Observation (EO) data, as policymakers recognized the capital importance of such information for the monitoring and management of everyday activities, including natural phenomena and/or climate-related crises (Salin, 1992; Corvino et al., 2019; Rapi et al., 2019; Koskina et al., 2023). In this context, Artificial Intelligence (AI) has allowed us to further optimize the use of existing EO datasets, inter alia (Gal et al., 2020), and better anticipate, for instance, droughts (Sardar et al., 2021) and wildfires (Kondylatos et al., 2022). As a result, initiatives were taken to create international databases that would ensure access to scientific information (ESA, 2023), containing data, like in the case of those delivered by the EU system "Copernicus"[23], that are available to citizens on a free, full, and open basis. In addition to that, states have put effort into improving their climate governance frameworks, such as by adopting climate laws setting goals that include emission reduction targets or short-term actions and measures, and more recently, they have also established climate change (advisory) bodies based on a multidisciplinary representation in climate-related areas of expertise (note that dedicated authorities may take different forms; still, they all aim at "injecting science into the policy-making process and enhance governmental accountability") (Evans & Duwe, 2021, p. 8).

More precisely, technological changes in the cleantech and green technology domain span a wide range of technological fields. Indeed, energy transitions require fundamental and long-term infrastructures, new enabling technologies, and long-time periods (Smil, 2017, 2022). Fossil fuels remain a dominant energy source, while solar and wind remain a smaller part of the mix (Smil, 2021). Concurrently, in the domain of energy transitions, technological innovations and policy design can accelerate technological change, while the energy transition may be a set of more discrete conversions (Sovacool, 2016). Moreover, the diffusion of new technologies follows diverse ways, and it is strongly associated, inter alia, with technological readiness, techno-economic efficiency of technologies, and commercial applicability and demand, as well as the availability of critical inputs and converging technologies.

In particular, converging technologies constitute a new area of technological advancement. As a result, space technologies provide tools with which to monitor and analyze satellite data related to climate change, while Artificial Intelligence (AI) provides new approaches and predictions for major climate trends. Green technologies are inextricably interlinked with a vast array of digital and other key enabling technologies allowing efficient use of new applications in clean and sustainable technologies (e.g., low-carbon energy, renewable energy generation, energy storage solutions, smart grids).

Similarly, the diffusion and the deployment of key cleantech technologies are interlinked with legal, institutional, and social parameters. Major changes in the energy and cleantech sectors interact with key prerequisites in the institutional and policy environment. In this context, open data platforms and climate data store APIs (application programming interfaces) create opportunities for the aggregation of climate data and could feed the predictive capabilities or monitoring of climate trends in specific geographical areas. The exploitation of sensors and monitoring technologies from various sources provide multilevel data for temperature trends and weather forecasts for cities or rural areas. The rapid and extensive use of mobile applications and Internet of Things might provide new experimental approaches for collecting, triangulating, and analyzing multimodal datasets for climate parameters and potential impacts.

In this respect, policy experimentation should be part of the policy mix for institutional interventions. The appropriate mix of policy interventions might combine both horizontal policy strategic plans, programs, and measures (e.g., green policies in the EU, the USA, and China) and also topic-focused interventions and initiatives to develop converging technological applications, to pursue collaborative innovation, and to provide new governance schemes for climate change. Even more importantly, the co-evolution of legal and institutional arrangements with technological applications allow technological openness, technological inclusiveness, collaborative innovation, and science-focused data for climate change, which might create new avenues for accessible technologies for citizens encouraging participation and active engagement.

In other words, technological advances allow for the involvement of new stakeholders, such as citizens. For example, the use of Artificial Intelligence (AI); the availability of data aggregated from data platforms, Internet of Things (IoT), and satellite data; and new algorithmic systems, software applications, and AI-powered micro-processors provide opportunities for broader inclusion, even of micro-stakeholders. Indeed, the emerging technological context leaves room for the participation of minor actors in the science domain and policymaking process, such as individual citizens, by providing multi-layer data and inputs to address climate change. It is worth noting here that the direction and the character of technological change is not of deterministic nature. That is, the technological advances might have differentiated effects on production processes based on their characteristics. For example, Acemoglu and Restrepo (2019) described how new technologies not only increase the productivity of capital and labor but also impact the allocation of tasks to these factors of production; and under this prism, they illustrated the major differences between automation technologies that enable capital to be substituted for labor in a range of tasks (displacement effect) and factor-augmenting technologies that do not impact the task content of production (ibid.). Similarly, several emerging technologies or technological areas might reflect more inclusive characteristics depending on their use from end users (e.g., companies, citizens). A larger part of emerging technologies provides technical specifications allowing for the involvement of users, such as citizens, into the collection of data, providing real-time information and enriching multi-layer available knowledge for social and natural phenomena. Different set of technologies for differentiated uses of technological applications might enhance inclusive, interactive, and participative functions and roles for citizens, including them as new nodes of information into the science process and climate monitoring.

On top of that, technical, organizational, and further institutional dimensions allow for the deployment of "data networks", data aggregation, data exploitation on the basis of interoperability and interconnection, and the use of AI-enabled decentralized technologies (e.g., blockchain-driven decentralization and distributed algorithm systems used as cryptographic methods to collect and manage data and digital twins for collecting climate-related data from multiple sources, such as citizens, smart sensors, and satellites).

6. Discussion: What Is the Role of the 'Science Citizen'

In legal theory, different participation models have been studied up to now, ranging from government involvement in community initiatives to citizens' participation in policymaking, including climate change issues like flood safety risks (Mees et al., 2019). In truth, such measures, which fundamentally originate from the framework laid down in the Aarhus Convention (1998)[24], stipulating, inter alia, the right to public participation in environmental decision making (Lee & Abbot, 2003), could be significantly improved. To this end, it is crucial to define the potential contribution of the "science citizen" by examining their role and capacity in contributing to the tackling of climate-related challenges (Section 6.1) and to developing a conceptual approach for integrating their involvement into broader frameworks for sustainable solutions (Section 6.2).

6.1. Defining the Contribution of Citizens to Scientific Endeavors

In practice, reality has shown that, despite a number of rights established for individuals and groups regarding environmental governance in international law, such as under the Aarhus Convention (e.g., stipulating the right to access environmental information held by public authorities; or providing the public with the right to seek judicial or administrative review when their access to information is denied), obstacles persist in their implementation (see ARTICLE 19, 2009). In fact, it is often noted that governments tend to restrict opportunities for citizen-led initiatives and participation, particularly when addressing climate risks that are perceived to be urgent (Mees et al., 2019). However, citizens (and citizen-led organizations) could play an important role, first, on a preventive—but still systematic—basis, such as by assisting state authorities in collecting and verifying data related to the climate and to climate-related disasters, especially given that comparable forms of citizen engagement have already been established and encouraged in other or relevant fields.

By way of illustration, public reporting systems and platforms have been utilized since the 2000s by administrations to enable citizens to report problems in public spaces or to suggest improvements; the data collected through these platforms are then used to facilitate modernization projects by local authorities. More precisely, in France, applications like "Dans ma rue" (used in Paris) allow citizens to report real-time issues, such as matters of the illegal dumping of waste. As a next step, reports are drafted and submitted to municipal services to facilitate prompt action (Chambon, 2022). A closer example to mention is the Citizen Weather Observer Program (CWOP), a public–private partnership aiming at, inter alia, "collecting weather data contributed by citizens; and making these data available for weather services and homeland security"[25]. Notably, regarding the importance of citizen participation in the collection of such information, it is highlighted that "These data are also ingested into computer forecast models, which lead to more accurate forecasts and warnings for your area. So, your observations, especially those in the more remote areas (. . .) are extremely valuable!"[26]. This demonstrates how citizen-contributed data not only improve the precision of weather forecasts but also are used to enhance public safety and to support decision-making processes for disaster preparedness and response, especially when taking into account the vast amount of data provided by citizens ("The number of North American CWOP stations sending data over the past several days is normally more than 7000 stations sending 50,000 to 75,000 observations every hour. The number of world-wide citizen weather stations sending data to CWOP is shown increasing over the past decade[27]").

Therefore, this kind of solution could, mutatis mutandis, be applied in the context of climate-related issues in general and as a rule—particularly considering that platforms for the collection of climate information are already in place—to enable the engagement of citizens in ways similar to the Citizen Weather Observer Program (CWOP). For instance, citizens could participate in assessing and reporting the efficiency of cleantech and green technologies in situ (e.g., using climate change mitigation technologies (CCMT) in transportation and buildings; using waste and wastewater treatment technologies; etc.), in terms of the air, water, or soil quality (e.g., provide data on the levels of specific pollutants using personal sensors; measurements of temperature in rivers; data on the depletion of local water resources, on soil erosion in agricultural areas, or on the destruction of ecosystems), etc. In this sense, the science citizen could play a role in bridging the gap between large-scale research and local insights, providing real-time and very specific information. Furthermore, such kind of participation would allow us to also determine the investments in green technologies that should be planned and (to a certain extent) minimize technological and commercialization uncertainties by providing real-world feedback on the performance and practicality of innovative approaches.

6.2. Developing a Conceptual Approach to the Science Citizen

Following on from the above, it may be argued that there is a more dynamic role for proactive citizen involvement in the climate-related decision-making process by actively participating first in the collection and assessment of climate related data. On a theoretical level, the science citizen could be defined as any individual actively engaged in climate-related efforts, using their own means or not, to assist competent authorities via a structured and formal collaboration with them, providing support precisely in (climate-related) research, data collection, and/or decision-making. This kind of citizen participation is supported, in general terms, by international agreements, such as the Aarhus Convention (1998), establishing the right of the public to participate in environmental decision-making, and also international environmental law treaties (e.g., the Paris Agreement, 2015) stipulating the obligation for states to use the best available science to address climate-related issues. The added value of the "science citizen" concept lies in its emphasis on moving beyond the Aarhus Convention, which focuses on granting citizens access to environmental information, in a general manner. Instead, it allows for the implementation of the Aarhus Convention in a very specific way, leveraging current technologies to enable citizens to be efficiently included in the institutional framework, based on their feedback that would be officially considered in the implementation, improvement, and adoption of policies and measures.

However, despite the prospects of this proposal, considerable challenges need to be tackled in practice. Indeed, on the one hand, not all citizens have equal access to (or familiarity with) technology, which could create inequalities in participation; on the other hand, public authorities might struggle to collect and process large volumes of citizen feedback, as well as control the accuracy and reliability of data reported by citizens (which could lead to inaction on behalf of the competent authorities). As a result, citizen participation should be regulated at the state level and facilitated, e.g., through the adoption of specific mechanisms. More precisely, detailed rules could be adopted, at the national or regional level, to lay down guidelines and standards (and facilitate the collection and processing of data), safeguards to prevent the misuse of collected data, and frameworks to integrate citizen feedback into decision-making processes in a meaningful way.

Be that as it may, a major challenge remains in successfully integrating citizens' active participation into the decision-making process while ensuring that they can effectively influence its outcomes. Indeed, along with providing citizens with technology, necessary (e.g., through tools, platforms, but also educational resources) legal mechanisms should be developed to serve this objective, such as to realize the following: (i) to enable them to raise the alarm or facilitate the mobilization of competent authorities about climate-related issues; (ii) to facilitate the submission of appeals or proposals to competent bodies (on climate-related issues and under pre-determined conditions); (iii) to enable participation in determining climate-related priorities (e.g., by creating official platforms allowing citizens to contribute to policy discussions, provide their opinion on legislative proposals or measures adopted, etc.); or (iv) to participate in the development and implementation of related technologies and strategies, taking into account practical experience or local necessities to ensure that the solutions are not only technically sound but also grounded in the realities of the area in question. Taking these aspects into consideration, legislation should aim to establish a balance between encouraging citizen participation on both levels (scientific and policymaking), ensuring the quality and reliability of individuals' feedback. If this course of action was followed, citizen participation could become a pillar of governance, enhancing inclusivity and public trust while allowing us to better address climate-related problems.

Overall, from a macro-critical perspective, the historical pathway of science activities can be traced back to the individual scientists and inventors; the institutionalization of science; the formulation of science and technology systems; the configuration of international and interconnected technology value chains; and then to the more recent emergence of a new possibility/role for "science citizens" through the use of emerging technologies to confront multifold sustainable challenges. Thus, the role of "science citizens" and technological communities might be a critical additional parameter within data collection and technological advancement within the funnel of science progress. This would be a significant challenge within the quest for a new citizen role within the new technology era. Consequently, the co-evolution of technological, legal, and institutional change will further accelerate the formulation of a new technology governance approach.

7. Foresight and Future Directions

Is climate change reversible? Is it possible to address the challenges posed by climate change effectively? These are the critical questions that science community, governments, international organizations, companies, and citizens seek to answer by developing new technologies, deploying new policy measures, and adopting new practices in recent years.

A major part of initiatives during the last years involved multilevel progress in several different aspects but mainly consisted in top-down efforts. New legal frameworks seek to formulate new sets of incentives and regulations. New technologies aim to provide solutions for energy, transport, manufacturing, and other socio-economic activities in order to limit and reduce greenhouse gases and carbon dioxide emissions, while at the same time developing and deploying carbon-free energy technologies. The green transition is interlinked with several aspects of unpredictability and the combinatory dynamics of technological, economic, political, and geostrategic dimensions (Angelakis & Manioudis, 2024). In recent years, new policy formulas and new generation policies have been deployed for sustainability with the aim to tackle climate crisis and subsequent challenges. Their major features combine macro-schemes with horizontal macro-effects and several problem-focused mechanisms and bottom-up interventions (e.g., programs and initiatives engaging decentralized technologies, organizations, systems, and new science tools such as data-monitoring platforms and satellite systems) (Table 1). In this respect, policies that efficiently tackle climate change effects involve aspects of public and private investments, science and technological progress, economic and social transformations in terms of business practices, production models, consumption patterns, and energy paradigms.

Table 1. Two-pronged policy approaches.

Policy Approach	Dimensions and Parameters
Current macro-policy approaches	Energy and technological infrastructures; legal frameworks; research infrastructures; technologies; funding tools; institutions; policy measures; international cooperation; international antagonisms and tensions
Bottom-up approaches	Legal and institutional frameworks securing and encouraging citizens' participation; emerging and decentralized technologies; open platforms; open technologies; science tools and systems; smart sensors and data; data provided/assessed by science citizens; need for international cooperation

Source: own processing.

However, given both the current legal framework and technological developments that all allow for a more dynamic participation of individuals, it is more than apparent now that top-down efforts should be combined with (a more dynamic) bottom-up involvement. Namely, the pathway to managing climate change in the future should incrementally be based on a two-pronged policy approach with wide-scale top-down policy strategies compiling legal, institutional, and technological parameters as well as bottom-up topic-focused approaches engaging local communities, social groups, and citizens (Table 1).

More precisely, integrating top-down and bottom-up strategies to empower the "science citizen" requires actionable policy tools and clearly defined goals. In the short term, governments and organizations could give priority to creating user-friendly platforms where individuals (i.e., citizens) may upload environmental data, using their own sensors or amateur technology, such as air or soil quality measurements; existing programs or initiatives could be used as a blueprint. To ensure inclusivity, free training on AI-topics, data-driven applications, and digital tools could be provided to bridge the digital divide. In addition to this, policy frameworks should ensure that the unstructured or structured data provided by citizens are controlled and integrated into decision-making processes, coupled with incentives like public recognition to encourage active participation. Following this line of reasoning, governments should aim at promoting and encouraging, in the next decades, the widespread participation of citizens; they should also ensure that citizen-driven environmental information is taken into account in local and national policies through standardized frameworks. Relatedly, the design and deployment of policies focused on integrating top-down and bottom-up strategies to empower the "science citizen" approaches, involve crucial aspects such as the formulation of appropriate legal frameworks, the support of technologies and technological applications with open and inclusive and participatory character, the formulation of infrastructures, and the enhancement of collaborations, synergies, and citizen networks initiatives (Figure 1). Based on this, the development of "science citizen ecosystems" emerges as an additional precondition for an evolving and dynamic process of science citizens' involvement. For example, facilitated access to high-performance computing and software focused on AI and science (OECD, 2023) constitutes a crucial element of such an ecosystem as well as the availability of open research data across various fields (e.g., climate) through the formulation of federated data infrastructures (e.g., GAIA-X) and the large-scale creation of findable, accessible, interoperable, and reusable (FAIR) data (ibid.).

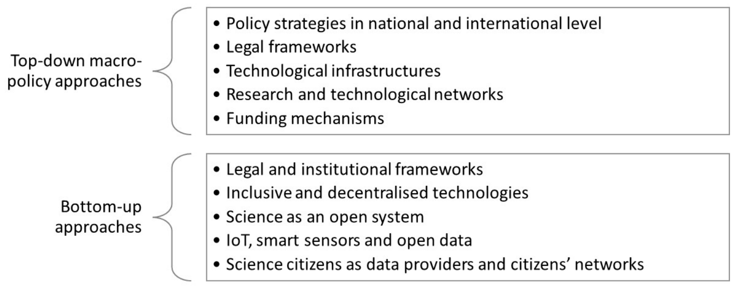

Figure 1. The two levels and the sub-categories of the two-pronged policy approaches. Source: own processing.

In particular, with respect to the latter, the path to a "science society" is tightly interlinked with the active encouragement and engagement of citizens' roles regarding the use, adoption, and diffusion of technologies and information, in addition to the assessment of climate policies and related measures. Following on from that, the involvement of "science citizens" would actively contribute to the policymaking as well as to the progress of technology and science, with the aim to better address sustainability challenges of local, regional, and global concern.

8. Conclusions: An Open Discussion for a Sustainable Science Society

This paper aims to explore new approaches of tackling challenges related to the climate crisis through interdisciplinary perspectives and novel types of interventions focusing on the role of the institutional framework and new technologies. Concurrently, the present paper provides novel insights into new directions related to the multi-layer aspects of designing and implementing policy approaches to tackle climate crisis with the use of emerging technologies and institutional reconfigurations. For example, the development of actions focusing on facilitating the engagement of citizens toward the acceleration of scientific discoveries has been a core issue related to data collection and processing activities (Bonney et al., 2016). Moreover, there is a vast potential for citizens' contribution through the exploitation of data, advanced algorithms, and Artificial Intelligence (OECD, 2023). Data provided by science citizens might contribute to the more effective solutions of current societal challenges in several areas, such as climate change and infectious diseases.

Technological direction is an important aspect of the opportunities provided for users to contribute to social activities, such as science for climate monitoring. From this perspective, several future research directions could emerge under the spectrum of the technologies through which citizens can actively contribute to the science domain. Further avenues for research include, among others, the need to identify and develop citizens' inclusive technologies and technological applications that facilitate the collection and sharing of data and ideas from the crowd and citizens' activity. Overall, the identification of the major pre-conditions for the formulation of "science citizen ecosystems", including, inter alia, digital infrastructures, federated open data, new inclusive and accessible technological applications, and science citizens' engagement, constitute a major area of further research.

This paper aims to elucidate new approaches that involve practical steps and policy-relevant tools. The practical steps to operationalize the "science citizen" concept involve the design and deployment of topic-focused policy initiatives to support citizen engagement, data collection, data sharing, and collaboration. More research programs and large-scale initiatives could further mobilize citizen participation in science activity to build-up background knowledge and enhance the use of science education. The consolidation and deployment of new policy tools and actionable steps (e.g., integrated systems and open interoperable data platforms with which to collect, analyze, and predict climate crisis trends and challenges through advanced algorithms and topic-focused large language models/LLMs) include the incorporation of inclusive technological directions into the core research and funding priorities for research and technological and innovation policies. Then, the successful integration of top-down and bottom-up strategies constitutes a major pre-condition for the formulation of a large-scale and long-term strategic orientation not only to tackle but also to predict challenges and to prevent large-scale climate crisis effects. Expanding and facilitating the role of citizens and society at large could be a near-future policy goal for topic-focused policy approaches.

Following this perspective, this paper aims to also elucidate the importance of those novel approaches for tackling "grand social challenges". According to Voegtlin et al. (2022), "grand societal challenges (GSCs) represent complex, multi-level, multi-dimensional problems that require concerted efforts by various actors (public, private, and non-profit–to be successfully addressed" (Voegtlin et al., 2022, p. 1). In this respect, science citizens' policy initiatives might facilitate the contribution of citizens toward addressing emerging challenges. Moreover, the science citizens' policy initiatives might be aligned with the deployment of robust innovation ecosystems, as the latter requires comprehensive approaches of engaging and mobilizing regional actors and identifying their needs and priorities toward sustainable development (Manioudis & Angelakis, 2023).

The future research directions to further delve into the concept of the "science citizen" include three integrated areas: (i) which technologies and technology areas might be more compatible with encouraging the involvement of citizens in the science domain and the thematic areas of climate monitoring, (ii) which major institutional and legal fundamental parameters will facilitate and encourage citizens to participate in "science citizen networks" and contribute to science activity, and (iii) which are the appropriate policy tools with which to formulate "science citizen ecosystems" with the perspective to further establish computing infrastructures, to enhance AI-based tools and advanced algorithms, to provide access to open data, multimodal data systems, and open platforms, to further develop and adopt accessible, inclusive, and collaborative technological applications, and to establish supportive legal frameworks, citizen networks, policy initiatives, and measures and organizational configurations. The latter is also interlinked with the perspective of the operationalization of the "science citizen" concept through the deployment of "science citizen ecosystems". These ecosystems could be based on the capacity of societies to build a framework of action points to pursue climate monitoring, provide inputs for climate science, and thus contribute to tackling climate crisis effects. Overall, the emergence of "science citizen ecosystems" could crucially contribute to societies' climate resilience by approaching science as a public good with widely beneficial outcomes.

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Notes

1 For GEF see: https://www.imf.org/en/Publications/Staff-Discussion-Notes/Issues/2023/01/11/Geo-Economic-Fragmentation-and-the-Future-of-Multilateralism-527266 (accessed on 2 July 2024).

2 Available at: https://science.nasa.gov/climate-change/ (accessed on 1 August 2024).

3 Available at: https://science.nasa.gov/climate-change/evidence/ (accessed on 8 August 2024).

4 Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R1119 (accessed on 3 September 2024).

5 Available at: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (accessed on 1 June 2024).

6 Available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed on 1 July 2024).

7 The four pillars of the Plan are: a predictable and simplified regulatory environment, speeding up access to finance, enhancing skills, and open trade for resilient supply chains. Available at: https://commission.europa.eu/document/41514677-9598-4d89-a572-abe21cb037f4_en (accessed on 10 June 2024).

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11 Available at: https://www.wipo.int/pct/en/ (accessed on 21 August 2024).

12 The study is based on the EPO's dedicated classification scheme for climate mitigation technologies. The analysis consists of 372 cross-sectional classes that cover specific clean energy technologies that have been applied to over 3 million documents (EPO & IEA, 2021).

13 According to the report (EIB & EPO, 2024), clean and sustainable technologies, often referred to as cleantech or green tech, involve a broad range of processes, products, and services that aim to reduce or eliminate negative environmental impacts.

14 Low-carbon energy technologies, including those for generating power from renewable sources and energy storage solutions, are the most prevalent in the cleantech patent landscape, accounting for 78,000 of the total 244,000 patent families recorded between 2017 and 2021 (EIB & EPO, 2024).

15 Based on the data of EIB and EPO (2024)'s report, clean and sustainable manufacturing (more than 43,000 IPFs between 2017 and 2021) and clean tech solutions related to buildings, ICT, and adaptation to climate change are following while climate-friendly hydrogen-related technologies, wastewater treatment and waste management, smart grids, carbon capture and storage are the smaller sectors within clean and sustainable technologies (less than 10,000 IPFs between 2017 and 2021). In geographical terms, the report describes two distinct recent phases in cleantech patenting (i) the period 2006–2012, driven mainly by the EU and Japan (27% and 26% of the total increase in IPFs); and (ii) 2017–2021, led by China (70% of the surge in IPFs applications), followed by the EU (16%) (ibid.).

16 Available at https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf (accessed on 1 July 2024).

17 Available at https://unfccc.int/resource/docs/convkp/kpeng.pdf (accessed on 2 October 2024).

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