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Green Technologies: Innovations for Sustainable Development

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ABSTRACT

Sustainable development has placed a center stage on green technologies. This is due to the fact that they pledge to address the heavy environmental, economic and social crises and threats of the 21 st century. The necessity of this shift towards appropriate technologies is the urgency and high demand of climate change, depletion of resources, and implications of those changes on human well-being and international stability.. This paper explores green technologies by outlining where they have been, a roadmap for their future, where they have or could be used and ways in which they can be focused to yield the best possible outcomes for people and the planet. The key aspects of the technologies identified in of energy efficiency, carbon footprints, circular economies and importantly ethical, legal and social aspects in their adoption, through discussing more than a dozen innovations, classified broadly by the areas of Sustainability, Agriculture, Waste & Circular Economy, Transport, Construction and Spaces. The inclusion of various case studies from different regions adds to the discussion by contributing examples of successes and limitations in the practice of green innovations. Throughout the discussion, two important challenges to scaling up the transition to the desirable green and sustainable technologies were identified: economic challenges, policy and government action challenges, and technology challenges. The report concludes with recommendations for global cooperative research and renewable energy focused policies to have the biggest impact on reaching the UN Sustainable Development Goals (SDGs). Green technologies occupy the place of responsibility between science society and policy - they are vital for the present and future of society and the planet, so the aim in this academic report is to demonstrate their importance for a sustainable future.

Keywords

Green technologies; sustainable development; renewable energy; circular economy; environmental innovation; sustainable agriculture; green infrastructure

INTRODUCTION

The world we live in has certainly experienced unparalleled advancements in health education, transportation, communication....in the last two centuries due to industrial and technological progress. Despite the incredible and unique developments of the human society, there are very high prices. Via fossil fuel dependence, unsustainable industrialization, unplaned consumption, climate shifts, and pollution of ecosystems have been experienced (Rockström et al., 2009). We should bear in mind that the human society has now entered the two hundred years in the global society where the technological innovation should be accompanied by environmental practice in case we would be able to develop the sustainable and viable civilization. It is in this regard that we are finding that so-called green technologies, which simply are innovations which reduce environmental harm, enhance efficiencies of materials and resources, and/or lead to the sustainability of renewable resources, are highly significant tools in aiding in alleviating the ecological and global development dilemma (Panwar et al., 2011).

Green technologies are not domain specific rather they cover an array of areas and sectors such as renewable energy, waste management, sustainable farming, water saving, green transport and green building systems. Their increasing import is driven by climate change accords, increased consumer awareness and the desire to achieve the United Nations Sustainable Development Goals (SDGs), for instance, SDG 7 concerns the guaranteed provision of affordable and clean energy, and SDG 13 requires that urgent actions are taken to combat climate change, and both SDG 7 and SDG 13 are directly associated with the development and deployment of green technologies (United Nations, 2015). Green technologies serve to achieve an improved environmental performance while enabling continued innovation in technological development and economic growth - suiting sustainable contexts whereby innovation is decoupled from environmental degradation and economic growth occurs without ecological harm.

In the past, adopting environmentally friendly technologies has typically happened out of necessity as a result of crises (oil calamities, urban pollution, and climate-based disasters). Today, green technologies are not simply a reaction to crises. They are pro-active pathways to new business models, employment opportunity, and sustainable economic development (OECD, 2017). Governments, private companies, and research institutes are investing into renewable energy systems (solar PV, wind turbines, bioenergy), and are researching new technologies such as battery storage, carbon capture, and green hydrogen (IRENA, 2021). These trends reflect a transition to a low-carbon economy that embraces prosperity while protecting human and planetary health.

Even so, the development and actual implementation of green technologies still face considerable challenges: initial costs, uncertainty around technology, and inequity between developed and developing countries in terms of access (Sachs et al., 2019). Likewise, ethical and social factors raised by technological deployment—such as digital divides, land use conflicts and labour transitions—are among many other issues. So, the green technologies can have a transformative potential but its effective implementation will require regulatory frameworks, inclusive governance and international cooperation.

The research article will consider the broad spectrum of dimensions of the green technologies as the carriers of sustainable development. It will then overview the historical history of environmental innovations and then explain what principles and dynamics underlie the innovations. Subsequently, it will take into consideration some of the applications in the areas of interest, ethical and social concerns, international cases, hurdles and future perspectives. In the union of the green technologies, and the general discussions concerning sustainability, this paper aims to prove that green technologies cannot be left out in case there is any chance of alleviating environmental catastrophes, and at the same time enhancing the social, economic as well as political welfare of people.

THE HISTORIES OF GREEN TECHNOLOGIES

The concept of green technologies did not materialize in the thin air. Instead, it has evolved over time as we have come to know more about the harmful nature of our actions towards the environment, energy insecurity because of overindulgence in industrialization, and the constraints of our natural resources.. When technology was historically developed, local economics and the progress of industry drove the adoption of projected technology with little regard for its ecological ramifications. When the ecological costs were realized in the 19th and 20th centuries, societies started to realize the importance of considering alternative projects that aligned with sustainable development. This arc of development can be characterized by the following: pre-industrialization, early industrialization reform, the rise of the environmentalist movement, and a current resurgence of green technologies today.

Pre-Industrial & Traditional Uses

Social and human groups prior to the Industrial Revolution relied extensively, even almost exclusively, on renewable resources, namely wind, water, and biomass. For example, throughout Europe, traditional windmills were used to mill grain, while waterwheels were extensively used in Asia for grain milling, irrigation, and textile manufacturing (Smil, 2010). Biomass, both as wood and agricultural waste or residues, was the primary source of household energy for heating and cooking. There was not an explicit intention for environmental protection, but they existed within natural limits and cycles and exerted very little ecological pressure compared to fossil fuel–based systems.

Industry & Fossil Fuel Paradigm

The Industrial Revolution of the 18th and 19th centuries represented another major turning point as fossil fuels (first coal, and later oil and natural gas) became the dominant energy source used in factories (heavy industry), transportation, and domestic energy consumption. Not surprisingly, this energy transformation led to important economic development and population growth in urban areas, but simultaneously led to serious environmental damage from air pollution, deforestation, and, of course, greenhouse gas emissions (Mokyr, 1998). The industrial paradigm obviously made more emphasis on efficiency and productivity rather than sustainability, but it has also brought numerous other innovations (e.g., public sanitation systems, electrification) that had a positive environmental health in an indirect way..

The Early Stirrings of Environmental Consciousness (late 19th – mid-20th century)

Towards the end of the nineteenth century, there had been initial appeals on conserving the environment and protecting the natural environment because of their perceived adverse impacts of industrialization.. Influential figures such as John Muir in the United States and Sir Ebenezer Howard in the UK would speak about the need to protect natural landscapes, and also to build urban spaces more in line with natural influences (Muir, 1916/1992; Howard, 1902). On the technology front, there were early, small breakthroughs, such cleaner combustion engines, and early attempts experimenting with solar energy. For example, in the 1860s, Augustin Mouchot was reported to be using solar steam engines and is understood to have made the first recorded attempts to use renewable energy for industrial purposes (Butti & Perlin, 1980).

The Development of the Environmental Movement (1960s-1980s)

It was a prosperous period after the World War II, as well as a period of enormous ecological destruction that incorporated smog, poisonous waste, and disastrous industrial accidents. Silent Spring (1962) by Rachel Carson is often considered the trigger of the contemporary environmental consciousness as it discusses the harm of excess usage of pesticides. It saw the germination of the large environmental regulatory bodies, such as the U.S. Clean Air Act (1970), the U.S. Clean Water Act (1972), and the development of the United Nations Environment Programme (UNEP) in 1972 (Carson, 1962; UNEP, 2019). These led to the triggering of dollars to pollution control technologies, renewable energy research, and sustainable agriculture techniques.

Even the oil crises of the 1970s served to generate further interest in the alternatives to fossil fuels as the states started to consider more in the ways in which they could move beyond the current degree of reliance on fossil-based energy sources. During this time, substantial funding on solar photovoltaics and wind power was injected and the foundation of the modern renewable energy industry was established during this time (Kaldellis & Zafirakis, 2011).

GLOBALIZATION AND SUSTAINABLE DEVELOPMENT (1990s–2000s)

Transparency (2013)

The late twentieth century also heralded the beginning of a deeper and more committed global cooperation on issues related to the environment. Sustainable development emerged as an important notion first introduced in the Brundtland Report, Our Common Future in 1987. The report indicated that technological innovation must better balance the present need for growth and development against the risks of undermining the needs of future generations (World Commission on Environment and Development [WCED], 1987). The 1992 Earth Summit, in Rio de Janeiro, strengthened this idea in setting expectations on the importance of green technology for project development that addressed climate change, biodiversity, and development needed for sustainable growth.

Beginning in the 1990s, the Kyoto Protocol (1997) required industrialized countries to commit to reduced greenhouse gas emissions and pushed investments into renewable energy technologies, energy efficiency, and carbon capture technologies. The same pattern emerged with information technology investments that addressed the systems needed for a smart energy management system. This was the beginning of the early vision for smart grids and sustainable cities (Goldemberg, 2000).

Modern Green Technology Revolution (2010s–Present)

The burning of the revolution of Green Technologies that started at the beginning of the 21 st century is associated with the appearance of the climate change and necessity to resolve the climate crisis to increase human existence. The formulation of effective international policy frameworks, including the 2015 Paris Agreement, are extensive and concurrently directed at the reduction of near and long term warming of the planet to average temperatures that are far below 2 o C. The accord was used to jump-start an unanticipated surge in, typically disruptive, innovations in solar and wind energy set up technologies, green hydrogen creation technologies, battery reservoir technologies, and carbon neutral forms of transportation.

Moreover, the endowment of digital technologies with green technologies, including artificial intelligence, blockchain, and other solutions based on the Internet of Things (IoT) is quickly streamlining energy systems, including smart homes, and monitoring emissions.. Furthermore, digital technological advancements are facilitating and improving sustainability reporting for businesses, which has become an imperative for many organizations (George et al. 2021). Simultaneously, the idea of a circular economy has emerged and been embraced by producers and consumers as part of a paradigm shifting from the longer-entrenched waste minimizing alternatives of reduction and recycling, a prioritizing and accepting and implementing a reconsideration to production and consumption alternative, which focuses on closed production systems as alternatives to linear production and consumption systems (Geissdoerfer et al. 2017).

Also, the success of grass-roots movements and youth movements organized around activism movements such as Fridays for Future have strengthen and actualized society's increasing socially and environmentally just demand that green policies and green innovation be considered in the face of continuously declining societal wealth during technological advancement.

Central Principles and Mechanisms of Green Technologies

In the context of innovation, the terms green technologies, clean technologies, or environmental technologies mean similar but not just synonymous things, like principles that attempt to reduce harm while also providing more efficiency, resilience, and sustainability. These technologies are circularity systems-based oriented lines of thought, which not only entail the use of environmental values in the innovation process but also social and economic values and outcomes. In order to comprehend the connotations of green technologies in the context of sustainable development, one will have to consider the fundamental orientations that inform the design of these technologies and processes of action.

FUNDAMENTAL PRINCIPLES OF GREEN TECHNOLOGIES

Sustainable development and Efficiency of Resources

The key principle associated with green technologies is sustainability, or meeting the needs of the present without preventing future generations from meeting their own needs (WCED, 1987). Sustainability relies on efficient use of resources, or use of less energy, water, or raw materials. Technologies improve sustainability by developing products and systems with fewer inputs and waste, or lower environmental footprints, while increasing resource lifetimes. For example, energy efficient consumer appliances and LED lights reduce electricity requirements which reduces greenhouse gas emissions.

Pollution prevention and Waste reduction

Green technologies focus on preventing pollution rather than managing waste after it is created. This principle is exemplified in cleaner production where industry modifies industrial design in order to reduce toxic by-products, emissions and waste streams (Allen & Rosselot, 2009). For example, the closed-loop manufacturing process avoids wasting materials by recycling materials directed back into the production process. Using fewer resources minimizes reliance on virgin resources therefore has small environmental impact.

Renewable Input and Circularity

Green technologies consider renewable inputs, and concept of circular economy. Renewable energy technologies (e.g. solar, wind, bioenergy) have a place of finite fossil fuels with natural mechanisms to replenish over long time periods. Likewise, the principles of circular economy are to drive reuse, recycling, and remanufacturing, which would have previously been waste, much like the underpinnings of re-design thinking (Geissdoerfer et al. 2017). By doing this we lessen the reliance on extractive industries and develop sustainable ways of consuming.

Life Cycle Thinking

Another principle of green technologies is thinking about the environmental impacts beyond the technology itself. Life cycle thinking is an approach which considers and values overall environmental aspects at scale (Finnveden et al. 2009) against their entire life cycle (i.e., raw material extraction, production, use, and disposal). For example, an electric vehicle (EV) produces neither emissions nor uses fossil fuels while in-use (e.g., during vehicle operation - 0 emissions). However, there are environmental costs related to battery mining, manufacturing, and battery recycling. Life cycle analysis is one technique to ensure that green technologies provide real net ecological benefits.

Systems Integration and a Holistic Approach

Green technologies are generally only successful when they are applied within larger ecological and social and economic systems. This principle echoes the fact that technologies are working in interconnected systems and the optimization of a specific element in isolation will not always result in sustainable outcomes and advantages. One of the ways in which technologies can be incorporated into our energy systems to form efficient and resilient networks and ecosystems is smart grids that control the distribution of renewable energy, storage and demand-response systems (Lund et al., 2015).

Equity and Inclusivity

Sustainability is not only ecological, but it is the motivation of social relations and structures. The approaches and frameworks that shape green technologies are informed by inclusiveness and equity in such a way that benefits and access are equally distributed among communities- particularly those who are usually marginalized (Sachs et al., 2019). Clean energy provides access to affordable energy that, by way of example, can set about health improvement in low-income areas, as well as economic empowerment.

MECHANISMS OF GREEN TECHNOLGIES

Whereas principles provide a groundwork of ethics and concepts, mechanisms are a practice of all tools, processes, and technologies which make green innovation possible.

Renewable Energy Systems

The biggest mechanism is that of the delivery of renewable energy systems. Solar photovoltaic systems convert the sun rays to electricity using semiconductor substances; wind turbines are used to create electricity by converting the kinetic energy or flow of air currents; bioenergy systems convert organic waste to heat, electricity, or fuels via combustion, gasification, or anabolic digestion (Panwar et al., 2011). The technologies change the reliance on fossil fuels and decrease greenhouse gases jointly.

Energy Storage and Smart Grids

Overcoming the intermittent character of the renewable energy sources, energy storage technologies such as lithium-ion batteries and new hydrogen storage systems can contribute to this task. Together with smart grids, i.e., digital infrastructures enabling a more efficient real-time adjustment of both supply and demand of energy, these technologies can assist in enhancing the efficiency, stability and resilience of energy (IRENA, 2021). Demand-response programs are some of the mechanisms that enable the consumer to adjust his consumption pattern to ensure that he or she demand less on his local grid and optimize the integration of renewable energy sources.

Sustainable Agriculture Technologies

Another substantial mechanism is the agricultural technology advancements. Precision agriculture employs GPS, drone and sensing technologies so as to make use of resources including irrigation, fertilizer and pest control more efficient, which will lead to a reduction in wastage of vital resources as well as fewer environmental effects (Gebbers & Adamchuk, 2010). Both vertical farming and hydroponics seek to optimize yield using less land and water use, and are instances of the hype of controlled-environment, or other new agricultural regimes.

Green Manufacturing and Material Innovations

Green technologies function through rethinking and redesigning industrial production processes. For example, additive manufacturing (3D printing) creates objects layer by layer significantly reducing material waste, while biodegradable materials and bio-based plastics take the place of petroleum-based materials (Shen et al., 2010). Clean production technologies further encapsulate emissions with efficiency through energy savings, and chemical substitution.

Water and Waste Management Systems

Novel water purification products such as membrane filtration, desalination, and UV disinfection offer for safe drinking water and limited reliance on chemical treatment. Waste management systems, using anaerobic digesters, capture the methane produced from organic waste with these systems generating usable energy from these circular resource flows (Börjesson & Berglund, 2007).

Carbon Capture and Storage (CCS)

Carbon capture and storage technologies are being used more widely to deal with emissions from hard-to-abate industries. These systems capture CO_2 emissions from a power plant or industrial process and store the carbon underground in geological formations. CCS is considered controversial due to costs and long-term risks but is viewed as a mechanism to bridge towards net-zero economies (IEA, 2020).

Digital and Data-Driven Solutions

To sum up, it is possible to take advantage of digital technology to enhance the performance of green technologies. A lot of value can be achieved by leveraging AI (artificial intelligence) algorithms to predict energy demand, optimize supply chains to the requirements of energy demand, and predictively keep renewable energy systems (George et al., 2021). Blockchain technology can provide an auditable, transparent function for tracking carbon credits and supply chain sustainability, and the Internet of Things (IoT) can provide real-time monitoring on energy consumption, waste levels, and environmental conditions and subsequently increase efficiency and accountability.

APPLICATIONS ACROSS SECTORS

Green technologies provide their greatest benefits when utilized across multiple sectors, shifting industries away from traditional processes and practices that allow for more sustainable models that balance economic growth and environmental protection. Cross-sector use of green technologies has drastically improved an industry's operations by addressing how it uses energy, drives fossil fuel dependency, reduces carbon emissions, and produces waste as it promotes a circular economy. This section highlights how green technologies have been applied across renewable energy, green transportation, sustainable agriculture, circular economy and waste management, and green buildings, sharing examples that demonstrate their capacity to transform industries as a whole.

Renewable Energy

The renewable energy sector is one of the most widely recognized aspects of green technology adoption. Fossil fuels were the dominant sources of global energy for decades. However, the effects on the environment, which included greenhouse gas emissions, pollution, and ecosystem destruction, needed to be overcome for the world to change to renewable energy sources.

Technological developments in renewable energy have greatly improved solar photovoltaic (PV), wind energy, hydropower, and geothermal technologies as primary parts of global energy strategies. Solar energy is more affordable and accessible due to increased solar cell efficiency and battery storage systems (Shahsavari & Akbari, 2018). Innovations of offshore and onshore wind energy technologies have increased the efficiency and size of turbines and increased the electrical generation with digital monitoring technologies.

The advancement of smart grids and energy management systems have improved the distribution and reliability of renewable energy systems, integrating them into national power grids. For example, significant progress in renewable energy penetration without impact on energy security can be seen in Denmark and Germany (REN21, 2021).

Eco-Friendly Travel

Transportation produces almost 25% of carbon emissions globally. Thus, it is one of the largest opportunities to develop new green technologies (IEA, 2020). Vehicle innovations in the industries of electric vehicles (EV), hydrogen fuel-cell vehicles, and biofuels have revolutionized travel.

The rapid expansion of electric vehicles to date has to do with lithium-ion battery innovations being found with each cell consisting of higher levels of energy densification and increased journeying distance. All governments are incentivizing both small and larger organizations to switch to EV's through subsidies, tax rebates, and installation of charging infrastructure. As a result, companies that are pure-play EV models such as Tesla, BYD, and Nissan are revolutionizing transportation at a rapid pace - not to mention traditional automotive manufacturers that are shifting towards producing EV models.

Another example of green transport outside of the EV space is hydrogen fuel-cell vehicles, which have significant potential for long-haul travel and non-passenger commercial applications, especially since they provide similar driving ranges, replenishment times and convenience of conventionally fueled vehicles (Bicer & Dincer, 2018). However, like EV's there is a limited fuel fill infrastructure.

Innovations to support public transport systems include metro systems utilising electricity generated from renewable energy sources, electric buses, and shared mobility offerings in urban areas to lower emissions. In lightweight and heavy-duty transport modes, cities such as Oslo and Shenzhen have shown how the adoption of electric vehicles is successful, with Shenzhen being the first city that introduced fully electric buses for public transport in 2017.

Sustainable Agriculture

Agriculture is both a victim and contributor to climate change, emitting nearly 25% of world greenhouse gases in the form of methane, nitrous oxide, and deforestation (FAO, 2020). Green technologies in agriculture thus aim to fulfill food security while protecting the environment. Examples of innovations include:

- **Precision agriculture which uses drones,** sensors, and satellite imagery to optimize irrigation, pesticide use, and crop production with minimum waste.
- **Vertical farming and hydroponics** that reduce land use and conserve water by growing crops in controlled environments.
- **Biotechnology** to obtain drought-resistant and pest-resistant crops thus decreasing the need for chemical fertilizers and pesticides.
- **Bio-fertilizers** and organic farming reduce the chemical input while playing a protective role over the soil. A fitting case in point is Israel's adoption of drip irrigation, a technology recognized worldwide for good water management in arid lands. In a similar vein, Singapore's vertical farms attest to the role of green technology in enhancing food security through dense urbanization.

Waste Management and the Circular Economy

The circular economy is part of the green economy and technology movement in the development and application of green technologies. The circular economy is about reducing, reusing, and recycling waste. Traditional linear economies operate on a model of "take, make, dispose," while the "circular economy" is a sustainable system, promoting longer lifecycles for products.

Models of waste management are changing, as with the development of new technologies, including the advanced recycling of materials such as chemical recycling of plastics, which can turn materials back into source items for reuse. Waste-to-Energy plants buy municipal waste to produce electricity, heat, and other useable forms of energy, reducing the amount of waste that goes to landfill (Zaman & Lehmann, 2013).

E-waste management is necessary due to the rapid growth of the e-waste market. Green technologies present rare chances of discovering and reusing important metals such as gold, platinum and rare earth elements that pose great concern to the environment.

An example that can reveal the potential futures of the circular economy regarding the expansion of producer responsibility and a variety of methods to innovate the sustainable packaging items in the origins are the European Union Circular Economy Action Plan, which illustrates the nature of the use and services provided by the producers that minimized waste.

Green Buildings

It is estimated that the construction industry contributes almost forty percent of the total carbon emissions in the world, which causes the construction industry to adopt sustainable operations (UNEP, 2020). Green buildings use new technologies to reduce energy consumption, consume less water and make people feel healthier.

Innovations relate to:

- **Energy-efficient materials,** such as insulated panels or reflective roofing.
- **Smart building systems** that control energy consumption automatically.
- **Renewable energy sources**, such as rooftop solar.
- **Water recycling systems,** such as using rainwater or greywater recycling systems.

The Leadership in Energy and Environmental Design (LEED) certification system has set global benchmarks for sustainable buildings. The examples of the application of these systems are the Edge building in Amsterdam relying on smart technologies in order to reduce the energy consumption and Marina One in Singapore are green architecture and biodiversity united in one building.

Cross-sector synergies

The largest effects of green technologies are attributed to the convergence within sector innovations. As an example, electric transport and the smart buildings can be facilitated by renewable energy (renewables), and the construction and expansion of the buildings can be achieved through circular economy strategies that decrease the amount of waste. Each of these strategies react to a general system and offer a direction towards (SDG) Sustainable Development Goal 7 - Affordable and Clean Energy, SDG 11 - Sustainable Cities and communities, and SDG 13 - Climate Action.

Ethical, Legal, and Social Implications of Green Technologies

Green technologies will provide revolutionary chances of climate change reduction and sustainable development, yet they are likely to pose intricate moral, legislative, and societal challenges. These problems will define the nature of technologies development, implementation, and control as they transverse or traverse national and international locations. The problems related to equality of access, rights of people, intellectual property, environmental justice, and community engagement overlap with policy frameworks, regulatory mechanisms, cultural biases and other problems. By determining ethical, legal, and social implication of new technologies, we will be able to prevent or mitigate those, which may have negative implications in order to ensure the touted developments are ethically, legally, and socially responsible in addition to minimizing environmental impacts.

ETHICAL IMPLICATIONS

Environmental Justice and Equity

A significant ethical issue arises when other countries use green technologies and this is done in an equity manner. As richer nations take steps toward renewable energy sources, electric cars, and, not to mention, smart infrastructure, low- and middle-income nations have several obstacles, including costs, technology transfer, and lack of infrastructure (Sovacool et al., 2021). This brings us to the idea of environmental justice: would it be more just to have the more developed economies share more in the funding and relocation of green technologies to the weaker areas?

Also, the communities belonging to the marginalized groups that may face more energy transition burdens that reflect environmental injustices. As an example, the mining business of the developing countries that lithium, cobalt, and rare earth metals (used in batteries and solar panels) imply that a significant portion of local communities are exploited and harmed (Amnesty International, 2019). As such, ethical methods of utilization of green technologies should demonstrate fair labor practices and responsible sourcing of raw materials in any company where raw materials are mined.

Intergenerational Responsibility

Green technologies are usually discussed in the terms of intergenerational justice that focuses on our responsibility to preserve resources and ecosystems to the future. One can say that it is a moral duty to invest in renewable energy and sustainability but temporary costs of the green transition like loss of jobs in the fossil fuel industries, ethically should be balanced against the future advantage of the welfare of the life of the planet in general (Rawls, 1999).

The Ethical Use of Innovation

Both the rate and magnitude of innovations are the subject of ethical debate. As an example, during the bioengineering in the agricultural sector, lowering the level of pesticide usage would probably cause numerous ethical controversies regarding GMOs. Geoengineering initiatives like carbon capture and storage (CCS) and others are massive projects with numerous uncertainties of negative ecological impacts and precautionary principle emerges as a major ethical principle in this case (Gardiner, 2011).

LEGAL ASPECTS

Intellectual Property Rights and Technology Transfer

Legal structures influence access to green technologies. While intellectual property rights (IPR) promote innovative activities, they also restrict clean technologies from diffusing worldwide. Developing nations have suggested that patents substantially impede their potential to adopt renewable energy solutions on a significant scale (Haščič & Migotto, 2015). There seems to be a disconnection between nations' competing interests related to innovation and access to the environment, and there have been calls for international agreements that equalize global equitable access to protecting innovation, notably in the health sector where additional licensing terms have emerged from work at the World Health Organization, to address issues with research and development and drug pricing.

Legal mechanisms to enforce equitable technology transfer are limited, despite language in the United Nations Framework Convention on Climate Change and the Paris Agreement recognizing technology transfer and technology transfer is central to global cooperation on climate change (UNFCCC, 2015). We noted previously that developing nations were often at a disadvantage with regard to their contributions to global climate change and influence over decisions made through these frameworks.

Legal Standards and Regulations

Green technologies must comply with environmental safety, performance, and quality requirements imposed by law. For example, as part of the development of renewable energy sources, proposed projects must complete environmental impact assessments (EIAs) to demonstrate the project will not pose an unacceptable risk to biodiversity or wider ecosystems. For electric vehicles and the production of batteries for these vehicles, compliance must also be done concerning hazardous waste treaties and regulations, such as the Basel Convention (UNEP, 2019).

Third-party institutions like the International Organization for Standardization (ISO) have established sustainability-based certifications, for example ISO 14001, for environmental management systems. Legal frameworks certainly help establish accountability but they also can impose compliance costs that can limit smaller enterprises like small and medium enterprises (SMEs).

Willingness and Responsibility

Legal ambiguities often arise with the rapid growth of green technologies related to issues of liability. As an example, in the case of a wind turbine failure that damages surrounding property, it can be easy to create problems in determining who was responsible in the failure of the turbine itself, the operators and the assessors. To expound on this, the issues of liability concerning carbon capture and storage projects will probably have a time span of decades in deciding on long-term liability in unsafe storage in the event of leakage of the storage. The governments and corporate organizations should be at a position to openly define the regimes of liability in order to alleviate most of the emerging and arising legal threats.

SOCIAL CONTEXT

Employment and Workforce Transformation

Replacement of green technologies has significant social consequences in terms of employment. When the fact that the renewable energy industries will create millions of new jobs in each country of the world is taken into consideration, the nations or the areas that are already dependent on fossil fuels will lose the employment position in post-carbon economies (ILO, 2019). The strategies that will be based on climate action will initiate the need of just transition policies to compensate the displaced workers by retraining, reskilling and social protection. As an illustration, Germany, which is an element of its coal exit strategy, which entails social dialogue and government subsidies, can generate a significantly lower level of friction during the transition and transformation of communities.

Public Perception and Acceptance

Green technologies can only be adopted with social acceptance. Although the projects involving renewable energy are met by a positive response by the people, there will be cases where groups will emerge locally opposing development of such projects in a phenomenon that is called the Not In My Back Yard phenomenon (NIMBY) (Devine-Wright, 2009). Social engagement, transparency and participative decision making is very essential in earning the community trust.

Culture is another stratum which has an effect on the minds of people. Most of the green technologies that are considered are viewed on the other side of a cultural system; because of distrust in government or lack of understanding of what the long-term effects of some of these technologies may have on society; GMOs or even nuclear energy (which concentrates on the aspect of green through its low emissions) etc. Thus, social aspects of adoption depend on the context.

Social Inclusion and Accessibility

Unless they are designed with the goal of inclusivity in mind, green technologies may be deployed in a manner that only strengthens the current digital and social inequalities. To illustrate, the smart energy systems, and electric vehicles can be used as a good example, and only the households that are wealthier can enjoy the benefits of using them, as low-income households will be blocked by high initial expenses. The policies that favor the social inclusion of the underprivileged groups are: subsidies, microfinance, and decentralized renewable energy systems (e.g. solar microgrids in rural Africa) so that the disadvantaged groups are not locked out of the transition toward green innovations (IRENA, 2020).

A Balanced scorecard: Innovation and Responsibility

The need to have responsible innovation is presented through the ethical, legal, and social implications of the green technologies. This means the creation of a conglomerate of actors in the context where the technological progress can be discussed, as well as the questions of justice, responsibility and inclusion. Most of these tensions can be solved using inter-disciplinary methodologies which acknowledge the relevance of the law, ethical theory and governance procedures that engage people, communities and other stakeholders into the process.

Responsible Research and Innovation (RRI) approach provides fresh values in the process of leading innovation. In particular, RRI integrates the theme of anticipation, reflexivity, openness to society and the values (Owen et al., 2012). Using the RRI framework, green technologies enhancing the sustainability will be created, as well as the actions taken to safeguard the endangered groups and ecosystems against the negative effects.

CASE STUDIES & GLOBAL EVIDENCE

The world is moving towards practice of green technologies away and guaranteeing evidence of their sustainability potential. Using various case studies one can easily comprehend how nations, industries and societies have adopted green technologies in order to promote environmental safety, economic growth and social good. This section will identify select examples around the world including renewable energy, green transportation, sustainable food production, waste management, and green building.

Case Study 1: Renewable Energy Transition in Denmark

Denmark is generally recognized as a global leader in terms of renewable energy uptake. Denmark initiated its renewable energy transition in response to the oil crisis in the 1970s, and significant investments were made into wind energy technological development and infrastructure. As of 2019, Denmark is generating nearly 50% of its electrical generation from wind energy, with a majority of generation sourced from onshore and offshore turbines (Danish Energy Agency, 2020).

Denmark's community ownership model is important; however, the success in Denmark is attributed to community ownership in the form of cooperatives and local residents investing in their own wind facilities. This has improved the acceptance of wind energy projects, has decreased resistance against wind energy projects, and has localized the economic benefits (Sovacool, 2013). In addition, the collaboration with the smart grid in Denmark has allowed renewable energy production to work with traditional systems to provide energy reliability and energy security.

This case study illustrates how long-run policy support, innovation, and community ownership, can be used to successful scale up renewable energy technologies.

Web page Case Study 2: Electric Mobility in Norway

Norway offers an interesting example of green transport with strong government incentives in the form of tax exemptions, free tolls, and preferred parking for EVs. Norway has reached the highest per capita EV ownership in the world, with 65 plus percent of new car sales in the country being fully electric (IEA, 2021).

In addition to its incentives, where EVs contribute to emissions reduction is the country's commitment to renewable electricity, with most electricity being produced from hydropower. This fact allays fears that EVs are not a true alternative to gasoline models. Similarly, they have also devoted significant investments into charging infrastructure nationwide to confront one of the biggest obstacles to consumer adoption of EVs.

Norway demonstrates how regulated incentives and renewable energy can facilitate the green transport revolution and build consumer acceptance.

Case Study 3: Israel's Drip Irrigation and Agricultural Innovation

As water-intensive, agriculture in an arid environment is sustainable only if it has technological innovation. Israel was among the first to develop a series of drip irrigation technologies that direct water straight into the plant's roots while drastically reducing water consumption and improving crop yields. This technology was developed in the 1960s and is being adopted worldwide, particularly in drought-prone areas (Postel, 2011).

The advent of Israel's drip irrigation, the embrace of desalination plants, wastewater recycling, precision agriculture, and technological innovation to conserve scarce natural resources are a consideration of higher education institutions in the United States looking to engage with technology that helps agriculturalists. Today, more than 80% of the waste produced by the country is treated and reused towards agriculture, which is the highest recycling rate in the world (OECD, 2020).

Finally, the case demonstrates the potential of the green technologies in the agricultural sphere as the tool of the food security without the overexploitation of the limited natural resources.

Case Study 4: Circular Economy in the European Union

The European Union (EU) is in the forefront in circular economy transition. The EU member states are working on the measures to curb the production of waste, recycling, and sustainable product development, and make them the new standard with the EU Circular Economy Action Plan (2020).

Others like the Netherlands, with its aim of becoming a completely circular country by 2050, are looking into such a practice as urban mining, or reusing all the materials of demolished buildings. The incentive to encourage consumer renewables rather than replacements in Sweden is facilitated by its tax incentive that reduces repair services (European Commission, 2020).

All these illustrate the role of systemic and programmed policy framework in giving way to innovation of waste management and circular economy practices, which in turn significantly reduce the reliance of finite resources on the expanding green economy.

Case Study 5: Green Buildings in Singapore

On many levels, Singapore has developed leading examples of sustainable urban development. While there are certainly limitations on space, and the nation is largely deemed 'built-out', Singapore has adopted a strong commitment to greener space in the urban area. The Building and Construction Authority (BCA) of Singapore introduced its Green Mark Scheme in 2005 to guide developers and designers on greener building workout and designs.

One paradigm example of this commitment to sustainable urban development is Marina One, which includes a mixed-use complex with an abundance of urban greenery, natural ventilation, rainwater harvesting systems, and a range of energy-efficient building services technologies. Singapore has also committed to greening "80% of its buildings" by 2030 (BCA, 2020).

The example of Singapore demonstrates how urbanized areas can adopt green building technology to reconcile a greater density of urban living and national environmental sustainability.

Case Study 6: Off-Grid Solar in Sub-Saharan Africa

In many areas of Sub-Saharan Africa, centralized electricity grids are severely inadequate or nonexistent, leaving millions of people with unreliable access to energy. In contrast, off-grid solar technologies have become groundbreaking innovations. In Kenya, off-grid energy company M-KOPA provides pay-as-you-go solar systems, unlocking rural energy access to energy-weary households without relying on fossil-fuel-based energy systems (IRENA, 2020).

These systems provide improved standards of living by replacing kerosene lamps with clean lightening, aiding indoor air quality and educational opportunity by increasing study hours at night. Decentralized solar also increases financial inclusion as households can acquire these goods by making mobile payments to receive the service.

This case study demonstrates the supporting role green technologies play in advancing energy equity and aiding in meeting the United Nations' Sustainable Development Goal 7 (Affordable and Clean Energy).

Difficulties and Dangers in Implementation

Though green technologies hold the capacity to transform the way we pursue sustainable development, a number of difficulties and dangers exist in the implementation of green technologies. These difficulties and dangers include economic, technological, political, social, and environmental dimensions. These barriers must be understood and addressed when developing implementation strategies that also promote changes through the equitable, effective and scalable implementation of green technologies around the world.

Economic Difficulties: High Start-Up Costs

One of the major barriers to widespread adoption of green technology is the high up-front investment costs associated with green technologies, and renewable energy projects, green buildings, and electric vehicle infrastructure involve especially high capital cost investments compared to the alternatives (IRENA, 2021). Although ongoing operating costs may indeed be less than those of conventional technologies, the need for upfront financing is a major barrier, particularly for developing countries, and small businesses.

Disproportionate Access to Financing

Access to climate finance remains unbalanced. Wealthier countries and corporations can mobilize green financing, whether from bonds, Subsidies or private capital. Low- and middle-income countries tend to disincentivize international financing due to a fear or unwillingness to engage with perceived risks in these countries; weak financial systems; lack of capacity to generate investable or bankable projects (UNEP, 2020). This imbalance perpetuates global gap a gap in green technology uptake.

THE ISSUE OF TECHNOLOGY

Intermittency and Storage

The variable nature of generation at renewable energy sources like solar and wind due to weather dependency leads to intermittency challenges. Battery storage technologies are now readily available, they remain expensive and have limited capacity - which present challenges for the large-scale integration of renewables into national grids (IEA, 2021).

Resource Dependence

Green technologies are dependent on critical raw materials like lithium, cobalt, and rare earth elements. The mining of these depends on the environmental degradation caused, as well as the potential supply chain vulnerabilities, and geopolitical issues. The issue of dependence is amplified with concentrations of production in a few countries, for example cobalt being mined essentially only in the Democratic Republic of Congo causing dependence, and potential instability (World Bank, 2020).

Skip and Husher (2022) identified two major barriers preventing businesses from adopting green engineering practices: infrastructure barriers and political and policy barriers.

Infrastructure Barriers

Many regions do not have the infrastructure to enable the use of green technologies. For example, the lack of charging stations for electric vehicles, or the poor grids for example in developing countries that prevent a national rollout of renewable energy technologies. While many of these are technological limitations, they will still slow the adoption of green transitions.

POLITICAL AND POLICY BARRIERS

Policy Uncertainty

Both political will and consistency of policy are important if we are to see adoption of green technologies. If policies are constantly changing or there are no clear regulatory frameworks or competing interests, it is difficult to encourage long-term investment. For example, the sudden removal of subsidies for solar energy in Spain resulted in the entire solar sector suffering serious financial liquidity issues (del Río & Mir-Artigues, 2012)

SOCIAL AND CULTURAL CONSTRAINTS

Public Acceptance and Resistance

While green technologies are generally supported in principle, it is common to see localized resistance. For example, wind farms, waste to energy plants and large solar farms often encounter strong opposition by local communities based on aesthetic values, perceived health impacts or uses of land (for example, Devine-Wright, 2009). Poor consultation from organizations and lack of engagement with citizen stakeholders can lead to unintended delays or termination of projects.

Displacement

Movement away from fossil fuel industries toward green technologies can also create social disruption wherever there are people who depend primarily on coal, oil or gas industries. Job losses associated with these industries can result in social unrest if the government does not adopt "just transition" policies, which consider the re-training of workers and diversifying the local economy (ILO, 2019).

Unequal Access

There is also a potential for green technology to exacerbate social inequities when access is limited to higher-income groups. For example, electric vehicles and energy efficient homes can be more accessible to higher-income groups than to those with fewer financial resources; as a result, poorer populations are left behind in the sustainability revolution (Sovacool et al., 2019).

ENVIRONMENTAL RISK

Life Cycle Effects

Green technologies result in lower emissions while they are in operational use but life cycle effects also need to be examined. There are energy inputs and raw material extraction required to manufacture solar panels, wind turbines, and batteries, and these processes may create emissions and pollution. There are also environmental impacts from the disposal of old batteries and electronic waste (Zeng et al., 2017).

Land and Ecosystem Considerations

Utility-scale renewable energy developments can cause unintended environmental effects. For example, hydropower dams can alter river ecosystem functions and disrupt communities, while wind farms can influence bat and bird numbers (Kiesecker et al., 2011). Thus, seeking to enhance environmental outcomes with ecological protection continues to pose a challenge.

Systemic and Global Challenges

Barriers to Technology Transfer

Barriers remain to transferring green technologies from developed countries to developing countries, despite international agreements in place. These include intellectual property protections, inadequate infrastructure, and a lack of capacity-building (Haščič & Migotto, 2015). Therefore, inequalities remain regarding access to sustainable solutions across the globe.

Climate change uncertainty

Green technologies will also have some vulnerable aspects produced because of climate change. Extreme weather may interfere with renewable energy infrastructure, supply chain and cost of maintenance. As an example, hail and dust may adversely impact solar farms and hurricanes and sea-level rise may negatively influence offshore wind farms (IPCC, 2021).

Projected Future Trends of Green Technologies

Both scientific progress, policy-making, and the will of the global community towards sustainable development are contributing factors to the future of green technologies. The climate change and shortage of resources will rise, and green technologies will bring disruptive transformation through energy systems, industries, and societies. Despite the fact that the future "perspectives" of green technologies will provide the remedies and direction to solve the environmental issues, there is even a possibility of economic growth, employment prospects and technology-resistant scenarios.

The future energy context is assured by the areas of renewable energy development. Renewable energy industry remains the initial field of future development. Examples of performance targets by technology developers in the case of solar include new efficiency records projected by the use of perovskite solar cells, tandem technologies, and flexible solar system. The additional areas of focus will be off-shore wind turbines, wave energy, and floating solar panels will by augmenting the capacity augment the actual renewable infrastructure. Future designs would have green hydrogen as a new clean fuel which will determine the storage of energy and help to decarbonize the hard-to-abate sectors, such as steel and cement (IEA, 2022).

Circular Economy and Sustainable Manufacturing

The shift towards circular economy activities will begin to shift industries towards a linear model of take- make-dispose. Green technologies of the future will be based on such advanced recycling techniques as chemical recycling of plastics, as well as bio-based materials which are re-usable and/or re-manufacturable (Geissdoerfer et al., 2017). Renewable-powered additive manufacturing (3D Printing) has a potential to open the prospects of localized and sustainable production, less waste production and less carbon emissions.

Digitalization and Smart Systems

Green technology and sustainable manufacturing will also be transformed by AI, IoT, and blockchain/ new technologies, which can define efficiency and be expanded. Smart grids will enable the distribution of renewable energy sources in a more efficient way, and AI-based predictive models will help optimize the amount of energy used in the real-time.. Blockchain provides more transparent and traceable supply chains to ensure raw materials are sustainably sourced in the production process. Together these new technologies can deliver increased environmental benefits and improved economic performance (Kumar et al., 2021).

Transportation and Mobility

Electrification and alternative fuels will shape the future of transportation with electric vehicles (EVs), aided by improved battery technologies such as solid-state batteries, achieving greater ranges, shorter charge times, and suitably lower costs (BloombergNEF, 2023). Hydrogen vehicles and green aviation technologies - including sustainable aviation fuels and hybrid-electric aircraft - will extend decarbonization and mobility beyond traditional sectors. Furthermore, public transportation systems will be expected to also integrate more sustainable technologies, improving urban pollution and congestion.

Climate Adaptation and Resilience

Future green technologies will also increasingly look at climate adaptation, as well as mitigation. Innovations in renewable energy-powered water desalination, precision agriculture systems, and nature-based solutions such as urban greening, will enable many societies to better manage increased heat, droughts, and floods (United Nations Environment Programme [UNEP], 2022). In addition to sustainability, these technologies will also contribute to resilience to climate-induced interruption.

International Collaboration and Policy Considerations

The proliferation of green technologies will depend largely on global collaboration and specific multilateral agreements. The Paris Agreement and UN Sustainable Development Goals (SDGs) are two notable examples. Key financial mechanisms including green bonds, carbon pricing, and international technology transfer will assist the process by ensuring equal access to innovations across countries (OECD, 2021). Moreover, rapidly urbanizing and industrializing economies may serve as both barriers and facilitators to the uptake of green technologies.

Vision for the Future

The ultimate prospect of green technologies will be in the shift towards a regenerative economy where we not only reduce harm but restore ecosystems. Emerging innovations such as carbon capture and utilization (CCU), bioengineered materials, and renewable storage systems (to name a few) will create opportunities for future energy and industrial systems. Provided that governance, finance, and education support this transition, green technologies can support system transformation towards sustainable development by the year 2050.

CONCLUSION

Green technologies are at the forefront of sustainable development, providing cutting-edge options for climate change adaptation and mitigation, environmental degradation reduction, and economic resilience. From renewable energy, sustainable transportation, smart manufacturing, and the circular economy, they represent a fundamental shift to more responsible forms of production and consumption. The historical trajectories of green technologies demonstrate how science, social movements, and policy development have intersected to fuel their implementation. Green technologies have evolved from being viewed as niche innovations to global imperatives quickly driving transformation in various sectors.

To successfully use green technologies, we must recognize that the pathway to adoption is not only fairly constructed on understanding the underlying technologies, but that their legitimization is equally dependent on socio-political and economic considerations as well. Without equitable access, just governance, and long-term investment, green technologies may not represent viable and effective contributions to achieving the UN's Sustainable Development Goals (SDGs) and Paris Agreement targets. The potential outcomes associated with these innovations—green hydrogen; smart energy grids; and nature-based solutions—show great promise for enabling both mitigation and adaptive pathways to a sustainable future.

LIMITATIONS

This research has provided an overview of green technologies, but several limitations must be acknowledged.

1. **Scope of Coverage -** The spectrum of green technologies is enormous, and this study focuses mainly on key sectors and fields of green technology, such as energy, transport, agriculture, and waste management. In spite of the niche but emerging innovations like nanotechnology of clean water development or genetic engineering of sustainable crops, the review did not delve into these areas.
2. **Geographical Representation -** Despite the inclusion of evidence and case studies across the world, due to the type of case studies used and studied, this analysis has a bias towards the areas where there is a high volume of research output, namely, Western Europe, North America and part of Asia, which maybe not a true reflection of an insight shared among the developing nations that deliver lessons in the current research using localized and focused challenges and adaptations.
3. **Various Technological Changing Environment -** The pace of technological change is also a major possible constraint as innovations occur quite quickly, and emerging technologies develop rapidly, introducing new pieces of evidence on a regular basis in relation to efficiencies, scalability, or cost-savings of green technologies.
4. **Socioeconomic Dimensions-** The ethical, legal, and social consequences of the problems in which green technologies are placed were addressed in a more relevant way as compared to the labor transitions that green technologies represent, indigenous knowledge systems, and cultural acceptability of green technologies that would require a further investigation in the future.

RECOMMENDATIONS

Under sustainable development, some recommendations to encourage the use of green technologies include:

1. **Sturdier Policy Frameworks -** Governments ought to target strategies which holistically depend on the use of green technology to progress growth at the nation-wide stage, e.g. renewable energy quotas, carbon levies, or cycle economy bonuses..
2. **Increased funding/financing -** Green innovations need a greater supply of funding through measures such as capital markets and green bonds, public-private sector ventures (i.e., blended finance) and/or through climate financing using trust or endowment funds that could give priority to assistance in low-income countries in order to manage sharing of technologies more equitably.
3. **Global cooperation and sharing of knowledge -** Greater efforts for international co-operation and sharing of knowledge, encouraging technology transfer, and capacity building and sharing of best practice between regions, benefit everyone and help to eliminate gaps between developing and developed.
4. **Integrating digital technologies -** The adoption of wider range of digital innovations (not just green, but measures such as artificial intelligence (AI), internet of things (IoT), blockchain) will allow green technologies to scale and improve efficiency. Both governments and industries must invest in R&D as well as encourage building regulatory frameworks that allow safe and ethical engagement with digital innovations.
5. **Community engagement and education -** The public acceptance and engagement of people or society is crucial. Consideration must be placed (billions of people) in public campaigns, involvement in community projects and education, in order to encourage a change in behaviour and ensure that what shapes green technologies align with community values.

REFERENCES

BloombergNEF. (2023). *Electric vehicle outlook 2023*. Bloomberg New Energy Finance. https://about.bnef.com

Chu, S., & Majumdar, A. (2012). Opportunities and challenges for a sustainable energy future. *Nature*, 488(7411), 294–303. https://doi.org/10.1038/nature11475

Ellabban, O., Abu-Rub, H., & Blaabjerg, F. (2014). Renewable energy resources: Current status, future prospects and their enabling technology. *Renewable and Sustainable Energy Reviews*, 39, 748–764. https://doi.org/10.1016/j.rser.2014.07.113

European Commission. (2021). *A European green deal*. European Union. https://ec.europa.eu

Fawzy, S., Osman, A. I., Doran, J., & Rooney, D. W. (2020). Strategies for mitigation of climate change: A review. *Environmental Chemistry Letters*, 18, 2069–2094. https://doi.org/10.1007/s10311-020-01059-w

García-Olivares, A., Solé, J., Osychenko, O., & Vázquez, J. (2018). Transport in a 100% renewable energy system. *Energy Conversion and Management*, 158, 266–285. https://doi.org/10.1016/j.enconman.2017.12.053

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production*, 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Global Wind Energy Council. (2022). *Global wind report 2022*. GWEC. https://gwec.net

International Energy Agency. (2021). *Net zero by 2050: A roadmap for the global energy sector*. IEA. https://www.iea.org

International Energy Agency. (2022). *Global hydrogen review 2022*. IEA. https://www.iea.org

International Renewable Energy Agency. (2021). *World energy transitions outlook*. IRENA. https://www.irena.org

Kumar, A., Prakash, G., & Kumar, V. (2021). Digital technologies for achieving circular economy goals: A review. *Sustainable Production and Consumption*, 28, 254–272. https://doi.org/10.1016/j.spc.2021.05.002

National Renewable Energy Laboratory. (2023). *Next-generation solar cells research*. U.S. Department of Energy. https://www.nrel.gov

Organisation for Economic Co-operation and Development. (2021). *Financing climate futures: Rethinking infrastructure*. OECD Publishing. https://doi.org/10.1787/9789264308114-en

Owusu, P. A., & Asumadu-Sarkodie, S. (2016). A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Engineering*, 3(1), 1167990. https://doi.org/10.1080/23311916.2016.1167990

Panwar, N. L., Kaushik, S. C., & Kothari, S. (2011). Role of renewable energy sources in environmental protection: A review. *Renewable and Sustainable Energy Reviews*, 15(3), 1513–1524. https://doi.org/10.1016/j.rser.2010.11.037

Pearce, J. M. (2012). The case for open source appropriate technology. *Environment, Development and Sustainability*, 14(3), 425–431. https://doi.org/10.1007/s10668-012-9337-9

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., ... & Foley, J. A. (2009). A safe operating space for humanity. *Nature*, 461(7263), 472–475. https://doi.org/10.1038/461472a

Sachs, J. D., Woo, W. T., Yoshino, N., & Taghizadeh-Hesary, F. (2019). Importance of green finance for achieving sustainable development goals and energy security. *Handbook of Green Finance*, 3–12. Springer. https://doi.org/10.1007/978-981-13-0227-5_1

Schot, J., & Steinmueller, W. E. (2018). Three frames for innovation policy: R&D, systems of innovation and transformative change. *Research Policy*, 47(9), 1554–1567. https://doi.org/10.1016/j.respol.2018.08.011

Smith, P., Calvin, K., Nkem, J., Campbell, D., Cherubini, F., Grassi, G., ... & Soussana, J. F. (2020). Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation? *Global Change Biology*, 26(3), 1532–1575. https://doi.org/10.1111/gcb.14878

United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development*. United Nations. https://sdgs.un.org

United Nations Environment Programme. (2022). *Emissions gap report 2022*. UNEP. https://www.unep.org

United Nations Industrial Development Organization. (2020). *Industrial development report: Industrializing in the digital age*. UNIDO. https://www.unido.org

U.S. Department of Energy. (2020). *Hydrogen program plan*. U.S. DOE. https://www.energy.gov

Wang, Q., Su, M., Li, R., & Ponce, P. (2019). The effects of energy policies on energy consumption in China. *Energy Policy*, 129, 1130–1141. https://doi.org/10.1016/j.enpol.2019.02.030

World Bank. (2020). *State and trends of carbon pricing 2020*. World Bank Group. https://openknowledge.worldbank.org

World Economic Forum. (2022). *Fostering effective energy transition 2022 edition*. WEF. https://www.weforum.org

Zhou, Y., Li, H., & Wang, K. (2021). The role of innovation in green development of economies: Evidence from emerging markets. *Journal of Cleaner Production*, 285, 124827. https://doi.org/10.1016/j.jclepro.2020.124827