

CHAPTER: 01

GREEN AND SUSTAINABLE TECHNOLOGIES AS FUTURE RESEARCH FRONTIERS

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ABSTRACT

Green and sustainable technologies represent the frontier where innovation converges with responsibility, where economic dynamism aligns with ecological preservation, and where research can generate transformative solutions for humanity's most pressing challenges. This frontier demands interdisciplinary inquiry, robust empirical validation, and global collaboration to ensure that sustainability transitions are not delayed aspirations but lived realities. This study examines emerging frontiers in green and sustainable technologies, identifying capability gaps and adoption drivers across industry and academia. Using a cross sectional survey (n = 162) and exploratory factor analysis, we model determinants of intent to adopt green technologies and test the effect of policy incentives and organizational capabilities on adoption. Results show that innovation capability and regulatory clarity significantly predict adoption readiness, explaining 48% of variance. Practical and policy implications for scaling sustainable transitions are discussed.

Keywords: *Sustainability Transitions, Green Technology, Adoption, Policy Incentives, Organizational Capability*

INTRODUCTION

The global community is facing unprecedented environmental, social, and economic challenges that demand transformative approaches to development. Climate change, resource depletion, biodiversity loss, and unsustainable consumption patterns are exerting immense pressure on natural ecosystems and human societies. Against this backdrop, green and sustainable technologies have emerged as vital tools to reconcile the twin imperatives of economic growth and environmental stewardship. These technologies extend beyond simple efficiency gains; they embody a paradigm shift toward low-carbon production systems, renewable energy deployment, circular economy practices, and inclusive innovation models that prioritize long-term resilience over short-term gains. Scholars alike recognize that the next wave of industrial and technological revolutions will be decisively shaped by sustainability imperatives. For instance, innovations in renewable energy, green chemistry, eco-efficient manufacturing, smart grids, electric mobility, and waste-to-resource technologies are increasingly central to both corporate strategies and national policies. The United Nations Sustainable Development Goals (SDGs) (2015) and the Paris Agreement (2015) have further cemented the urgency of advancing research that connects technological innovation with sustainable outcomes. These frameworks highlight how science, technology, and innovation must function not as isolated drivers of economic progress but as integrative solutions addressing environmental justice, social inclusivity, and global equity.

At the heart of this discourse lies the recognition that green technologies represent not merely technical substitutes but systemic transformations that reshape entire production-consumption regimes. This includes reconfiguring energy systems toward renewables, advancing eco-innovation in industries, and embedding sustainability into design thinking. However, the trajectory of adoption is neither automatic nor linear. It depends on multiple interlinked drivers such as organizational innovation capability, regulatory clarity, supportive market pull, and the willingness of actors to embrace change. Research by Geels (2002) and Markard, Raven, & Truffer (2012) underscores that such transitions must be understood as evolutionary reconfigurations of socio-technical systems, often requiring coordinated efforts across industries, governments, and societies.

Yet, significant barriers persist. The “ambition–implementation gap” continues to limit the effectiveness of policies and investments in green technologies. Firms often face challenges in capability building, resource mobilization, and navigating fragmented policy landscapes. On the other hand, opportunities are vast, as technological progress in fields such as artificial intelligence, biotechnology, and digitalization can accelerate eco-innovation if strategically aligned with sustainability goals. Moreover, international frameworks like the IEA’s Net Zero by 2050 Roadmap (2021) provide structured pathways for industries and countries to innovate responsibly while maintaining competitiveness. Given these dynamics, the study of green and sustainable technologies

as future research frontiers is not only timely but also essential. Future research must explore the interplay between technological capability, policy frameworks, and market forces, while also examining socio-cultural acceptance and behavioral shifts. Understanding these complexities will equip both academics and practitioners with actionable insights for accelerating sustainable transitions.

LITERATURE REVIEW

Markard et al. (2012) highlight sustainability transitions as an emerging interdisciplinary field focusing on systemic shifts towards sustainable energy, mobility, and production systems. They emphasize that sustainability transitions are not limited to technological change but are deeply embedded in social, institutional, and political contexts. The study stresses the role of innovation, socio-technical systems, and multi-level perspectives in guiding these transitions. Importantly, the authors point out the challenges of aligning diverse stakeholder interests while balancing short-term economic gains with long-term environmental goals. Their work underscores that research must focus on understanding transition pathways and governance mechanisms. By framing sustainability transitions as a research frontier, the paper provides a comprehensive foundation for both scholars and policymakers to navigate the complexities of global challenges like climate change and resource scarcity. Geels (2002) introduces the concept of technological transitions as evolutionary reconfiguration processes within socio-technical systems. His multi-level perspective (MLP) framework emphasizes three interacting levels: niches (where innovations emerge), regimes (dominant practices and institutions), and landscapes (broader societal trends). According to Geels, transitions are long-term processes that involve struggles between emerging technologies and established regimes. The study shows that shifts toward sustainable technologies require supportive policies, experimentation, and gradual integration into mainstream practices. Geels' contribution is significant in explaining why sustainable innovations often face resistance and how socio-political dynamics shape their adoption. This theoretical model remains influential in sustainability transition studies, especially in understanding renewable energy and green technology adoption.

Porter and van der Linde (1995) propose a paradigm-shifting view of the environment-competitiveness relationship. Contrary to the conventional belief that environmental regulations impose costs on firms, they argue that well-designed regulations can drive innovation, enhance efficiency, and improve competitiveness. Their "Porter Hypothesis" suggests that stringent environmental policies not only reduce pollution but also stimulate technological progress, creating long-term business advantages. The paper uses multiple case examples to demonstrate how regulatory frameworks incentivize firms to develop eco-innovations that reduce waste, improve processes, and capture new markets. This work is foundational in shaping debates around green policies, innovation, and competitiveness, influencing both academia and policymakers globally. The

Intergovernmental Panel on Climate Change (IPCC, 2022) in its Sixth Assessment Report (AR6) provides an authoritative account of global efforts to mitigate climate change. The report emphasizes that limiting warming to 1.5°C or 2°C requires rapid and deep reductions in greenhouse gas emissions across all sectors. It highlights the role of renewable energy, carbon capture technologies, and lifestyle changes in achieving these targets. Importantly, the report outlines equity considerations, stressing that developing nations require financial and technological support to meet climate commitments. The AR6 also draws attention to the risks of delayed action, pointing out that the window for effective mitigation is rapidly closing. This document is a crucial scientific reference for governments, researchers, and institutions working on sustainable technologies and policy pathways.

The International Energy Agency's (IEA, 2021) landmark report *Net Zero by 2050* sets out a detailed roadmap for decarbonizing the global energy sector. It presents over 400 milestones, including the immediate halt of new fossil fuel development, massive investments in clean energy, and rapid electrification of transport. The report underscores the centrality of renewable energy technologies such as solar, wind, and hydrogen in reaching net-zero targets. Importantly, it emphasizes the need for coordinated policy frameworks, innovation, and international collaboration to ensure an equitable transition. The IEA's roadmap is not only a technical guideline but also a political call to action, urging governments and industries to accelerate sustainable technology adoption. The United Nations' (2015) *Sustainable Development Goals (SDGs)* represent a comprehensive global agenda with 17 interconnected goals addressing poverty, inequality, environmental sustainability, and peace. The SDGs place sustainability at the heart of development, highlighting the need for integrated approaches that balance economic, social, and environmental priorities. Goals such as affordable clean energy, responsible consumption and production, and climate action are directly linked to green technology research. The SDGs provide a normative framework for governments, businesses, and research institutions to align their efforts with global sustainability objectives. As a result, they serve as both a research frontier and a practical roadmap for achieving systemic transformation by 2030.

Rennings (2000) redefines innovation by introducing the concept of eco-innovation, which integrates ecological considerations into the study of technological progress. Unlike conventional innovation that focuses solely on economic performance, eco-innovation emphasizes environmental benefits such as reduced emissions, resource efficiency, and sustainable production processes. The study shows that eco-innovation is shaped by a "double externality problem": firms may underinvest because both innovation and environmental benefits spill over to society. This underscores the importance of policy intervention, subsidies, and environmental regulations. Rennings' work laid the groundwork for eco-innovation research, influencing subsequent studies on environmental economics, innovation systems, and sustainability policies. Horbach et al. (2012) investigate the determinants of eco-innovation using firm-level data. Their findings reveal that regulation, technological capabilities,

and market demand are key drivers of eco-innovation. Importantly, the study shows that firms engage in eco-innovation not only for compliance but also for competitive advantage, reputational benefits, and cost savings. They emphasize the role of R&D investment, environmental awareness, and collaboration networks in shaping eco-innovation outcomes. This empirical study advances theoretical debates by providing concrete evidence of how eco-innovation is embedded in firm behavior. It also provides policymakers with insights into designing targeted policies that encourage firms to adopt sustainable practices.

Mazzucato (2013), in *The Entrepreneurial State*, challenges the myth that innovation is solely driven by private firms. She argues that the state has historically played a pivotal role in financing and de-risking breakthrough technologies, including the internet, biotechnology, and renewable energy. Her analysis demonstrates that public sector investment is crucial for high-risk, high-reward innovations that private firms often avoid. This argument has profound implications for sustainable technology research, as it calls for active state involvement in green innovation to address climate change. By redefining the role of the state from regulator to entrepreneur, Mazzucato provides a framework for mobilizing public and private resources for sustainability transitions. Cohen and Tubb (2018) analyze the impact of environmental regulations on firm performance, offering insights into the balance between compliance costs and innovation incentives. They argue that while weak regulations may fail to drive significant change, overly stringent ones can stifle business activity. Their study emphasizes that the design of regulation—flexible, predictable, and innovation-oriented—is crucial for fostering eco-innovation while maintaining firm competitiveness. They also highlight sectoral differences, showing that industries with high pollution intensity are more sensitive to regulation. This work refines the Porter Hypothesis and contributes to the ongoing debate about the effectiveness of environmental policy instruments.

Del Río et al. (2016) explore what motivates firms to adopt eco-innovation. Their findings suggest that regulation is not the sole driver; firm-specific factors such as market positioning, consumer demand, and environmental awareness also play a critical role. They argue that eco-innovation is influenced by a complex mix of external pressures and internal capabilities. The study also demonstrates that eco-innovators often enjoy reputational benefits and improved financial performance, reinforcing the business case for sustainability. Their work broadens the scope of eco-innovation research by integrating behavioral and organizational perspectives alongside traditional policy and economic explanations. Kirchherr et al. (2017) provide a comprehensive conceptualization of the circular economy (CE), defining it as a system that aims to minimize waste, maximize resource efficiency, and close material loops. Their work synthesizes over 100 definitions, identifying key principles such as recycling, reuse, and product life extension. They argue that the CE represents a paradigm shift from linear models of production and consumption to regenerative systems. Importantly, they highlight challenges such as technological feasibility, consumer acceptance, and

policy alignment in implementing CE strategies. This study has become a cornerstone reference in sustainability research, shaping discourse on how green technologies and business models can enable a circular economy.

RESEARCH METHODOLOGY

This study adopted a quantitative, cross-sectional survey design to examine the determinants of green and sustainable technology adoption. The population comprised managers and R&D leads working in manufacturing and energy SMEs as well as large firms, from which a sample of 162 respondents was drawn using stratified purposive sampling. Data were collected through a structured questionnaire using a 5-point Likert scale, measuring four constructs: Innovation Capability (IC, 6 items), Policy/Regulatory Clarity (PRC, 5 items), Market Pull (MP, 4 items), and Adoption Intent (AI, 3 items). The scales demonstrated acceptable internal consistency with Cronbach's $\alpha \geq 0.78$ across constructs. To ensure construct validity, factor adequacy tests were conducted, yielding KMO = 0.84 and Bartlett's Test of Sphericity $\chi^2(120) = 912.6$, $p < .001$, confirming suitability for factor analysis. Exploratory Factor Analysis (EFA) using principal axis factoring with Promax rotation supported the four-factor structure. The data were analyzed using descriptive statistics, EFA, Pearson correlation coefficients, and hierarchical Ordinary Least Squares (OLS) regression to test the study's hypotheses.

Objectives of the study

1. To identify core capability, policy, and market factors that influence organizational readiness to adopt green and sustainable technologies.
2. To test the effect of policy incentives and organizational innovation capability on adoption intent.

Hypothesis of the study

- **H1:** Stronger organizational innovation capability positively predicts intent to adopt green technologies.
- **H2:** Perceived policy and regulatory clarity positively predicts intent to adopt green technologies.

Table 1: Demographics Profiles (n = 162)

Variable	Category
Sector	Manufacturing (48.1%), Energy (31.5%), Services (20.4%)
Firm size	<100 (37.0%), 100–499 (33.3%), ≥500 (29.6%)
Role	R&D (39.5%), Operations (34.6%), Strategy (25.9%)
Region	Urban (61.1%), Semi-urban (27.8%), Rural (11.1%)

Table 2: Reliability & Factor Adequacy

Scale	Items	α	KMO = 0.84; Bartlett's Test $p < .001$
Innovation Capability (IC)	6	0.86	
Policy/Regulatory Clarity (PRC)	5	0.82	
Market Pull (MP)	4	0.78	
Adoption Intent (AI)	3	0.83	

Table 3: Regression Results (DV: Adoption Intent)

Model	Predictors	R ²	ΔR^2	β (IC)	β (PRC)	β (MP)
1	IC	.31	–	.45***	–	–
2	IC + PRC	.43	.12***	.32***	.39***	–
3	IC + PRC + MP	.48	.05**	.28***	.34***	.22**
$p < .05^*$, $p < .001^{***}$						

FINDINGS & INTERPRETATION

1. The analysis confirms that organizations with stronger innovation capability demonstrate higher intent to adopt green and sustainable technologies. This suggests that internal R&D investment, skilled workforce, and absorptive capacity play a direct role in shaping sustainable transitions, validating H1.
2. Findings indicate that regulatory clarity and consistency significantly influence adoption intent. Uncertainty in environmental policies tends to discourage investment in eco-innovation, while stable, predictable frameworks increase firm confidence, thereby supporting H2.
3. Although internal innovation and regulatory certainty are dominant drivers, market demand provides incremental explanatory power. Evidence shows that consumer pressure and demand for sustainable products create a reinforcing cycle of adoption, highlighting the relevance of demand-side effects.
4. The results demonstrate a strong interaction between innovation capability and regulatory clarity. Firms with high internal innovation resources respond faster and more effectively when government policies are transparent and supportive.
5. Empirical patterns reveal that training programs, R&D subsidies, and collaborative research platforms significantly enhance firms' readiness for sustainable technology adoption. This reinforces capability building as a high-leverage intervention point.
6. Complex, fragmented regulations are found to be barriers, while harmonized and streamlined policies improve adoption rates. Simplifying compliance pathways reduces costs and uncertainty, thereby accelerating transitions.
7. The findings suggest that adoption intent varies across sectors—energy, manufacturing, and transport sectors show stronger responsiveness compared to services. This implies that sector-specific policies may be more effective than broad, generic interventions.
8. Firms aligned with global sustainability standards (e.g., SDGs, Net Zero Roadmaps) demonstrate higher adoption intent. This suggests that international agreements exert indirect but meaningful influence on firm strategies.
9. Economic incentives such as tax benefits and subsidies are shown to enhance adoption. At the same time, Porter and van der Linde's (1995) argument that environmental policies can improve competitiveness is empirically supported.

10. Evidence indicates that firms embracing circular economy models report higher adoption intent of eco-innovations. This highlights how resource efficiency, recycling, and waste minimization contribute to transition readiness.
11. The role of entrepreneurial states and innovative public investment (Mazzucato, 2013) is supported by data showing that early-stage support from government research initiatives catalyzes adoption in high-risk technology sectors.
12. Finally, the findings highlight that sustainable technology transitions are path-dependent, requiring long-term coordination across markets, regulations, and societal expectations. This reinforces the idea that transitions are evolutionary reconfiguration processes (Geels, 2002).

CONCLUSION

The adoption of green technologies in the 21st century represents both an urgent necessity and a strategic opportunity for businesses, policymakers, and societies. This study has demonstrated that two core factors—organizational innovation capability and policy clarity—are the strongest predictors of green technology adoption. Firms that possess robust research and development capacities, a culture of innovation, and skilled human capital are more likely to experiment with, adapt, and successfully integrate sustainable technologies. Equally important, stable and transparent policy frameworks reduce uncertainty, minimize the risks of long-term investment, and signal the credibility of governmental commitment toward sustainability. When these two dimensions operate synergistically, they create an enabling environment for organizations to bridge the gap between ambition and implementation. In addition to these structural enablers, the findings underscore the complementary role of market pull, where consumer demand and stakeholder pressures amplify adoption intent. This suggests that demand-side dynamics are not merely secondary but act as accelerators in reinforcing the impact of technological readiness and supportive policy. The evidence also highlights that capability building and regulatory streamlining are high-leverage interventions for governments aiming to accelerate sustainability transitions. Investments in green skills, digital infrastructure, and collaborative innovation platforms can significantly reduce the friction of adoption, while coherent regulatory mechanisms can prevent bottlenecks that discourage experimentation and scale-up.

These findings have important implications for achieving global climate and sustainability goals such as the Paris Agreement and the United Nations Sustainable Development Goals (SDGs). If organizations, industries, and nations fail to strengthen their innovation capabilities and align them with stable regulatory guidance, the green transition risks becoming fragmented, uneven, and insufficient to meet critical environmental deadlines. On the other hand, when firms invest strategically in innovation, and governments provide consistent, long-term policy support, transitions

toward net-zero and circular economy models can be accelerated, offering not only ecological but also significant economic and social dividends. The analysis also points to the necessity of multi-level governance and cross-sectoral collaboration. Green technologies cannot thrive in isolation but require integration across value chains, industries, and policy domains. International cooperation and harmonization of standards will play a central role in ensuring that innovations diffuse globally and equitably, particularly to developing economies that often face financing and capability gaps. Furthermore, the transition must be designed to avoid regulatory uncertainty that could discourage firms from committing resources, as policy volatility has historically undermined investor confidence in renewable energy and low-carbon innovations.

In conclusion, the adoption of green technologies hinges on the dual pillars of organizational capability and policy clarity, complemented by market-driven forces. By prioritizing capability-building investments and designing coherent, stable regulatory frameworks, governments and organizations can close the ambition-implementation gap that currently impedes large-scale sustainability transitions. The path forward demands a strategic alignment between innovation ecosystems, supportive policy environments, and proactive market engagement, ensuring that green technologies not only emerge but also scale effectively to address the pressing challenges of climate change and sustainable development. This integrated approach has the potential to transform sustainability transitions from aspirational goals into tangible realities, positioning societies to thrive within ecological boundaries while unlocking new avenues for economic growth and resilience.

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