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History of Renewable Energy Development: Global Trends and Milestones

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Abstract

Concerns about environmental degradation and energy security have spurred sustained international interest in renewable energy technologies. Historical developments are important for clarifying the possibilities and limits that have shaped global trends. Specifically, growing public concern about oil supply disruptions during World War II and the first Arab Oil Embargo were formative events that linked the search for renewable energy to the dual objectives of environmental sustainability and energy independence. As a prelude, historical evidence indicates that efforts to harness renewable energy intensified from the mid-19th century onward, owing to industrialisation, urbanisation, and growing awareness of environmental degradation (Baus, 2017). Various eco-initiatives and related expressions, including "green industry," "clean development," and "sustainable development," as well as institutional strategy papers and reports from international organisations and research institutions, increasingly emphasise the vital significance of renewable energy.

Keywords: *Renewable Energy Development, Energy Transition, Oil Crisis, Climate Change, Energy Policy, Sustainable Development.*

1. Introduction

The increasing use of renewable energy sources is stimulating national and international economies, creating jobs, reducing greenhouse gas emissions and air pollution, enhancing energy security and decreasing dependence on fossil fuels. Accordingly, the question of how to harness renewable energy has attracted global attention. Energy from renewable sources is becoming increasingly important in order to promote sustainable development. The threat of climate change and depletion of fossil fuel reserves is driving growth.

Renewable energy harnesses natural phenomena: sunlight, wind, waves, tides, temperature differences between seas, and geothermal energy from the Earth's crust. Factors such as awareness of global environmental issues, the implementation of various policies, support for research institutes, and technical development and technology transfer have contributed to the growing popularity of renewable energy (Baus, 2017; Ershadul Karim et al., 2018).

2. Early Foundations of Renewable Energy

The pre-industrial economy largely depended on renewable resources. Nearly all energy came from the sun, whether directly in biomass or indirectly in wind, water, and waves. People shaped fuel use through technological developments—from the domestication of crops and draught animals in Neolithic times to the emergence of the windmill in Mesopotamia and the watermill in the Roman Empire. While agricultural and biomass residues accounted for more than 90% of energy, other energy sources gradually gained prominence.

Timber played a crucial role in energy supply and became a strategic resource. The demand for fuelwood began to exceed supply in antiquity, triggering an energy transition toward coal (L. Davies, 2018). Still, timber remained essential in construction, shipping, manufacturing, and domestic industries long after the major shift to coal. During the early modern period, timber resources became scarce. Colonial expansion and international trade enabled regions with timber shortages to import wood from areas with a surplus. The energy transition toward recognising wood as a strategic resource became a necessary component of national energy policies.

Indigenous peoples, farmers, and aristocrats used hydropower in western Europe for irrigation and grain grinding long before industrial waterpower reached the region. Technologies transferred from the Roman Empire paved the way for water technology. Roman architectural treatises revitalised hydraulic knowledge in the early modern period. The pre-industrial economy relied on hydraulic development, which matured into the industrial economy. The 18th-century Enlightenment not only concentrated agriculture on a larger scale but also demonstrated windmill technology across northern Europe. The Dutch concept of using wind directly to turn a shaft inspired the design of modern windmill turbines.

3. World War II to 1970s: Emergence of Modern Interest

Fifty-five per cent of the energy consumed in the United States during

World War II came from electricity, with petroleum, coal, and gas accounting for nearly the remainder (Johnstone & McLeish, 2020). Wartime energy demand stimulated postwar interest in alternative energy sources. The Federal Interest in Alternatives to Oil (FIATO) was one of the earliest systematic attempts to explore alternative energy sources. Toward the end of the decade, scientists at the Massachusetts Institute of Technology proposed a water power conversion program. These early policy efforts produced no significant follow-up funding for renewables, but reports further countered the notion that renewable energy could not contribute to the overall energy supply. These typically followed the adoption of broader energy policies that included renewable energy development but did not prioritise it. The 1952 presidential election was catalysed by a record heat wave, which spurred discussions of energy in the media and among public officials. After the election, both national parties and federal officials market significant policy initiatives focused on electricity, atomic energy, and natural gas. A gas research and development program stemmed from the discussions. Despite policies, political talk about energy at both the national and international levels evaporated once price controls were removed, except for a major initiative in the newly independent state of Alaska. World War II catalysed modern interest in energy, yet it remained disconnected from Federal Interest in Alternatives to Oil. Interest further intensified in June 1945, when energy policy discussions resurfaced following President Franklin D. Roosevelt's ill health and death.

4. The 1970s Energy Crisis and Policy Response

The 1970s Energy Crisis and Policy Response

The 1970s witnessed two severe oil shocks: the 1973 Arab-Israeli war triggered an embargo by Arab oil producers, pushing up petroleum prices by 400%, while the 1979 Iranian revolution provoked panic on international markets and the occlusion of Iranian exports (L. Davies, 2018). Even before these events, however, the vulnerability of industrial and developing countries dependent on oil imports had been highlighted by rising oil revenues for the OPEC cartel (Ratnikova, 2010), prompting calls in some quarters for a shift to renewable energy. The oil price shocks provided the impetus for more coherent energy policies, such as feed-in tariffs, accelerated research, technology, and engineering programs, and adjustments to tax and subsidy policies to facilitate the entry of renewable technologies into energy markets. The perceived urgency surrounding energy alternatives enabled some countries to move beyond simple demand-reduction measures to policies that encourage the development of renewables. In the United States, these were often described as a 'new energy policy' and included a tacit acknowledgement that renewables should become part of the energy economy.

5. 1980s to 1990s: Technological Advances and Global Diffusion

International institutional and national policy support were central to the transfer of renewable technologies, finance, and knowledge between regions and countries, particularly among industrialised countries. The International Energy Agency conducted joint research and development and held numerous meetings and conferences. The United Nations Conference on New and Renewable Sources of Energy in 1981 led to the establishment of the United Nations Centre for New and Renewable Sources of Energy, which coordinated an umbrella programme on renewable energy deployment in developing countries. The Solar and Wind Energy Resource Assessment initiative aimed to promote renewable energy resource assessment projects in more than 140 developing countries and to provide technical assistance in formulating coherent and consistent projects (Ratnikova, 2010).

6. 2000s: Global Policy Frameworks and Market Growth

This period was characterised by the development of global and regional policy frameworks that enabled, incentivised, and sometimes mandated the broad adoption of renewable energy technologies across a range of countries and regions. The Kyoto Protocol and other treaties established explicitly agreed-upon international targets, while the European Union enacted legislation that imposed mandatory preconditions for market sharing (Tang, 2013).

Kyoto catalysed an unprecedented surge in renewable-energy-specific policies across many industrialised and emerging economies. Following earlier bilateral agreements on climate cooperation, Canada, Denmark, Japan, the Netherlands, Norway, and Switzerland were among the first to negotiate multi-year strategies that set national greenhouse gas targets, in part by implementing domestic renewable energy projects. Canada and Sweden launched their initial frameworks in 2000 and 2001, respectively. Australia, Brazil, China, India, Mexico, Morocco, South Africa, and Tunisia subsequently advanced due diligence activities in connection with their Kyoto obligations (L. Davies, 2018).

7. 2010s: The Rise of Solar and Wind Dominance

In the 2010s, renewable energy technologies grew rapidly, driven by policy support, falling prices, and increased investment. The acceleration of wind and solar capacity added momentum to domestic and international policy processes addressing climate change and energy access. Following several decades of research and demonstration, renewable energy resources established themselves at significant levels in some regions, enabling large-scale implementation and supporting emerging business models.

In the United States, installed wind capacity more than tripled, while solar photovoltaics jumped by a factor of nearly 70. By the end of the decade, about 20% of electricity came from renewables. Despite the remarkable U.S. progress, countries such as China and Germany took the lead with large-scale initiatives and far greater overall investment. By 2018, wind and solar energy supplied 25% of total generation and more than 30% of annual investments across the European Union. In China, the share of energy from renewable sources remained low, but total investment in renewable energy dwarfed that of other nations. Global annual investments in renewable power and fuels rose steadily from about $45 billion to $300 billion. Nationwide feed-in tariffs and international agreements accelerated deployment (Ratnikova, 2010; L. Davies, 2018).

8. 2020s: Decarbonization Imperatives and Accelerated Deployment

To achieve net-zero targets across economies and industries, corporate procurement of renewables, supported by public finance, has accelerated since 2020; supply chain diversification and cross-border connections have driven growth, especially in emerging markets. Operational bottlenecks for commissioning, grid development, site availability, and financing have emerged. Co-benefits—chiefly energy access, pollution reduction, resilience, and resource management—are increasingly integrated into renewables planning and financing (Fankhauser & Jotzo, 2017; G. Kratzenberg et al., 2021).

9. Regional Trajectories: Americas, Europe, Asia-Pacific, Africa

Numerous factors shape the trajectory of renewable energy development in four global regions: the Americas, Europe, Asia-Pacific, and Africa. First, the degree of policy support varies significantly. A combination of generous, long-term, rules-based support and technology-specific instruments has facilitated the ramp-up of technologies such as wind and solar in many parts of the Americas and Europe. However, policy regimes governing renewables development differ markedly across regions. In the

Asia-Pacific region, policy regimes tend to involve less generous, often suboptimal, and less predictable support. On the African continent, policy plays an even more subordinate role. Renewable energy development there is mostly limited to small-scale projects, often privately financed and closely oriented toward meeting basic needs due to severe energy poverty. None of the linear stages of renewable energy development observed in other global regions apply; important lessons could thus be gained from outside the continent.

Second, regional resource endowments influence the capability to deploy renewable energy. Every country on the African continent possesses one or more renewable energy resources with significant deployment potential, including solar, wind, hydro, geothermal, and biomass residues. Some regions of the Americas possess low-hanging-fruit resources such as high-quality hydropower or onshore wind, while in Europe, only parts of Spain and Portugal enjoy comparable wind resources; policy regimes, infrastructure, and social acceptance have slowed development even in those privileged locations.

Third, the extent and nature of regional infrastructure—grids, transport, and technology development systems—shapes the character and pace of development. In parallel with other systems, African national electricity grids vary widely in technological, regulatory, and institutional maturity, and several large, interconnected systems cover several countries. Importantly, development systems for renewable technologies—including know-how, financial models, maintenance, and manufacturing—are often limited, especially for more sophisticated systems. Countries typically expend considerable resources on project design, structuring, and funding, and grapple with unanticipated operational unavailability in pre-packaged systems, such as solar home systems.

Fourth, patterns of public and private support differ substantially. Industrialised countries, emerging economies, and small island developing states all play roles in international assistance for renewable energy technologies, but the nature of that assistance varies widely. Another dimension, inaccessible from global aggregates, is the social acceptance of renewable energy technologies—acceptance remains insufficient or uncertain in many countries, particularly concerning larger onshore wind systems. Despite these difficulties, a few approaches that have succeeded in fostering more rapid deployment of renewable energy technologies elsewhere can be highlighted (Grimaldi, 2018; Marinova, 2008).

10. Milestones in Technology, Policy, and Finance

The co-evolution of technology, finance, and policy milestones has shaped the trajectories of renewable energy development. Significant technological breakthroughs in solar, wind, bioenergy, geothermal, hydropower, and marine energy. Policy milestones facilitating non-fossil energy modernisation in China and France, and initiatives that secured substantial international financing for concentrated solar power development in Spain and Morocco. Financial innovations in revenue-sharing agreements enabled the rapid expansion of grid-connected rooftop solar photovoltaic systems in Japan and Europe between 2000 and 2010. Transparent feed-in-tariff schemes led to surging investment in wind power, notably in Germany, India, and Spain.

11. Challenges and Barriers to Adoption

Currently, too many renewable energy-generating facilities are connected to the grid. If no decisive action is taken, the annual increase in renewable energy production will culminate in a cruel paradox: going too fast will cause long-lasting stagnation, with zero annual additions in the future. It is time to rethink the acceleration strategy. Emerging economies in Southeast Asia and Africa have a unique opportunity to accelerate the adoption of renewable energy. By not relying on the legacy of fossil fuels, these countries can accelerate access to cheap, zero-emission electricity, achieving socio-economic development that decouples growth from fossil fuel consumption. The slowdown in renewable energy adoption opens an unprecedented window of opportunity for India and Indonesia to shape a future in which fossil fuels no longer constrain energy. Such a paradigm shift can be achieved through localised, low-cost, district-based electricity systems (Burke et al., 2019).

12. Pathways Toward a Sustainable Global Energy System

Since the industrial revolution, global energy and electricity systems have relied primarily on fossil fuels, hydropower, and biomass. The urgent challenge of climate change—exacerbated by the ongoing conflict in Ukraine—has prompted a focus on transforming global energy and electricity systems. Deep decarbonization pathways point to the extensive deployment of renewable energy sources, such as solar and wind, by mid-century across all regions of the world (Bogdanov et al., 2019).

Deep decarbonization pathways emphasise extensive deployment of renewable energy sources, particularly solar photovoltaics and wind energy, while adhering to the 1.5 °C target established by the Paris Agreement (Zimm et al., 2019). Energy modelling indicates that achieving this goal requires a global energy transformation in almost all regions, with renewables supplying more than 70% of global final energy demand by 2050.

Several obstacles need to be addressed to facilitate the transition towards a clean and secure energy system. The global energy transition offers considerable co-benefits that can accelerate and enhance climate action. A significant response is considered feasible; for the energy system transformation to enable progress towards net-zero GHG emissions while securing energy access and reducing air pollution, interregional cooperation should be strengthened, and greater attention should be paid to cross-sectoral reductions in energy demand. Reinforcing the global clean energy transition would provide multiple global co-benefits. Easing bottlenecks remains a priority; however, building synergies and coherence across technology roadmaps, improving access to financing, strengthening risk management, and removing barriers to interconnections would have positive implications for a broader range of other goals beyond renewable energy deployment.

13. Conclusion

The development of renewable energy technologies has been neither linear nor smooth, but rather the result of waves of interest driven by diverse signals. New air quality regulations, the oil shocks of the 1970s, the scientific consensus regarding climate change, high-profile net-zero commitments by many national and subnational jurisdictions, and corporate purchasing strategies have all turned attention toward renewables. These technologies can play a key role in decarbonising global energy use by the middle of the twenty-first century. However, despite double-digit annual growth rates for several years and the emergence of truly global markets for renewables, concerns abound about the speed and scale of deployment needed to meet stated climate goals.

Diverse challenges persist, and new concerns emerge: Can enough wind and solar plants be built to provide 80 or 90 per cent of the world's electricity? Will national supply chains and local content rules for critical inputs delay the ramp-up? Can energy storage emerge quickly enough to balance large shares of variable generation? Do the energy transition and climate action remain legitimate social priorities amid rising prices and shortages of fossil fuels? Will rapid growth in China and investment flows to emerging markets bring risks of backlash and even conflict? Questions such as these have always shaped the fate of renewables and remain central today.

References:

1. Baus, D. (2017). Energy production and environmental protection areusta prerequisites for sustainable development.
2. Karim, M. E., Munir, A. B., Karim, M. A., Muhammad-Sukki, F., Abu-Bakar, S. H., Sellami, N., Bani, N. A., & Hassan, M. Z. (2018). Energy revolution for our common future: An evaluation of the emerging international renewable energy law.
3. Davies, L. L. (2018). Eulogising renewable energy policy.
4. Johnstone, P., & McLeish, C. (2020). World wars and the age of oil: Exploring directionality in deep energy transitions. *NCBI*.
5. Ratnikova, D. (2010). Evaluation of renewable energy policies: The determinants of wind power adoption under a quota obligation.
6. Tang, A. (2013). Leveraging policy for renewable energy development in industrialised countries and emerging markets.
7. Fankhauser, S., & Jotzo, F. (2017). Economic growth and development with low-carbon energy.
8. Kratzenberg, M. G., Zürn, H., & Rüther, R. (2021). 100% renewable energy generation in 2030 using the lowest-cost commercially available power plants.
9. Grimaldi, J. (2018). Models of growth and colonial implications in Africa's renewable energy sector.
10. Marinova, D. (2008). Renewable energy technologies in Asia: Analysis of US patent data.
11. Burke, P. J., Widnyana, J., Anjum, Z., Aisbett, E., Resosudarmo, B. P., & Baldwin, K. G. H. (2019). Overcoming barriers to solar and wind energy adoption in two Asian giants: India and Indonesia.
12. Bogdanov, D., Farfan, J., Sadovskaia, K., Aghahosseini, A., Child, M., Gulagi, A., Oyewo, A. S., Barbosa, L. D. S. N. S., & Breyer, C. (2019). Radical transformation pathway towards sustainable electricity via evolutionary steps. *NCBI*.
13. Zimm, C., Goldemberg, J., Nakicenovic, N., & Busch, S. (2019). Is the renewables transformation a piece of cake or a pie in the sky?

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Social Dimensions of Renewable Energy Adoption: Culture, Behaviour, and Change

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Abstract

The utilisation of renewable energy technologies is vital in enabling countries to make a sustainable energy transition to combat climate change. As RETs become more feasible for households due to technological improvements, social-scientific scholarship is revealing that culture, behaviour, and social norms, which are often considered 'soft' or indirect factors, are among the main determinants of adoption decisions. The social aspects of RET adoption will be discussed in this paper. In preparing this paper, it has been assumed as a theoretical premise that large-scale adoption will require simultaneous action and participation by several people. Through a systematic examination of the cultural and behavioural factors affecting RET adoption, it identifies broadly observable patterns across local contexts, reveals the conditions that shape the potential for adoption, and considers the relationship between adoption and larger socio-technical transitions. The study is divided into three parts. To begin with, it examines how national and local cultures shape the values, beliefs, worldviews, identities, and institutions that guide collective decision-making on RET adoption. It seeks to identify behavioural drivers of RET adoption that operate at a more micro or individual level, examining the factors that shape how collective choices translate into actual uptake. The third thing it shows is a comparison of the specific barriers and facilitators faced by different societies regarding RETs yet to be deployed, highlighting both enabling and inhibiting factors across diverse contexts and clarifying how social dynamics continue to inform uptake (Brambati et al., 2022).

Keywords: *Renewable Energy Adoption, Social Norms, Cultural Values, Behavioural Change, Energy Transition, Technology Diffusion*

1. Introduction

Energy sits at the heart of modern civilisation; it fuels industry and transportation, powers buildings and technologies, and provides heating, cooling, and lighting for our homes. Ever since the Industrial Revolution, there has been a growing concern about the impact of energy consumption on the environment, community life, and human well-being. Since then, the world of energy has changed significantly, and changes in consumption remain the focus of scholarship and public policy. Scientific analysis has concluded that renewable energy sources such as geothermal, hydropower, ocean, solar, and wind are critical to enabling a clean energy transition. These sources present an important opportunity to replace fossil fuels and reduce greenhouse gas emissions during the ongoing climate crisis and global environmental degradation. Renewable energy generation is a top priority for governments worldwide.

Despite the availability of actionable technologies globally, public and industrial adoption of clean energy technologies remains low. None of the clean energy technologies has achieved a 15% market share in 42 countries. Efforts to remove barriers to the adoption of renewable energy technologies have been widely studied. Addressing the social dimension remains critical if society truly is to accelerate the energy transition to meet the climate threat. Creative models that account for social commitments, cognitive limits, social openness, social innovation, and social capital need to be developed to explain the phenomenon. A systematic and thorough exploration of the subject is needed to provide actionable insights for policymakers and practitioners in climate policy and renewable energy planning (Brambati et al., 2022).

2. Conceptual Frameworks for Social Dimensions

A thesis on renewable energy adoption must integrate theoretical insights into the culture or behaviour that influences energy adoption choices. Energy transitions demand behaviour change for sustainable living and collective action on climate change. Energy decisions shape everyday experiences and reveal choices driven by political, moral, and social concern. Worldviews (e.g., nature-based and indigenous perspectives) inform acceptance of renewable technologies. Political beliefs (individualism, governance) affect support for alternative energy. Shared community values and common aims increase participation and pro-environmental activity (Burger et al., 2015).

Energy consumption connects materiality, information, institutions, economic systems, governance, and social norms (Shin & Bull, 2019), and innovations stimulate adoption. Rogers diffusion theory proposes innovation visibility, relative advantage, compatibility, pilot supply, cost, and acceptance risk (Smaliukiene & Monni, 2019). Theories on perceived efficacy, capability, need, and expectation drive participation. The Theory of Planned Behaviour examines attitudes, subjective norms, perceived control (exposure, experience), and intention. Nudge interventions heighten awareness of the benefits of supply-use cycles, flexible consumption, and energy-saving.

2.1. Culture and Energy Transitions

Cultural factors shape how and why societies adopt renewable energy technologies. As the existing literature examines culture and energy transitions, three influential approaches emerge: cultural values, cultural cognition, and social representation theory.

Culture extends beyond the arts or traditions to encompass "the shared norms, values, beliefs, and ways of life of a people group." Researchers invoke the idea of cultural cognition to explain and predict perceptions of risk and policy receptivity. Cultural cognition theory builds on the assumption that human beings rely on socially constructed conceptions of the world to integrate vast amounts of information. Individuals' worldviews influence the information they seek, the interpretations they make, and the conclusions they reach. Cultural cognition scholars typically identify "a small set of value-based worldviews—individualism, egalitarianism, hierarchism, and fatalism—that shape citizens' perceptions of risk in diverse areas, including technology." Cultural-cognition-based models of public attitudes can enhance understanding of renewable energy technology adoption and of policies—such as economic incentives, regulatory mandates, and tax credits—that encourage or discourage it (Richard Snape et al., 2011).

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* 'cite_from': "(Lennon & Dunphy, 2024)" 'cite_id': "dea99fc3-ea16-4eb2-b2f9-0a1c8f4e19e1"

2.2. Behavioural Theories in Adoption

Rogers' classic theory of the diffusion of innovations is pertinent because the introduction of renewable solutions constitutes an innovation that takes time to spread through a relevant population.

The theory identifies five key adopter categories—innovators, early adopters, early majority, late majority, and laggards—that vary by social category and influence the overall diffusion rate. The theory has been extended, for instance, through the "Technology Acceptance Model" (TAM) and related explorations of the roles of social–cognitive aspects and contextual variables in adoption, to address a wide range of innovations (Moore & Boldero, 2017).

The Theory of Planned Behaviour (Ajzen, 1991) builds on the Theory of Reasoned Action (Fishbein & Ajzen, 1975), which helps clarify the routes through which public action can increase sustainability. The model postulates that adoption—here of renewable options, but applicable to diverse behaviours—derives from intention comprising three components: attitudes toward the conduct, perceived norm, and perceived behavioural control.

Nudge approaches (Thaler & Sunstein, 2008) and insights from behavioural science are playing an increasing role in shaping individual and collective decisions, including those related to sustainability and energy use. These approaches have yielded disparate instruments that intervene at key mental "decision points" and can improve uptake of renewables.

2.3. Social Norms and Collective Action

Predicting acceptance and adoption of renewable energy community solutions: the prosumer psychology

Social norms are formed in group settings and serve as standards for individuals' perceptions and judgments. Deviation from social norms leads to conformity, a process shaped by social influence, in which attitudes, cognitions, or behaviours are changed through others' actions. Sharing values and norms enhances cooperation and prosocial behaviours like helping and sharing. National identity and a sense of belonging also influence acceptance of renewable energy technologies. Understanding these collective social factors is crucial for fostering community acceptance and overcoming collective action problems related to renewable energy adoption (Brambati et al., 2022).

Pro-environmental behaviour involves rational choice and moral motivation—social and political trust influences energy-saving actions. Social norms significantly impact climate-related behaviours and sustainable consumption, including electric vehicle adoption. Norm-based nudging encourages environmentally friendly actions, such as avoiding disposable cups. Factors influencing residents' energy-saving habits include altruism and egoism. Social capital, including organisational and community networks, provides organisational advantages and economic benefits. Leveraging social capital can promote pro-environmental behaviours like waste recycling. The value-belief-norm theory explains support for environmental social movements. Sustainable education and youth confidence are essential for future civil society engagement (Caferra et al., 2023).

The norms associated with climate change: understanding social norms through acts of interpersonal activism

Social norms can act as both barriers and facilitators of pro-environmental behaviour. Currently, a dominant norm in the West is a carbon-intensive lifestyle, which hampers environmental actions. For social norms to promote change, processes of norm change must be emphasised. Psychological research shows that perceived discrepancies between injunctive and descriptive norms undermine behaviour change, creating a cycle where people do not adopt pro-environmental actions because others are not perceived to do so. The stability of social norms explains the maintenance of an environmentally unsustainable status quo, but how norms change is less understood. Strategies for norm change include community interventions and sanctions, which rely on observable behaviours to shift normative expectations. Social norms are active expressions of approval or disapproval within social environments, emphasising their interactional nature. Norms are enacted and policed through social interaction, including interpersonal confrontation of norm violations (Steentjes et al., 2017).

3. Cultural Variability in Renewable Energy Adoption

Culture influences how societies adopt renewable energy technologies. Previous work identifies several cultural forces that shape technology adoption patterns: values and worldviews, trust in institutions, and heritage and identity (Brambati et al., 2022). People's fundamental beliefs affect their attitudes towards technologies. Trust in institutions influences the perceived legitimacy and credibility of public policy, as well as the fit between proposed solutions and local contexts. Heritage, identity, and place underscore the importance of conservation and emphasise the need to align energy projects with local values and needs (Abdul Hai, 2019).

3.1. Values, Beliefs, and Worldviews

Adoption of technologies stabilising the global climate varies significantly by context—across geographic regions, social settings, and demographic groups.

Understanding drivers and barriers in diverse settings improves the diffusion of climate technologies. Concepts of individualism-communitarianism and hierarchy-egalitarianism—foundational to research on social values, beliefs, and worldviews—provide a useful lens, as do notions of trust (Brambati et al., 2022) and fit between institutions, cultural values, and technology. Information seeking and communicating decisions are influenced by social networks and peer effects. Energy planning and technology choices manifest place, identity, and a range of cultural practices shaping stewardship.

3.2. Trust, Institutions, and Governance

Social acceptance and adoption of technologies are reliant on the interplay of complex cultural, social, and institutional factors. Systems of trust are integral to this social landscape. Trust is among society's most delicate resources, built too slowly to endure the destructive forces of dynamic upheaval that can render social norms inconsistent with rapidly evolving institutions. Historically, there tends to be greater trust in governments and corporations in more socially cohesive societies. Trust decreases in more politically fragmented societies, not only in the electoral sense but also in ruling parties' ability to implement their electoral promises. Rapid change requires establishing new operating assumptions sooner rather than later. One of the biggest differences in institutional continuity is the extent to which policy decisions and frameworks merit legitimacy. Societies that assign high legitimacy to institutions tend to have lower political and economic risk premiums. Trust in institutions and policy credibility represent two critical components of policy legitimacy.

Renewable energy technologies are associated with more and richer cultural content than their fossil fuel counterparts. Renewable energy project development—whether undertaken by authorities or members of civil society—typically stirs concerns about the interplay between heritage conservation and identity formation. Cultural governance is often instrumental to the foundational human impulse to preserve cherished sites. Cultural governance mechanisms have socio-political, administrative, and socio-technical dimensions. At the socio-political level, statutory heritage regimes favour citizen participation over expert opinion. Such systems render exploration of renewable energy projects that inflict significant impacts on the heritage fabric contentious and complex. A growing form of cultural governance reflects the influence of local history or national culture on the framing of contemporary energy projects. Placing or meeting such conditions may accelerate adoption. Historical legacies do not retain equal significance under either view; sharp boundaries outline pertinent dimensions of socially negotiated energy. (Marra & Colantonio, 2022)

3.3. Heritage, Identity, and Place

Across many societies, energy projects encounter significant opposition: initiatives that improve energy security or facilitate decarbonization may flounder due to local heritage and identity considerations (H. Llewellyn et al., 2017). Industry and consumers alike have vested interests in the ongoing extraction of fossil fuels; yet policies geared toward a transition from coal to low-carbon alternatives trigger popular unrest among communities reliant on coal or connected to coal-extracting heritage. Similarly, waves of opposition have emerged against adapting existing power plants for biomass burning or the growing installation of renewable energy plants and infrastructure, especially in rapidly urbanising peri-urban zones. In regions regarded as sites of significant hydropower heritage, public opposition diminishes the feasibility of establishing renewable energy alternatives. Where citizen participation in energy transitions is already low, numerous heritage-related physical and social determinants hamper progress (Lennon & Dunphy, 2024).

4. Behavioural Drivers of Adoption

Behavioural drivers of adoption represent micro-level determinants that explain uptake of renewable energy technologies within specific social contexts. Individual and collective assessments of perceived benefits and costs influence acceptance. Quantitative studies commonly distinguish among economic, environmental, and social dimensions, measuring risk perceptions and trade-offs (Johnson, 2016). Threshold models apply to both aggregate-level diffusion and individual-level adoption decisions, linking prior uptake actions within communities to subsequent adoption probabilities. Information, awareness, and understanding also shape individual and collective assessments, with projections that higher levels of pre-existing awareness facilitate diffusion (Brambati et al., 2022). Information channels—including media, campaign interventions, and demonstration projects—exert influence. Few studies address the quality of information received, yet incorrect or misleading information can inhibit adoption. Channel formats play an important role, as do information density and literacy. Sustainable technologies like solar electricity and biogas require extensive knowledge beyond a general understanding of energy. Promotional campaigns often concentrate on technical features or economic returns, despite the potential salience of social and environmental co-benefits. More broadly, information points to the need for communication that acknowledges and accommodates initial perceptions.

Social influences, such as inter-personal peer effects and community leadership, contribute to adoption through social networks. Threshold and diffusion models indicate that early uptake drives subsequent adoption within networked populations. Initial adoptions serve as information and visibility signals, reducing uncertainty. Community leadership shapes project initiation and attracts further participation. Multi-dimensional networks, comprising different actors and interactions, foster collective uptake by transcending barriers across multiple dimensions. Models of network diffusion remain sparse in the context of renewable energy choices, although limited evidence suggests transitions within national leadership networks.

Collective practices—shifts in technology-oriented behaviours that extend beyond individual action—emerge at the intersection of social influence and collective-action frameworks. Numerous pro-environmental behaviours follow established patterns of social transmission identified through empirical research across many domains. Collective-action problems can also facilitate widened participation, since dependencies among technologies or practices tie individual actions together. Individual adoption of water-efficient shower-heads, for instance, may hinge on collective practices within an institutional setting.

4.1. Perceived Benefits and Costs

For many years, the differing perceptions of the economic and social benefits of renewable energy have been argued as a significant barrier to its uptake in various contexts (Weaver, 2017). Since gaining prominence, the quotations of these benefits have been targeted toward specific groups and individual characteristics. Recognition of these characteristics has been framed through a proximal analysis lens termed the 'accommodation of interests'. This approach draws on similar quotations for cost-benefit analyses proposed by Bohr and other scholars (Brambati et al., 2022). Knowledge of such provisions has helped establish widespread community solar projects across the United States. In particular, the evaluated statewide policies, localised political appetite, and alternative regional frameworks—such as variable solar resource, population density, and existing policy schemes—are influential.

Turning recognition toward regional conditions, the capacity for payback approaches of renewable energy technology often intersects with a region's degree of technological readiness. The anticipated readiness for an energetic transition varies across formal dimensions, such as availability, reliability, maintenance capacity, and equipment interoperability. The perceived importance of such conditions accordingly varies across diverse sociopolitical realities, momentary relationships, and actors.

4.2. Information, Awareness, and Understanding

People sometimes do not adopt renewable energy technologies (RETs) because they lack comprehensive information and a thorough understanding of their features and performance. Comprehensive information and understanding of RETs are required to evaluate their advantages and suitability. For instance, knowledge of specific RET characteristics, performance metrics, and available financing options can help estimate life-cycle costs (Brambati et al., 2022). It has also been argued that engaging people through multiple methods, even seemingly trivial ones (such as different technical issues), may stimulate exploration of additional RET information.

A common misconception is that renewable energy technologies can never match the reliability of fossil fuel technologies. The belief probably stems from the intermittent nature of renewable energy sources, which are often characterised as uncertain or hard to forecast. Such interpretations restrict the adoption of RETs.

4.3. Social Influence and Networks

Social influence and networks contribute to a more fine-grained understanding of the diffusion of renewable technologies. Peer effects and social norms accelerate the adoption of energy-saving infrastructure, such as rooftop solar photovoltaics, by altering the perceived benefits and costs of different solutions (Serra-Coch et al., 2023). Disseminators also vary the latitude of acceptance for the project depending on its social significance, social distance, and their participation in community organisations. The diffusion process is driven by various community leaders and their spatial influence within municipalities (Caferra et al., 2023).

5. Barriers and Facilitators in Diverse Contexts

Adoption, upgrading, and maintenance of renewable energy technologies occur within specific socioeconomic, institutional, geographic, and infrastructural settings – hence, additional adoption factors shape the transition process (Brambati et al., 2022). Barriers arise across multiple dimensions, but the econometric literature has focused primarily on economic obstacles. The analysis reveals diverse barriers to household adoption and demonstrates that national-level modelling of adoption is inconclusive in identifying the most pressing factors across most countries. Considerable progress remains to be made in understanding all the barriers to renewable energy adoption across diverse contexts and their role in national-level adoption of energy technologies.

5.1. Economic and Policy Barriers

Economic considerations are a significant factor influencing the uptake of renewable energy technologies. Surveys reveal that lower costs, either up-front or on an ongoing basis, would encourage greater adoption. Economic barriers appear to be the most significant barrier in Australia, preventing those who wish to install systems from doing so. As such, the consideration of economic barriers constitutes a major part of the analysis (Dell, 2015).

Economic and policy barriers constrain the adoption of pro-environmental renewable energy in various settings. Economic barriers include high upfront costs, lack of affordable credit, and price uncertainty, while policy barriers include government incentives or subsidies, global emissions-reduction commitments, regulatory frameworks, and compliance obligations.

5.2. Technological and Infrastructural Readiness

Technological and infrastructural readiness relates to the availability, reliability, maintenance capacity, and interoperability of technologies. The adoption of renewable energy technologies is constrained by both access to the technology and access to knowledge of how to use it (Brambati et al., 2022). Constraints arise from equipment and skill shortages, low reliability, high maintenance costs, limited spare-part availability, and low compatibility with existing systems. Adoption is further hampered when repair activities are constrained by regulations that prohibit improvised repairs, equipment modifications, or the import of used parts.

5.3. Cultural Conflicts and Accommodation

Cultural conflicts may impede progress toward low-carbon energy systems. The technological advances underlying renewable energy systems are sometimes viewed as symbolic instances of modernity, reflecting a shift from older, retrievable technologies. Paradoxically, modernities, as much as older technologies, can threaten cultural continuity. Renewable energy systems may have intergenerational consequences, affecting future generations. They may even be perceived as instruments of domination that radically shift cultural patterns, influencing life practices and customs beyond energy systems. Lastly, they may challenge perceptions of indigeneity, requiring framing and redefinition.

Cultural reconciliation with energy systems may take several forms. Framing the rationale for transition in terms congruent with cultural systems (e.g., dignity, sovereignty) can facilitate greater acceptance and support. Various mediation devices (e.g., representative assemblies, collaborative agreements) can be employed to align energy initiatives with local preferences and aspirations. A tandem of older and renewable energy systems may be combined as a transitional pathway to ease the transition. Integrating traditional energy sources with new, expanding technologies has facilitated acceptance, as seen in the provision of overhead electricity to conserve kerosene (Frank Pidgeon & Demski, 2012).

6. Policy Design for Socially Inclusive Transitions

The transition to renewable energy systems involves considerable changes to social, economic, and energy-dominating structures, as well as accompanying behavioural responses (Verbruggen et al., 2015). Many energy, housing, and transport systems depend on fossil resources. Transition may constrain development opportunities for energy-dominant sectors in low-income countries, where populations depend largely on fossil energy. The arrangements governing energy systems create rules about how resource advantages are generated and distributed. Such systems tend to favour resource monopolies and strategies that fulfil demand and supply ahead of political arrangements capable of adapting to changing circumstances. Maintaining incentives for change without eroding established freedoms demands new models that realistically promote transition without crippling neighbouring sectors. Energy initiatives seldom consider society's broader absorptive capacity for complementary developments (Brambati et al., 2022). Dominating energy systems impose values that signify what constitutes acceptable both for energy and for neighbours. Consistent with energy-dominant systems, renewables are often judged principally on their potential contribution to energy supply rather than wider social, cultural, economic, or environmental considerations. Transition efforts overlook the challenge of aligning each complementary development in a manner that conserves existing freedoms, constraints and dominances. Energy transition works against marginals by attempting to constrain neighbouring functions—worthwhile objectives that are blocked by dominant energies. Sustainable transition requires policies that slow growth in energy systems that overshadow neighbouring margins and accompanying spoiling pressures.

Even when renewable adoption patterns closely align with energy-dominants, energy-marginals tend to ground their energy initiatives elsewhere within the energy portfolio. To realise energy initiatives that complement adjoining systems, authorities must be capable of matching complementary supplies of both culture and technology. More broadly, each established optional energy system signifies a different perspective on how energy can develop across society; so, entry to the renewable portfolio may be harder for culture-margins already committed to energy-marginal ideologies than for dedicated energy-dominants on the same margin.

6.1. Participatory Governance and Co-Creation

Localised energy generation provides a strategy to manage energy transitions through a broader picture of community, technology, and market demand, highlighting the role of public and cooperative participation and local ownership (Lennon & Dunphy, 2024). Recognising energy citizenship as a lens for viewing participation in community energy projects provides additional theoretical insight into participatory governance and co-creation processes that influence such projects. A review of community energy in Europe indicates that distinguishing participation levels has been useful for analysing the degree of public involvement in projects (J Hewitt et al., 2018).

Enlightened governance that accompanies and facilitates engagement and other strategies centred on local citizenship will be of great value in mapping stakeholder deliberation processes and appropriate engagement measures, using techniques such as stakeholder mapping, deliberative processes, and public engagement. Such governance approaches not only help map continuity throughout project design but also build social trust from the outset, an enabling factor linked to greater overall take-up, since proactive trust-building measures that address layperson concerns can foster a sense of ownership and co-responsibility across projects.

6.2. Tailored Communication and Education

Tailored Communication and Education

Effective strategies are needed to motivate the adoption of renewable energy technologies aligned with the socio-cultural characteristics of specific target groups. These strategies are best formulated based on a well-defined segmentation of the population by relevant social and cultural variables, with the specific aim of enhancing the uptake of renewables. The segmentation results define the communication and education maps and indicate which values to capitalise on to promote residential renewables (Smaliukiene & Monni, 2019). These emphasising concepts resonate with the target group.

Shared values guide the design of persuasive messages intended to foster the uptake of renewables. Low-cost technologies with broad application potential, such as roof-mounted solar PV systems, require messaging that aligns with recipients' values, beliefs, and worldviews to achieve significant deployment. The values of a homogeneous target group, such as the cohort of new homebuyers in urban neighbourhoods, represent a useful entry point for tapping related benefits that may motivate installations. The motivational constructs of perceived benefits and values have received considerable attention in the social psychological literature and hold promise for crafting messages addressed to specific audiences (Brambati et al., 2022).

6.3. Equity, Justice, and Just Transitions

Many energy transitions promise more equitable access to clean and affordable energy while safeguarding and creating opportunities for historically disadvantaged groups. Renewables disproportionately benefit individuals and areas not previously served by conventional energy systems. However, uncertainty exists regarding renewal benefits for economically vulnerable households. Examples abound of large-scale deployment of renewables and other low-carbon alternatives marginalising or intensifying disadvantage among minority, traditional, or historically disadvantaged socio-economic groups (Biswas et al., 2022). An ethical mandate emerges for those leading energy transitions to prevent reinforcing or igniting new forms of injustice, particularly the structural inequalities endemic to conventional carbon-based energy systems, and to adopt culturally sensitive and socially inclusive approaches to the design and implementation of low-carbon energy systems.

An ethical imperative for just, equitable, and fair energy transitions surfaces across renewable contexts and projects worldwide (E. H. Jenkins & Martiskainen, 2018). The shift from carbon-intensive energy systems to low-carbon alternatives, well recognised as prerequisites for mitigating climate change and related disasters, introduces economic risks and uncertainties—such as challenges in gaining access to yet another energy source or difficulties in adjusting during the transition phase. Several energy-access concerns require consideration, including physically reaching the necessary expanded energy nexus and affordably maintaining access to designated energy-oriented services. Energy transitions that privilege low-carbon technologies while disregarding broader systemic interdependencies and socio-economic connectivity risk unintended injustices. Such transitions threaten to extend existing inequities across economic, social, and cultural dimensions, or to dominate energy narratives and practices of non-hegemonic groups. Societies subjected to long-standing colonial and structural injustices risk reproducing already stark inequalities across emerging low-carbon energy systems.

7. Case Studies in Cultural Contexts

Social, cultural, economic, and climatic factors shape the uptake of renewable energy technologies in developing countries (Smaliukiene & Monni, 2019). Levels of awareness, understanding, and information availability differ widely in most contexts. For instance, rural and urban communities in South Africa exhibit contrasting patterns of household energy use, leading to divergent levels of interest, familiarity, and capacity to adopt solar energy. The broader regulatory environment, economic landscape, and social perceptions of renewable energy vary across locales. However, deeper cultural forces profoundly shape policy frameworks, the institutional relationship between citizens and the state, and the range of viable governance models (Williams, 2019).

Marginalised groups often experience disproportionate energy burdens and do not benefit equitably from renewable transitions. Cultural, socio-political, and policy structures mediate access to services and modern energy, affecting uptake and influencing perceptions of renewable energy technologies in ways that differ between rural, indigenous, and urban settings.

7.1. Urban Residential Adoption

Metropolitan solar uptake predominantly revolves around two housing types—single-family homes and multifamily structures. Detached single-family houses are typically favoured, as metro residents perceive them as offering greater independence from central utilities. Oregon regulations provide additional incentives: weatherization policies create barriers for rental units, and regulations limit the hours renters can be home for installers. When evaluating service options, Portland urban residents prefer installers familiar with local site and permitting requirements, a preference not shared by other Oregon residents (Weaver, 2017).

7.2. Rural and Indigenous Contexts

Local contexts play critical roles in shaping renewable energy proposals and installations. Indigenous peoples seeking to develop or protect natural resources must ensure that they receive equitable benefits and maintain control of land, governance, and cultural sites. One "wealth of knowledge" that Indigenous communities can tap is their ways of assessing proposals across these dimensions before any investment is made. In solar photovoltaic (PV) training programs for off-grid communities in six countries across Africa and Asia, participants emphasised that it was vital for energy systems to be located in places of significance to them before any technical assistance was provided. Solar PV training programs that engaged and empowered local communities to develop light, water, and other applications at their own pace became widely adopted. In both remote and urban settings, community members advocating for these resources expressed scepticism about mainstream energy systems, unsure whether they would meet the pressing needs of local individuals and institutions.

Traditional or growing aspirations to become a politically, socially, or economically independent body require appropriate responsibilities, authorities, and governance mechanisms. Supporting a community's efforts to achieve or enhance such autonomy while addressing energy development has proven successful in various countries, such as Canada and the United States. Strikingly similar approaches emerged from the development of cooperative wind and solar PV installations, commercial fishing activities, renewable energy policies, and energy availability across diverse cultural settings. In the Canadian North and the outer region of French Polynesia, communities draw on their own resources and seek recognition to assert authority and responsibility, or to aspire to become independent entities. Space and active ingredients play crucial roles in acquiring and maintaining energy on the corresponding scales to address emerging needs. Regular reexamination of energy needs, their historical triggers, and contemporary supply routes directly engages a community's social, economic, and political aspirations, lending legitimacy to control over selected developments. Between community-led forms and their contemporary expression, parallelism has been observed in Mongolia, Northern Europe, and the outer region of French Polynesia (F. Moran et al., 2022).

7.3. Cross-National Comparisons

Different national contexts exhibit distinctive patterns of household-level renewable energy use, shaped by localisation strategies and cultural characteristics, with the transfer of practices and policies from one location to another achieving limited success. Comparative studies enhance understanding of the role of cultural differences in the adoption rates of renewable energy technologies and the associated policy measures. The cross-national nature of the data allows the examination of socio-political influences on urban energy sustainability and highlights the limitations of national indicators in assessing technological advancement.

The design of training wedges combines convergence theory and task-technology fit, while extending actor-network theory to frame implementation as a strategic effort requiring skilled actors. It captures features of training and attempts to incorporate the interactional dimension that socio-technical perspectives have neglected. Empirical illustrations are derived from a comparative examination of Luxembourg City and Geneva, selected for their comparable size, political arrangements, urban forms, and energy portfolios. In Geneva, the socio-spatial integration of energy-related uses and the ambition of the municipal master plan reduce energy consumption and enhance the desirability of fossil-fuel-free energies. Energy savings complement or substitute incremental increases in energy supply, while the portfolio of energy supply technologies helps to circumvent lock-in and promotes further energy savings (Williams, 2019; Brambati et al., 2022; Seidl et al., 2017).

8. Methodological Approaches to Studying Social Dimensions

Studying the social dimensions of renewable energy adoption requires methodological approaches aligned with theoretical frameworks governing culture and behaviour, as well as with the specific insights garnered from diverse contexts. Consequently, a robust array of complementary methods is necessary to engage these multiple axes and capture micro-level phenomena, values, and social networks that are excessively simplified by large-N surveys, which remain prevalent in diffusion studies. Qualitative ethnographic approaches offer a distinctive lens, enabling nuanced examinations of social dimensions, culturally grounded context, and specific adoption pathways. Ethnography strives to attain depth of understanding: participant observation of informational meetings, policy forums, and procurement discussions illuminates the role of public participation in governance processes; informal discussions alongside formal interviews with suppliers, installers, users, and rejectors reveal local perspectives and values; and thematic analysis of such insights—coupled with extensive cultural mapping—effects identification of specific values and relationships influencing the adoption of contemporary renewable technologies in diverse urban settings.

Although purely qualitative studies contribute substantively to comprehension of socially grounded adoption, blending multiple methods captures a wider range of determinants, retains sensitivity to context, and facilitates comparative analysis. Mixed methods constitute a promising route, yet straightforward quantitative surveys reduce informational complexity without pursuing explanatory depth; a preference for perceived cost-benefit ratios occludes the cultural contours that shape such estimates. Concurrent implementation of quantitative surveys, focused qualitative interviews, and visual participatory approaches enables triangulation of results across different data types, engaging micro-level specifying factors and contrasting urban and rural influences across a large metropolitan region. This configuration explores not only the perceived significance of a diverse array of potential drivers but also the interaction of contextually specific prioritizations in heterogeneous settings. Quantitative investigation then centres on indicators that shape residuals within a Rogers-diffusion framework, allowing for a systematic exploration of whether the adoption rate of a given technology conforms to a normal distribution over time. Longitudinal studies of local communities illuminate the evolution of approvals for dwelling-related technologies.

8.1. Qualitative Methods and Ethnography

Scholars have long recognised the necessity of integrating social dimensions into analyses of renewable-energy transitions. Qualitative methods, for instance, can shed light on the implications of culture and behaviour for technological adoption (Brambati et al., 2022). Ethnography, which emphasises context-specific insights acquired through immersive engagement with lived experience, is particularly relevant. To pinpoint social values that align with emerging energy technologies and the infrastructures required to support them, multiple qualitative methods can be deployed: participant observation within community initiatives; semi-structured interviews with residents, municipal staff, and leaders; and thematic analysis of documents, reports, and visual material about projects. These approaches enable the examination of the social contours shaping energy and technology choices and deepen understanding of the significance of particular technologies in specific settings.

These complementary methods permit exploration of energy transitions and associated concepts—such as transition initiatives, prosumer communities, shared installations, neighbourhood battery projects, community energy, place, heritage, and identity—over varying spatial and temporal scales. Such flexibility accommodates micro-level studies examining the individual justifications that accompany decisions to adopt specific technologies and the neighbourhood diffusion of energy-saving behaviours, as well as research focused on macro-level discussions concerning broad-value orientations among a wide range of actors engaged in addressing climate change, urbanisation, and energy—often underpinned by ethical concerns about equity, fairness, and justice. Time dynamics are also amenable to analysis, encompassing trajectories such as the transition from water power to coal or oil or the rapid adoption of electric vehicles.

8.2. Quantitative and Mixed-Methods

The quantitative examination of social dimensions complements qualitative approaches by examining the individual-level cognitive and behavioural factors central to technology acceptance, while allowing for broader sampling and analysis.

Adoption of renewable energy technologies remains constrained across social, cultural, and institutional contexts. The extent of adoption is determined by values, perceptions, norms, and wider economic, political, and infrastructural conditions (Brambati et al., 2022). Survey and econometric data provide insights into the influence of micro-level dynamics in various settings and facilitate comparisons across geographical and social contexts.

The relationship among culture, behaviour, and energy transitions integrates data collected through different methodologies into a coherent empirical exploration of the social dimensions of adoption. Theories of cultural cognition and diffusion identify strategies for overcoming barriers and leveraging context-specific assets. Computational representations of cultural and behavioural variables establish agent-based models to trace their evolution under different uptake scenarios, extending observations into the future.

8.3. Intersectional and Longitudinal Analyses

Adoption of solar energy and related investments is found to be inconsistent over time, across space, and between social groups within the same context. This inconsistency illustrates the salience of sociocultural factors and highlights the need for an intersectional approach that incorporates multiple dimensions of identity (Talevi & Standal, 2020). Such an approach adds depth to a static analysis of dominant identities, allows attention to people with multiple or competing identities, and accommodates temporal dynamics, acknowledging that identities may vary over time.

Infrastructure and service provision across different housing and land tenure types interact with these values. Several studies, for example, show that socioeconomic benefits are among the most important arguments for residential rooftop photovoltaic systems in less affluent urban areas. In contrast, costs and other arguments carry more weight in middle- and high-income municipalities (Schulte et al., 2021).

These analyses frame technology adoption across diverse situations by focusing on a range of interactions between culture and sociotechnical systems; they underline the importance of pluralism in societal responses to pressing energy challenges; and they reveal the scope for technology-led transitions to become more inclusive for particular social groups, thereby strengthening political viability overall (Lazoroska et al., 2021).

9. Implications for Technology Diffusion and Energy Policy

Renewable energy systems can fail spectacularly due to social misalignment or inadequate diffusion. During the almost three decades of global R&D investment support for solar energy technology to the beginning of 2005, the publicly perceived benefits of investment policy in photovoltaics (PV), passive solar architecture, and concentrated solar power were extreme in some societies but largely nonexistent in others (Weil, 2013). In the traditional nuclear sector of the latter, approval of PV for mass-market grid capability in the early 2005 timeframe would have been impossible: the available “fixes” to disinfect public acceptance of the technology were already in place in other societies. The required investment to achieve a grid-capable PV system remained beyond the capabilities of all enterprises isolated within those societies. The socially congruent adoption of a minor high-value application, e.g., solar hot water heating, could, on the margin, facilitate consideration of the acceptance of larger-scale technologies thereafter, yet none were socially available.

Energy conservation and renewable energy technologies could contribute significantly to addressing the structural economic problems faced by the USA. However, program and policy convergence to maximise the penetration of these approaches in the affected sectors, especially in the building, transportation, and equipment sectors, remained weak prior to 2005 due to social acceptance issues. The function of community governance for total energy systems within the city of Davis, California, had succeeded in accommodating and aligning many of the conflicting aspects relevant to energy conservation and renewable energy technology, thus far, and could be a source of experimental validation for co-public policy initiatives to solicit academic support for these approaches across the USA in 2005.

9.1. Aligning Technology with Social Values

Renewables have the potential not only to meet society's energy needs but also to overcome the "energy crisis." Technology has not filled renewable energy generation (Brambati et al., 2022). In developing countries, national economic transformation and energy supply are growing more crucial; many are seeking to increase supply-side renewable energy generation. Technology diffusion is a pivotal means to enhance generation. In addition, Japan has been implementing its Comprehensive 2030 Strategy to promote Rooftop Solar Photovoltaic Power Generation for Houses. Energy supply problems and the significant share of privately owned buildings work to the nation's advantage; thus, the second-best strategy of harnessing the diffusion of Rooftop Solar Photovoltaic Technology has been prioritised. Japan was an early adopter of smart-city efforts. In advance of the diffusion of Rooftop Solar PV Technology, the proponent has endeavoured to identify the socio-cultural context surrounding the uptake in Japan. Such exploratory and detailed analysis informs the policy measures to promote subsequent diffusion. The findings suggest a proactive stance to foresee the socio-cultural context of adoption. The pivotal context is to tap into society's reservoir of social values and culture.

Acknowledgement of fundamental social culture and values surrounding technology provides a macro socio-cultural enabling condition. Such a socio-culture governs the formation and emergence of social norms. Once the social norm surrounding the new technology becomes well established, technology diffusion occurs, and socio-cultural fit and socio-cultural governance are essential for the diffusion of embedded technology.

The concept of Cultural Object stands out. Social constructionists argue that new technology is a social product. Social constructionism is rooted in social context and values. Social values of adoption become central. The broad understanding of social values examines the correspondence of the socio-technical practices surrounding technology with society's broader reservoir of macro social values. The westernised Comprehensive 2030 Strategy of Rooftop photovoltaic Power Generation for Houses, Practical Guide for Title II, Japanese Style Workations, Paper-based Technical Report for Title C, two-pronged Cultural Object as message-carrier, widespread awareness and learning are the socio-technical practices that would benefit from explicit acknowledgement of the surrounding social values. Furthermore, rooftop photovoltaic power generation technology adoption, its macro socio value, policy, sources, and availability have come to predominant attention in the national public arena.

9.2. Designing Incentives for Behavioural Change

The provision of effective policies and programmatic incentives can promote social and behavioural change in favour of renewable energy adoption (Smaliukiene & Monni, 2019). Regulations and programs designed to address energy-user behaviour, often deployed alongside technical regulations, can yield significant reductions in greenhouse-gas emissions across many economic sectors. Modelling the user and reframing user behaviour also appear to be supervisory concepts of behaviour-based regulation (Lockton et al., 2010): they frame the energy transition challenge, identify suitable instruments for regulation or encouragement, and reveal which actions can result in the intended outcome.

9.3. Monitoring, Evaluation, and Learning

Monitoring, evaluation, and learning (MEL) frameworks give structure to reflecting on a project or programme's progress, areas for improvement, and broader insights applicable to future initiatives. Nurturing MEL can cultivate adaptive governance, promoting more reflective approaches to energy transitions. Theoretically grounded reflection helps surface the precise interactions among cultural, technological, behavioural, and context-specific factors that underpin adoption, thereby enhancing operational effectiveness, policy relevance, and scholarly contribution. Further interrogation—whether by the initiating organisation or external audience—by diverse agents with overlapping or alternative interests boosts systemic learning (Brambati et al., 2022). In the context of renewable energy, key indicators span technology appreciation, deployment decisions, and ongoing infrastructural transformation (Williams, 2019).

Renewable technologies succeed when their value propositions resonate with individual and collective priorities. Technologies that reinforce prevailing social norms or more easily adjust institutional functions gain acceptance. Valuation frameworks should therefore map local and national projects to prevailing cultural values, behaviour-change incentives, and parallel technologies that draw on established social frameworks. Incentive frameworks for complaint resolution, environmental benefits, energy conservation, and cost savings can further bolster acceptance. Theoretical models can then assess anticipated diffusion rates, informing policy and gauging compatibility with ongoing transitions.

10. Conclusion

Energy transitions that rely on renewable sources and technologies are a critical pillar for mitigating and adapting to climate change within social-ecological systems. Projections indicate that total anthropogenic greenhouse gas emissions must drop by 45% from 2010 levels by 2030 to keep global warming to 1.5°C, and net-zero emissions must be achieved by 2050. However, despite their demonstrated sociocultural sustainability, many renewable technologies with wide-ranging benefits continue to encounter social resistance and lag well behind target uptake rates (Brambati et al., 2022).

The social dimensions of this renewable-energy adoption problem are considerable and multifaceted, comprising culture (values, beliefs, and identity), behaviour (knowledge, attitudes, and norms), and the interactions between the two. This study sought to identify and characterise the key mechanisms linking the social dimensions of culture and behaviour to renewable-energy adoption. A diversity of cultural and subcultural contexts, drawing from established social-science theory foundations, contributes to a more holistic understanding of the energy transition problem and enables greater openness to new solutions and policies.

References:

1. Brambati, F., Ruscio, D., Biassoni, F., Hueting, R., & Tedeschi, A. (2022). Predicting acceptance and adoption of renewable-energy community solutions: Prosumer psychology. *NCBI*.
2. Burger, P., Bezençon, V., Bornemann, B., Brosch, T., Carabias-Hütter, V., Farsi, M., Hille, S. L., Moser, C., Ramseier, C., Samuel, R., Sander, D., Schmidt, S., Sohre, A., & Volland, B. (2015). Advances in understanding energy consumption behaviour and the governance of its change: Outline of an integrated framework.
3. Shin, H. D., & Bull, R. (2019). Three dimensions of design for sustainable behaviour.
4. Smaliukiene, R., & Monni, S. (2019). A step-by-step approach to social marketing in energy transition.
5. Snape, J. R., Irvine, K. N., & Rynikiewicz, C. (2011). Understanding energy behaviours and transitions through the lens of a smart grid agent-based model.
6. Moore, H., & Boldero, J. (2017). Designing interventions that last: A classification of environmental behaviours in relation to the activities, costs, and effort involved for adoption and maintenance.
7. Caferra, R., Colasante, A., D'Adamo, I., Morone, A., & Morone, P. (2023). Interacting locally, acting globally: Trust and proximity in social networks for the development of energy communities. *NCBI*.
8. Steentjes, K., Kurz, T., Barreto, M., & Morton, T. (2017). The norms associated with climate change: Understanding social norms through acts of interpersonal activism.
9. Hai, M. A. (2019). Rethinking the social acceptance of solar energy: Exploring states of willingness in Finland.
10. Marra, A., & Colantonio, E. (2022). The institutional and socio-technical determinants of renewable energy production in the EU: Policy implications. *NCBI*.
11. Llewellyn, D. H., Rohse, M., Day, R., & Fyfe, H. (2017). Evolving energy landscapes in the South Wales Valleys: Exploring community perception and participation.

12. Lennon, B., & Dunphy, N. (2024). Sustaining energetic communities: Energy citizenship and participation in an age of upheaval and transition. *NCBI*.

13. Johnson, E. (2016). *Attitudes, social context, and environmental behaviour: Essays explaining voluntary household energy conservation*.

14. Weaver, A. (2017). The social acceptance of community solar: A Portland case study.

15. Serra-Coch, G., Wyss, R., & Binder, C. R. (2023). Geographic network effects to engage people in the energy transition: The case of PV in Switzerland. *NCBI*.

16. Dell, M. (2015). The adequacy of NSW programs in supporting vulnerable households to transition to renewable energy.

17. Pidgeon, N. F., & Demski, C. (2012). From nuclear to renewable: Energy system transformation and public attitudes.

18. Verbruggen, A., Di Nucci, R., Fischedick, M., Haas, R., Hvelplund, F., Lauber, V., Lorenzoni, A., Mez, L., Nilsson, L. J., del Río González, P., Schleich, J., & Toke, D. (2015). Europe's electricity regime: Restoration or thorough transition. *International Journal of Sustainable Energy Planning and Management*.

19. Hewitt, R. J., Bradley, N., Compagnucci, A. B., Barlagne, C., Ceglarz, A., Cremades, R., McKeen, M., Otto, I. M., & Slee, R. W. (2018). Social innovation in community energy in Europe: A review of the evidence.

20. Biswas, S., Echevarria, A., Irshad, N., Rivera-Matos, Y., Richter, J., Chhetri, N., Parmentier, M. J., & Miller, C. A. (2022). Ending the energy-poverty nexus: An ethical imperative for just transitions. *NCBI*.

21. Jenkins, K. E. H., & Martiskainen, M. (2018). A normative approach to transitions in energy demand: An energy justice and fuel poverty case study.

22. Williams, S. (2019). Investigating household energy conservation behaviours in Johannesburg, South Africa.

23. Moran, E. F., Lopez, M. C., Mourão, R., Brown, E., McCright, A. M., Walgren, J., Bortoleto, A. P., Mayer, A., Johansen, I. C., Ramos, K. N., Castro-Diaz, L., Garcia, M. A., Lembi, R. C., & Mueller, N. (2022). Advancing convergence research: Renewable energy solutions for off-grid communities. *NCBI*.

24. Seidl, R., Moser, C., & Blumer, Y. (2017). Navigating behavioural energy sufficiency: Results from a survey in Swiss cities on potential behaviour change.

25. Talevi, M., & Standal, K. (2020). Engaging men and women in energy production in Norway and the United Kingdom: The significance of social practices and gender relations.

26. Schulte, E., Scheller, F., Sloot, D., & Bruckner, T. (2021). A meta-analysis of residential PV adoption: The important role of perceived benefits, intentions and antecedents in solar energy acceptance.

27. Lazoroska, D., Palm, J., & Bergek, A. (2021). Perceptions of participation and the role of gender in engagement with solar energy communities in Sweden. *NCBI*.

28. Weil, B. (2013). *Solar city, bike city, growth city: Governance and energy in Davis, California*.

29. Lockton, D., Harrison, D. J., & Stanton, N. A. (2010). Modelling the user: How design for sustainable behaviour can reveal different stakeholder perspectives on human nature.