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INTEGRATING RENEWABLE ENERGY AND SMART GRID SYSTEMS: A PATHWAY TO CARBON-NEUTRAL COMMUNITIES IN SOUTHEAST ASIA

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Abstract

The transition toward carbon-neutral communities has become a global priority, especially in Southeast Asia, where rapid economic growth continues to intensify energy use and carbon emissions. Although the region has substantial renewable energy potential, it remains highly dependent on fossil fuels due to weak grid infrastructure, limited digitalisation, and inconsistent policy support. This study systematically synthesises recent scientific research on the role of innovative grid technologies and renewable energy integration in supporting the development of carbon-neutral communities. Using a Systematic Literature Review (SLR) approach guided by PRISMA, 24 peer-reviewed Scopus articles published between 2017 and 2023 were analysed. The selected literature met predetermined inclusion and exclusion criteria, focusing on the adoption of renewable energy, the deployment of smart grids, and low-carbon community initiatives. The review identifies five major theoretical foundations frequently used in contemporary research: Energy Transition Theory, Smart Grid Theory, Diffusion of Innovation Theory, Resilience Theory, and Socio-Technical Systems Theory. Evidence consistently shows that smart grids powered by IoT, digital automation, advanced metering, and sensor technologies enhance energy efficiency, improve load management, increase grid stability, and facilitate the integration of renewable sources. The analysis further highlights that socio-technical conditions, innovation characteristics, digital readiness, policy frameworks, and community participation significantly shape the adoption of renewable technologies. However, empirical studies remain unevenly distributed, with limited research focusing specifically on rural or tourism-based communities in Southeast Asia. To address these gaps, this study proposes a comprehensive conceptual model that integrates renewable energy, intelligent grid systems, and socio-technical enablers to advance carbon-neutral communities.

Keywords: renewable energy, intelligent grid systems, carbon-neutral communities, energy transition, socio-technical systems.

INTRODUCTION

Southeast Asia's economy is expanding at one of the fastest rates globally. The majority still rely on fossil fuels, but this progress is accompanied by a sharp increase in energy demand (IEA, 2023). According to data from the ASEAN Centre for Energy (2023), fossil fuels continue to account for more than 80% of the region's energy demand, which significantly increases global carbon emissions.

However, Southeast Asian nations fall into the "Insufficient" category in reaching the Net Zero Emission (NZE) 2050 objective, according to the Climate Action Tracker (2023). By combining smart grid technology with renewable energy, this highlights the urgency of a clean energy revolution.

Numerous disadvantages of conventional centralised energy systems include their dependence on fossil fuels, ineffective energy distribution, and susceptibility to severe climatic disruptions (Y. Zhou et al., 2022). To build more effective, resilient, and sustainable carbon-neutral societies, the

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smart grid emerges as a contemporary solution that integrates automation, digital technologies, and renewable energy (Hossain et al., 2023).

The International Renewable Energy Agency (IRENA, 2023) projects that Southeast Asia's energy demand will rise by 50% by 2040, potentially worsening carbon emissions. The local economy and quality of life are deteriorating due to an increase in natural catastrophes, air pollution, and rising global temperatures (J. Chen et al., 2023).

Solar energy (10,000 GW), wind energy (25 GW), and hydropower (250 GW) have enormous potential in Southeast Asia (Agency, 2023). However, due to poor infrastructure and subpar integration of the electrical grid, its use remains relatively low (Lin & Sun, 2023).

By combining sensor technologies, big data, AI, and IoT, smart grids offer a groundbreaking approach to balancing energy supply and demand in real time (Fang et al., 2022). According to research by Zhu et al. (2023), the deployment of smart grids can reduce carbon emissions by 40% and increase energy efficiency by up to 30% in densely populated metropolitan regions.

Vietnam (50% clean energy by 2045) and Indonesia (23% renewable energy by 2025) are two ASEAN nations that are beginning to set green energy goals (ASEAN Energy Cooperation Report, 2023). Due to a lack of investment, improved technology, and coordination, these accomplishments are still well short of the goals (World Economic Forum, 2023).

LITERATURE REVIEW

Sustainability Transition Theory (Multi-Level Perspective /MLP)

Sustainability Transition Theory explains how societies transition from old, unsustainable systems, such as fossil-fuel-based energy systems, to new systems that are cleaner, more efficient, and lower in carbon emissions. The most well-known framework is the Multi-Level Perspective (MLP) developed by Geels (2002) and Geels (2005).

Three levels interact to create a sustainable transition: the first is the Landscape Level (Macro), which comprises extensive external factors, including global technology, international rules, climate change, and cultural shifts (Geels, 2002). The second is the Meso-Socio-Technical Regime. The current dominant systems include PLN, national energy policy, power infrastructure, oil firms, and energy use standards. These are often steady and unreceptive to change (Geels & Schot, 2007). Third, Niche technologies (Micro), which are still in their infancy, include electric batteries, solar energy, smart grids, and the Internet of Things. Smart communities, green tourist village initiatives, pilot projects, and other protected areas are where these grow (Geels & Schot, 2007).

Transformation Pathway: Regimes are forced to adapt but not entirely alter due to landscape constraints. Ideal for the ASEAN region, which is progressively embracing renewable energy (Geels & Schot, 2007). Reconfiguration Pathway: The regime progressively absorbs and incorporates little niches. The PLN electrical system's use of smart grids, sensors, and IoT is the best example. Technological Substitution: In more technologically developed nations (Europe, Japan), new inventions quickly replace outdated technology. Dealignment and Re-alignment: When new ideas take over the market, the old regime crumbles. It seldom happens in the energy sector outside of emergencies (Geels & Schot, 2007).

Smart Grid Theory

The concept of smart grid theory explains how digital technology, sensors, communication systems, and contemporary automation enhance the sustainability, dependability, and efficiency of electrical systems. A smart grid, according to Fang et al. (2012), is the upgrading of the conventional power system by integrating ICT, sensor networks, big data, automation, and renewable energy sources to achieve sustainability and efficiency.

Two-way communication and Advanced Metering Infrastructure (AMI) smart meters are the key elements of smart grid theory. Automation & Control: real-time grid monitoring, SCADA. Renewable energy integration, including solar, wind, micro-hydro, and storage. Demand Response (DR): Customers help control power use patterns. Digitalisation encompasses digital platforms, IoT, AI, and big data analytics reliability and resilience, which refer to the grid's capacity to withstand shocks.

Smart grids' primary roles in the energy transition are to stabilise the integration of renewable energy (Y. Zhou et al., 2022), lessen reliance on fossil fuel power plants (Lin & Sun, 2023), enhance the dependability of electrical systems in rural and tourist villages, and allow real-time energy monitoring (Zhu et al., 2023). Becoming a catalyst for low-carbon energy systems.

Socio-Technical System (STS) Theory

According to the Socio-Technical Systems (STS) theory, people, institutions, infrastructure, regulations, cultural values, economics, and user behaviour all influence technology. A socio-technical system, according to Geels (2004), is a configuration of players, technologies, laws, cultural norms, and infrastructures that together facilitate social activities, such as energy delivery. Technology (smart grid, sensors, IoT), actors (government, community, tourism village managers), institutions (energy policy, regulations), infrastructure (electricity networks, communication towers), social practices (energy consumption behavior, community participation), and the tourism market and economy (green tourism demand) are the components of STS (Geels, 2004).

New technology necessitates institutional and societal change, but this is not the only reason for the shift. Public acceptance, legislative backing, village technical competence, energy consumption culture, and financial incentives are all critical to the success of smart grids (Zhu et al., 2023; Jenkins et al., 2018).

Innovation Diffusion Theory (IDT)

Everett M. Rogers' Diffusion of Innovations Theory (IDT) describes how a new technology, practice, or concept spreads over time among members of a social system through specific channels. The features of the invention, as well as human and organisational decision-making processes, communication channels, social structures, and contextual elements, all impact this process (Rogers, 1983).

IDT is the proper theoretical framework to explain the rate and determinants of adoption because smart grids and renewable energy are viewed not only as technology but also as technical social innovations that need to be spread among actors (residents, tourism entrepreneurs, village governments, utilities) (Smart Grid in ASEAN : Overview and Opportunities to Support the ASEAN Renewable Energy Aspirational Target, 2023).

According to Rogers, adoption speed is primarily determined by five characteristics: relative advantage, the degree to which the innovation is perceived as superior to the previous method (in terms of economic gains, dependability, and environmental sustainability). Compatibility refers to the innovation's fit with local requirements, experiences, and beliefs, encompassing aspects such as complexity (or simplicity), usability, and comprehensibility. Trialability is the opportunity to test an idea on a small scale before making a full commitment. Observability refers to the degree to which an innovation's effects and advantages are apparent to others (Rogers, 1983).

Information campaigns (Knowledge), demonstrations/pilots (Persuasion/Trial), incentives & technical assistance (Decision/Implementation), monitoring & testimony (Confirmation), and other stages must all be the focus of interventions to hasten adoption. Research on the uptake of smart meters highlights the significance of the pilot program and evidence to lower scepticism (Rogers, 1983)

METHOD

The present corpus of research on Renewable Energy and Smart Grid Systems: A Pathway to Carbon-Neutral Communities is synthesised in this study using a Systematic Literature Review (SLR) technique. To guarantee openness, reproducibility, and rigour in the process of identifying, choosing, and synthesising literature, the approach adheres to the Preferred Reporting Items for Systematic Reviews criteria (Kamaluddin et al., 2025);(Graciafernandy & Ferdinand, 2024).

Inclusion and Exclusion Criteria

Before the screening procedure, a set of inclusion and exclusion criteria was devised to guarantee the quality and relevance of the literature evaluated. The following are the inclusion criteria: Articles published in 2018 or after are deemed appropriate for inclusion if they directly address Renewable Energy and Smart Grid Systems: The Road to Carbon Neutral Communities. On the other hand, research that did not meet these three requirements, such as conference proceedings, non-peer-reviewed sources, or papers that fell outside the designated time range or scope, was excluded from the final review. To ensure the coherence and scholarly significance of the literature base, this phase was crucial (Kamaluddin et al., 2025; Graciafernandy & Ferdinand, 2024).

Data Source And Search Strategy

The Scopus database, chosen for its comprehensive indexing of peer-reviewed papers in the social and environmental sciences, was utilised for the literature search. The keywords "Renewable Energy," "Smart Grid Systems," and "Carbon-Neutral Communities" were used in the search approach. Articles published between 2018 and 2025 were covered by this search.

Fifty items were found in the initial search. After that, sixteen duplicate records were eliminated. After the remaining 34 papers underwent title and abstract screening, 30 articles that did not align with the review's methodological or thematic emphasis were excluded. 24 papers that met the predetermined inclusion criteria were kept for final analysis following a full-text eligibility evaluation (Kamaluddin et al., 2025);(Graciafernandy & Ferdinand, 2024).

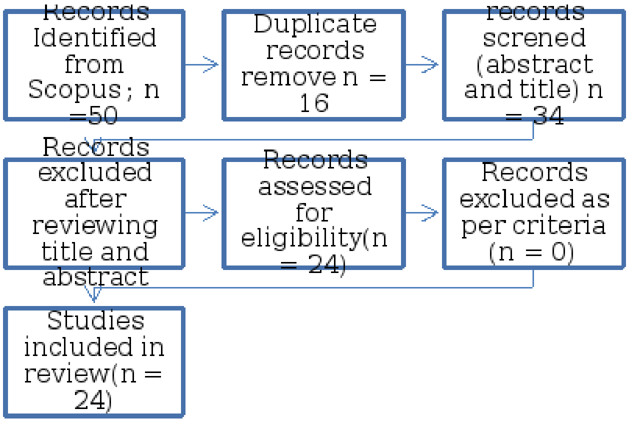

Figure 1 Article Selection Process

RESULT AND DISCUSSION

Twenty-four publications were identified as meeting the inclusion criteria and aligning with the study's aims following a methodical screening and synthesis process. Based on the year of publication, methodology, theory, limits, and principal conclusions, the publications were examined and grouped. Although there is a noticeable concentration in renewable energy, intelligent grid systems, carbon-neutral communities, and, in some cases, insufficient theoretical foundations, the distribution of research demonstrates a wide geographical and thematic variety.

Table 1. Summary Of SLR

Author & Year	Methodology	Theoritical	Limitations	Key Findings
(K. Zhou et al., 2019)	Review	Smart Grid Theory, Cyber-Physical Systems, Energy Management Theory	Focusing on technical aspects	Smart grids improve efficiency and load management
(Gupta et al., 2020)	Policy Analysis	Diffusion of Innovation Theory,	Does not discuss smart	High potential for RE, regulatory barriers

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Author & Year	Methodology	Theoritical	Limitations	Key Findings
		Renewable Adoption Theory	grid integration	
(Kim et al., 2018)	Review	Resilience Theory, Energy Security Theory	Not discussing the tourism sector	Decentralisation increases resilience
(Aghaei & Alizadeh, 2017)	Review	Demand Response Theory, Smart Grid Control Theory	Not discussing the tourism community	DR improves efficiency
(Wang et al., 2021)	Review global	Energy Transition Theory, Carbon Neutral Pathway Theory	Not specific to a region	RE + smart technologies effectively reduce emissions
(Wu et al., 2022)	Technical Study	Socio-Technical Systems Theory, Smart Community Theory	Focus on cities, not rural areas	IoT improves community energy efficiency
(Liu et al., 2019)	Review	Hybrid Energy Systems Theory, Renewable Optimisation Theory	Do not integrate the smart grid	Hybrid RE improves electrical stability
(Rahman et al., 2021)	SLR	Sustainable Tourism Theory, Green Energy Theory	Not discussing smart grids	RE supports sustainable destinations
(Almeida et al., 2020)	Review	Energy Storage Theory, Smart Grid Optimisation Theory	Not focused on Southeast Asia	Storage = the key to RE stability
(C. Chen et al., 2023)	Empirical Study	Carbon Neutrality Theory, Sustainable Tourism Theory	Not discussing ASEAN	Digitalisation & RE play a major role
(Nguyen et al., 2020)	Nasional Study	Renewable Adoption Theory, Energy Policy Theory	Do not integrate smart grids	Solar PV is growing rapidly
(Ming et al., 2022)	Technical Study	Smart City Theory, Socio-Technical Systems Theory	Not discussing rural areas	Smart grid succeeds in the city
(Lee et al., 2019)	Policy Study	Energy Policy Theory, Sustainability Governance Theory	Not discussing ASEAN local issues	Policies determine the success of transformation
(Han et al., 2021)	Case study	Community Energy Theory, Resilience Theory	Not discussing tourism	Microgrids improve resilience
(Zhang et al., 2023)	Technical study	IoT Systems Theory, Smart Grid Efficiency Theory	Technical focus	IoT → high efficiency
(Lim et al., 2020)	Policy review	Energy Policy Theory, Regional Integration Theory	Do not integrate the smart grid	ASEAN begins moving towards RE
(Cheng et al., 2019)	Review	Carbon Footprint Theory, Urban Sustainability Theory	City focus	Identification of emission components

Author & Year	Methodology	Theoritical	Limitations	Key Findings
(Fan et al., 2021)	SLR	Community-Based Energy Theory, Transition Theory	Not discussing smart grids	Key social factors for success
(Oliver et al., 2022)	Review	Digital Transformation Theory, Energy 4.0 Theory	Not discussing tourism	Digital tools accelerate RE
(Xu et al., 2023)	Regional analysis	Carbon Neutrality Theory, Energy Transition Theory	Not specific to tourism	RE + governance is important
(Teng et al., 2022)	Global study	Sustainable Tourism Theory, Green Energy Adoption Theory	Not discussing smart grids	Green the destination's energy → reduce emissions
(Ahmad et al., 2021)	Panel analysis	Smart Grid Theory, Energy Transition Theory	Lack of community focus	RE reduces emissions
(Kang et al., 2023)	Empirical	Energy Efficiency Theory, Technological Innovation Theory	Lack of smart grid integration	Efficiency = the key to carbon neutrality
(Smith et al., 2021)	Empirical	Climate Adaptation Theory, Renewable Transition Theory	No discussion of energy digitalisation	RE supports climate resilience

Distribution Of Literature By Year

The distribution of studies across time, as shown in Figure 2, shows irregular scholarly attention rather than a clear rising or declining trend. There were two publications for each of the following years: 2017, 2018, 2019, 2020, 2021, 2022, and 2023. Interest in renewable energy, intelligent grid systems, and carbon-neutral communities may occasionally rise. The most recent study included in this review was released in 2023, while the oldest was published in 2017. This irregular publishing pattern highlights the need for a better-planned, sustainable research agenda in the areas of carbon-neutral communities, innovative grid systems, and renewable energy.

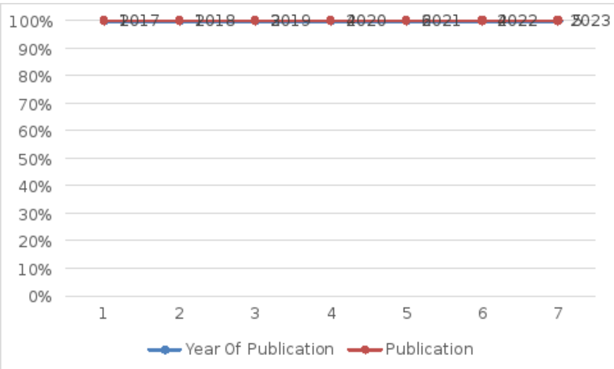

Figure 2. Distribution Of Literature By Year

Distribution Of Literature By Methodology

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Based on Figure 3, the most widely used methods for research studies on renewable energy, Smart Grid Systems, and Carbon-Neutral Communities are the review method with a total of 8 articles, 3 articles using the policy analysis method, 3 articles using the technical study method, and 3 articles using the empirical study method.

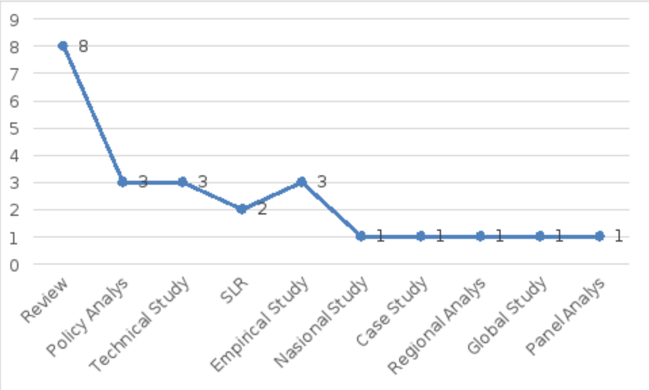

Figure 3. Distribution Of Methodology

Distribution Of Literature By Theoretical

Based on Figure 4, the most frequently used theories in research on renewable energy, Smart Grid Systems, and Carbon Neutral Communities are energy transition theory with a total of 10 articles, Smart Grid Theory with 6 articles, Diffusion theory with 5 articles, Socio Technology System with 2 articles, and Digital transportation with 1 article.

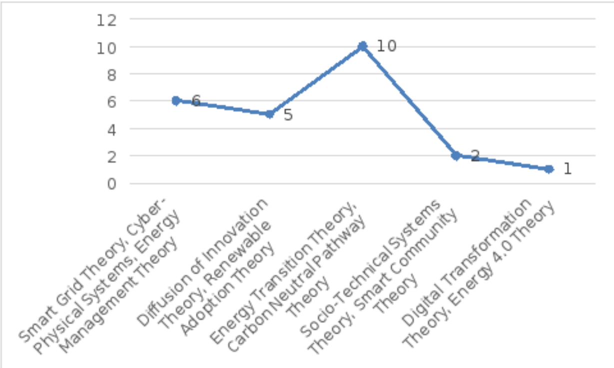

Figure 3. Distribution Of Methodology

Theory Used

Smart Grid Theory is used in this study since the primary goal of the research (Ahmad et al., 2021; Zhang et al., 2023; K. Zhou et al., 2019)Zhou 2019 is to modernise the electrical system, which calls for a theoretical framework that describes how digital technology, electricity systems, automated Control, and energy management are integrated. Smart grid theory provides an analytical foundation for comprehending IoT, sensors, demand response, and renewable energy integration, serving as the fundamental element of these investigations. The factors that are the subject of this article, efficiency, stability, load management, and dependability of the system, are best evaluated using this theory.

Diffusion and Innovation Theory (DIT) is the most well-established theory explaining why an innovation (such as solar panels) is adopted or rejected by society, and it is employed in this research (Gupta et al., 2020) because it examines the adoption of renewable energy in Southeast Asia. When examining the dissemination of new technologies, adoption factors such as relative benefit, compatibility, complexity, and observability are relevant. Due to the diverse socio-cultural dynamics across ASEAN, IDT may be used to observe variations in adoption rates across nations**.**

The research (Han et al., 2021; Kim et al., 2018) utilises Resilience Theory and Energy Security Theory to examine how resilient energy systems respond to shocks (such as weather, load changes, and disasters). The resilience theory charts the system's capacity to endure, adapt, and recover from shocks. The primary focus of the study is decentralised energy (microgrids), which necessitates a theoretical framework that prioritises stability, adaptability, and resilience.

This study (Aghaei & Alizadeh, 2017) employed demand response theory to manage power demand in a smart grid. Demand response theory explains how customers adjust their power usage patterns in response to price signals or peak loads. Due to its technical complexity and specificity, this theory is best suited for studies examining dynamic load regulation.

In their studies (Fan et al., 2021; Wang et al., 2021; Xu et al., 2023), the authors apply the Energy Transition Theory. This study examines the switch from fossil fuels to renewable energy sources. A worldwide theory that describes this transition process is the Energy Transition Theory (MLP). Three layers are combined in the MLP: Regime (current energy structures), Landscape (global pressures, such as climate change and net-zero objectives), and Niche (innovations, like smart grids). This theory is applied in this study because it discusses energy transition paths at the national or regional level.

The research by Ming et al. (2022) and Wu et al. (2022) utilises socio-technical systems theory, as the integration of digital technology and renewable energy is a socio-technical phenomenon rather than a purely technical one. According to STS, actors, institutions, culture, laws, and infrastructure all play a part in a technology's success. This study examines digital innovation, smart cities, and energy communities, all of which align well with the STS paradigm.

CONCLUSION

According to the study's findings, the key to achieving a sustainable energy transition in Southeast Asia lies in combining renewable energy, intelligent grid systems, and the creation of carbon-neutral communities. The study found that Smart Grid Theory is the most applicable and popular theoretical framework for describing the modernisation of energy systems in the digital age, as determined through a Systematic Literature Review (SLR) of 24 Scopus-indexed works. In addition to supporting the integration of renewable energy sources, such as solar, wind, and hydro, smart grids have been shown to increase energy efficiency, improve load management, and enhance network stability. The use of IoT, sensors, and digital automation is a crucial component in enhancing energy security in various areas, according to findings from several studies.

Energy Transition Theory and the Multi-Level Perspective (MLP) approach form the primary basis of global research on the transition from fossil-based energy systems to clean energy. This theory is particularly relevant in Southeast Asia, which remains highly dependent on fossil fuels but faces international pressure to achieve Net Zero Emissions targets. The literature suggests that landscape factors (global pressure), socio-technical regimes (including infrastructure and policies), and niche innovations (such as renewable and smart grids) influence the dynamics of energy system change in the region.

The unequal adoption of smart grids and renewable energy across nations can be explained by the Diffusion of Innovation Theory (IDT). Relative advantage, compatibility, complexity, trialability, and observability are key elements that influence adoption success. Research indicates that nations with excellent digital infrastructure, regulatory support, and strong cultural alignment with technological innovation typically adopt low-carbon energy systems more quickly.

According to Socio-Technical Systems (STS) Theory, government policies, community behaviour, local infrastructure preparation, institutions, and cultural values are all social elements that contribute to the success of integrating renewable energy. The body of research suggests that institutional actors and communities have a substantial impact on the pace of the energy transition.

The STS findings generally indicate that integrating digital transformation, smart grids, and renewable energy has been successful in reducing carbon emissions, enhancing energy resilience, and accelerating the achievement of carbon-neutrality goals. The majority of research, however, still has shortcomings, such as the dearth of studies that concentrate on rural regions, tourist communities, and the unique setting of Southeast Asia.
Provide a review.

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