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Review

A Multi-Level Perspective on Transition to Renewable Energy in the Indonesian Transport Sector

Ferry Fathoni [1,2], Jon C. Lovett [1,*] and Muhammad Mufti Rifansha [3]

[1] School of Geography, Faculty of Environment, University of Leeds, Leeds LS2 9JT, UK; gyff@leeds.ac.uk
[2] PT Pertamina (Persero), Jakarta 10110, Indonesia
[3] Department of Mechanical Engineering, Institut Teknologi Bandung, Bandung 40132, Indonesia; 13123170@mahasiswa.itb.ac.id
* Correspondence: j.lovett@leeds.ac.uk

Abstract

A transition from fossil fuels to renewable energy is underway to achieve net-zero emissions. The institutional arrangements in Indonesia's energy transportation sector are crucial for various stakeholders involved in the energy transition. This study combines historical institutionalism with a multi-level perspective to analyze how policy formulation, critical junctures, and path dependence shape institutional changes toward sustainable mobility. The evolution of institutional arrangements can be categorized into three phases: the establishment of fuel-oil-based infrastructure and dependency (1970–2003); the diversification of cleaner fuels through compressed natural gas and biofuels (2004–2014); and the development of affordable and clean energy, focusing on biofuels and electrification (2015 to present). In parallel, a quantitative total cost of ownership analysis of vehicles using different fuel types demonstrates how institutional reforms, fiscal incentives, and regulatory support reshape the economic feasibility of low-carbon technologies. Landscape pressures—such as global decarbonization, fuel import dependence, and energy security challenges—interact with niche innovations, including biofuels, electric vehicles, and hybrid systems, to drive systemic transformation. The findings indicate that institutional changes, supported by quantitative economic evidence and technology diffusion, play a pivotal role in realigning Indonesia's transport energy regime toward a more resilient, inclusive, and sustainable transition.

Keywords: transportation energy; net-zero transition; sustainable development; path dependence; institutional change

Academic Editor: Piotr Borowski

Received: 17 September 2025
Revised: 13 October 2025
Accepted: 22 October 2025
Published: 30 October 2025

Citation: Fathoni, F.; Lovett, J.C.; Rifansha, M.M. A Multi-Level Perspective on Transition to Renewable Energy in the Indonesian Transport Sector. *Energies* **2025**, *18*, 5723. https://doi.org/10.3390/en18215723

1. Introduction

The goal of reaching net-zero emissions has been the main spotlight of climate policy nowadays [1]. The net-zero concept emphasizes maintaining global emissions within certain limits; thus, excess emissions must be captured and removed through either natural or technological reservoirs [2]. To achieve the ambitious target of net-zero emissions, international cooperation is very important. Common problems such as global warming, climate change, and achieving net-zero emissions will require comprehensive solutions [3]. Nevertheless, national governments are responsible for deciding on how to commit to global agreements on emissions reduction and how to integrate these global standards into their policies and laws. They have the authority to shape institutions and actors within their borders through the laws and regulations they enforce [4].

The development of institutions and the formulation of policies are shaped by a series of events that occur over time. Many studies on the history of institutional development emphasize the significance of "path dependence" in understanding the background for forming institutions and organizational actors. Path dependence refers to formulated and implemented decisions dependent on previous decisions or experiences. Institutions and actors are formed by "lock-in" experiences that lead to positive feedback or increasing returns for adopting pre-selected technologies, which affect political and social decision-making behavior [5–8]. Political and social behavior play a significant role in policymaking for indigenous cultures, as they provide the necessary insight into the specific challenges these cultures encounter [9–11].

This study aims to contribute to an understanding of the HI processes that govern energy transition in the Indonesian transport sector. The MLP framework has been used to examine changes in the socio-technical landscape, triggered by multi-level and cross-border actors, both global and local, as well as niche innovations involved in formulating regime policies related to the sustainable development of affordable and clean energy. This study emphasizes key events, referred to as exogenous shocks, which serve as critical junctures that alter institutions and create path-dependent processes. Additionally, it explores endogenous factors that contribute to gradual changes and the establishment of institutional stability.

This study examines the impact of the global agenda, technology advancement, the orientation of transportation infrastructure development, and national environmental policies on the transition to net-zero emissions (NZE). The energy sector for transportation in Indonesia presents an intriguing case study due to its supply chain's intersection with global politics and trade [12], the adoption of eco-friendly technologies [13], and the issue of the threat to the preservation of the environment [14]. We view TCO 2025 as a key indicator of institutional arrangements rather than a primary driver of change. Its significance lies in the impact of underlying policy and governance choices related to pricing, taxes, incentives, infrastructure, and risks [15,16]. This research uses Indonesia as a case study to address the following research question: How do institutional legacies influence energy transitions? How do niche innovations disrupt or align with socio-technical regimes? What multi-level interactions drive or hinder institutional change toward sustainability in Indonesia's transportation sector? Indonesia is the largest archipelagic country in Southeast Asia and presents a significant case study due to its challenges in the transportation sector. The country's high reliance on fossil fuels, particularly imported fuels, makes transportation a major contributor to national energy consumption and carbon emissions. However, Indonesia also has vast potential for renewable energy, alongside a large transportation market, positioning it strategically to drive the transition to sustainable energy in the region.

2. Literature Review

2.1. Historical Institutionalism Approach

Historical institutionalism (HI) analyzes a series of historical events arranged chronologically and elucidates the impacts of the instances when important institutional changes occur and create new pathways for historical development as critical junctures. Institutional development usually occurs gradually in the period between critical junctures and is influenced by path dependence and the "lock-in" effect [6]. In HI, the "lock-in" effect refers to a situation where previous institutional choices limit current and future policy options, even when those earlier choices are no longer the best or most efficient. This lock-in occurs due to path-dependence, where initial decisions or developments create self-reinforcing mechanisms that make it increasingly challenging to implement change over time [17].

HI has been used extensively for analyses related to institutions across national–global borders by combining several political, economic, social, and technological contexts. The HI approach considers the factors of ideas, individual behavior, and structural influences that interact within an institution based on a series of events over a certain period of time [18]. HI does not only test institutions or processes at any single time because institutions, as a complex set, change over time. HI theory offers a framework with three essential characteristics, namely, the substantive agenda, arguments based on time sequences, and comprehensive emphasis [10]. First, HI focuses its questions on substantive matters that attract broad public and research interest. Second, HI explores transformations and processes of various scales based on time. Third, HI combines the impact of institutions and processes over a period rather than just at one time of testing, emphasizing macro-context analysis [10].

Public policymaking as a change in the institutionalization process varies in each case. In the context of HI, these variations are influenced by path-dependence, which asserts that the timing and sequence of events are crucial; numerous social outcomes are possible; and even minor, unpredictable events can lead to significant consequences. Additionally, reversing a course of action can often be very difficult, if not impossible, regardless of the consequences. Consequently, critical junctures play a significant role in political development and shape the broader framework of social life [19].

Path dependence influences political phenomena where the inheritance of past experiences “locks in” and limits the choices available to the formation of institutions and actors [20]. This institutional policy inheritance was originally a solution to past institutional problems. However, because it provides many benefits, the dominant actor tries to maintain institutional stability by maintaining the policy [19]. HI approaches institutional stability over a long period of time, creating a dichotomy related to institutional change. On the one hand, institutional change is slow, gradual, and takes place in a limited scope [20] but remains transformative [21,22]. Under other conditions, a radical exogenous shock at the “critical juncture” can change equilibrium and create new arrangements [23].

The HI approach examines the process of institutional change, which is often characterized by opposing dichotomies [24]. The previous institutional legacy consisted of long-standing policies aimed at addressing a specific issue, driven by the benefits obtained by the dominant actor [8,19,25]. This longevity of the policy led to institutional stability, resulting in endogenous institutional change. Endogenous institutional change arises from internal institutional processes that are slow, gradual, and transformative within the existing institutional framework [21,22].

On the other hand, dynamic institutional change can be triggered by external sources affecting the institution, known as exogenous shocks [24]. An exogenous radical shock [8] that occurs at a critical point [26] can disrupt the balance and lead to new institutional arrangements. HI elucidates the mechanisms of institutional inventions through displacement, replacing old rules with new rules, and layering, which occurs when new rules are placed above or next to existing regulations [27]. Repeated interactions can affect equilibrium, and if they continue, they will affect institutional stability [28]. Historical institutionalism also analyzes the comparison of cross-national public policies as a result of national political institutions [18]. Historical institutionalism is a complement to sociological institutionalism or socio-technical analysis in energy transition studies [29] toward the sustainability of national energy security.

In the context of Southeast Asia, transportation policies are entrenched in long-standing institutional arrangements. These include the dominance of state-owned enterprises (SOEs), centralized governance structures, and subsidy regimes [30–32]. For instance, Indonesia’s historical reliance on fossil fuel subsidies has entrenched petroleum-based transportation, which has impeded the diffusion of more sustainable alternative fuels [30]. The historical institutionalism approach has allowed scholars to examine how institutional embeddedness interacts with emerging niche innovations, particularly in the fields of biofuels and electric vehicles (EVs) in Indonesia [4,30]. This interaction significantly shapes the pace and direction of socio-technical transitions [33].

2.2. Multi-Level Perspective Framework

Recent research has utilized the multi-level perspective (MLP) framework to investigate socio-technical transitions in the energy transition toward sustainability [34,35]. MLP analyzes evolutions in socio-technical systems by examining interaction at three levels: niche, regime, and landscape. The first level involves radical technological advancements in micro-level niches, which act as precursors to a sustainable transition. These micro-niches are where novel innovations and inventions occur.

Radical novel innovations at the niche level often encounter resistance from established socio-technical systems at the second level, which can hinder energy transition. The meso-level encompasses established regulations, institutions, and technologies that shape "socio-technical regimes". The literature highlights that socio-technical regimes experience various "lock-in" mechanisms that impede change due to the entrenchment of existing structures, interests, and stability [34,36]. The energy transition in emerging economies suffers from financial and technological lock-ins due to reliance on fossil fuel infrastructure, reinforcing the existing regime [17,37]. Furthermore, political and institutional lock-ins stemming from regulatory bias toward conventional industries and the lobbying of dominant actors have preserved the status quo and hindered the emergence of radical innovation [38]. The third level of analysis is the socio-technical landscape, which represents the broader external environment that influences socio-technical systems. Interactions at this macro-level create trends and pressures affecting innovation and transitions within regimes and niches. This landscape can cause sudden shocks and gradual changes in macroeconomic or macro-cultural aspects [39].

In the first phase, radical innovations of cleaner energy emerge in small niches at the periphery of the existing system. These innovations mature through a process of experimentation. These radical innovations establish themselves in one or more market niches in the second phase. As they become more stable, they converge into a dominant design and become institutionalized. However, niche innovations often struggle against an entrenched system locked in by a path that is dependent on fossil fuels [34].

In the third phase, the green innovations diffuse into the mainstream market and compete directly with the existing fossil fuel system. Landscape pressures challenge the regime, creating cracks and destabilization. When regime actors can no longer ignore or suppress these niche innovations, windows of opportunity open. In the fourth phase, if the green innovations are mature enough, they can break through and replace or transform the regime, leading to a systemic socio-technical transition [34].

The diffusion of niche innovations, including biofuel blends, EVs, and compressed natural gas (CNG), is gaining traction in emerging markets such as Indonesia, Thailand, and India, primarily driven by state policies and subsidy schemes [40–42]. However, they encounter challenges from well-established regimes focused on private vehicle ownership, road-centered infrastructure, and entrenched oil interests. Meanwhile, broader landscape pressures, primarily climate action and urban congestion, create a window of opportunities to scale these niche innovations and challenge existing regimes [40,41].

3. Materials and Methods

This study utilizes a qualitative method that employs HI and the MLP as analytical frameworks to examine Indonesia's energy transition toward sustainability in the transportation sector. These frameworks allow for a multi-dimensional analysis of institutional inertia, policy evolution, and socio-technical dynamics across different levels of actors over historical periods [43]. The HI approach identifies critical junctures by selecting factors determining crucial decision-making processes in Indonesia's energy transition policy, the net-zero transition [44].

Meanwhile, the MLP offers a robust analytical framework for examining interactions across three levels: landscape, regime, and niche [34]. Through MLP utilization, this study investigates how innovations emerge at the niche level and subsequently compete with existing transport energy regimes in Indonesia. Furthermore, the MLP framework evaluates the pressures from the socio-technical landscape, enabling eco-friendly fuel innovations to ultimately take advantage of "windows of opportunity" to transform the current energy regime [45].

Moreover, the integration between HI and the MLP provides an understanding of the long-term investment decisions that underpin energy sustainability policies, which are heavily influenced by institutional arrangements within a country [44]. Furthermore, HI and the MLP broaden the perspective to examine domestic institutional affairs through the lens of international relations [46]. This analysis covers the period from 1970 to 2025, with a focus on the 2015-to-2025 period and considering both the external factors of global socio-technical landscape dynamics, as well as the internal influence of the socio-technical landscape and the diffusion of niche innovations.

3.1. Data Collection

This study uses both primary data and secondary data. The primary data were collected to cross-check secondary data and explore institutional developments. This study utilized semi-structured interviews to gather primary data from twenty-eight actors representing various stakeholders associated with the energy transportation sector. The selection of these actors uses purposive sampling to capture representative key persons, not dominated by certain groups, and covers a broader range of institutions related to the transportation energy sector. These stakeholders consist of the government, energy companies, automotive manufacturers, transport providers, global institutions, energy associations, members of the public involved with transportation, NGOs, the standardization bureau, newspapers, and academics. Semi-structured interviews were conducted to explore several themes. These included the roles and involvement of stakeholders in developing institutions for energy transition, the impact of landscape-level factors on national energy policies, and the interactions between niche actors and existing regimes in the collaborative innovation of emerging AVF technologies. File S1 in Supplementary Materials displays the semi-structured interview format used in this study.

This study utilized stratified snowball sampling to ensure adequate representation of diverse stakeholders involved in Indonesia's transportation energy transition. Potential participants were approached through email, telephone, and LinkedIn. They were given one week to respond to the invitation to participate or to decline. Response times ranged from two days to three weeks after receiving the invitation. During the COVID-19 pandemic, interviews were conducted online using the MTeams, Zoom, or WhatsApp platforms. Online interviews were conducted from August 2020 to May 2023.

This study used secondary data collected from various sources, especially the Indonesian energy sector, for transportation regulations from 1970 until 2025, with a focus on the 2015-to-2025 period, international rules, global agendas, and technological advancement related to the concept of the sustainability of energy supply for transportation. Data were also collected from documents of international organizations on their websites, scientific publications, historical books, news articles on media websites, newspapers that contain historical developments, and multi-level actors' interactions in institutional arrangements in the energy sector relating to Indonesia's transportation sector. This study also gathered secondary data from quantitative analyses of survey results published in academic journals, institutional press releases, and newspapers. The quantitative analysis focuses specifically on public preferences regarding the adoption of EVs, including both the vehicles themselves and the supporting infrastructure, as part of Indonesia's emerging low-carbon technology initiative.

3.2. Analysis

The data analysis in this study has emphasized examining the HI characteristics and MLP framework of transport energy policy and explaining path dependencies, key events at critical points, and contingencies in energy sector institutional formulation and implementation. We also analyze the types of changes that occur and determine sources of the dominant change factors, for example, whether they originate from an exogenous global agenda or endogenous national environmental policies.

Interviews explored various statements from the participants regarding the institutional dynamics of energy for transportation, primarily focusing on Indonesia's mass public transportation, biofuels, and electrification as case studies. The documentation process for stakeholder responses was recorded using a digital voice recorder, and the transcript was processed using NVivo. NVivo enabled effective tracking of themes across interview transcripts and indicated when data saturation was achieved, signifying that no new themes emerged. This study follows four steps secondary data analysis methods: defining research topics and questions; identifying sources of data/information; gathering existing data; and structuring analysis and presentation of findings [47,48].

This study uses secondary data analysis methods to define research problems with the aim of new research related to energy transportation institution sustainability in Indonesia, which is different from previous research [49]. Secondary data research can utilize existing data to generate new ideas [50]. Secondary data analysis is a systematic research strategy utilizing the abundance of existing quantitative and qualitative data [49,51]. The secondary data analysis method also explores data from several different points of view [52].

This study examines the TCO to outline vehicle ownership costs across various technologies. The TCO comprises the purchase price, operational costs, maintenance, taxes, insurance, and resale value. It is vital for comparing ICEVs, HEVs, BEVs, and FCVs in consumer decisions and sustainable policies. Previous research shows that the TCO better reflects the competitiveness of new technologies, such as EVs, and is influenced by battery price declines, usage patterns, and energy price variations [53–55].

TCO calculation in this study uses the net present value (NPV) approach, based on the following formula:

$$TCO = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} - \frac{RV_n}{(1+r)^n} \quad (1)$$

In this formula, C_t represents the total cost in year t, which includes fuel or energy costs, maintenance, taxes, insurance, administrative expenses, and battery replacement if applicable. The variable r denotes the discount rate, n is the analysis period (10 years), and RV_n indicates the resale value at the end of year n.

To facilitate comparison between vehicles with different annual mileages, the TCO results are normalized accordingly.

$$TCO_{/\text{km}} = \frac{TCO}{Annual\ Mileage \times n} \quad (2)$$

We used data triangulation to cross-validate our interview findings by comparing them with secondary data sources. This approach helps ensure accuracy and minimizes biases from both the researcher and participants. Previous studies have shown that using data triangulation enhances the reliability and credibility of qualitative research [56].

Qualitative analysis was carried out using content analysis on historical records related to international and national regulations, policies, global agreements, and events on the energy transition that affect transportation energy sustainable development in Indonesia. Critical junctures were identified, such as radical innovation of the sustainability concept in the context of global institutions and adoption into national policies or the constitution. Content analysis was also used to identify policies of institutions and global actors in the form of campaigns, prohibitions, boycotts, and technological advancements related to transportation energy to observe their interactions with the institutional development of the transition toward sustainable transportation energy. Socio-technical evolutions at multiple levels, including the micro-niche, meso-regime, and macro-landscape levels, such as shifts in energy, were also examined, and a time series of related key events was constructed. The validity of the analysis of the secondary data was verified using triangulation with the results of the primary data analysis of interview transcripts.

This research is not without limitations. The authors were unable to interview certain high-level government officials due to access barriers, which limited their understanding of the bargaining process at the elite level [57]. Responses from stakeholders like SOEs and large multinational corporations may align with official discourses, which can introduce bias. Documentary sources show mixed trends: corporate reports often present sustainability strategies in ideal perspectives, while NGOs focus on critical viewpoints. This study required careful triangulation of various data sources [58,59]. This research only covers developments up to early 2025, so findings may quickly become outdated due to policy changes or advancements in second-generation biofuels, EVs, and FCVs [36,60,61]. One of the authors, currently working in Indonesia's energy sector, might also introduce bias. To address this, the authors practiced reflexivity and discussed the findings periodically with all team members to ensure objectivity [62,63]. While these limitations are important, they do not invalidate the findings. Nevertheless, they should be taken into consideration when interpreting the study's conclusions.

4. Results

After Indonesia gained independence in 1945, Soekarno, the first president, implemented a nationalist strategy by nationalizing Dutch colonial institutions to manage natural resources. During this period, coal served as the primary energy source for transportation [64]. The energy transition of railways occurred with a switch to diesel power throughout the 1940s and 1950s, particularly in the US and Europe. Dieselization in Asia started in the 1950s, initiated by Japan. Diesel locomotives have been Indonesia's primary train movers since 1952. [65,66]. In response to the growing demand for petroleum, the government established a management institution in 1950. Indonesia joined the Organization of the Petroleum Exporting Countries (OPEC) in 1962 as a petroleum-producing nation. In 1968, Soeharto became Indonesia's second president, facing economic challenges from the failure of Soekarno's Guided Economy and longstanding defense and territorial issues. Figure 1 illustrates a schematic representation of the historical institutional evolution of energy transition within Indonesia's transportation sector. Landscape dynamics are represented in orange boxes, while the diffusion of niche innovations is illustrated in green boxes. Institutional dynamics are shown in blue boxes. Dashed line arrows indicate the creation of windows of opportunity.

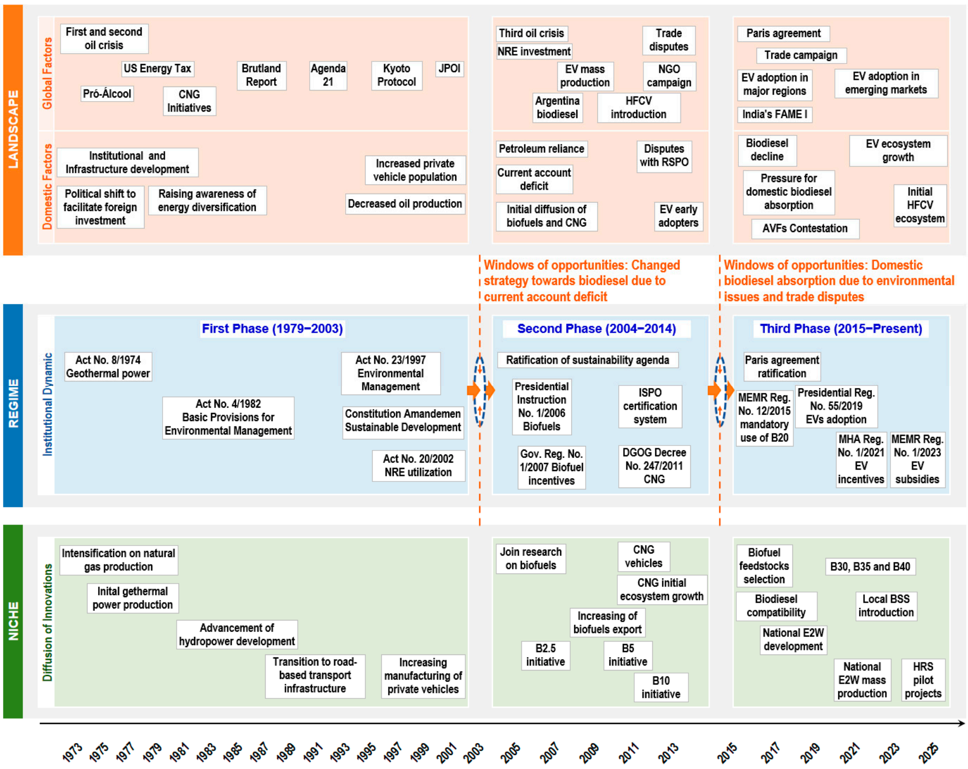

Figure 1. The national and global influences on Indonesian transportation energy sustainability institutional arrangements. Source: Authors.

4.1. Socio-Technical Landscape Dynamics

In the 1970s, Soeharto shifted away from Soekarno's nationalistic approaches by opening the economy to foreign investment. The government emphasized exploiting natural resources, particularly oil production and exports, to support economic recovery and infrastructure development [67]. Meanwhile, in the global sphere, the Organization of Arab Petroleum Exporting Countries imposed an oil embargo in 1973, which led to a massive oil crisis. A second crisis occurred in 1979 due to reduced oil production during the Iranian Revolution. These oil crises prompted many countries, including Indonesia, to seek alternative energy sources [68].

Several countries have developed biofuels as alternative vehicle fuels (AVFs). While biofuels have been used since the early 1900s, significant expansion began with Brazil's Pró-Álcool Program in 1975, which focused on sugarcane-based ethanol. This initiative, led by the Institute of Alcohol and Sugar (IAA), saw the launch of alcohol-fueled cars in 1978 [45,69]. The Energy Tax Act of 1978 initiated the development of ethanol in the US by requiring vehicle fuel to contain 10% ethanol (E10). Following the 2000s, implementing the Renewable Fuel Standard (RFS), subsidies, and the increased use of corn as feedstock significantly boosted ethanol production [70].

Since the 1980s, fuel diversification has involved using CNG as a low-emission AVF for public transportation, trucks, and taxis. Countries such as Iran, Pakistan, Argentina, Brazil, and China have widely adopted CNG vehicles. Strong government policies have supported the expansion of CNG refueling stations in these countries [71].

Concerns about environmental preservation began to gain global attention in the 1980s. The World Conservation Strategy has promoted "sustainable development" to protect the Earth's natural resources. This essential vision aims to stem practices that harm the environment, leading to significant effects on a global scale. Ongoing discussions on Global Sustainable Development have resulted in several key agreements, including the 1987 Brundtland Report, the 1992 Agenda 21, the 1997 Kyoto Protocol, and the 2002 Johannesburg Plan of Implementation (JPOI) [72].

From 1980 to the late 1990s, infrastructure development significantly improved Indonesia's economy and citizens' welfare. However, this development prioritized road infrastructure, without adequate planning for mass public transport, increasing private vehicle usage. This situation deteriorated further as declining oil production and increasing fuel consumption compelled the government to allocate more funds for subsidies [73].

The third oil crisis occurred between 2003 and 2008 due to a surge in global demand, the war in Iraq, and limited reserve production capacity. This oil crisis surged oil prices, causing the cost of fuel subsidies to rise from USD 4.4 billion to USD 7.4 billion [74]. The 2000s oil crisis has raised concerns about energy security, prompting European and Asian countries to include energy policies in their economic strategies. Many developed nations focused on reducing their reliance on oil and investing more in the innovation of renewable energy sources.

The diversification of AVF has included the development of biodiesel, which was institutionalized by the Argentine government through Biofuel Law 26.093 in 2006. This regulation mandates a 5% biodiesel blend (B5) in diesel fuel, with plans for future increases. Argentina's biodiesel production has rapidly grown, especially following the EU market's opening under the Renewable Energy Directive in 2009 [45].

The diffusion of biofuels has expanded to include countries in Southeast Asia. The Philippines has promoted domestic production to reduce crude oil imports by implementing a sugarcane-based E20 strategy. As the world's largest producer of coconuts, the Philippine government has also introduced B5 biodiesel derived from palm oil. In contrast, Thailand has diversified its feedstock using sugarcane and cassava to produce ethanol. The Thai government has widely adopted E20 and E85 ethanol blends for gasoline-fueled vehicles and B20, a palm oil-based blend, for heavy-duty vehicles [31,75].

Simultaneously with the re-emergence of biofuels following concerns about climate change and energy security, the world has seen the rebirth of EVs. Significant advancements in lithium-ion battery technology and government subsidies have driven China's transition to EVs since the 2000s [76,77]. Several developed countries, such as Germany and the United States, have pursued electrification for the energy transition. In 2004, Germany updated its vehicle tax system to reduce taxes on low-emission vehicles, including hybrid electric vehicles (HEVs), based on CO_2 emissions. The U.S. introduced the Energy Policy Act of 2005, which provides advanced vehicle credits for HEVs. The global trend toward EVs was propagated by the mass production of the Tesla Roadster in 2008 and the Nissan Leaf in 2010. With strong regulatory support and subsidies, the adoption of EVs rapidly spread across the EU, US, Japan, and South Korea during the 2010s [78].

Meanwhile, some countries in Latin America, Asia, and Africa have seen limited transition to EVs, as many emerging economies still face significant challenges, particularly high upfront purchase costs, and insufficient charging infrastructure. As an emerging economy, India launched the FAME I program in 2015 to offer subsidies for HEVs and battery electric vehicles (BEVs) based on battery capacity and vehicle efficiency. This program was replaced by FAME II in 2019, which focused primarily on transitioning to battery electric vehicles (BEVs). Thailand has led Southeast Asia in promoting HEVs. From 2007 to 2017, the country offered a lower tax of 10–15% on HEVs based on CO_2 emissions, while ICEVs faced higher rates of 20–30%. In 2015, the Eco Car Program Phase II included HEVs as low-emission vehicles. Starting in 2017, the focus shifted to BEVs and plug-in hybrid electric vehicles (PHEVs), with EV Roadmap 2030 aiming for 30% of car production to be electric [78].

Another AVF that has recently emerged is the hydrogen fuel cell vehicle (FCV). FCVs have evolved from laboratory concepts to commercial markets over the past sixty years. Initially used in NASA's 1960s space program, FCVs saw automotive applications in the 1990s with demonstration buses and prototype cars [79,80]. The 2010s marked the commercial launch of limited-production models like the Toyota Mirai and Honda Clarity [61,80]. However, global adoption of FCVs remains low and has not met deployment targets in early-adopter markets such as Japan, South Korea, and California [81]. The mass production of FCVs faces key barriers, including high costs, limited refueling infrastructure, and policies that favor EVs [60,61].

The recent literature emphasizes the shift in FCV innovations from passenger cars to heavy-duty transportation, where their range and rapid refueling offer significant advantages [60]. As battery and fuel cell costs decrease, their use in freight applications is expected to grow beyond 2030 [82]. Hydrogen refueling stations (HRSs) require intensive investments and are reliant on usage rates, worsening the chicken-and-egg dilemma [81]. Innovations are also focused on reducing reliance on platinum and enhancing durability with non-precious catalysts [61,80].

Climate change is a critical global issue that the Kyoto Protocol was not able to address effectively, primarily because it did not fully include developing nations due to the principle of differentiated responsibilities, resulting in the rejection of the protocol by the United States of America in the Byrd–Hagel Resolution. In response to this limitation and ongoing negotiations at the UNFCCC, the Paris Agreement was adopted at COP21 in Paris in 2015 with a goal to keep global temperature increases below 2 °C, with a target of limiting the rise to 1.5 °C above pre-industrial levels. It focuses on Nationally Determined Contributions (NDCs) and aims for carbon neutrality by the mid-century [2].

A reliance on fossil fuel-based routes has marked the landscape of Indonesia's energy transportation sector since 2000. In 2024, the transport sector contributed 36.11% to Indonesia's final energy consumption, making it the second-largest sector after industry at 45.94% [83]. The crude oil and oil products were the final energy consumption sources, totaling 507.76 million BOE out of 1292.34 million BOE, or 39.29% of the total consumption [83]. This fossil fuel path dependence has been triggered by the development of highway capacity and mass public vehicles, which have struggled to keep pace with the rapid growth of private vehicle ownership. At the same time, the global pressure for decarbonization highlights the necessity for low-emission transportation systems. However, these systems still face significant challenges related to infrastructure, technology, and societal habits.

4.2. Socio-Technical Regime Evolvement

Transportation is an energy-intensive sector in emerging economies, including Indonesia. Niche innovations and landscape dynamics have shaped the institutional dynamics of the energy transition. The evolution of the energy regime has gone through several policies and institutional changes, which are divided into three phases, as follows:

1. First phase: Development of energy institutions and infrastructure that fostered dependence on fuel oil (1970–2003).
2. Second phase: Encouragement of energy diversification through cleaner fuels, especially natural gas and biofuels (2004–2014).
3. Third phase: Development of affordable and clean energy, focusing on biofuels and electrification (2015 to present).

4.2.1. First Phase: Development of Energy Institutions and Infrastructure That Fostered Dependence on Fuel Oil (1970–2003)

During the first phase, the government focused on boosting economic growth and infrastructure development by leveraging crude oil production and export. The Soeharto administration enacted Law No. 8 of 1971, which designated Pertamina as the sole SOE responsible for managing the upstream and downstream oil and gas sectors [84].

The government has been exploring alternative energy sources to fossil oil, particularly natural gas. This exploration has drawn foreign investment through a production-sharing contract with Pertamina. In 1971, Mobil Oil Indonesia discovered natural gas fields in Arun and Lho Shukun, located in North Aceh. In 1972, Huffco Inc. discovered a second natural gas field, Badak, in Bontang, East Kalimantan [85].

The first and second oil crises were critical junctures that prompted the government to diversify energy sources beyond petroleum. During this phase, the diversification of renewable energy sources focused mainly on hydropower and geothermal energy in the electricity generation sector. Geothermal energy development has been formalized through several key policies: Presidential Decree No. 64/1971, Act No. 8/1974, and Presidential Decree No. 16/1974. These policies designated Pertamina to survey, explore, and exploit geothermal resources for electricity production. The operation of Kamojang Geothermal Power Plant Unit 1, with a capacity of 250 kW, in 1983 marked the beginning of the geothermal era in Indonesia. The government deregulated the sector to encourage geothermal development further and invited foreign investment through Presidential Decree No. 49/1991 [86].

During the Soeharto regime, especially in the 1980s and 1990s, there was a significant shift in the development of public transportation infrastructure from rail-based systems to road-focused construction. This transition to road-based transportation coincided with the growth of private car manufacturing. Policy changes prioritizing road transportation and private vehicles have led to "institutional lock-in" to petroleum dependency. As a result, the government's shift in focus promoted the use of private vehicles, as highlighted by Respondent 10:

> *"The development during the Soeharto administration [was intensive]. As we began building infrastructure, we were introduced to personal vehicle technology. . . We recognized the importance of mobility, . . .but we became accustomed to relying on private cars. At that time, many of our graduates were influenced by the US, where the use of private vehicles was predominant." (Respondent 10, Academic).*

Our findings align with secondary sources, indicating a drastic increase in private vehicles compared to public transportation, such as buses. The number of motorcycles saw the most dramatic surge, from 2.67 million units in 1980 to a staggering 120.10 million units in 2018. There was a significant increase in passenger cars, from 639,464 units in 1980 to 16.44 million units in 2018. In contrast, buses experienced the slowest growth, from 86,284 units in 1980 to 2.54 million units in 2018 [87]. The unbalanced growth in private vehicle ownership, inadequate public mass transportation, and the growth in road capacity have created a pressing issue of congestion in urban areas [73]. Congestion greatly reduces environmental quality due to air and noise pollution. The congestion also reduces the efficiency of energy use in the transportation sector.

The substantial increases in fuel consumption, which began in the late 1980s, are a cause for concern. In 1987, fuel consumption was 0.493 MBPD, and it increased at an average rate of 4.53% to 1.72 MBPD in 2013. Along with the decline in Indonesian crude oil production, the government has been forced to import fuel oil to meet domestic needs. In 2004, Indonesia became a net importer of oil as consumption surpassed production [73].

To mitigate the adverse environmental effects of transport energy consumption, the government has taken a proactive approach. It passed Act No. 4/1982 on Basic Provisions for Environmental Management and enforced Road Traffic and Transportation Act No. 14/1992 in the transportation sector to curb air pollution and noise from motor vehicles, thereby safeguarding environmental sustainability. The government has committed to addressing climate change by ratifying international agreements, including the UNFCCC (Act No. 6 of 1994) and the Kyoto Protocol (Act No. 17 of 2004). The government also enacted Act No. 23 of 1997 and amended the Indonesian Constitution, Article 33, paragraph 4, in 2002 regarding environmental management. In line with this, the government introduced Act No. 20/2002, focusing on NRE source utilization [4].

4.2.2. Second Phase: Encouragement of Energy Diversification Through Cleaner Fuels, Especially Natural Gas and Biofuels (2004–2014)

The rise in global oil prices, along with the burden of fuel subsidies, led to a current account deficit in 2004. "Indonesia's current account deficit due to imports... Most of this deficit was attributed to fossil fuel imports, particularly petrol" (Respondent 2, Energy Company). The statement confirms OECD/IEA (88), which emphasizes that increased oil imports have burdened the budget, triggering a current account deficit, thus pressuring the government to balance energy supply with GHG emission reductions [88]. At this pivotal stage, the government has continuously attempted to balance the three critical challenges of the energy trilemma, ensuring that energy security is the main priority, which involves diversifying accessible and affordable alternative fuels. In addition, the government has implemented institutional arrangements to promote environmental sustainability. The government has also addressed key issues related to energy sustainability in the transportation sector.

Events leading to the current account deficit have become critical junctures, encouraging the government to institutionalize the energy transition. This institutional change has developed through layering, which involves the diffusion of low-emission vehicle fuels, including biofuels, CNG, and EVs. In 2005, the Indonesian government took significant steps to develop eco-innovations in biofuels to reduce reliance on fuel oil. The focus was on biodiesel made from palm oil and ethanol. These biofuels not only reduce dependency on traditional fuels but also open up new market opportunities for palm oil products [4]. Furthermore, the government established a regulatory framework for promoting biofuels by implementing Presidential Instruction No. 1/2006, followed by Presidential Decree No. 10/2006. Additionally, Government Regulation No. 1/2007 granted fiscal incentives for biofuel development [73].

The Roundtable on Sustainable Palm Oil (RSPO), established in April 2004, has impacted the global palm oil certification system by promoting sustainability. However, its implementation has raised concerns among stakeholders, particularly farmers, about limited engagement with local producers and the high certification costs affecting smallholders [4]. In response, the Ministry of Agriculture introduced the Indonesian Sustainable Palm Oil (ISPO) certification through MOA Regulation No. 19/2011. This initiative aims to reduce costs and eliminate membership fees, positioning ISPO as a viable alternative to the RSPO certification [4].

Indonesia pledged to reduce greenhouse gas (GHG) emissions at the 2009 COP conference in Copenhagen, resulting in policies focusing on energy efficiency, cleaner fuels, renewable energy, clean technologies in power plants and transportation, and sustainable mass transit. To support this, the government issued Presidential Regulation No. 61/2011 to launch the National Action Plan to Reduce GHG Emissions (RAN-GRK), targeting reductions in agribusiness, forestry and peatlands, energy, transportation, and waste management [73].

The Indonesian government has also implemented a decarbonization program that utilizes CNG for domestic transportation, as outlined in the Director General of Oil and Gas (DGOG) Decree No. 247/2011. This policy establishes the specifications for CNG fuel used in this sector. Additionally, the Minister of Energy and Mineral Resources (MEMR) has appointed two SOEs—PT Pertamina, under Ministerial Decree No. 2435/2014, and PT Perusahaan Gas Negara, under Ministerial Decree No. 2436/2014—to oversee the supply and distribution of gas fuel for road transportation [73].

Indonesian biodiesel diffusion and its sustainability have faced increased scrutiny from environmental NGOs. In March 2010, Greenpeace's report "Caught Red-Handed" revealed that Sinar Mas, a major Indonesian palm oil producer and Nestlé supplier, was expanding its cultivation into orangutan habitats in rainforests and peatlands. In October 2013, Greenpeace issued "License to Kill," exposing Wilmar International for sourcing palm oil from plantations in Tesso Nilo National Park, threatening endangered species like the Sumatran tiger [4]. In the same year, the EU imposed anti-dumping measures on Indonesian biodiesel [12], leading the Indonesian government to bring the dispute to the World Trade Organization in 2014. This commitment is further underscored by the increase in Indonesian biofuel production capacity from 1800 million liters in 2011 to 3000 million liters in 2014 [89].

4.2.3. Third Phase: Development of Affordable and Clean Energy, Focusing on Biofuels and Electrification (2015 to Present)

The dynamics of the Indonesian biodiesel diffusion, driven by environmental concerns and trade disputes, have led to a significant decrease in Indonesia's biofuel production to 1180 million liters in 2015 [89]. The impact at the farmer level has been more noticeable because it has led to the neglect of palm oil harvests. To address this, the MEMR issued Ministerial Regulation No. 12/2015, which mandates biofuel use and accelerated adoption in the transportation, industrial, commercial, and power generation sectors [73].

Concurrently, the government needs to decrease its dependence on petroleum imports, which has significantly strained the national budget. The changes in the socio-technical landscape have created critical junctures that have prompted the government to institute a policy mandating 20% biofuel blending (B20) in diesel fuel by 2016 [73]. To improve the competitiveness of biodiesel, the Palm Oil Plantation Fund Management Agency (BPDPKS) was established through Presidential Regulation No. 61/2015. This agency manages funds from palm oil export levies to support biodiesel sustainability in areas like human resources, research, plantation promotion, plantation rejuvenation, and infrastructure [90]. This initiative has encouraged energy companies and automotive manufacturers to take advantage of "windows of opportunity" and adopt biodiesel more widely as an AVF in Indonesia.

In 2016, the Indonesian government enacted Law Number 16 of 2016, which ratified the Paris Agreement. The ratification of the Paris Agreement has drawn significant attention from various groups in Indonesia regarding the global EV trend [54]. Promoting EVs through mainstream and social media has attracted interest from early adopters. Over time, these early adopters have shared their knowledge about the latest advancements in EV technology and their personal experiences in brand enthusiast groups on social media. The presence of these groups has educated the public about the benefits of EVs, contributing to an increase in the population of these eco-friendly vehicles.

At the end of the 2010s, under President Joko Widodo, Indonesia shifted toward closer ties with China. This change has led to critical junctures in the development and adoption of EVs. The socio-technical landscape has adjusted to focus on technology transfer and investments from foreign manufacturers such as Hyundai and Wuling.

Key policies include Presidential Regulation No. 55/2019, which introduced BEVs [91] and several fiscal incentives, such as tax reductions (Ministry of Home Affairs Regulation No. 1/2021) and title transfer fee exemptions (Government Regulation No. 74/2021). However, significant growth in EV adoption began following the introduction of limited subsidies under Minister of Industry (MoI) Regulation No. 6/2023 [91]. The government has started to provide regulatory support for the adoption of FCVs as potential future AVFs through Minister of Industry Regulation No. 29 of 2023 and the National Hydrogen and Ammonia Roadmap (RHAN) [92].

4.3. Niche Innovations in Low-Carbon Mobilities

4.3.1. Advancing Biofuels for Alternative Vehicle Fuels

The diffusion of biofuels in Indonesia began in 2006 with the formation of the National Biofuel Team (Timnas BBM). This organization comprises several key stakeholders: government agencies, energy companies, research institutions, the Indonesian Palm Oil Association (GAPKI), the Association of Biofuel Producers (APROBI), automotive manufacturers, and NGOs. In addition, research institutions and universities play a significant role in developing and diffusing biofuels through technology transfer and eco-innovation [93].

The Indonesian government initiated a mandatory program to incorporate biofuels into fuel oil, starting with a 2.5% biodiesel blend (B2.5) in 2006. The government's strategic focus on the EU market, following the adoption of the Renewable Energy Directive in 2009, underscores the country's dedication to expanding its biofuel exports. Indonesian biofuel companies have responded to take advantage of this "window of opportunity" by actively pursuing international certification for their products bound for the EU, a testament to Indonesia's potential in the global biofuel market. This figure gradually escalated to B5 by 2010 and B10 in 2013, demonstrating Indonesia's commitment to meeting the increasing global demand for biofuels [73].

The government has been instrumental in promoting biofuel production and enforcing regulations to fulfill domestic and international demands. In 2005, Indonesia's biofuel exports amounted to 6.82 million liters, dramatically growing to 607 million liters by 2008. In 2011, Indonesia began implementing its sustainability commitment, resulting in an increase in biofuel production capacity from 1800 million liters to 3000 million liters by 2014 [89].

In 2015, biofuel production declined due to sustainability issues and trade disputes. Bappenas utilized the Analytical Hierarchy Process (AHP) to identify suitable raw materials, evaluating potential biofuel plants based on factors such as feedstock availability and productivity. The plants were categorized into biodiesel producers (oil palm, coconut, and jatropha) and bioethanol producers (sugarcane, cassava, and corn) [93].

Automotive manufacturers were facing a challenging decision: whether to adopt biofuels or to shift toward EVs. To maintain their market dominance, the automotive industry leaders preferred to focus on increasing R&D investments to ensure that their existing engines were compatible with biodiesel rather than shifting their transition to EVs. Furthermore, automotive market leaders formed coalitions with palm oil companies to advocate for policies prioritizing biodiesel in the trajectories of AVF diffusion. This preference is reflected in the comments of the following respondents:

> *"Between 2015 and 2017, [the coalition of automotive industry leaders] united to resist the adoption of EVs. Consequently, to stay in business, they shifted their focus to biofuels" (Respondent 18, NGO).*

The policy mandating B20, supported by incentives, successfully restored biodiesel production levels in 2015 [94]. Biodiesel production gradually increased again in 2016, reaching 2700 million liters, and continued to rise to 3872 million liters by 2023 [89].

Following a steady increase from B30 in 2020 to B35 in 2023, the government plans to raise the biodiesel content to B40 in 2025. According to government reports, the progress of biodiesel diffusion in Indonesia has contributed to enhancing energy resilience, saving foreign exchange by reducing diesel imports, creating jobs, and lowering greenhouse gas emissions, as stated in the following:

> *"The mandatory biofuels program will help reduce petrol imports and save foreign exchange… The B40 program has brought important benefits for society and the environment. It has raised the value of CPO, …created over 14,000 off-farm jobs, and provided about 1.95 million off-farm jobs. It has also helped cut GHG emissions by 41.46 million tons of CO_2 equivalent annually."* [95].

The advancement of biodiesel has led to a path dependence in the development of AVFs in Indonesia. The advancement of biodiesel has driven "institutional lock-in" in Indonesian biofuel development, resulting in path dependence for the diffusion of AVFs in Indonesia. In contrast, the adoption of ethanol as another biofuel—derived from sugarcane and jatropha—has not progressed rapidly. Since 2023, E5 fuel has been market-tested on a limited scale on the island of Java. The diffusion of ethanol as an AVF still faces several challenges in Indonesia, particularly due to limited local feedstock and a lack of incentive support. These issues make it difficult for ethanol to compete with gasoline, as stated by the Director of Biofuel at the MEMR, quoted by a secondary source.

> *"In its implementation, there are still many challenges, including the limited production of bioethanol and the absence of incentives to address the price difference between the Market Index Price of gasoline and bioethanol."* [96].

4.3.2. Natural Gas Utilization

The substantial growth in natural gas production has prompted the government to promote CNG technology as an AVF. In 2011, a key milestone was achieved by establishing four natural gas refueling stations in Palembang. In 2012, more CNG refueling stations were developed in East Java Province. During this time, the MEMR also initiated two pilot workshops for natural gas vehicles. By 2013, the Greater Jakarta Province had four CNG refueling stations, four mobile refueling units (MRUs), and a gas distribution pipeline in place. Four more CNG refueling stations were also constructed in East Kalimantan Province [97].

Several companies have contracted with Pertamina to manage the natural gas supply. The Palembang region's supply is sourced from Pertamina EP, while East Java receives its natural gas from Pertamina WMO and Santos. In the Greater Jakarta region, natural gas is provided by Pertamina EP, Pertamina ONWJ, Medco E&P, and Pertamina-Talisman Jambi Merang [97].

The government fostered CNG adoption by distributing converter kits for public vehicles, including buses, taxis, and motorized rickshaws. In 2011, 500 kits were distributed in Greater Jakarta and Palembang; the government increased the distribution to 1000 in 2012 and 2000 in 2013 [97]. CNG consumption grew from 1159 TJ in 2011 to 2349 TJ in 2012 but dropped to 983 TJ in 2022 due to the pandemic [98]. The use of natural gas for transportation in Indonesia is still very limited. In 2022, the industrial sector used 69.06% of natural gas, while transportation used only 0.14%. As of 2024, there are only 72 gas refueling stations and MRUs [98].

Despite the benefits of CNG, such as low emissions and competitive costs compared to petrol, private vehicle users remain hesitant to adopt it. This lack of interest among consumers has led to a shortage of automotive manufacturers producing CNG vehicles. Furthermore, the focus on biodiesel has impeded the adoption of CNG as an AVF. Additionally, the growing trend of EVs in Indonesia has further diverted attention from CNG among private vehicle users. Key barriers to CNG adoption include unclear regulations, inadequate infrastructure, and significant price differences with petrol, as stated below:

> *"The development of cars with CNG engines is currently hindered by three main obstacles: unclear government regulations, a lack of infrastructure, and the price difference between gasoline and CNG."* [99].

4.3.3. Electric Vehicles Diffusion

Global electrification prompted some Indonesian consumers to seek cleaner mobility in the early 2010s. Since 2012, the government has backed EV research. Several electric four-wheelers (E4Ws), such as electric car and bus prototypes, were developed in 2013 through a collaboration between universities and SOEs, but progress has stalled due to unclear regulations and insufficient funding [100]. Despite limited government support, early adopters of EVs have continued to grow by forming groups of brand enthusiasts. Sharing experiences and operational challenges related to EVs on social media has indirectly helped promote EVs to the public [54].

Evolving market demand and technological advancements have prompted industries to create new business opportunities through the adoption of EVs. Collaborative innovation has emerged among automotive manufacturers, energy companies, green suppliers, and research institutions to develop electric two-wheeler prototypes (E2Ws). Between 2017 and 2019, the development of E2Ws saw notable innovations led by companies like Viar and Gesits, which then shifted toward mass production. The enactment of Presidential Regulation No. 55/2019 has allowed both companies to market their E2W products to niche markets successfully. Support from both the central and regional governments has facilitated the transition to EVs within government and SOE fleets. Additionally, electrification has been implemented in buses for BRT TransJakarta, taxis, ride-hailing services, and logistics [101].

Since 2023, a range of fiscal and non-fiscal policies and minimal subsidies with minimal local content requirements have contributed to a significantly increasing number of local manufacturers entering the E2W market. The subsidy policy was provided for low-income communities. However, the initial stage's lack of coordination among government agencies temporarily delayed public interest in purchasing EVs. While subsidies increased EV purchases, stakeholders sought to expand the program, drawing inspiration from models in developing countries like India, which relate battery capacity to reduced GHG emissions [101].

The increasing number of EVs has led PLN, the state-owned electricity company, to expand its EV charging infrastructure. Similarly, oil and gas companies like Pertamina and Shell have established charging and battery swap networks at their fuel stations. The state has offered incentives for local and foreign private entities to invest in automotive manufacturing and the development of charging infrastructure. Some companies are working to facilitate the transition to EV battery charging by establishing a battery swap system (BSS) network. Gogoro has introduced its BSS system from Taiwan. Swap Energi and Volta have also developed innovative business models that embrace local cultural practices in energy purchasing, similar to conventional fuel refilling methods [101].

EVs are gaining popularity, especially as more people recognize their financial benefits. Low energy costs, affordable electricity predominantly sourced from coal, and reduced maintenance expenses have begun to change consumer perceptions about EVs [41]. The growing number of EVs has significantly supported the ongoing energy transition. In 2017, only 32 E2Ws were registered in the country. However, niche innovative developments and landscape pressures have led to regime policy changes that encourage EV adoption. As a result, by 2024, the number of registered E2Ws had surged to 160,578, alongside 34,504 units of E4Ws [102]. Figure 2 shows the growth of the diffusion of EVs in Indonesia from 2017 to 2024.

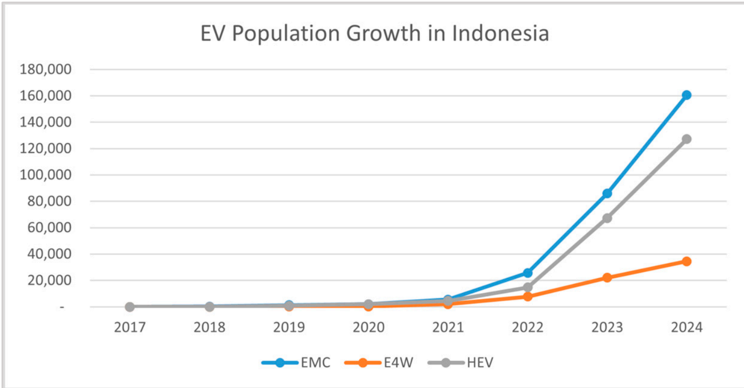

Figure 2. The growth of the diffusion of EVs in Indonesia. Source: Data from [102].

The adoption of EVs offers significant advantages, including reduced emissions and decreased reliance on fuel imports. Additionally, EVs facilitate the integration of renewable energy sources into the final energy mix, particularly within the transportation sector. However, Indonesia's persistent reliance on coal for electricity generation has led various stakeholders to advocate for a "movement aimed at discontinuing investments in coal-fired and other environmentally detrimental power plants" (Respondent 18, NGO).

The adoption of EVs will continue if stakeholders can overcome substantial challenges, primarily the high upfront purchase price, insufficient charging infrastructure, and lack of public awareness about sustainability [54]. To address these issues, automotive leaders have introduced HEVs as a socio-technical transition. In 2024, Indonesia had 127,243 HEVs, nearly reaching the number of E2Ws [102]. However, regulatory support for HEVs in Indonesia is still limited. "To reduce emissions and fuel consumption, the government should provide proportional incentives for hybrid vehicles, instead of offering the same incentives as for BEVs" [103].

4.3.4. Hydrogen Fuel Cell Vehicle Innovation

In Indonesia, HFCVs are still in the early stages of development, but pilot projects indicate a gradual transition from innovation discourses to demonstration phases. These hydrogen initiatives include the mobility and energy sectors. Regulatory support for hydrogen utilization in Indonesia's transportation sector was evidenced by Minister of Industry Regulation No. 29 of 2023 and the National Hydrogen and Ammonia Roadmap (RHAN) [92]. PLN launched a pilot HRS in Senayan, Jakarta, in 2024. This station was designed to serve buses starting in August 2024 and passenger vehicles from October 2024, with commercialization planned for 2027 [104]. In February 2025, Toyota Indonesia inaugurated the country's first hydrogen refueling station at its xEV Centre in Karawang. This facility is equipped with both 350-bar and 700-bar dispensers, catering to demonstration vehicles such as the Toyota Mirai, as well as forklifts [105].

Pertamina Geothermal Energy (PGE) is advancing into green hydrogen production utilizing geothermal power. The Ulubelu Green Hydrogen Pilot Project in Lampung, which launched in September 2025, aims to produce approximately 100 kg of hydrogen per day through anion exchange membrane (AEM) electrolysis [106]. Additionally, PGE has entered into a Joint Study Agreement with Pertagas to explore the integration of geothermal electricity in the production of hydrogen and ammonia. This initiative will leverage Pertagas' existing infrastructure for potential distribution [107]. Furthermore, Hyundai Motor Group has proposed a waste-to-hydrogen ecosystem in West Java. This initiative aims to integrate hydrogen production from waste with on-site refueling stations, with support from Pertamina and local governments, and is expected to be operational by 2027 [108].

Recent research demonstrates that health-conscious and AI-driven energy management enhances FCVs. Jia et al. [109] developed a thermal management strategy that integrates cabin climate control with fuel cell and battery systems, optimizing coolant flow and compressor operation. The results showed an 8–9% increase in system efficiency and an over 12% reduction in fuel cell ageing, confirming that this approach lowers hydrogen consumption [109]. Additionally, studies by Huang et al. [110] and Sellali et al. [111] support the notion that health-conscious control frameworks extend stack life while ensuring passenger comfort, thereby promoting sustainable FCV operation [110,111].

Building upon these frameworks, Jia et al. [112] developed an advanced energy management system utilizing an enhanced deep deterministic policy gradient (DDPG) algorithm with driving-intention speed prediction and health-aware optimization. By integrating LSTM predictions with deep reinforcement learning, the model improved the hydrogen economy by 6% and reduced degradation by 15–16% [112]. Research by Zhang et al. [113] further supports the benefits of predictive and degradation-aware algorithms. Overall, these studies demonstrate that AI-driven, health-focused control strategies are crucial for next-generation fuel cell vehicles, enhancing efficiency, prolonging component life, and improving hydrogen utilization for low-carbon mobility [113].

4.4. TCO Comparison

This study compares the TCO of various fuel types for passenger cars available in the Indonesian market. We selected several ICEV variants, including the Daihatsu Ayla (A-segment hatchback gasoline), Mitsubishi Xpander (low MPV gasoline), Toyota Innova Reborn (mid-MPV diesel), and Toyota Innova Zenix (mid-MPV gasoline). Additionally, we included hybrid cars such as the Suzuki Ertiga Hybrid (a mild hybrid MPV) and the Honda HR-V e:HEV (a full hybrid C-SUV). For the BEV segment, we examined the BYD Atto 1 (A-segment hatchback) and the Hyundai Kona Electric (Crossover). Lastly, the FCV segment is represented by the imported Toyota Mirai. Table 1 presents the assumptions utilized in the TCO calculation. These assumptions include the exchange rate (1 USD ≈ IDR 16,600), energy tariffs, annual mileage (15,000 km/year), a discount rate of 10%, vehicle tax (approximately 1.50% of the book value), insurance rates (1.50%), administrative costs, and the residual value at year 10 for each powertrain type. Additionally, it includes EV charging tariffs (public and premium) and an estimate of retail hydrogen fuel prices in USD. Meanwhile, Table 2 summarizes the TCO calculations for 10 years of usage for various types of passenger cars available on the Indonesian market. File S2 in Supplementary Materials presents a summary of the TCO components for several types of vehicles examined in this study.

Table 1. The assumptions utilized in the TCO calculation.

Parameter	Value	Parameter	Value (USD)
Exchange rate USD to IDR	16,600	Maintenance cost per km for gasoline ICE	0.04
Annual mileage (km)	15,000	Maintenance cost per km for HEVs	0.04
Discount rate	10%	Maintenance cost per km for diesel ICE	0.05
Motor vehicle tax rate annual	1.50%	Maintenance cost per km for BEVs	0.02

Table 1. *Cont.*

Parameter	Value	Parameter	Value (USD)
Insurance rate annual	1.50%	Maintenance cost per km for FCVs	0.05
Resale year 5 (pct of OTR)	55.00%	Non-subsidized gasoline (per liter)	0.78
Resale year 10 (pct of OTR)	30.00%	Non-subsidized diesel (per liter)	0.84
BEV battery replacement year	8	Home charging (per kwh)	0.10
HEV battery replacement year	7	Public charging (per kwh)	0.21
Admin insurance per year (USD)	10	Fast charging (per kwh)	0.24
Battery pack cost per kWh (USD)	115	Hydrogen liquid (per kg est)	14.50
HEV aux batt replacement (USD)	900		

Table 2. Ten-year TCO calculation for several different fuel passenger cars.

Vehicle	Type	OPEX Cost (USD/km)	Upfront Purchase (USD)	TCO NPV 10 y (USD)	TCO per km 10 y (USD per km)
Daihatsu Ayla 1.2	ICE Petrol	0.09	9789	14,682	0.098
BYD Atto 1	BEV	0.04	12,952	15,860	0.106
Toyota Avanza	CNG	0.08	16,438	19,524	0.130
Suzuki Ertiga Hybrid	Hybrid Mild	0.09	17,280	21,949	0.146
Mitsubishi Xpander	ICE Petrol	0.12	19,053	24,530	0.164
Toyota Innova Reborn	ICE Diesel	0.14	26,114	31,989	0.213
Honda HR-V e:HEV	Hybrid	0.09	26,744	31,035	0.207
Toyota Innova Zenix	ICE Petrol	0.13	27,672	32,883	0.219
BYD Atto 3	BEV	0.05	29,819	32,311	0.215
Hyundai Kona Electric	BEV	0.05	37,795	39,574	0.264
Toyota Mirai (import est.)	FCEV	0.26	93,012	103,719	0.691

The TCO differs among vehicle types. The BYD Atto 1, a compact BEV priced at about USD 13,000, offers a ten-year TCO of approximately USD 31,000, including an eight-year battery replacement. Hybrids like the Honda HR-V e:HEV (USD 27,000) and Suzuki Ertiga Hybrid (USD 17,200) are also competitive. The HR-V has a ten-year TCO of USD 46,000 (USD 0.31/km), while the Ertiga's TCO is about USD 39,000 (USD 0.27/km) for ten years. Both hybrids show strong long-term cost stability, closing in on small BEVs.

Conventional ICEs, such as the Daihatsu Ayla, at almost USD 9700, face long-term disadvantages due to rising fuel costs, totaling around USD 14,600 over ten years (USD 0.098/km). Larger models such as the Mitsubishi Xpander (USD 19,000), Toyota Innova Reborn Diesel (USD 26,000), and Innova Zenix gasoline (USD 27,600) have ten-year total ownership costs of approximately USD 24,500, USD 31,900, and USD 32,800, respectively, all of which are higher per kilometer than BEVs, hybrids, and CNG. Mid-range BEVs, like the BYD Atto 3 (USD 32,300) and the Hyundai Kona Electric (USD 39,500), are more affordable than larger ICEVs. However, with battery costs estimated at USD 7000 to USD 7400, their ten-year TCO is USD 32,300 to USD 39,500. The Toyota Avanza CNG (USD 16,400) has a ten-year TCO of around USD 19,500 (USD 0.13 per kilometer). The Toyota Mirai, starting at USD 93,000, has a ten-year TCO of USD 103,700 (USD 0.69 per kilometer).

The BYD Atto 1, as a small BEV, has the lowest cost efficiency per kilometer over the first five years of utilization. However, over ten years, the cost efficiency per kilometer changes as follows: gasoline low-cost green cars (Ayla), small BEVs (Atto 1), hybrids (Ertiga, HR-V), ICE MPVs/SUVs (Xpander, Innova), medium BEVs (Atto 3, Kona), and FCEVs (Mirai). Figure 3 displays the TCO per component for various vehicles with different fuel types.

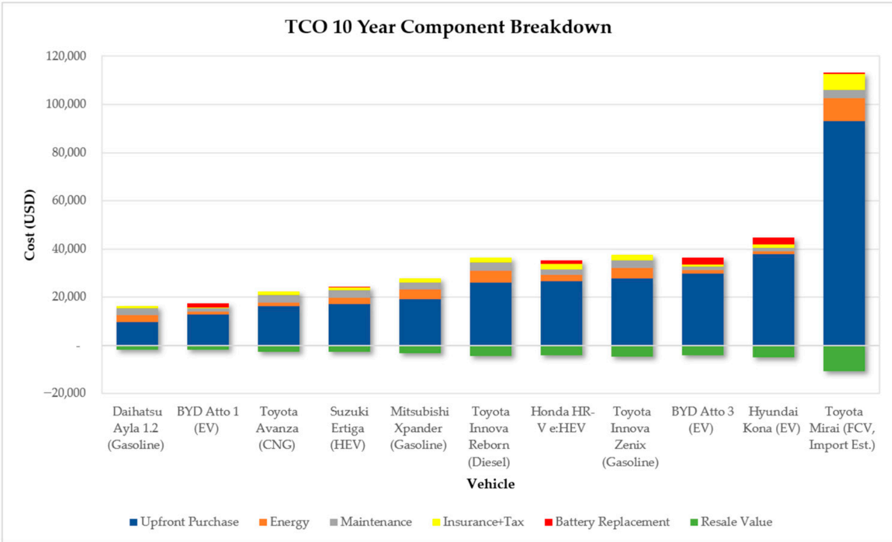

Figure 3. TCO per component for various vehicles with different fuel types.

The 2025 TCO analysis reveals an exciting insight: Indonesia's adoption of low-carbon technology is significantly driven by strong institutional factors rather than market forces alone. The government's strategic fiscal planning, thoughtful policy implementation, and focused actions play a crucial role in determining the success of these technologies.

Our study also examines several secondary sources that gather data through surveys of the Indonesian public on the adoption of EV technology in Indonesia. Indira Ayu et al. (2025) [114] surveyed 1360 respondents across six provinces in Java and conducted expert interviews with stakeholders from government agencies, OEMs, and charging infrastructure operators. Using a Mixed Multinomial Logit (MMNL) model, they identified purchase price, operating cost, range, and charging duration as the most significant factors influencing the adoption of BEVs. Consumers showed a preference for BEVs priced below USD 25,000 with operational costs under USD 0.05 per kilometer. Stakeholder perspectives highlighted critical barriers, including policy inconsistency, reliance on battery supply, and limited charging infrastructure, all of which impede market growth [114].

According to complementary findings from PwC (2025) [115], 60% of Indonesian consumers plan to purchase an EV within the next five years. Currently, 7% of respondents already own an EV, while 78% are potential adopters, and 15% remain skeptical about the transition. The primary motivations for considering an EV include fuel cost savings—up to 60% compared to gasoline—and environmental benefits. However, the main concerns among consumers are related to charging time, range limitations, and battery lifespan. The survey highlights a growing interest in EVs among the urban middle class, but gaps hinder actual sales conversion in infrastructure, as does uncertain policy direction [115].

5. Discussion

The findings indicate that Indonesia's transition in transportation and energy is a historically layered process, characterized by institutional continuity and selective adaptation rather than radical transformation. When analyzed through the frameworks of HI and MLP, this transition can be interpreted as a multi-scalar interplay between landscape pressures, regime resilience, and niche experimentation, mediated by policy feedback, layering, and conversion mechanisms.

5.1. Synthesizing Historical Institutionalism and Multi-Level Perspective in the Context of Indonesia's Political Economy of Transport

Indonesia's transportation energy sector has undergone phases of inertia and transition, often influenced by political dynamics. Throughout the Soeharto era, which began in the 1970s, the country relied heavily on fossil fuels, using oil production and exports to finance national development. However, during this socio-technical period, there was a significant shift in resource management policies, including efforts to invite foreign investment.

Initially, the economy relied on fossil fuels to drive development and ensure national energy security. However, external factors such as the 1970s energy crisis and fluctuations in petroleum prices have significantly impacted the sector. These landscape dynamics highlighted the critical junctures that prompted the government to diversify its energy and fuel sources. As a result of these institutional changes, there has been an increase in exploration and production activities focused on cleaner and more environmentally friendly sources, such as natural gas and geothermal energy. Indonesia's substantial fossil fuel reserves have impacted the country's energy diversification strategy, especially in promoting renewable energy from an energy security standpoint. However, the policy to shift toward renewable sources has mainly concentrated on the electricity generation sector. Consequently, renewable electrical energy has not yet been used to fuel vehicles or trains in the first phase.

The socio-technical landscape has evolved due to various global sustainability initiatives established in the 1980s and 1990s. Key global sustainability agendas included the Brundtland Report in 1987, Agenda 21 in 1992, and the Kyoto Protocol in 1997. The adoption of these initiatives led to significant institutional changes at the meso-level regime, marked by the enactment of Act No. 4/1982 on Basic Provisions for Environmental Management, Act No. 23/1997 on Environmental Management, and the fourth amendment to the 1945 Constitution. Our findings indicate that landscape dynamics pressured the socio-technical regime to formulate national policies that aligned energy production advancement with environmental preservation. Our study emphasizes the literature regarding the impact of the socio-technical landscape on institutional regime changes in energy transitions [34].

Our study reveals that urban-centered development has resulted in economic growth and a rise in population. However, this urbanization has not been well managed. Additionally, there has been a shift from trains to road transportation, leading to an increase in private vehicles without proper road planning or improvements to public transport. Evolutions in the landscape and regime policies have entrenched petroleum dependence. Incorrectly planned policies have led to significant traffic congestion. Despite commitments to global sustainability initiatives, the government has not effectively implemented fuel efficiency and emission restrictions.

According to the HI framework, this regime orientation describes enduring path-dependence, where policy choices focused on fuel price stabilization and state dominance in energy have yielded increasing returns that constrain future options [116]. Fuel subsidies, once viewed as redistributive instruments, have evolved into political institutions that shape state–citizen relations and fiscal priorities. When global oil prices spiked in the 2000s, the government faced a dual fiscal and legitimacy crisis, prompting a reactive institutional layering approach through gradual diversification policies without dismantling entrenched subsidy mechanisms [30,43,117,118]. Our study also revealed that these events had become critical junctures that pressured the regime to alter its policies to reduce fuel imports, thus creating "windows of opportunity" for enhancing the development of alternative vehicle fuels.

The MLP has elucidated how these macro-institutional structures interact with niche-level technological innovations. Oil price volatility and global climate commitments have changed the landscape, increasing pressure on regimes to implement diversification programs. However, state actors within these regimes have selectively adapted through institutional conversion—repurposing policy instruments to maintain rent distribution while incorporating new technologies.

The evolution of low-carbon mobility, including CNG, biofuels, EVs, and FCVs, illustrates this incremental institutional adaptation. Presidential Instruction No. 1/2006 represents a significant milestone in establishing biofuels institutionalization in Indonesia. The subsequent implementation of Government Regulation No. 1/2007, which introduces fiscal incentives, has effectively attracted increased private investment in biofuel development, including sugarcane-based ethanol and palm oil-based biodiesel. Our study highlighted the vital role of the National Biofuels Team in facilitating technology transfer from other countries that have successfully developed biofuels and promoting niche innovations from local companies. Thus, biofuel companies effectively have taken advantage of the "window of opportunity" offered by opening the biofuel market in the EU and the US. Our findings align with recent research highlighting the state's role in fostering and facilitating niche innovations by private and SOEs during the energy transition [119].

The transition to CNG in countries like Iran, Pakistan, Argentina, Brazil, and China has prompted governments to encourage its use in public transportation. This shift was formalized with the issuance of DGOG Decree No. 247/2011, which was supported by the establishment of two SOEs to manage the supply and distribution of CNG. However, despite Indonesia's abundant natural gas production, the CNG conversion program within the transportation sector has faced challenges and has been unsuccessful. We found that landscape influences and government support have not significantly affected the adoption of CNG at the micro-niche level. Moreover, while CNG has primarily been utilized in public vehicles, fostering niche innovations for private vehicles has encountered obstacles. These obstacles include unclear government regulations, inadequate infrastructure, and the price disparity between gasoline and CNG. The diffusion of CNG has reflected early diversification efforts but suffered policy drift due to inter-ministerial fragmentation and insufficient investment. Our findings are consistent with the literature showing that newcomers to radical innovation who encounter high levels of uncertainty and require significant infrastructure will enter and exit the socio-technical system [120]. The emergence of environmental issue reports, trade disputes, and the Paris Agreement between 2011 and 2015 has significantly changed the landscape of Indonesia's biodiesel exports. These developments have led to a decline in biodiesel production and neglected harvests at the farmer level. Our study highlights that these global and domestic shifts have created an exogenous shock, pushing the state to modify the institutional framework encompassing biodiesel. Conversely, this exogenous shock has opened "windows of opportunity" to promote energy transition through AVFs and reduce fuel imports.

Our study also reveals a contention between two groups of stakeholders: one coalition group advocates for the absorption of domestic biodiesel, while the other coalition prefers a transition to EVs. The results of the AHP conducted by Bappenas have become instrumental in determining the outcome of this contestation, ultimately establishing biodiesel as the state's primary preference. This decision has led to a path dependence in the development of AVFs in Indonesia. Indonesia's biofuel development trajectory differs from that of Thailand and the Philippines, which focus on ethanol rather than biodiesel. Significant institutional changes have occurred with the implementation of MEMR Regulation

No. 12/2015, which mandates the use of B20 biodiesel in various sectors, including transportation. The establishment of BPDPKS in 2015 stabilized the biodiesel market through export levies, embedding a policy feedback loop that favors the interests of palm oil [121,122]. These developments represent critical junctures so that energy companies can leverage the "windows of opportunity" to foster the expansion of Indonesian biodiesel. Our study contributes to the body of literature on the contention among stakeholders shaping energy transition projections through layering on the existing system, particularly in emerging economies [123].

The technological disruption brought about by the proliferation of EVs in Asia since 2017 cannot be overlooked. Early adopters have indirectly socialized the concept of EVs, leading to collaborative innovations at the micro-niche level. The diffusion of EV trends and a shift in political orientation have altered the socio-technical landscape and prompted government support for EV adoption. Presidential Regulation No. 55 of 2019 and MHA Regulation No. 1 of 2021 marked the initial institutional support for EVs in Indonesia, representing a more recent form of institutional conversion—redirecting fiscal instruments from industrial promotion to decarbonization objectives. This regulatory framework has facilitated the development of local products, starting with the E2W segment. Niche innovations in the battery swapping business model have emerged as a transition from the existing ICEV energy purchasing system. The increased regime support has become more noticeable with the implementation of a limited subsidy scheme since 2023. Gradually, the public has begun to recognize the benefits of transitioning to EVs, particularly from an economic perspective.

Meanwhile, MoI Regulation No. 29 of 2023 and the National Hydrogen and Ammonia Roadmap (RHAN) have institutionalized the utilization of hydrogen as an AVF. Furthermore, FCV pilot projects, such as those involving the construction of hydrogen refueling stations by PLN, Hyundai, and Toyota in recent years, have demonstrated initial displacement dynamics, although institutional support remains minimal.

The findings from the quantitative TCO analysis and the qualitative consumer perception survey present a consistent yet nuanced view of Indonesia's EV transition. The TCO analysis indicates that BEVs have achieved a level of economic competitiveness, with operational energy costs around USD 0.106 per kWh when charged at home. This cost is significantly lower than that of CNG, petrol, or diesel vehicles over a ten-year ownership period. Although BEVs have higher initial costs and incur mid-life battery replacement expenses, small-to-medium BEVs and hybrid models, like the Honda HR-V e:HEV (approximately USD 0.03 per km), demonstrate long-term cost-efficiency and resilience against fuel price volatility. In contrast, ICEVs face rising fuel costs, while infrastructural and refueling challenges hinder the adoption of CNG and FCVs.

The findings from our techno-economic analysis are supported by consumer insights from PwC Indonesia's 2023 nationwide survey conducted in eight major cities: Jakarta, Bekasi, Tangerang, Bogor, Surabaya, Semarang, Medan, and Depok [115]. The survey revealed that 78% of respondents are interested in purchasing an electric car, and 74% are interested in an electric motorcycle. However, public adoption is limited by concerns about affordability. Specifically, 87% of respondents feel that battery prices are prohibitively high, and 83% are worried about the cost of expensive spare parts. Additional recurring expenses, such as annual maintenance costs (USD 200–300) and mid-life battery replacement costs, are also significant deterrents [115].

This perception aligns with the TCO outcomes, which indicate that while BEVs have lower operating costs, the overall lifetime cost advantage only becomes clear after several years of use. This advantage is dependent on stable electricity tariffs and government fiscal incentives. PwC further emphasizes that tax exemptions ranging from USD 1000 to USD

1500 per vehicle could significantly reduce this psychological cost barrier, underscoring the importance of state-led incentives in promoting the adoption of EVs [115].

Triangulating these datasets indicates that Indonesia's transition to EVs hinges on more than just affordable technology; it also depends on consumer confidence and reliable infrastructure. TCO analysis shows that BEVs and hybrids are increasingly economically viable. However, survey results highlight the need for improved support in areas such as battery warranty transparency, charging accessibility, and post-purchase guarantees to convert interest into actual adoption. To address these challenges, sustained fiscal incentives, improved public charging infrastructure, and consistent policies are crucial for reducing the gap between cost-competitiveness and perceived consumer risk in Indonesia's EV market [114,115].

Our study found that Indonesia followed a different path in its electrification transition by facilitating the transition from HEVs to BEVs less. This approach contrasts with other developing countries such as India and Thailand, which provide substantial incentive support for HEVs to reduce GHG emissions. Our findings enrich the existing literature on the various trajectories of developed and developing countries in their energy transition toward sustainability in the transportation sector [124].

Hydrogen-as-an-AVF initiatives include the Indonesian mobility and energy sectors. However, they remain pilot-scale and heavily dependent on foreign partnerships and SOEs initiatives, contrasting sharply with the more established ecosystems in Japan, South Korea, or Germany. Collaborative networks have been established between state-owned energy companies and foreign manufacturers and licensors to develop a hydrogen ecosystem. Additionally, a pilot project has demonstrated the potential to utilize geothermal green energy sources for producing green hydrogen. This finding aligns with recent studies that emphasize the necessity for significant investment, particularly in infrastructure development, to enhance the adoption of HFCVs, especially considering the low uptake of HFCVs in Indonesia as a developing country [61,80].

5.2. Comparative Insights from Global and Regional Transitions

Our study utilizes a comparative analysis that positions Indonesia's hybrid trajectory within a broader framework of transition pathways among developing countries. Brazil's Pró-Álcool and RenovaBio programs serve as key examples of a coherent institutional structure where state intervention effectively aligns agricultural policy, energy security, and industrial innovation. The Brazilian government has implemented stable fiscal incentives, performance-based mandates, and carbon intensity assessments to ensure the competitiveness of ethanol without relying solely on subsidies [125].

Meanwhile, Argentina prioritizes soybean-based biodiesel, supported by the National Biodiesel Promotion Law (No. 26093/2006). However, the country faces challenges due to volatility stemming from weak institutional consistency and heavy reliance on exports. Frequent policy reversals, such as the suspension of the biodiesel mandate in 2017, underscore the impact of a lack of robust policy feedback on sustainability [126]. Similarly, Indonesia's biofuel governance relies on commodity rents; however, greater bureaucratic centralization through BPDPKS has set its biodiesel diffusion apart from that of Argentina [127].

In the diffusion of e-mobility, China's EV strategy has demonstrated the effectiveness of coordination among different levels of government institutions in achieving large-scale progress. By integrating EV development into its national industrial planning, including the Five-Year Plans and the new energy vehicle (NEV) credit system, China captured nearly two-thirds of the global EV market share by 2024. This strategy shows how a centralized institutional design can realign existing frameworks [60,128]. On the other hand, India's FAME-II policy combines fiscal incentives with domestic manufacturing requirements, reflecting Indonesia's ambitions in EV manufacturing. However, India has benefited from stronger inter-ministerial coordination [60].

Regional electrification in Southeast Asia is highlighted by Thailand's "30@30" policy, which aims for 30% of vehicle production to be electric by 2030. This initiative is supported by the Board of Investment (BOI) through tax breaks and straightforward integration with the expansion of renewable energy [60,61]. Vietnam has demonstrated effective public–private collaboration through VinFast, while Malaysia is advancing its hybridization efforts with the Proton program. Singapore is notable for its comprehensive EV approach, which combines carbon taxes, incentives, and the electrification of public transportation under a unified governance framework [60].

For comparison, Indonesia's transportation transition has been shaped by its hybrid institutionalism, where partial conversion occurs within a deeply entrenched structure of rent-seeking. The HI approach demonstrates that incremental change happens because self-interest is tied to the interest of large palm oil corporations, fossil fuel suppliers, and the fiscal dependence of SOEs, all of which limit radical transformation. The MLP contextualizes Indonesia's situation as a path of reconfiguration, where niche technologies—especially biofuels and EVs—coexist rather than completely replacing incumbents. Therefore, while landscape pressures, such as declining battery costs and global hydrogen initiatives, have impacted the regime, it is the adaptation of institutions that has led to different outcomes [32,92].

6. Conclusions

This study provides a comprehensive understanding of Indonesia's transport-energy transition by synthesizing the HI and MLP frameworks, demonstrating that the evolution of sustainability transitions in developing countries is inseparable from their political economy and institutional legacies. The findings reaffirm that Indonesia's pathway toward sustainable mobility is not driven by spontaneous technological competition, but rather by the historical sequencing of institutions, power-laden governance structures, and policy feedback mechanisms that shape how innovations emerge, compete, and stabilize within the socio-technical regime.

From a historical perspective, Indonesia's transport-energy trajectory reveals the deep imprint of state developmentalism and rent-based governance that emerged during the Soeharto era (1966–1998). This developmental model institutionalized the provision of cheap energy as a social contract, embedding fuel subsidies as a central mechanism of state legitimacy. Over time, these subsidies evolved into self-reinforcing institutions, creating fiscal path dependencies and constraining subsequent reform attempts. The transition from oil exporter to net importer in 2004 intensified the structural tension between fiscal sustainability and political stability. By the 2010s, fuel subsidies had become a significant burden on the national budget, limiting investment in alternative energy and infrastructure diversification. This historical legacy represents the archetype of increasing returns [19], where the cost of exiting established institutions grows over time, perpetuating fossil fuel-dependence.

Within the MLP framework, these institutional path-dependencies mediate how global pressures and technological niches—such as biofuels, CNG, EVs, and FCVs—are domestically embedded, producing a hybrid transition regime where existing and new institutions coexist. Empirical findings from semi-structured interviews indicate that policy change primarily occurs through layering and conversion, rather than radical displacement. Biofuel mandatory programs, backed by palm oil fund management, along with EV incentives, illustrate how new policies can reinforce existing fiscal frameworks. In contrast, the stagnation of CNG and FCVs reflects a drift owing to inconsistent support. In contrast, CNG has stagnated due to institutional drift, as political interest has decreased, and policy coherence has dissolved. Meanwhile, emerging FCV pilots hint at displacement dynamics, representing the early stages of a potential challenge to the existing regime. However, these niche innovations have not yet led to systemic reconfiguration of the institutional arrangement. Quantitative TCO analysis complements these insights, revealing that cost-competitiveness among technologies depends on the intensity of institutional support—through fiscal incentives, industrial mandates, and energy pricing—rather than inherent market efficiency. In summary, economic viability is shaped by institutional factors rather than being solely determined by technological advancements.

Compared to other developing economies, Indonesia's transition to sustainable energy is notably different. For instance, Brazil has successfully institutionalized its ethanol transition through stable fiscal incentives. In China, centralized coordination has enabled the widespread adoption of EVs. India's FAME programs have demonstrated a gradual yet consistent shift toward hybrid technologies. Meanwhile, Thailand and Malaysia have achieved moderate progress through industrial localization. In contrast, Indonesia's transition has been slower and more politicized, hindered by fragmented governance and fiscal dependencies that prioritize short-term stability over long-term structural decarbonization efforts.

This study makes theoretical contributions by integrating the HI–MLP framework in three ways. First, it shows that institutional mechanisms—such as layering, conversion, feedback, and drift—mediate the effects of multi-level pressures on policy outcomes. Global technological trends and growing environmental norms impact Indonesia's regime only through domestic policies.

Second, it describes hybrid transition regimes, where existing and new institutions coexist, as exemplified by Indonesia's biodiesel sector, which is supported by subsidies. The hybrid transition regimes challenge the straightforward regime vs. niche divide in early MLP theory, suggesting a continuum influenced by the domestic political economy. Finally, methodologically, this study combines qualitative institutional analysis with quantitative TCO modeling, bridging interpretive and economic approaches, grounding transition theory in measurable outcomes.

Policy implications emphasize the need to engage and consider the aspirations of multilayered stakeholders in formulating sustainability policies, particularly SOEs, the private sector, academics, NGOs, and the broader society. To effectively enhance the growth of the EV market, policymakers should focus on the TCO and the learning curve. China's experience demonstrates that time-limited and declining consumer incentives, along with a robust charging network, can help EVs move beyond the early adoption phase. In Thailand, incorporating export credit can help mitigate risks during the initial production phase. In Indonesia, reallocating fossil fuel subsidies to provide TCO-closing incentives—such as purchase rebates or tax credits for local content—can stimulate demand for EVs. Fiscal incentives should be targeted at making EVs affordable to enable mass adoption. This socio-technical transition must be inclusive, focusing on electric two-wheelers and three-wheelers in rural areas, supported by term subsidies, microcredit, and programs like EVs to villages. This initiative combines off-peak electricity rate discounts, micro-depot charging, and the public procurement of basic service fleets. Charging infrastructure needs to be developed along the rural–urban corridor using a matching grant model for local operators. This approach is similar to China's NEVs to the countryside campaign and India's FAME II, both of which have successfully increased penetration in non-metro areas. According to IEA data, the market share of EVs rises when charging infrastructure and incentives are developed simultaneously [60].

Biofuel policies should support smallholder farmers with minimum price contracts and sustainability premiums to ensure their long-term viability. Aligning ISPO with global standards is essential for market access [4,129]. Indonesia needs to develop second-generation biofuels from lignocellulose and agricultural waste while enforcing environmental conservation rules and offering performance incentives. Encouraging the use of used cooking oil (UCO) through collection systems and quality standards, like in the EU, is also important [130,131]. The government also needs to improve fuel quality standards and ensure vehicle compatibility, with support from manufacturers, similar to flex-fuel vehicles in Brazil [132].

The government needs to adopt more proactive policies that support emerging innovations, such as FCVs. Indonesia should establish carbon intensity standards for hydrogen, prioritize its use in fleets and logistics before introducing it to retail markets, and develop multi-energy hubs within Pertamina's and multinational corporations' gas station networks. Additionally, a regulatory sandbox for energy management in FCVs should be introduced. To further enhance research collaboration, it is important to address energy management concerns in FCVs, particularly by integrating driving intention, speed prediction, and health-aware control technologies. Providing financial support through green industrial credit based on technological readiness will ensure that Indonesia keeps pace with global energy innovation trajectories [133,134].

The limitation in this study occurs because of the limited number of interviews, as it is challenging to gain qualitative insight from all of the experiences of stakeholders involved in the sustainability of Indonesian transportation energy. Research encompasses many formations of institutional stability and institutional change over time and under the duality of external and exogenous influences on interactions between actors, including global, national, and local interactions. Conducting comparative studies in various countries would provide insights into the development of historical institutional theory, particularly in dealing with emerging technology and projecting the implementation of the technology trajectory in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en18215723/s1.

Author Contributions: Conceptualization. J.C.L. and F.F.; methodology. J.C.L. and F.F.; validation. J.C.L., M.M.R. and F.F.; formal analysis. J.C.L. and F.F.; investigation. J.C.L. and F.F.; resources. J.C.L. and F.F.; data curation. M.M.R.; writing—original draft preparation. J.C.L. and F.F.; writing—review and editing. J.C.L., M.M.R. and F.F.; visualization. J.C.L. and F.F.; supervision. J.C.L.; project administration J.C.L. and F.F. All authors have read and agreed to the published version of the manuscript.

Funding: The contribution of J.C.L. was funded by the project "Creating resilient sustainable microgrids through hybrid renewable energy systems" (EPSRC. EP/R030243/1).

Data Availability Statement: The data presented in this study are available upon request from the corresponding author because the data are part of an ongoing study.

Acknowledgments: Ferry Fathoni is fully supported by scholarships from PT Pertamina (Persero).

Conflicts of Interest: Ferry Fathoni was employed by the PT Pertamina (Persero). The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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