System dynamics modeling of energy transition impact on residential energy affordability in Indonesia

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Abstract

This study develops a system dynamics model to analyze Indonesia's transition from fossil-fueled electricity generation to renewables and its effects on residential energy affordability. The model integrates energy supply, demand, and fiscal modules to capture the interplay among generation mix, pricing, subsidies, and household income and affordability index for different consumer electricity segments, categorized as 450 VA and 900 VA recipients' group. Three policy scenarios—Business-as-Usual, Coal Phase Down, and Coal Phase Out—are simulated from 2020 to 2060. Results indicate that while an accelerated shift toward renewable energy supports national decarbonization targets, it also tends to increase electricity generation costs and prices. A rapid coal phase-out could impose higher tariff burdens and diminish affordability for vulnerable households if subsidy reforms are not carefully managed. These insights suggest that a balanced, gradual approach is needed—one that supports renewable capacity expansion while providing targeted measures to protect low-income consumers during the transition.

Keywords: energy transition; residential sector; electricity affordability; system dynamics; prescriptive analytics

1. INTRODUCTION

1.1. Background

Indonesia faces a major challenge: how to switch from fossil fuels to cleaner energy while keeping electricity affordable for its citizens, half of whom remain in middle- and lower-income brackets [1]. Indonesia's electricity capacities are dominated by fossil fuels (87%), comprising approximately 61% coal, 16% natural gas, and 10% oil-based generation [2]. This electricity source profile has underpinned energy security through coal's role as a low-cost baseload generation source, but it raises serious environmental concerns [3]. The Indonesian power sector accounts for approximately 40% of national energy-related greenhouse gas emissions, positioning electricity decarbonization as central to achieving net-zero targets by 2060. Therefore, shifting away from fossil-fuel-based

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electricity generation is fundamental as a mitigation measure [4]. Indonesia has pledged, through its National Energy Policy, to increase lower-carbon energy sources to 25% by 2030 [2].

However, the nation's ambitious policy would intensify the country's energy security risks, as the current power and economic sectors heavily rely on fossil fuels [5]. Specifically, the energy security challenge has four dimensions in the energy trilemma framework [6]: (1) availability—making sure there is enough electricity for growing demand, which is expected to grow 4.5% per year until 2040; (2) accessibility—keeping the power grid reliable and extending electricity to more homes (currently, 99.2% of households have access); (3) affordability—making sure electricity does not become too expensive as the system changes; and (4) acceptability—handling the environmental and social impacts. This study focuses on affordability, which is the main challenge determining whether Indonesia's transition will succeed.

Studies report that shifting away from fossil fuels could make electricity less affordable for poor households [7,8]. Affordability becomes a concern because NRE technologies have been portrayed as synonymous with high production costs, resulting in higher electricity tariffs [9–11]. However, recent research suggests that solar panels with battery storage could become very cheap—less than 60 USD per megawatt-hour by 2030—and could compete with coal when we account for environmental costs [9]. Yet in Indonesia's context—characterized by a state-monopoly electricity sector (PLN) that still favors fossil fuels. So, it is unclear whether global renewable cost reductions will help Indonesian households afford cheaper electricity [8].

About 32.5 million Indonesian households receive government electricity subsidies [12]. These households (24.3 million with 450 VA connections and 8.2 million with 900 VA connections) cannot easily reduce electricity use. When a household spends more than 10-15% of its income on electricity, it risks energy security. So, affordability is not just an economic issue—it is a matter of fairness and justice. Whether Indonesia's energy transition will help or harm poor people depends heavily on how affordability is managed.

1.2. Research gap & objectives

There are already studies on energy transition in Indonesia using various approaches, such as cost-benefit analysis [13], discrete choice experiment [14], and policy projections [15]. Although previous studies have contributed to the growth of the energy transition discussion, they are fragmented. There is a dearth of research that dynamically models how national transition policies toward low-carbon sources affect electricity costs over time, and specifically how these cost changes impact vulnerable household segments.

In response, this study addresses this gap by developing a system dynamics policy exploration model with three objectives: 1) Examine the links between changes in the energy mix, system costs, electricity prices, and household affordability under three scenarios (Business-as-Usual, Coal Phase-Down, Coal Phase-Out). Affordability is measured as yearly electricity spending divided by yearly household income; 2) Examine how the 450 VA households (24.3 million people, earning 1.2 million IDR per month, using 324 kWh per year, receiving a 30% subsidy) and 900 VA households (8.2 million people, earning 1.7 million IDR per month, using 648 kWh per year, receiving a 50% subsidy) are affected differently as prices change and subsidies decrease.

2. LITERATURE REVIEW

2.1. Energy transition and affordability

Energy transition is an evolving concept that is defined as a process of changing from one form of energy to another [16]. As there is a shift in paradigm due to the intensification of climate urgency, the definition is often modified to the transition toward lower carbon sources in the energy sector, including the power sector [17]. However, Wang and Lo [7] argue that the transition is not necessarily a complete shift from one set of dominant energy resources to another; rather, the process involves phasing out one dominant energy source while increasing the new resources. Scholars report that the transition pathway often intersects various aspects such as techno-economic factors, consumer behavior, market forces, and policy interventions [18]. However, recent growing literature often positions socio-economic aspects as the central discussion, as the shift will have a profound social impact [7].

Recent literature underscores the inherent risks accompanying energy transitions toward lower-carbon sources, although their potential to mitigate import dependence and bolster supply stability. Energy diversity— a balanced portfolio spanning renewables, natural gas, hydro, and other fuels—strengthens security by reducing exposure to price volatility [8]. However, realizing such diversity requires substantial infrastructure investments, which elevate consumer electricity tariffs even as emissions decline [8]. These upfront costs are often passed on to consumers, potentially making energy less affordable for vulnerable groups, who may already spend over 2 million IDR monthly, approximately 50% of middle-income households in Indonesia [8]. When household energy expenditure exceeds 10-15% of income, energy security is at risk.

Energy security is an umbrella term that encompasses the imperative of economic affordability in the energy transition agenda [19, 20]. Thus, the core tension: while energy diversification is crucial for long-term sustainability, it poses affordability challenges for vulnerable populations. This study centers on Indonesia's residential electricity sector, where the energy transition threatens household affordability through higher renewable costs, rigid tariff structures, and subsidy dependency. Affordability emerges as the critical index for modeling Indonesia's just energy transition, particularly for the approximately 32.5 million subsidized households (450 VA and 900 VA categories) [1, 21, 22].

2.2. Electricity transition analysis: Previous studies

Techno-economic studies use Levelized Cost of Energy (LCOE) to compare different generation methods and plan capacity expansion. Indonesian researchers have compared the costs of switching from coal to solar, modeled phased fossil fuel removal toward net-zero by 2050, and studied renewable scenarios with biomass and nuclear options [23]. This study calculates generation costs well but does not show how these costs affect household bills.

Political economy analyzes policy paths and institutional barriers. Indonesia-specific work looks at policy dynamics and electricity market rules [24]. These provide useful insights into what is politically possible and what institutional challenges exist, but they do not have numbers to estimate impacts on household affordability or model how affordability stress creates pressure to slow down the transition.

Social welfare analyzes deploy household surveys and energy poverty measures. Indonesian researchers have measured how price changes affect household well-being, created frameworks to measure energy poverty across regions, and analyzed household electricity spending patterns. While these studies measure energy poverty well, they have one major problem: they treat electricity prices as fixed inputs, analyzing how existing prices affect well-being, without modeling how changes in the energy mix create those price changes in the first place. This breaks the connection between supply-side policy (coal phase-out) and demand-side outcomes (household affordability) [25].

Scenario modeling evaluates renewable energy potential against coal dominance. Indonesia studies project that green energy scenarios could reach 12% renewable energy by 2025 (below the 23% target) and use system dynamics to assess big-picture policy effects on economic growth. However, these models either skip household-level details and feedback loops needed to assess fairness, or they struggle to cover multi-decade transitions. Existing Indonesian transition models remain separated: techno-economic models miss how changes in the energy mix drive up electricity bills, while social studies treat prices as disconnected from the supply-side generation policy that creates them.

Table 1: *This research's positioning in the energy transition literature*

Study	Driving mechanism				Economic analysis	Ecological analysis	Social analysis	Scenario analysis
	Techno-logical	Market	Policy	Cultural				
[26]	✓				✓			
[27]	✓				✓			
[28]	✓				✓			
[29]			✓		✓			
[30]	✓		✓		✓		✓	
[31]			✓		✓			
[32]		✓			✓			
[33]		✓			✓			
[34]		✓			✓			
[35]			✓	✓		✓		✓
[36]				✓		✓		
[37]				✓		✓	✓	✓
This study			✓		✓		✓	✓

2.3. Research positioning

This study addresses the identified gap by connecting fragmented approaches into one system dynamics framework. The framework traces the full causal chain: energy mix policy → generation cost → regulated prices → household affordability for 450 VA and 900 VA groups over 2020-2060.

Four contributions distinguish this work: (1) Methodological integration—Connects the full causal chain within system dynamics, allowing for feedback loops (such as affordability stress leading to policy changes) that static models cannot capture; (2) Specific household analysis—First prospective assessment, separated by the 450 VA and 900 VA household groups that Indonesian policymakers target in subsidy design; (3) Models Indonesia's actual transition scenarios rather than generic pathways; (4) Long-term scope—covers 2020-2060 net-zero horizon to capture delayed dynamics.

By tracing how scenario-specific energy mix changes create cost changes and price changes that affect household affordability (differently for each household group) over 40 years, this study provides the first complete, forward-looking, household-disaggregated assessment of how Indonesia's energy policy will shape residential electricity affordability—especially for vulnerable people for whom a "just" transition matters most.

3. METHOD AND PROBLEM ANALYSIS

3.1. Research scope and system boundary

The model boundary, illustrated in Fig. 1, focuses on the core feedback loops between the power generation sector and the residential sector. The simulation attempts to examine, with a particular focus on grid-connected households that are already integrated into the national grid, as well as the decentralized or off grid system. The model concentrates exclusively on households with existing grid access. Furthermore, the model divides households by their connection type (450 VA or 900 VA), which is linked to per capita income. This breakdown allows for different analyzes of transition impacts on different household types. The affordability and fiscal policy module models electricity pricing within the system, considering supply costs, government subsidy rates, and household income. Affordability indices are calculated for both household groups. The scenario allows for focused simulation of interactions between policy changes, energy mix changes, electricity price changes, and household affordability for different groups.

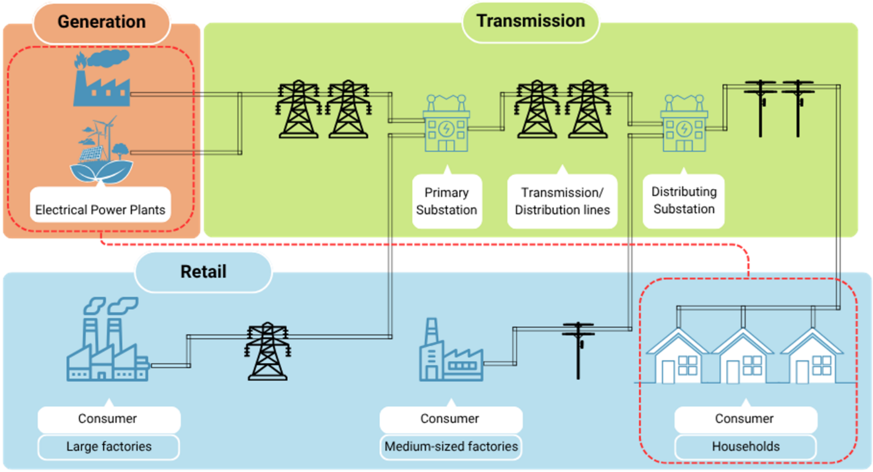

Figure 1: *This research focus in the electrification system constellation*

3.2. Justification for system dynamics approach

To effectively represent the complexity of the energy transition, the chosen method needs to simulate both the system's non-linear behavior and the associated uncertainties throughout the transition. A modeling approach like system dynamics (SD) is suitable for such problems. Hence, the use of system dynamics to model the problem is proposed. SD has become a widely adopted methodology over the last ten years for evaluating policy impacts via scenario simulation. Furthermore, the SD methodology can model the dynamic interrelationships between variables within complex systems—a capability demonstrated in fields ranging from economics and technology diffusion to energy systems. In addition, this research incorporates the feedback loops and accumulation processes (stocks and flows) over time. This makes SD the appropriate approach for this study, as it allows us to endogenously simulate the feedback loops within policy-driven changes in the electricity generation mix and their causal effects on household affordability.

3.3. Research conceptual model

Figure 2 shows the study's conceptual model. The study evaluates how three scenarios (Business as Usual (BAU), coal phase-down, coal phase-out) change the electricity mix in the generation sector and how this affects economic and social outcomes. Economic results include generation cost, electricity price, and subsidies. Social impacts are measured by the affordability index to capture electricity security during the transition. The conceptual model distinguishes between outside variables (determined by policy decisions) and inside variables (calculated dynamically within the model).

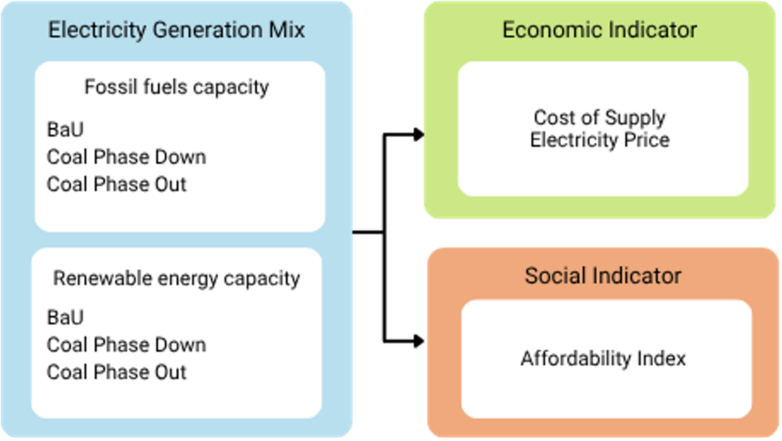

Figure 2: *The research conceptual model*

Exogenous variables include: (1) how fast fossil and renewable plants are built or shut down for each scenario, (2) subsidy policy changes for 450 VA and 900 VA groups, (3) the number of households and income growth rates, and (4) technology cost changes from outside sources (baseline cost for fossil and renewable sources). These outside inputs represent what decision-makers can influence.

Endogenous variables are calculated dynamically within the model: (1) total capacity by source type evolving through stock accumulation, (2) electricity mix shares determining the weighted-average generation cost, (3) average generation cost across the mix, (4) electricity prices from generation costs adjusted for policy and integration costs, (5) household-specific tariffs after subsidies are applied, and (6) affordability indices (yearly electricity spending divided by yearly household income) for each group. The dynamic calculation of these variables captures the feedback mechanisms central to how the model explains phenomena.

Key feedback loops include: (1) a balancing loop where higher electricity prices (from an increased renewable share) reduce affordability, potentially constraining the political viability of aggressive transitions; (2) a reinforcing loop (recognized but not explicitly modeled) where renewable capacity expansion could drive down costs through learning effects, though this study utilizes outside LCOE trajectories from research; and (3) an implicit policy feedback where affordability stress (high affordability index values) would realistically prompt subsidy adjustments or transition path changes, though the current model treats subsidy factors as outside scenario parameters rather than fully modeling this policy response.

3.4. Simulation setup and model structure

Figure 3 describes the simulation framework. The first stage collects data and makes assumptions about the electricity mix on the supply side before obtaining optimal energy mix parameters. In parallel, other input variables are used for the system dynamics model. Changing cost structures and affordability are modeled with system dynamics. Once the simulation starts, the electricity capacity mix (fossil and renewable sources) changes, and economic and social indicators are evaluated. The simulation produces two outputs: electricity price and affordability index for two groups of electricity consumers. Tables 2 and 3 present the detailed variables and parameters used in the system dynamics model. This study uses VENSIM® software. The simulation covers the electricity generation mix on the supply side and its impact on electricity price and affordability index on the demand side.

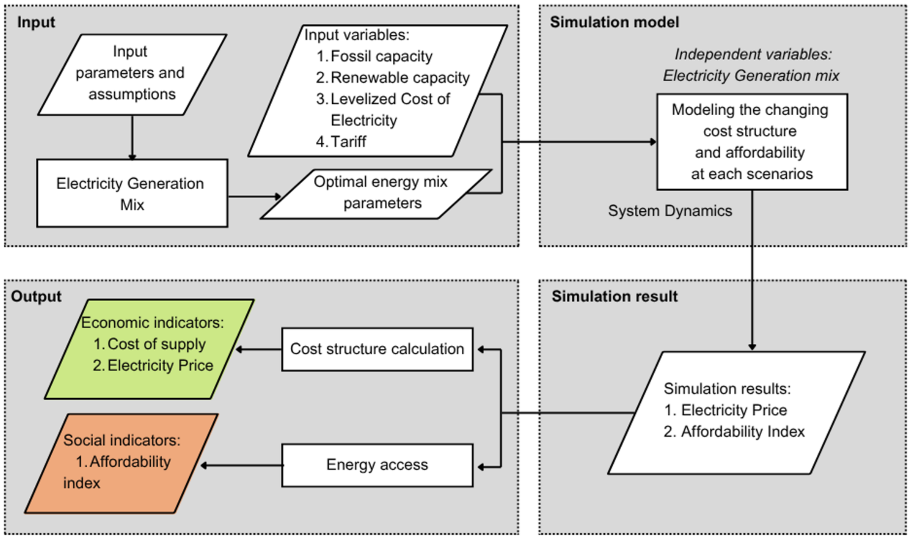

Figure 3: *The simulation framework*

The electricity generation mix is derived from the 2020 Indonesia Ministry of Energy and Mineral Resources statistics, since the simulation covers the period from 2020 to 2060 (40 years) for Indonesia's net-zero targets. Yearly rates for building and closing fossil and renewable plants are based on each policy scenario from Indonesia's energy pathway. Each capacity source contributes to the share of the generation mix, which defines how to calculate the average generation cost from each source. The electricity price is derived from the generation mix share plus the levelized cost of electricity from the literature. Finally, the electricity price is used to determine dynamic changes in tariffs and the affordability index for both household groups.

4. DISCUSSION AND RESULTS

Table 4 provides an overview of the results of the simulated scenarios. Indonesia's ambition for a clean energy transition, as modeled across the business-as-usual, coal phase-down, and phase-out scenarios, reveals a complex interaction between the evolving electricity generation mix, system costs, tariffs, and household affordability. In the business-as-usual pathway, fossil fuel dominance persists through 2060, as reflected in its share, while renewables have a modest proportion. This

Table 2: *The system dynamics model variables settings*

Variables	Value	Source
Fossil based electricity capacity	58 GW	[38]
Renewable based electricity capacity	11.2 GW	[38]
Capacity overbuild effect	0.2	Author's design
Levelized cost of electricity (base fossil)	1100 IDR	[39]
Integration cost RE	314	[40]
Financing premium RE	236	[40]
Policy incentive RE	50	[40]
Levelized cost of electricity (base RE)	1150 IDR	[39]
Subsidy factor 450 VA	0.3	[40]
Subsidy factor 900 VA	0.5	[40]
Population of 450 VA	24.3 M	[41]
Population of 900 VA	8.2 M	[41]
Use per HH of 450 VA	324 kWh	[41]
Use per HH of 900 VA	648 kWh	[10]
Income per month of 450 VA	1.2 M	[10]
Income per month of 900 VA	1.7 M	[10]

Table 3: *The simulation parameter of the system dynamics simulation*

Parameter	Description	Source
Scenario ID	Exogenous or endogenous index reflecting regulatory/political momentum, 1 for business-as-usual, 2 for coal phase-down and 3 for coal phase out	[40]

situation illustrates the dependence on coal as the preferred option for fulfilling electricity demand, while renewable electricity generation is only dominated by types of generators [42]. The phase-down scenario, by comparison, demonstrates that a more proactive retirement of coal—combined with moderate renewable build-out—produces modest gains in renewable share and gradual declines in fossil dependence. This finding aligns with previous studies that highlight the reliance of countries on an indirect transition, which, while having a lower carbon source, still utilizes mixed coal plants [43]. It is the phase-out scenario, however, that truly disrupts the system, driving renewable penetration sharply upward as fossil capacity is aggressively decommissioned, aligning more closely with Indonesia's net-zero targets [2,41].

Table 4: *Overview of each scenario result*

Indicator	BAU (1)	Coal Phase-Down (2)	Coal Phase-Out (3)
Fossil Share (2060)	50% (Moderate)	14% (Low)	Fossil is not generated
Renewable Share (2060)	50% (Moderate)	86% (High)	Renewable fully operate
Avg. Generation Cost	1500 IDR/kWh	1600 IDR/kWh	1800 IDR/kWh
Electricity Price	1700 IDR/kWh	1800 IDR/kWh	2000 IDR/kWh
Tariff 450 VA (IDR/kWh)	508 IDR/kWh	546 IDR/kWh	611 IDR/kWh
Tariff 900 VA (IDR/kWh)	843 IDR/kWh	910 IDR/kWh	1100 IDR/kWh
Total Subsidy (cumulative)	13 M	14.5 M	15 M
Affordability Index 450 VA	0.14%	0.15%	0.16%
Affordability Index 900 VA	0.31%	0.35%	0.39%

A comprehensive comparative assessment of the three scenarios reveals critical trade-offs between environmental ambition, economic feasibility, and social equity—dimensions that must be evaluated against Indonesia's stated research objectives of achieving decarbonization while maintaining electricity affordability for vulnerable populations. Drawing from multi-criteria scenario assessment frameworks, we evaluate each pathway across four key dimensions: (1) environmental effectiveness, (2) economic viability, (3) social equity, and (4) technical feasibility.

From an environmental perspective, the phase-out scenario best matches Indonesia's net-zero goals and the Just Energy Transition Partnership (JETP), which committed USD 20 billion to move Indonesia away from coal. This scenario offers the lowest immediate costs but ignores long-term

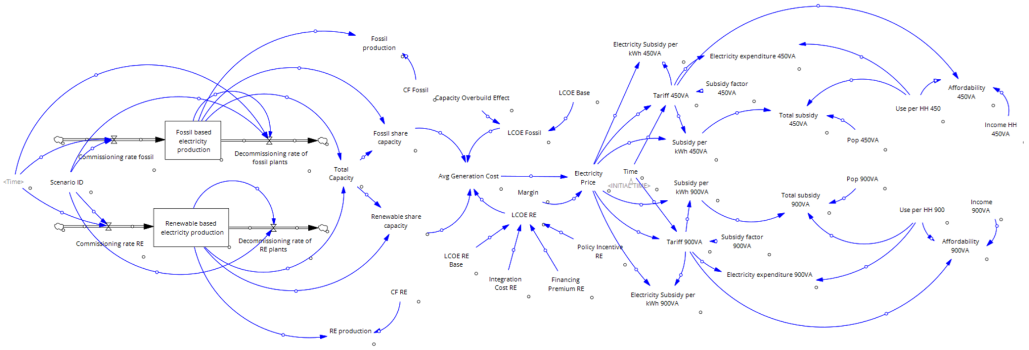

Figure 4: *Causal loop diagrams of the system dynamics model*

carbon problems, plant closure risks, and the falling cost of renewable technology. Recent research shows that solar-battery systems should reach costs below 60 USD per megawatt-hour by 2030, with integrated thermal-electrical storage systems reducing costs by 20-35% compared to single-storage. This suggests that the phase-out scenario's economic disadvantage will shrink substantially in the next decade. Meanwhile, the phase-down scenario produces moderate electricity price increases. This is because coal is often mixed with renewables and biomass, so generation costs remain more controlled than in phase-out.

From a social equity lens—which is central to this study's research objective— the phase-down scenario offers the best balance. It makes meaningful progress on climate goals while moving at a pace that allows gradual price adjustments and time to design subsidy reforms. This is consistent with research showing that social acceptance is as important as low costs for successful transitions. The phase-out scenario, despite its environmental benefits, risks creating "energy injustice," where rapid changes hurt vulnerable families unfairly. Technically, Indonesia's ability to manage energy change and grid infrastructure readiness also matters. Indonesia's regulatory system is fragmented, creating major implementation barriers. Closing coal plants too quickly without clear worker and community support creates significant social and economic risks. Research from Europe shows that successful renewable deployment requires not just technology but also fair treatment, transparency, and meaningful public participation—factors that are still underdeveloped in Indonesia's energy governance.

Based on this multi-dimensional assessment, we conclude that the phase-down scenario represents the optimal pathway for Indonesia's energy transition context. It balances environmental progress with economic feasibility and social equity, allowing time for: (1) renewable energy costs to decline further, (2) grid infrastructure to be upgraded, (3) just transition mechanisms for coal-dependent workers and communities to be established, and (4) subsidy reform policies to be carefully designed and gradually implemented. This conclusion aligns with scenario planning methodologies that emphasize the importance of technically realistic timelines and stakeholder acceptance over purely optimization-driven approaches.

Yet, this transition comes with economic trade-offs. The model shows that average generation cost and electricity price begin to diverge significantly after 2030, especially under the phase-out scenario. This is a direct result of the higher average generation cost of electricity generated from renewables, mirroring findings from several studies that reflect that the high cost of renewable development could hinder Indonesia's energy transition pathways. Furthermore, this finding confirms the previous study indicating that the scenario of coal phase out could potentially escalate electricity prices. However, it is crucial to contextualize these cost implications within the broader

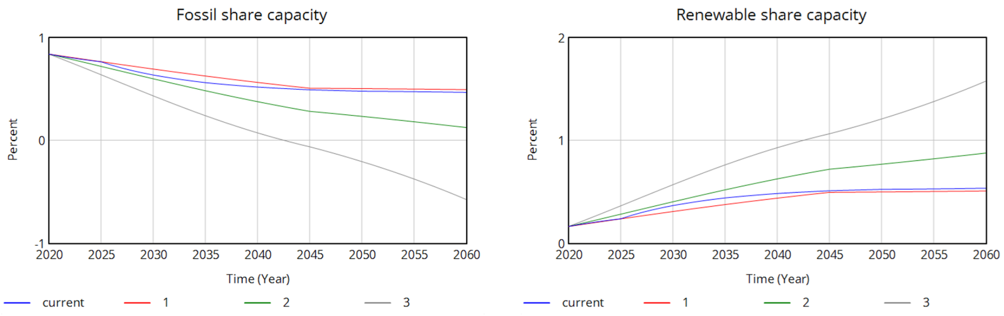

Figure 5: *Fossil and renewable share capacity in different scenario*

trajectory of renewable energy economics. The upfront capital intensity of renewable infrastructure creates a temporal cost burden that stabilizes and declines over its operational lifetime, unlike fossil fuel plants that face perpetual fuel cost exposure. Therefore, the cost-competitiveness of renewables is integral in adjusting the dominant renewable share in the future total energy supply to prevent any economic consequences. On the other hand, the phase-down scenario echoes "the probable" scenario output since the electricity price under this scheme does not soar as high as the previous one. It is understood that the practice of coal-firing, which combines fossil fuels with renewable sources, usually biofuels, keeps the generation cost predominantly from coal. Finally, the business as usual scenario reflects a stable electricity price due to the unchanging pattern of fossil fuel depletion for power generation plants. Yet, this stability is misleading, as it fails to internalize environmental externalities, carbon pricing mechanisms that are increasingly being adopted globally, and the long-term vulnerability to volatile fossil fuel markets.

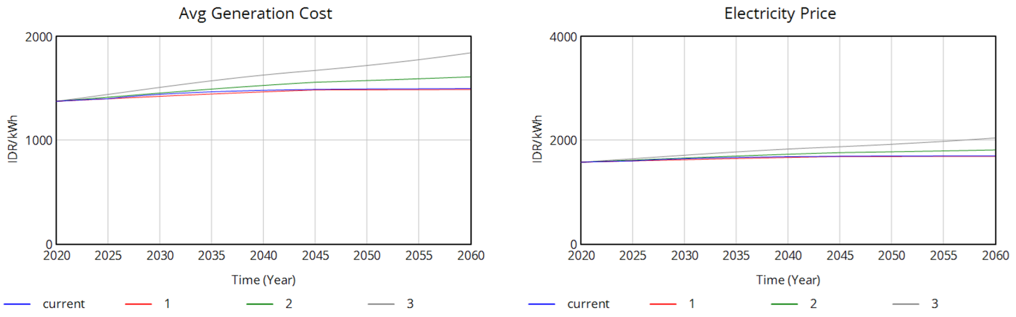

Figure 6: *Average generation cost and electricity price in different scenario*

In terms of the microscopic aspects of household's electricity prices, these upstream changes quickly translate into the lived reality of rising electricity tariffs, particularly for the most vulnerable groups, including subsidy recipients. As the simulation illustrates, both the 450 VA and 900 VA tariff groups remain flat until 2030 (under existing subsidy policies) but jump sharply subsequently as renewable sources take a higher proportion of the electricity mix. This result has been illustrated in a study that points out that the addition of renewable generation capacity may raise electricity prices [44]. This finding resonates with the previous finding that the transition can unintentionally lead to social inequity, resulting in increasing burdens on vulnerable communities to perform fundamental household activities, in this case, the recipients of subsidies for electrifications lower than 2200 VA [45,46]. The magnitude of these tariff increases warrants careful interpretation through the lens of energy poverty thresholds. International research on cash transfer programs and household expenditure patterns indicates that energy expenditures reaching 5-10% of household income represent a behavioral threshold, while expenditures exceeding 15-20% create conditions of severe energy poverty that compromise basic household functioning. Our affordability index results suggest that without intervention, vulnerable households under the phase-out scenario risk crossing these critical thresholds, potentially pushing them into multidimensional energy poverty—a condition characterized not only by high energy costs but also by inadequate access, poor energy quality, and compromised well-being. Consequently, it is imperative to produce a just pricing mechanism and fiscal mechanism in terms of electricity subsidy reform in the first phase of renewable installment to prevent any disadvantages of electricity transition.

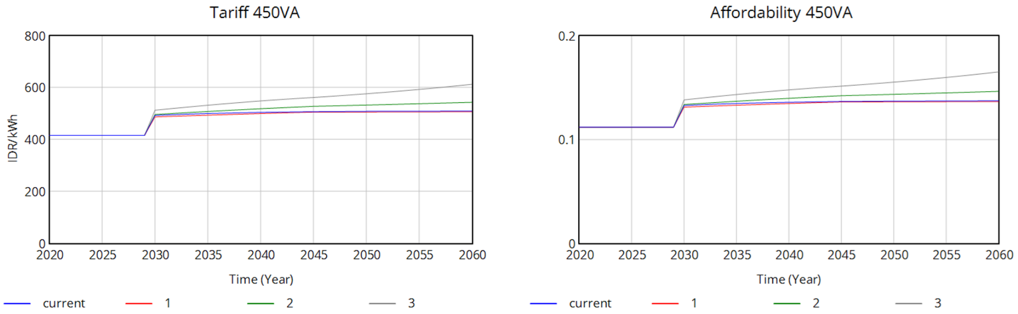

Figure 7: *Tariff and affordability index of 450 VA household group in different scenario*

Furthermore, the affordability index is measured as the share of income spent on electricity to emphasize the perspective of households as the consumers of this electricity mix transition. The simulation presents similar rises in the transition decades, and although it stabilizes after the initial shock, the new baseline remains significantly higher for both segments in the more ambitious decarbonization scenarios. However, there are quite differences between the tariff generated and its consequences on the affordability index between the two groups. As the tariff for 900 VA household consumers is relatively higher than that for 450 VA, the affordability index for this group is twofold higher. This situation proves the effect of taking out some portion of electricity subsidies for households with 900 VA connections [47], while keeping the 450 VA households receiving the benefits of subsidies. Empirical studies on Indonesia's 900 VA subsidy removal demonstrate that rural households exhibit higher price responsiveness than urban households, suggesting that regional disparities compound the socioeconomic impacts of subsidy reforms. This urban-rural divide reflects broader patterns of energy poverty and electricity access inequality that have been shown to contribute significantly to income inequality and poverty persistence across Indonesian provinces. These findings underscore the need for geographically differentiated policy responses that account for regional economic capacity, livelihood structures, and existing infrastructure disparities. This echoes the studies [48–50], which caution that energy poverty risks may intensify without targeted protections during periods of rapid reform. Thus, any subsidy reform, fiscal incentives, and market mechanisms should be implemented.

Overall, this research underscores a central policy tension: while accelerated fossil phase-out and robust renewable expansion are essential for climate targets, they can unintentionally undermine electricity affordability for vulnerable groups who are subsidized for their electricity—unless reforms are designed to smooth the transition. Navigating this tension requires a multi-pronged policy strategy that integrates four complementary elements: (1) strategic subsidy reform with progressive compensation mechanisms, (2) accelerated but paced renewable energy deployment aligned with cost reduction trajectories and grid readiness, (3) institutional capacity building and regulatory harmonization to enable coordinated implementation, and (4) robust just transition provisions that protect affected workers and communities.

This may involve gradually phasing out subsidies, directly compensating low-income users, or pacing renewable energy deployment in line with cost reductions and a strong commitment to halting coal-fired plant generations [2, 51]. More specifically, subsidy reform should transition from the current system of blanket consumption subsidies to targeted direct cash transfers for low-income households, coupled with lifeline tariff structures that protect basic consumption levels while introducing progressive pricing for higher usage tiers. Such targeted approaches have proven more fiscally sustainable and better at reaching vulnerable populations than universal subsidies. Renewable energy deployment should follow a strategic sequencing that prioritizes technologies and locations offering the best balance of cost-effectiveness, grid integration feasibility, and local acceptance.

Taken together, the findings indicate that Indonesia's decarbonization strategy will be most effective if it prioritizes a steady scale-up of renewable energy infrastructure, aligns electricity pricing with evolving system costs, and carefully redesigns subsidy mechanisms to protect affordability—particularly for lower-income households—while phasing out coal generation through a gradual, technically realistic timeline. Rather than pursuing abrupt fossil fuel closures, a well-adjusted approach that limits new coal investment and allows existing plants to retire naturally may offer a more politically and socially sustainable pathway to a just energy transition.

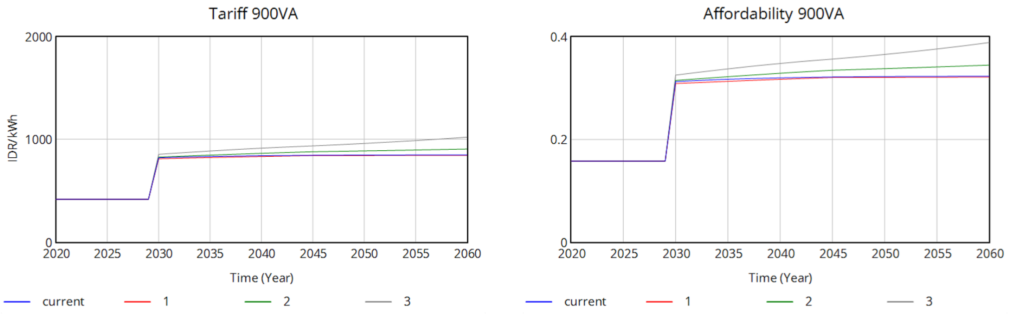

Figure 8: *Tariff and affordability index of 900 VA household group in different scenario*

5. CONCLUSION

This study addresses a key gap in Indonesia's energy transition discussion by showing how different electricity generation pathways affect household electricity affordability—especially for vulnerable subsidized families. First, the study traced how changes in the generation mix affect household affordability. As the renewable share grows from 16% (2020 baseline) to 30-35% (BAU), 55-60% (phase-down), or 80-85% (phase-out) by 2050, average generation costs rise due to renewable capital needs and grid integration. These cost increases flow through Indonesia's regulated pricing system, creating yearly electricity price increases of 2-7% depending on the scenario. Second, analysis separated by household type reveals significant fairness issues. The 900 VA household affordability index reaches 12-15% by 2045 under phase-out—approaching energy poverty thresholds of 10-15% of income—more than double the 450 VA index of 5-7%. This difference reflects both higher consumption (648 vs 324 kWh/year) and more aggressive subsidy removal for the 900 VA tier. Rural 900 VA populations face extra challenges given that they reduce electricity use more when prices rise.

Third, the 40-year simulation shows that affordability stress is concentrated in specific years, not constant. A U-shaped pattern emerges, indicating stability through 2030 under current subsidies, sharp increases during 2030-2045 when renewable capital costs peak, and old coal plants become worthless, followed by potential improvement after 2050 as renewable technology matures and costs fall. This pattern enables temporary support mechanisms rather than permanent subsidy expansion.

Fourth, comparing scenarios shows that coal phase-down best balances competing goals. It achieves substantial decarbonization (roughly two-thirds of phase-out results) with significantly lower affordability risk (roughly half the peak stress), while spreading transition costs to improve economic and political feasibility. The phase-out scenario, though environmentally superior, imposes affordability burdens that risk public backlash and transition failure. The BAU scenario locks in climate-incompatible trajectories.

The analysis offers five practical recommendations: 1) Adopt phase-down as the main transition strategy, with options to speed up if conditions allow. 2) Redesign subsidies from blanket consumption support to targeted lifeline tariffs and direct cash transfers, coordinated with renewable deployment. 3) Establish a Just Transition Fund and institutional authority to support coal-dependent workers and vulnerable households. 4) Invest in grid modernization and renewable integration infrastructure quickly.

Methodologically, this study combines previously separated analytical approaches—techno-economic cost modeling, regulatory economics, and household welfare analysis—within one system dynamics framework. This integration reveals dynamics that are invisible when examined separately and provides a template that other developing economies can use for similar energy justice challenges.

Key limitations include: (1) household electricity use treated as fixed despite potential behavior changes during affordability stress; (2) renewable costs parameterized from external sources rather than modeling how costs fall through learning; (3) national-scale analysis masking regional differences in grid constraints and integration costs; (4) subsidy parameters treated as scenario inputs rather than modeling how political pressure affects subsidy changes; (5) demand elasticity not modeled. These constraints limit the precision of exact affordability numbers but do not invalidate core findings regarding phase-down optimality, 900 VA vulnerability, and the temporal concentration of transition stress.

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