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Original research article



Strategies for Indonesia's low carbon energy transition based on a participatory energy system dynamic model

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ABSTRACT

Managing energy transitions in developing countries is essential to ensuring a stable and affordable energy supply for both society and industry. The social, economic, and environmental impacts of this transition are typically assessed using various energy models, with dynamic system approaches providing a more comprehensive representation than conventional methods. This study presents an Indonesia's energy system dynamics model, co-developed with key stakeholders—including experts from technical ministries, research institutions, NGOs, and energy companies—to evaluate energy security policies. A participatory approach enabled stakeholders to define the model's structure, select data, formulate policy scenarios, and assess simulation outcomes through meetings and focus group discussions, ensuring transparency and credibility. Stakeholders also play a crucial role in implementing scenario analyses and simulation insights. Notably, they emphasize the importance of maintaining fossil fuel supplies toward energy security, highlighting that policy modeling in Indonesia cannot overlook fossil fuel considerations. The resulting Participatory Energy System Dynamics Model (P/ESDM) integrates five interconnected sub-models: Demography and Macroeconomics, Final Energy Demand and Total Emissions, Total Energy Supply, Policy Interventions, and Impact Assessments. P/ESDM was applied to simulate eight policy scenarios, including oil production strategies, crude oil export restrictions, refinery capacity expansion, electric vehicle promotion, biodiesel blend mandates, renewable energy capacity expansion, coal production management, and urban gas network development. Policy implications are derived from simulation results, and the model offers adaptability for other nations pursuing energy security.

1. Introduction

The global energy landscape is undergoing rapid transformation driven by technological advancements, environmental concerns, and evolving societal needs [1]. Understanding the intricate interplay between energy supply and demand is crucial for developing sustainable energy systems [2]. However, many existing energy models predominantly focus on the supply side, neglecting complex energy demand dynamics [3]. Challenges also arise in assessing policy effectiveness and

stakeholder behaviour [4]. The need for novel or significantly adapted energy models is evident in developing countries, where distinct economic and social characteristics differ from developed nations [5,6].

Indonesia is a developing country undergoing an energy transition, the implementation of which will be shaped by various dynamics, including the burden of energy subsidies [7], the continued reliance of society on fossil fuels [8], particularly in the transportation sector [9], and the abundance of fossil energy resources [10]. Meanwhile, Indonesia has vast renewable energy potential—spanning bioresources

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[11], solar [12,13], wind [14–16], hydro [17], and geothermal [18]. Several studies have explored the potential of converting these renewable resources into alternative energy carriers such as biomass [19,20], biofuel [21–26], syngas [27–29], and hydrogen [30,31], highlighting their feasibility and scalability in supporting the energy transition. However, the oil and gas sectors are expected to remain a substantial part of the energy mix during the transition [9]. Moreover, previous NZE studies in Indonesia have often overlooked what will happen to coal and oil production and reserves when all energy demands are met by renewable energy [32–35]. Thus, rather than focusing on NZE pathways, the objective of our study is to assess manageable pathways of energy transition. Specifically, we estimate the impacts of five fossil energy policies, two renewable energy policies, and one electric vehicle policy on energy demand and supply, the renewable energy share, and the resulting emissions. These policies are a primary concern for the Indonesian government. We aim for our findings to support the formulation of the National Energy General Plan (RUEN), which integrates both fossil and renewable energy sources [36].

To achieve this objective, we developed a system dynamics model, called the Participatory Energy System Dynamics Model (or P/ESDM), to represent energy systems in Indonesia. A system dynamic approach provides an integrated framework that visualizes the interdependence of economic, social, and environmental factors through feedback loops, enabling effective communication with non-expert stakeholders [10]. The P/ESDM is distinguished by its capacity to integrate diverse perspectives, offering a comprehensive and adaptive framework for analyzing energy security strategies. By overcoming the limitations of traditional models—which often fail to capture the intricate interconnections between energy supply, demand, and socio-economic factors—the P/ESDM facilitates a more nuanced, context-specific understanding of energy systems in developing nations. This approach not only advances academic discourse in energy system modeling but also equips policymakers and industry leaders with a robust tool to navigate the complexities of energy security.

Moreover, our study engaged both academic and non-academic stakeholders in the development of P/ESDM. Participatory approaches to energy modeling have emerged as essential, fostering stakeholder engagement and enhancing the legitimacy and robustness of outcomes [37]. By leveraging a participatory approach, it contributes to advancing energy system research in developing nations, particularly in assessing energy security and promoting stakeholder involvement.

The remainder of this article is structured as follows: Section 2 reviews the relevant literature to support our novelty claim. Section 3 outlines the methodology and participatory tools employed in our analysis. Section 4 presents the results of model development through a case study on Indonesia, while Section 5 discusses the model's potential applicability in other developing nations. Finally, Section 6 synthesizes the findings and presents the conclusions.

2. Literature review

Various energy models have been utilized in energy system analysis in developing countries. The Low Emissions Analysis Platform (LEAP) model has been applied to estimate emission reductions as well as improvements in energy security and equity from the NZE strategy plan in Nepal [37]. Moreover, Pramudya [34] and Langer [32] employed the Balmore and Calliope energy models, respectively, to project electricity generation requirements, battery energy storage capacity, and inter-island grid interconnections to achieve NZE in Indonesia. The Latin American Deep Decarbonization Pathways project (DDP-LAC) used seven bottom-up and top-down energy models (GCAM, IMACLIM, LEAP, MESSAGE “ELENA”, OSeMOSYS, Pathways, and POLYSYS) to analyze the NZE transition in Argentina, Colombia, Costa Rica, Ecuador, Mexico, and Peru [38]. Other approaches used for low-carbon energy system analysis include agent-based modeling [39], econometric modeling [40], and input-output analysis [41].

System dynamics is an alternative approach for energy system analysis and has several advantages over other energy modeling approaches. It holistically analyzes the entire system as an integrated whole [10]. This model can simulate energy stocks and flows, utilize an energy accounting framework, and examine the interactions among economic, social, and environmental systems. These features provide a thorough understanding of complex and non-linear energy systems [42]. It includes feedback mechanisms, helping to assess the impact of changes in one part of the system on other parts and the system. This feedback is visualized simply through flow diagrams, making it easier to communicate the model and its assumptions to non-academic stakeholders.

The analysis of energy systems using a participatory approach is steadily increasing. Participatory processes involve through dialogue and information gathering at the local and national levels [43], engaging expert and non-expert stakeholders to foster energy democracy and build trust among them [44]. For example, Martinez-Hernandez [45] involved local community representatives, industry, and government to define bioenergy sustainability indicators. In terms of energy system modeling, Moallemi and Malekpour [46] formalized a participatory exploratory modeling framework consisting of three phases: computational model development, scenario exploration, and contingency planning. These phases are conducted in an iterative and participatory manner, incorporating new inputs as they emerge. One example is the involvement of key stakeholders from the energy and transportation sectors to identify driving forces in future Danish transport scenarios, which were simulated using the energy system model TIMES-DK [47].

To assess the integration of participatory processes with the system dynamics approach, we conducted a search on the Scopus database on 3 February 2025. We used the search string “system dynamic” OR “system dynamics” AND “participatory” applied to the article title, abstract, and keywords. This search yielded 478 articles, 13 of which are related to quantitative energy modeling as shown in Table 1. Most of the articles in Table 1 focus on studies at the state, city, and remote area levels.

Thus, participatory studies on dynamic energy systems at the national level remain relatively underexplored. Konara and Tokai [48] conducted an energy system analysis at the national level in Sri Lanka,

Table 1
Quantitative energy system dynamics studies using participatory processes.

Location	Participatory process	Studies
Cascina Municipality, Italy	Two workshops for system mapping and system dynamic model developments	[50]
Ethiopia	Stakeholder and expert consultation for scenarios and data	[49]
Flanders, Belgium	Workshops and presentations of the developed system dynamics model to thematic and model experts	[51]
Greater London, UK	Interviews and three workshops to build and validate the model	[52]
Mekong river basin, Cambodia	Six workshops, bilateral meetings, and expert interviews for visioning, CLD development, scenarios and policy interventions	[53]
Andalusia, Spain	Interviews, four workshops, seminars, and communication to develop a system dynamic model, scenarios, and policy recommendations	[54]
Sri Lanka	A questionnaire survey to determine the weights of sustainability indicators	[48]
Andalusia, Spain	Interviews and a workshop to identify challenges and scenarios	[55]
Minnesota State, US	Two regional workshops and two state-level workshops to provide scenarios	[56]
Remote area in Nepal	A scenario planning session for obtaining inputs from stakeholders	[57]
Varamin Plain, Iran	A workshop to develop a Mental Model	[58]
Sardinia, Italy	Participants play a serious game as policy makers in food, energy, water, climate and land management.	[59]

assessing sustainability using 13 indicators. To derive weight values for each indicator, they engaged in a participatory process that included a questionnaire survey targeting both energy suppliers and consumers. Utilizing these weighted indicators, they evaluated the sustainability of various scenarios simulated within a system dynamics model with three sub-models: energy demand, energy supply and transformation, and emissions. Similarly, Dagne [49] performed a national-level energy system analysis to determine an NZE pathway scenario in Ethiopia. Government officials were consulted on model design and assumptions used in the scenarios. The model with six sub-models (i.e., population, energy, infrastructure, economy, land use, and environment) estimates the NZE transition’s impacts on macroeconomics, economic growth, employment, labor productivity, poverty, income inequality, land restoration, and investment cost.

Our study aims to build upon previous national-level studies of participatory energy system dynamic models that have focused exclusively on net-zero emissions—often overlooking oil and coal supply and demand during the transition. To extend these insights, our research actively engages key stakeholders at every stage of the analytical process, while addressing both fossil and renewable energy supplies to secure energy security. Our system dynamics model comprises five interconnected sub-models: demography and macroeconomic factors, final energy demand and total emissions, energy supply, policy measures, and impact evaluations.

3. Method and data

This section provides a concise overview of the analytical methodology employed in this study. The research began with a kick-off meeting with UNDP and the Ministry of National Development Planning/BAPPENAS, where they provided guidance and outlined their expectations (Fig. 1). Subsequently, we developed a system dynamics model and conducted policy and scenario analyses in collaboration with government institutions, research organizations, energy companies, and non-governmental organizations (NGOs). Based on these analyses, we formulated policy recommendations. For a more comprehensive explanation and additional information, please refer to the Appendix.

3.1. Participatory process

The participatory process encompassed several strategic meetings held at various stages, including the initiative’s initial phase, the progression of model development, and the concluding presentation of the policy scenario analyses. Table 2 provides the details of the meetings and participants. The developed system dynamic model is named the Participatory Energy System Dynamics Model (P/ESDM).

The inaugural meeting, referred to as the kick-off meeting, took place on 7 January 2020. This meeting was organized by the Project Management Unit (PMU) of the Partnership for Action on Green Economy (PAGE) within the United Nations Development Programme (UNDP), which was the funding provider for the project. The meeting also invited the Director of Environmental Affairs from the Ministry of National Development Planning who initiated the project. The primary objective was to integrate this energy sector’s dynamic system model with the dynamic system model of Low Carbon Development Indonesia (LCDI) established by the Ministry of National Development Planning together

Table 2
Meetings and participants in the P/ESDM development.

Participants	Agenda						
	1	2	3	4	5	6	7
A. Ministry of National Development Planning/Bappenas							
1. Directorate of Environment	✓		✓			✓	✓
2. Directorate of Energy, Mineral, and Mining Resources				✓			✓
3. Directorate of Energy, Telecommunication, and Information					✓		✓
B. Ministry of Energy and Mineral Resources							
1. Secretariat of the Directorate General of New-Renewable Energy and Energy Conservation			✓				✓
2. Bureau of Communication, Public Information Services, and Cooperation	✓	✓	✓		✓	✓	✓
3. Bureau of Planning		✓	✓	✓	✓	✓	✓
4. Research and Development Centre for Electricity, New-Renewable Energy, and Energy Conservation Technology.	✓	✓	✓	✓	✓	✓	✓
5. Directorate General of Electricity							✓
6. Directorate General of Oil and Gas							✓
7. Directorate General of Coal and Mineral Resources							✓
8. Centre for Human Resource Development in Electricity, New and Renewable Energy, and Energy Conservation			✓	✓		✓	✓
C. Other key stakeholders							
1. Agency for the Assessment and Application of Technology		✓	✓	✓	✓	✓	✓
2. PMU UNPAGE Project, UNDP	✓		✓	✓	✓	✓	✓
3. System Dynamics Bandung Bootcamp	✓		✓	✓	✓	✓	✓
4. National Energy Council							✓
5. Ministry of Industry							✓
6. Ministry of Transportation							✓
7. The State-owned Electricity Company							✓
8. The State-owned Oil Company							✓
9. Indonesian Institute for Energy Economics (IIEE)			✓	✓			✓

Note: List of agenda: 1. Kick-off (7 January 2020), 2. P/ESDM development (28–29 April 2020), 3. P/ESDM review (8 June 2020), 4. P/ESDM review (23 July 2020), 5. P/ESDM integration to LCDI model (24 August – 23 November 2020), 6. P/ESDM Finalisation (23–25 October 2025), and 7. FGD (25 November 2020).

with the System Dynamics Bandung Bootcamp. The Director of Environmental Affairs outlined the objectives and expectations for the system dynamics model, followed by a discussion on the work plan led by the modeling team.

The initial model development was carried out by representatives from four units of the Ministry of Energy and Mineral Resources and representatives from the Agency for the Assessment and Application of Technology, from January to April 2020. On 28–29 April 2020, the modeling team then held a formal in-person meeting to review the progress of the dynamic system model development. The review concluded that it was necessary to create additional modules for EV policies, upstream oil and gas, oil and gas utilization policies for export and domestic use, as well as price and cost modules. The meeting also

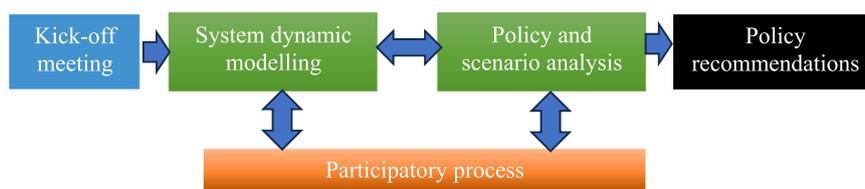


Fig. 1. Analysis steps.

provided updates on the latest data and information regarding key issues and programs in the energy and mineral resources sector.

The preliminary results and initial analyses were presented on 8 June 2020, to key stakeholders. In addition to the Director of Environmental Affairs at the Ministry of National Development Planning and the PMU of the PAGE/UNDP project, we invited stakeholders from clean energy policymaking bodies (i.e., the Secretariat of the Directorate General of New Renewable Energy and Energy Conservation), and external system dynamic modelers (i.e., the System Dynamics Bandung Bootcamp and the Indonesia Institute for Energy Economics).

This meeting served as a critical platform for gathering insightful feedback to enhance the model and refine the policy scenario analyses. Key recommendations included improvements to the renewable energy power plant sub-module, the oil refinery sub-model, and the development of a sub-model for land requirement impacts, as well as the simplification of economic calculations for electricity tariffs. Other suggested enhancements involved the addition of a simulation control panel for transportation policy, including panels for adjusting load factors, operational levels, and travel distances.

The meeting also addressed the selection of variables, aiming to use endogenous variables as much as possible. This could be achieved through econometric regression to define the necessary equation specifications. Additional issues discussed included carrying capacity related to constrained biodiversity and regional aspects. Detailed discussions were also held on biodiesel and coal policy scenarios. Another policy discussed was the green economy package, which includes the acceleration of solar energy programs, the sustainable energy fund, and market incentives.

Specifically, the UNDP requested an analysis comparing the effectiveness of two policies (namely EVs and rooftop solar PV) in reducing emissions. The meeting concluded with a recommendation for further coordination with the Ministry of Environment and Forestry, the Directorate General of Electricity, and the Directorate General of New and Renewable Energy and Energy Conservation to obtain the emission factors to be used, specifically tier-2 emission factors (national figures).

The amended results were re-evaluated with stakeholders on 23 July 2020. This online meeting also aimed to review the P/ESDM model and define scenarios for each policy analyzed. This subsequent meeting featured the participation of the Director of Energy, Mineral, and Mining Resources, as well as the Director of Electricity, Telecommunications, and Information from the Ministry of National Development Planning. They have different perspectives on energy supply and demand and thus offered enhanced insights regarding the model development and the associated policy scenario analyses.

From August 24 to November 23, 2020, we held 12 online meetings focused on refining the P/ESDM model and integrating it into the LCDI model. These meetings specifically addressed the development of each policy module, validation of simulation outputs, and integration of P/ESDM into the LCDI model. Additionally, discussions covered the policy implications of the simulation results.

The meetings were attended by the modeling team from the Ministry of Energy and Mineral Resources, representatives from the Ministry of National Development Planning of Indonesia, the System Dynamics Bandung Bootcamp, and the PMU UNDP. These 12 online meetings were later supplemented by an in-person meeting held from 23 to 25 October 2020, in Bandung, which focused on finalizing P/ESDM and conducting an in-depth analysis of the simulation results. On November 25, 2020, we conducted a focus group discussion (FGD) to disseminate the findings of the system dynamics model development and policy scenario analyses. The discussion involved representatives from the Ministry of Energy and Mineral Resources, the Ministry of National Development Planning, the PMU of the PAGE/UNDP project, and other relevant ministries.

During discussion, we explained that policies were simulated using three scenarios: the Business-as-Usual (BaU), Optimistic, and Custom scenarios. The results of the Custom scenario were not presented, as this

feature allows policymakers to modify the control panel menu for each module. The outputs from the policy simulation included projections of energy demand and supply, energy mix, greenhouse gas emissions, land requirements, and economic impacts (i.e., export revenues, import reduction, investments, and subsidy expenditures).

The FGD also addressed model improvements and simulation results based on feedback from previous meetings, including the simulation of biodiesel and palm oil price impacts, the limitations of energy reserves, the influence of electricity prices from renewable energy on electricity demand, and the algorithm for adding power plants by energy type based on their economic viability and changes in electricity demand. This FGD also sought to outline a subsequent agenda for the application of the model and policy scenario analysis results in strategic decision-making processes within the respective ministries and agencies.

3.2. The participatory energy system dynamics model (P/ESDM)

The P/ESDM was developed using a system dynamics model to integrate it into the larger LCDI system dynamics model. The P/ESDM is grounded in the fundamental principles of systems thinking and dynamic modeling [60,61] to address the complexity of Indonesia's energy sector.

System dynamics, pioneered by Forrester [60], provides a structured approach to understanding nonlinear behaviors, time delays, and interdependencies within the systems. This approach recognizes the interconnections and feedback loops between various components of the system, including production, demand, environmental impact, and socio-economic outcomes. Compared to other modeling approaches, the system dynamic model offers a more comprehensive understanding of the interactions and feedback loops of variables within a non-linear, complex system [62]. Additionally, the visualizations and interpretations of a system dynamic model are relatively easier, allowing the model to be adjusted with new data and information more efficiently [63].

The P/ESDM encompasses five interrelated sub-models: (a) Demography and Macroeconomic; (b) Final Energy Demand and Total Emissions; (c) Total Energy Supply; (d) Policy Interventions; and (e) Impact Assessments, as shown in Fig. 2. The final energy demand and emissions sub-model integrates distinct modules addressing transportation, industrial processes, residential consumption, commercial activities, miscellaneous energy users, and feedstock sectors. The total energy supply sub-model incorporates modules for the power generation sector, oil refining operations, biofuel production, gas and dimethyl ether (DME) utilization, coal conversion processes, and mining activities.

The policy interventions sub-model is structured into six modules: domestic market obligations (DMO) for coal and gas, renewable energy initiatives, biofuel mandates, and EV promotion. Finally, the impact assessments sub-model consists of two critical modules: land use dynamics and investment evaluations.

Each module interacts synergistically, forming a network of feedback loops that collectively shape the system's overall behaviour. The demographics and macroeconomic module serve as the primary driver of energy demand. The demographics module incorporates annual population growth projections, which are used to estimate total population and the number of households in rural and urban areas. These households are further classified into electrified and non-electrified categories based on electrification ratio data and projections. The macroeconomic module calculates total and sectoral GDP using annual GDP growth data for five energy-consuming sectors: transportation, industry, residential, commercial, and other sectors.

Consequently, the energy demand module represents the total energy demand from these five sectors plus the energy requirements for raw materials. Each of these six sectors is influenced by different factors. For instance, energy demand in the transportation sector is determined by the share of vehicles by technology type (e.g., internal combustion and hydrogen-electric vehicles), while energy demand in the industrial

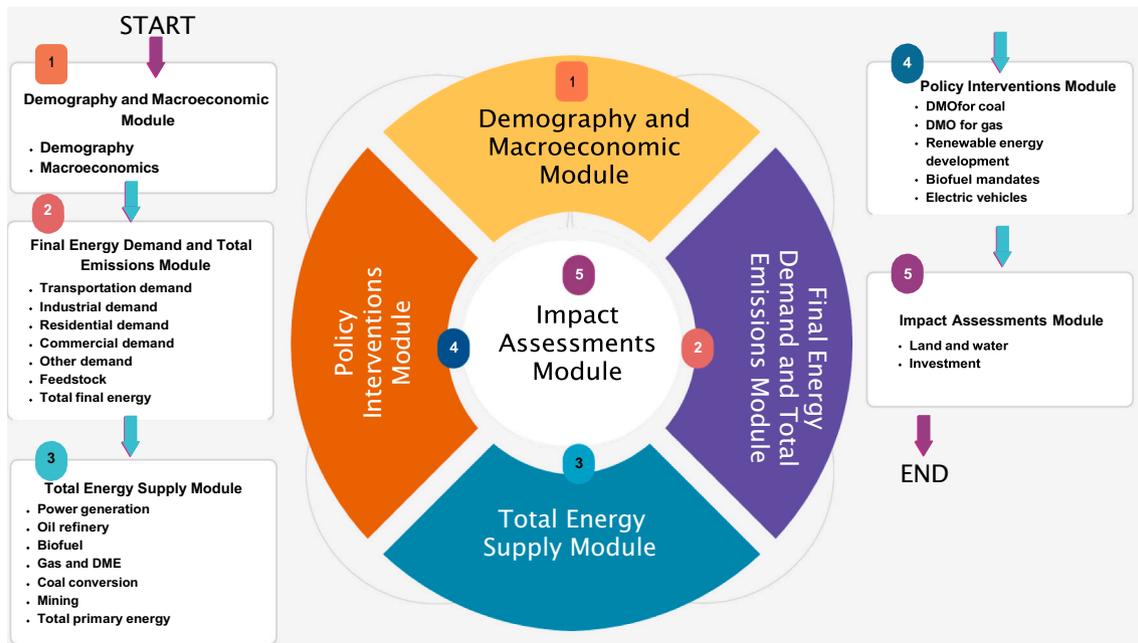


Fig. 2. Process flow of P/ESDM.
(Created by authors.)

sector is driven by industrial activity levels. The energy needs of each sector are then used to determine demand for various energy types, including electricity, coal, natural gas, petroleum products, LPG, renewable energy, and other refinery products.

Not all energy types are utilized across every sector. For example, electricity is used by the industrial, transportation, residential, and commercial sectors, whereas coal is exclusively consumed by the industrial sector, including power plants. Finally, the consumption of each energy type is multiplied by its respective emission factor to estimate the total emissions produced.

The total primary energy supply module utilizes the estimated energy demand by energy type in each sector, along with strategic policies and projects (e.g., increasing oil refinery capacity), to calculate total primary energy production, energy production by type, the volume of required energy imports, and the energy available for export. The primary energy sources considered include coal, bioethanol, biodiesel, natural gas, petroleum products, biomass, biogas, hydro, geothermal, solar, wind, ocean energy, and municipal solid waste.

This module also incorporates sub-modules for energy production, which encompass power plants, oil refineries, biofuels, gas, dimethyl ether (DME), coal conversion, coal production, petroleum production, and natural gas production. Each of these sub-modules includes strategic project parameters and links to the policy intervention module.

The policy intervention module consists of three sub-modules. The first sub-module, coal domestic market obligation (DMO), directly impacts coal exports. The coal trade balance then influences coal prices, which subsequently affect coal demand and investment in the coal sector. The final impacts analyzed in this sub-module include changes in GDP, employment, and community income resulting from variations in coal investment and production values. The second sub-module, gas DMO, functions similarly to the coal DMO sub-module. The third sub-module focuses on electric vehicles (EVs), evaluating the impact of EV targets on the number of vehicles by technology type, investments in the automotive sector, luxury goods tax, value-added tax, and the trade balance for petroleum products.

The impact assessment module examines the effects on land, water, and investment requirements. The land and water sub-module calculates the water and land required for the production of natural gas, petroleum, biodiesel, bioethanol, biomass, and electricity. The investment

sub-module estimates the capital requirements for the construction of power plants, DME plants, coal gasification plants, biodiesel plants, biorefineries, methanol plants, petroleum refineries, and smelters. Although the P/ESDM includes this module, our paper does not present its simulation results, as it is not the primary focus of our analysis.

3.3. Policy scenarios

The design and analysis of scenarios leverage insights from previous stakeholder engagements and model validations. These scenarios aim to identify pathways for achieving sustainability goals while balancing energy security (energy supply and demand), economic growth, and environmental preservation. This approach enables a comprehensive evaluation of how different policy choices influence the energy system and related sectors over time.

The simulation framework incorporates user-defined parameters via a sub-scenario panel within the P/ESDM interface. This design facilitates scenario customization, allowing stakeholders to examine the long-term implications of various energy policies. We simulated eight energy policy scenarios, analyzed under two perspectives: the Business-as-Usual (BaU) Scenario and the Optimistic Scenario.

Scenario simulations are conducted by adjusting sliders on the control panel of each module until the desired value or state is reached, as shown in Table 3. The first policy analysis focuses on the risk assessment of strategic project failures in the oil and gas sector, particularly regarding oil production and crude oil imports. Indonesia aims to produce 1 million barrels of crude oil per day [64], with several key projects initiated to achieve this goal, including oil exploration, the implementation of enhanced oil recovery (EOR), and reserve-to-production projects in oil and gas fields, such as Tangguh Train-3, Jambaran Tiung Biru (JTJB), Indonesia Deep Water Development (IDD), and Masela [65]. The BaU scenario assumes these projects fail to be executed, while the Optimistic scenario assumes that these projects are fully completed on schedule.

The second policy analysis examines the DMO for crude oil production [66]. In the BaU scenario, the DMO accounts for 90 % of total crude oil production. The optimistic scenario proposes increasing the DMO to 100 %, ensuring that all domestically produced oil is consumed within the country, aims to reduce reliance on oil imports.

Table 3
Policy scenarios to achieve energy security.

Policies	Descriptions
Oil production of 1 million bpd	<p>The success rates of oil exploration and EOR:</p> <ul style="list-style-type: none"> • 0 % for BaU scenario; and • 100 % for optimistic scenario. <p>The development progresses for IDD, JTB, Masela, and Tangguh projects:</p> <ul style="list-style-type: none"> • Cancelled for BaU scenario; and • On-track for optimistic scenario.
Redirecting oil exports for domestic needs	<p>The DMO for crude oil production in 2020 to 2050:</p> <ul style="list-style-type: none"> • 90 % for BaU scenario; and • 100 % for optimistic scenario.
Constructions of six oil refineries	<p>The construction progresses of RDMP Balongan #1 & #2, RDMP Balikpapan #1 & #2, RDMP Cilacap, RDMP Dumai, GRR Tuban, and GRR Bontang:</p> <ul style="list-style-type: none"> • Cancelled for BaU scenario; and • On-track for optimistic scenario.
EVs	<p>EV adoption rate in 2050:</p> <ul style="list-style-type: none"> • BaU scenario: 8 % for cars, 4 % for motorcycles, and 0 % for buses; and • Optimistic scenario: 50 % for cars, 100 % for motorcycles, and 20 % for buses.
Increased biodiesel mix	<p>Mandatory biodiesel mix:</p> <ul style="list-style-type: none"> • BaU scenario: 30 %; and • Optimistic scenario: 50 % since 2024, and green diesel production for 3.6 million kilo litres since 2024. <p>Biodiesel price and subsidy:</p> <ul style="list-style-type: none"> • BaU scenario: CPO price for US\$ 250 per tons, MOPS for US\$ 40 per bbl, 0 % VAT and no additional CPO export levy; and • Optimistic scenario: CPO price for US\$ 1250 per tons, MOPS for US\$ 140 per bbl, and additional CPO export levy for US\$10 per tons of CPO.
Renewable energy development	<p>Annual increase of renewable energy power plant capacity:</p> <ul style="list-style-type: none"> • BaU scenario: 600 MW for all renewable energy and no phase-out of oil-fuelled power plants. • Optimistic scenario: 750 MW for geothermal, 2000 MW for hydro power, 300 MW for wind turbine, 1000 MW for solar energy, and 800 MW for bioenergy. In addition, nuclear power plants with total capacity 2600 MW will be constructed gradually and oil-fuelled power plants will be phased-out after 2025.
Coal production management	<p>Exploration and exploitation rate of coal reserves:</p> <ul style="list-style-type: none"> • BaU scenario: No new reserves and 3.28 % increases per year of coal production. • Optimistic scenario: 12 % increases per year of coal reserves and 0.5 % increases per year of coal production.
Expansions of urban gas networks	<p>Total customers of urban gas networks by 2050:</p> <ul style="list-style-type: none"> • BaU scenario: 887,000 customers with gas price for 15.6 cUS\$ per m³; and • Optimistic scenario: 30 million customers with gas price for 28 cUS\$ per m³.

(Sources: [66–72].)

The third policy analysis evaluates the impact of new refinery capacity on crude oil, gasoline, and diesel imports. Indonesia has launched the Refinery Development Master Plan (RDMP) to expand refinery capacity at four existing facilities: Cilacap, Balongan, Balikpapan, and Dumai. Additionally, two new Grass Root Refineries (GRR) are under construction in Tuban and Bontang [72]. The initial projects scheduled for completion include RDMP Balongan Phase 1 and RDMP Balikpapan

Unit 1, each designed for a 50,000 barrels per day (bpd) capacity. By 2025, three additional RDMP projects—Balongan Unit 2, Balikpapan Unit 2, and RDMP Cilacap—are expected to commence operations. By 2026, RDMP Dumai (100,000 bpd), along with the new Tuban refinery (300,000 bpd) and the new Bontang refinery (300,000 bpd), is projected to become operational, collectively adding 952,000 bpd of refining capacity by 2026. The BaU scenario assumes the cancellation of all refinery projects, whereas the Optimistic scenario assumes that all projects are completed on schedule, ensuring increased domestic refining capacity and reduced reliance on fuel imports.

The fourth policy analysis assesses the effects of accelerating the EV adoption on gasoline and diesel imports. In the BaU scenario, the EV market share is projected to reach 8 % for cars, 4 % for motorcycles, and 0 % for buses by 2050. In contrast, the optimistic scenario anticipates a market share of approximately 50 % for electric cars [69], 100 % for electric motorcycles, and 20 % for electric buses by 2050.

The fifth policy analysis examines the impacts of increases in the biodiesel mix, crude palm oil (CPO) prices, Mid Oil Platt's Singapore (MOPS), and CPO export levies on biodiesel utilization and diesel imports. The Optimistic scenario proposes a gradual increase in the biodiesel and green diesel blend rate to 50 % [70] and the addition of an export levy on CPO if CPO prices exceed the reference export levy. Indonesia is actively promoting the development of green fuels through its existing refining infrastructure, utilizing both co-processing techniques and dedicated refineries. Key initiatives include the establishment of co-processing facilities for green diesel at Refinery Unit (RU) II Dumai, RU IV Cilacap, and RU VI Balongan, collectively designed to achieve a processing capacity of 2000 barrels per day (bpd), equivalent to 100,000 kiloliters (KL) annually [73]. Additionally, plans are underway to construct a standalone refinery unit at RU III Plaju with a capacity of 1 million KL per year, alongside modifications to RU IV Cilacap to enable the conversion of CPO into green diesel, green jet fuel, naphtha, and LPG at a rate of 6000 bpd [67].

The sixth policy analysis concentrates on the imperative acceleration of renewable energy capacity expansion. Under the BaU scenario, the historical average capacity augmentation over the past five years has been approximately 600 MW annually [74]. In contrast, the optimistic scenario forecasts a substantial increase to an average of 5 GW per year. This additional capacity in the optimistic scenario derives from a diverse array of renewable energy technologies: hydropower and mini-hydro systems contribute 2000 MW annually, geothermal energy adds 750 MW, solar power accounts for 1000 MW, wind energy contributes 300 MW, and bioenergy supplements the mix with 800 MW. Furthermore, it is anticipated that diesel power plants will be systematically decommissioned by 2050.

The seventh policy analysis focuses on optimizing coal production. The BaU scenario assumes a coal production growth rate of 3.28 % per year [74], despite no corresponding increase in proven coal reserves. In contrast, the Optimistic scenario envisions a more conservative coal production growth rate of 0.5 % per year, accompanied by an annual increase in proven coal reserves of approximately 12 %. Under this Optimistic framework, Indonesia maintains its reliance on coal, complemented by the implementation of clean coal technology and Carbon Capture, Utilization, and Storage (CCUS) systems, ensuring a more sustainable approach to coal-based energy production.

The eighth policy analysis examines the implications of expanding the city gas network to reduce liquefied petroleum gas (LPG) consumption, imports, and subsidies. The government plans to develop urban gas networks in residential areas near natural gas sources or existing gas pipeline infrastructure. Since domestically produced natural gas is more efficient for direct use than for export or conversion into LPG, the government offers city gas at a lower price than LPG to incentivize households to transition to the urban gas network. In the Optimistic scenario, the number of city gas connections is projected to increase to 10 million households by 2030 and 30 million households by 2050 [68]. In stark contrast, the BaU scenario assumes that no additional

city gas connections will be established after 2024.

3.4. Input data on demography and macroeconomic

Demographic and macroeconomic forecasts, such as population and gross domestic product (GDP), are key input data for modeling (see Table 4). For instance, RUEN utilized population and GDP data from 2015 [75]. In our analysis, we assumed a declining population growth rate [76], resulting in a population increase from 255.6 million in 2015 to 318.9 million by 2045 and 325.87 million by 2050, which is lower than the RUEN projection of 335.3 million. Similarly, GDP growth in RUEN was projected at 7.5 % in 2018, whereas actual values recorded 5.17 % [36]. Therefore, we adopted data from [36], which projected GDP growth in 2050 at 4.73 %, compared to 6.3 % in RUEN. Consequently, per capita GDP is expected to rise from 19.98 million IDR in 2000 to 183 million IDR in 2050. Additional data and assumptions are available in the P/ESDM.

4. Results

4.1. Oil production

In Fig. 3a, the BaU scenario forecasts that oil production will reach 364 thousand bpd by 2030. From 2020 to 2050, the anticipated average oil production is projected to be 525 thousand bpd, or an average decline of 3 % per year. The average oil export will be 48 thousand bpd annually, generating approximately US\$0.9 billion in revenue. Meanwhile, the average oil import will be 632 thousand bpd per year, or equivalent to US\$12 billion annually.

In contrast, oil production under the optimistic scenario is anticipated to escalate to 1 million bpd by 2030, as illustrated in Fig. 3b. The average oil production from 2020 to 2050 is expected to be 942 thousand bpd, exhibiting an annual decline of only 0.6 %. The increase in oil production results in average annual oil exports rising to 114 thousand bpd, while at the same time, average annual oil imports drop to 114 thousand bpd. Both exports and imports are valued at US\$2.1 billion each. Compared to the BaU Scenario, the Optimistic Scenario has US\$9.9 billion lower oil import values and US\$1.2 billion higher oil export values, resulting in a total benefit of US\$11.1 billion.

4.2. Diversion of oil exports for domestic refinery needs

Fig. 4 delineates the implications of increasing the DMO of crude oil production from 90 % (BaU) to 100 % (Optimistic Scenario). In the BaU scenario, the average annual export volume of is around 48 thousand bpd, equating to approximately US\$ 905 million. Consequently, the anticipated average annual crude oil import volume is estimated at 632 thousand bpd, incurring costs around US\$ 12 billion.

The optimistic scenario leads to a significant reduction in the average annual export volume, which is 4.7 thousand bpd from 2020 to 2050, equating to approximately US\$ 89 million. Concurrently, the forecasted average annual oil import volume is expected to diminish to 382 thousand bpd, with a value of US\$ 7.3 billion, in stark contrast to the BaU scenario. This optimistic outlook yields an average annual savings of US \$ 3.9 billion in the oil trade balance between 2025 and 2050. Such

Table 4
Assumptions on GDP and population growth.

Year	GDP growth (%)	Population growth (%)
2020	5.40	1.21
2025	6.00	1.00
2030	5.93	0.80
2035	5.63	0.62
2040	5.43	0.48
2045	5.03	0.36
2050	4.73	0.24

savings are realized through a reduction in oil imports amounting to US\$ 4.8 billion, notwithstanding a potential loss in export revenue totaling US\$ 815 million.

4.3. Addition of refinery capacity

In the BaU scenario, the absence of enhanced refining capacity is poised to exacerbate the disparity between gasoline and diesel production and consumption, as illustrated in Fig. 5. The average annual crude oil import required for refineries stands at approximately 585,000 bpd, resulting in an economic outlay of around US\$ 11.1 billion per year from 2025 to 2050. Furthermore, the average annual imports of gasoline and diesel are estimated at 773,000 bpd, with a financial implication of US\$ 16.2 billion. Total average values of crude, gasoline, and diesel import will be US\$ 27.3 billion per year.

In the optimistic scenario, average annual crude oil imports will escalate to 1.1 million bpd (Fig. 6), costing US\$ 20.2 billion per year. In other words, crude oil imports will increase by approximately 477,000 bpd, with a corresponding financial impact of US\$ 9.1 billion annually, compared to the BaU scenario. However, domestic production of gasoline and diesel will rise, leading to a reduction in average annual gasoline and diesel imports to 407,000 bpd, valued at US\$ 8.4 billion.

A comparative analysis of total oil, gasoline, and diesel imports between the BaU and optimistic scenarios indicates an average annual increase in import expenditures amounting to US\$1.3 billion. This finding implies that the optimistic scenario may not represent an ideal outcome when evaluated solely based on the yields of gasoline and diesel refining processes, as the import value of crude oil outweighs the savings derived from gasoline and diesel imports. These losses will turn into benefits if the DMO crude oil production policy in the previous section can be fully implemented. Moreover, the overall import value may be enhanced when considering additional refinery outputs, including aviation fuel, LPG, and various petrochemical products.

4.4. Electric vehicles (EVs)

Fig. 7 illustrates the demand and production for gasoline and diesel under both the BaU and optimistic scenarios. In the BaU scenario, the average annual imports of gasoline and diesel are projected to be approximately 773 thousand bpd, amounting to an economic value of US\$ 16.2 billion per annum. In contrast, the optimistic scenario forecasts a reduction in average annual gasoline and diesel imports to 535 thousand bpd, with an import value of US\$ 11.3 billion per year. This represents a significant decrease of about 238 thousand bpd, translating to a savings of US\$ 4.9 billion annually in fuel imports.

Nevertheless, the optimistic scenario for EV adoption presupposes the continuation of the BaU framework for renewable energy development, resulting in a substantial dependence on coal-fired power plants for electricity generation. Consequently, emissions under the optimistic EV scenario are projected to be higher, with an estimated 964 million tons of CO_{2e} equivalent (CO_{2e}) in 2030 and 2145 million tons of CO_{2e} in 2050. In comparison, the BaU scenario for EVs yields emissions of 960 million tons of CO_{2e} in 2030 and 2085 million tons of CO_{2e} in 2050.

4.5. Increased biodiesel mix

In the BaU scenario, the policy of maintaining a 30 % biodiesel blend without the establishment of green refineries yields an average biodiesel consumption of 227,500 bpd annually, as illustrated in Fig. 8a. The average annual diesel import stands at approximately 116,000 bpd, incurring an import expenditure of US\$2.5 billion per year. The renewable energy mix is projected to reach 10 % by 2025 and 8 % by 2050. This trajectory is expected to culminate in CO_{2e} emissions of 775 million tons by 2025 and 2085 million tons by 2050.

Conversely, the optimistic scenario would augment biodiesel utilization by 62 % relative to the BaU scenario, reaching 368,700 bpd as

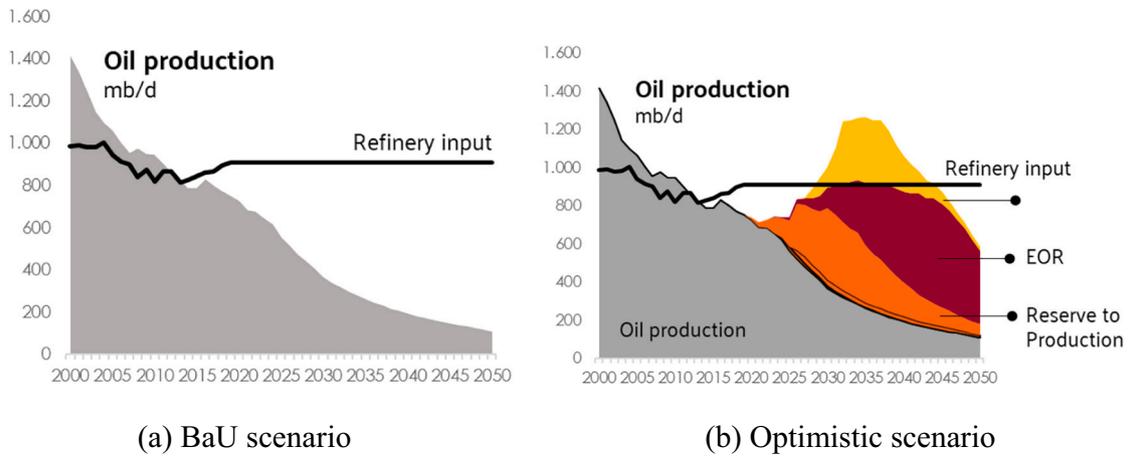


Fig. 3. Projections for oil productions. (Created by authors.)

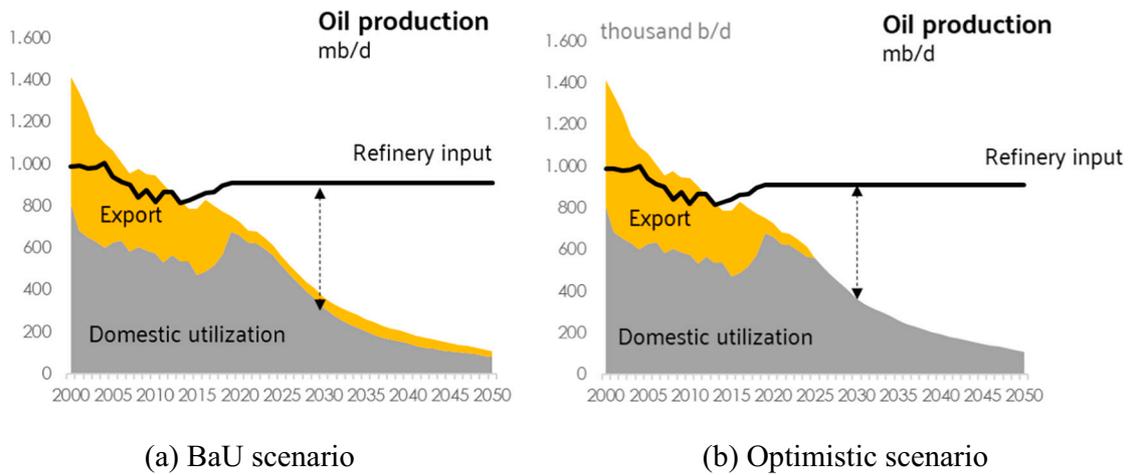


Fig. 4. Projections of oil export and utilization. (Created by authors.)

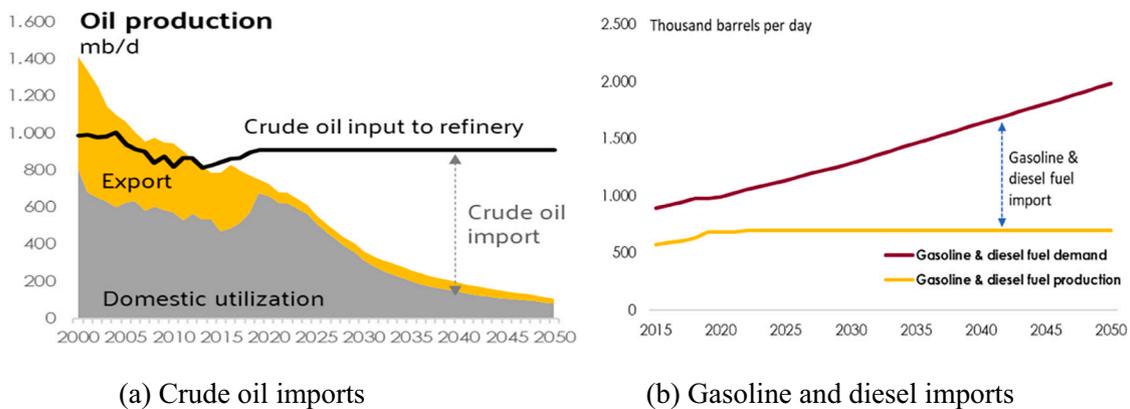


Fig. 5. Crude oil, gasoline, and diesel imports at the BaU scenario. (Created by authors.)

depicted in Fig. 8b. This scenario would result in a surplus diesel production of 26,000 bpd annually, facilitating exports with a potential revenue generation of US\$557 million per year. The renewable energy mix is anticipated to expand to 13 % by 2025 and 10 % by 2050. Emissions in the optimistic scenario would amount to 757 million tons of

CO_{2e} in 2025 and 2045 million tons of CO_{2e} in 2050. The increase in biodiesel production under the optimistic scenario necessitates a rise in land usage from 10,000 km² in the BaU scenario to 25,000 km² by 2030. By 2050, the land required for biodiesel cultivation is projected to escalate to 19,000 km² in the BaU scenario and 35,000 km² in the

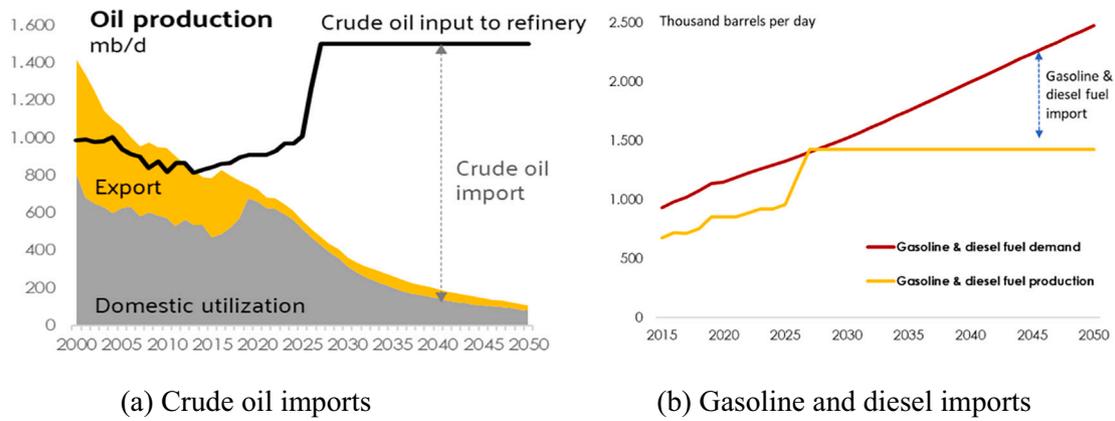


Fig. 6. Crude oil, gasoline, and diesel imports at the Optimistic scenario. (Created by authors.)

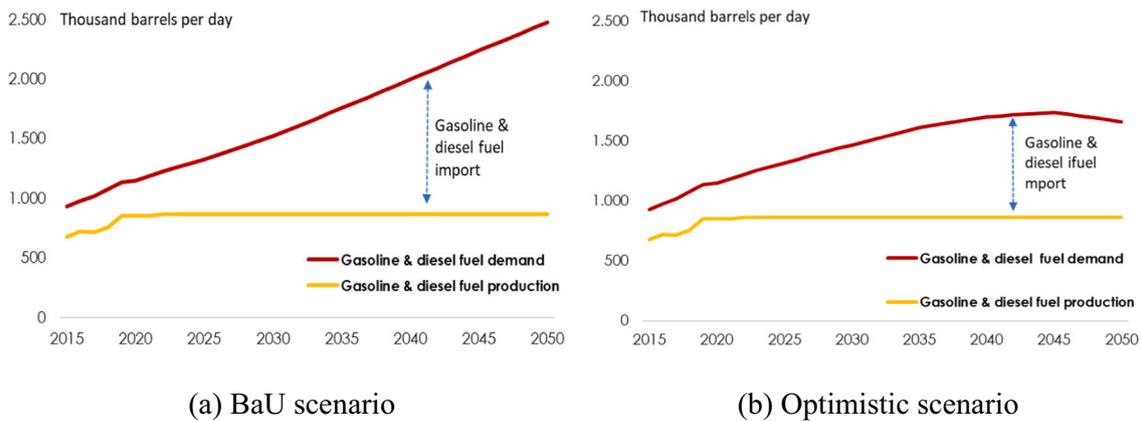


Fig. 7. Projections of gasoline and diesel production and consumption. (Created by authors.)

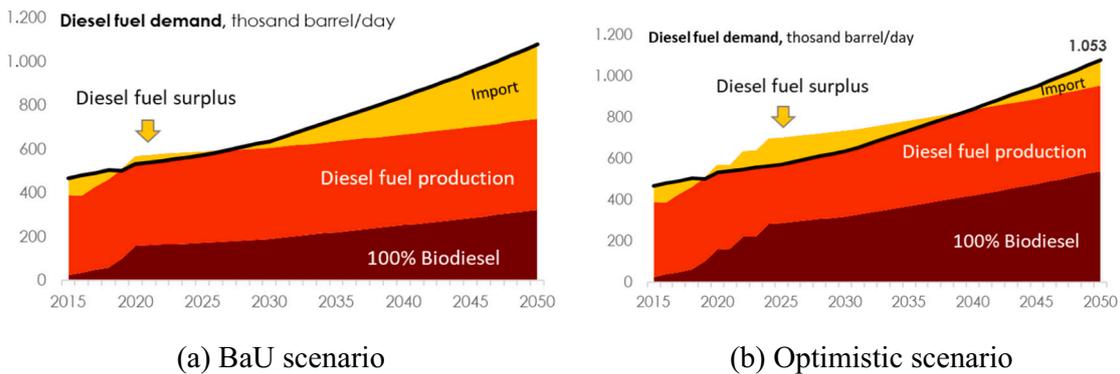


Fig. 8. Projections of diesel and biodiesel demands. (Created by authors.)

optimistic scenario.

4.6. Renewable energy developments

Fig. 9 illustrates the comparative growth trajectories of renewable energy generation capacity across two distinct scenarios. In the BaU scenario, the projected increase in renewable energy capacity reflects the historical trend observed over the past five years, which averages approximately 600 MW annually. Under this scenario, renewable energy

capacity is anticipated to expand from 12 GW in 2025 to 26 GW by 2050, resulting in a contribution of 10 % to the energy mix in 2025, with a slight decline to 9 % by 2050.

Conversely, the optimistic scenario posits a more aggressive trajectory, forecasting an average annual increase of approximately 5 GW until 2050. In this scenario, renewable energy capacity is expected to surge from 23 GW in 2025 to an impressive 149 GW by 2050. The proportion of renewables within the primary energy mix is projected to escalate to 15 % by 2025 and 34 % by 2050. This optimistic outlook is

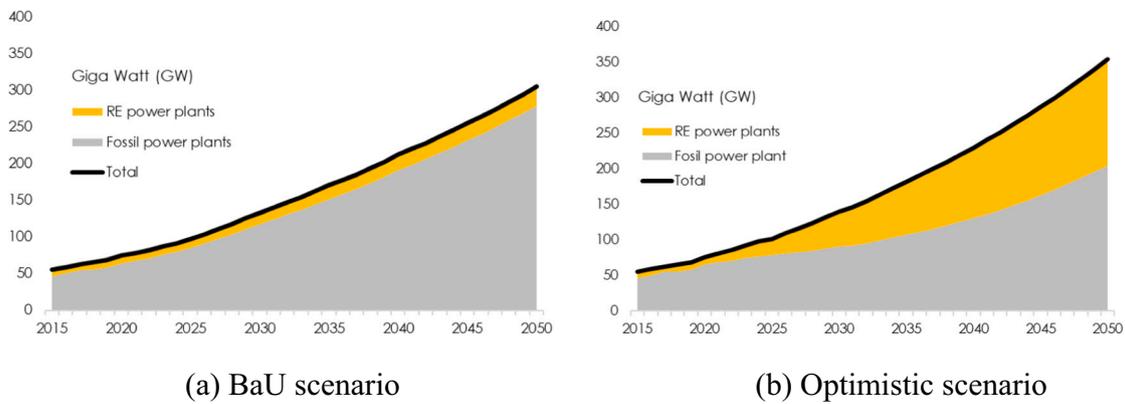


Fig. 9. Projections of renewable energy capacity. (Created by authors.)

associated with a significant reduction in greenhouse gas emissions, with carbon dioxide equivalent emissions estimated at 726 million tons in 2025 and escalating to 1494 million tons by 2050.

4.7. Coal production management

This policy simulation posits that, in addition to the variations in production scenarios and enhancements in coal reserves, all other parameters remain aligned with BaU conditions. Notably, an average escalation in coal demand of 5.1 % per year is anticipated from 2020 to 2050. As illustrated in Fig. 10a, the BaU scenario forecasts a compound growth rate of 3.28 % per year in coal production, projecting an output of 1.5 billion tons by 2050, which represents a substantial increase of 2.5 times the production level recorded in 2019. Concurrently, coal exports are expected to expand at 2.4 % per year, or 615 million tons per year, with an estimated export valuation of US\$ 51.3 billion annually. Consequently, by 2050, the residual coal reserves are projected to possess a lifespan of merely 5.5 years, indicating that, in the absence of new reserve discoveries, national coal resources may be depleted by 2055.

Conversely, the Optimistic scenario depicted in Fig. 10b adheres to the national medium-term development strategy for coal production until 2024, after which production is anticipated to increase at a subdued rate of merely 0.5 % per year from 2025 to 2050. In this context, coal exports are projected to decline at 3 % per year, culminating in an average export volume of 346 million tons per year and a corresponding export value of US\$ 28.9 billion per year. With this tempered production trajectory, coal output is estimated to reach approximately 715 million tons by 2050, thereby extending the reserve lifespan to an estimated 25

years.

4.8. Expansions of urban gas networks

In the BaU scenario, the expansion of urban gas networks, exclusively financed by the national budget, results in a total of 887,000 connections between 2020 and 2050 (Fig. 11). This constrained expansion facilitates the reduction of LPG consumption for only 0.1 million tons per year. Consequently, average yearly LPG imports are projected to hover around 11.35 million tons, amounting to a financial burden of approximately US\$ 6.35 billion per year.

Conversely, the optimistic scenario posits a more robust development of urban gas infrastructure. This strategic expansion would enable the conversion of 1.7 million tons of LPG consumption per year within the same timeframe. As a result, LPG imports would diminish to 9.8 million tons annually, valued at US\$ 5.5 billion. This optimistic trajectory would yield a significant reduction of 1.5 million tons in LPG imports each year, translating to savings of approximately US\$ 0.8 billion.

5. Policy implications

Our study was designed and initiated before the COVID-19 pandemic; however, much of its implementation was carried out during large-scale social restrictions, which impacted the participatory process and policy analysis conducted. Most of the participatory process was conducted online, which, surprisingly, worked well. Concerns about a lack of participant engagement and limited collaboration due to the absence of face-to-face interaction and the possibility of multitasking were minimized because the participants were committed to the study's

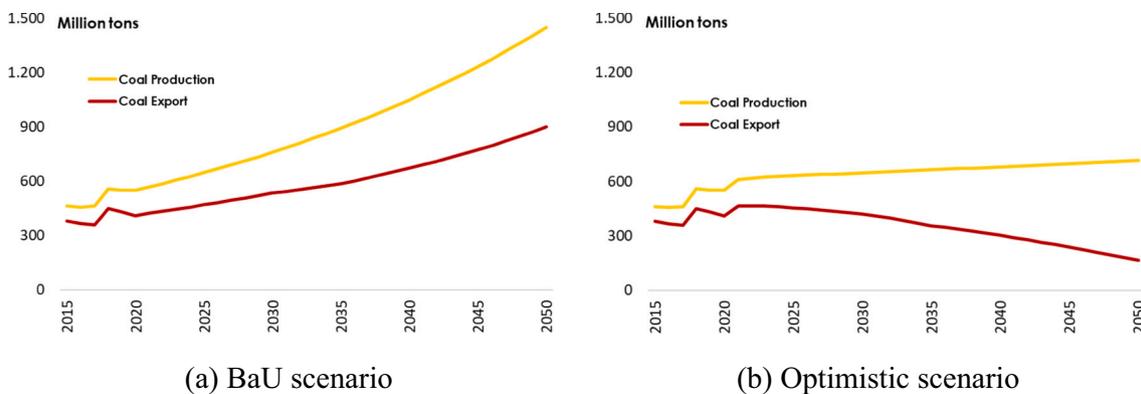


Fig. 10. Projections of coal production and exports. (Created by authors.)

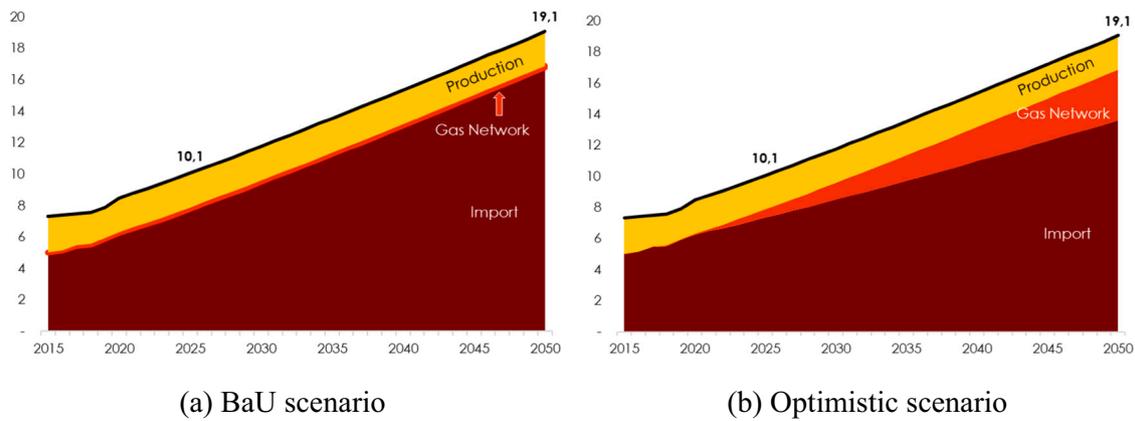


Fig. 11. Projections of imported LPG and gas network. (Created by authors.)

implementation. Participants were highly critical when selecting the policies to be analyzed, such as whether it was still feasible to increase the biodiesel blend during the global oil price drop caused by the pandemic. They also actively criticized the modeling simulation results, which they felt did not align with actual conditions. Another discussion that arose was whether the research direction should focus on the transition to clean energy toward NZE or on simulating the impacts of the success or failure of various strategic policies and projects currently underway on energy security.

The principle of energy justice needs to be applied in Indonesia’s energy transition, as the country still has a low per capita income, to prevent social unrest. For an example, the government’s efforts to limit the distribution of subsidized LPG cylinders in February 2025 led to long lines at official LPG distribution centers, resulting in a death from exhaustion, prompting the government to resume the open distribution of subsidized LPG [77]. Consequently, the government still relies on coal for cheap electricity production and as a revenue source to fund the high energy subsidies (LPG, electricity, and fuel).

Indonesia is currently exploring a range of energy transition mechanisms to ensure that cleaner electricity remains affordable for all segments of society. One key strategy is to boost revenue from the adoption of clean energy in more affluent communities and then reinvest those funds to expand renewable energy capacity and keep affordable electricity prices for less affluent households. For example, higher electricity tariffs are imposed on users of electric vehicles and induction stoves who require larger power capacities. In addition, the state-owned electricity company sells voluntary renewable energy certificates at a premium to individuals and companies seeking to reduce their carbon footprints [78].

Our study assesses eight policies related to both fossil and renewable energies in two contrasting scenarios. The optimistic scenario simulated in this study presents a pathway to energy security. This scenario still accommodates the continued use of fossil fuels—coal, oil, and natural gas—all of which remain integral to Indonesia’s energy landscape. For example, a considerable number of Indonesia’s coal-fired power plants are relatively modern; thus, their premature decommissioning would incur substantial compensation costs and necessitate significant investments in renewable energy infrastructures.

Only three simulated policies can enhance the production of renewable energy and reduce emissions as shown in Table 5. The biodiesel policy will increase the share of renewable energy and lower emissions. The transition to renewable energy and the electrification of the transportation sector represents protracted processes that demand extensive timeframes for comprehensive implementation. During this transitional phase, biodiesel initiatives serve a crucial role as a primary energy source. The efficacy of Indonesia’s biodiesel program is largely contingent upon the Indonesian Oil Palm Estate Fund Agency (BPDPKS),

Table 5
Emission reduction from simulated policies.

Policies	Renewables share by 2050		Emissions by 2050 ^a	
	BaU	Optimistic	BaU	Optimistic
Biodiesel	8.5 %	9.9 %	2085	2045
RE development	8.5 %	34.0 %	2085	1494
Urban gas networks	8.5 %	8.5 %	2085	2064

^a In million tons of CO_{2e}.

which underwrites the initiative through export levies on palm oil and its derivatives [79]. These financial resources are allocated to bridge the price gap between biodiesel and conventional diesel in the market. However, escalating the mandated biodiesel blending ratio places additional fiscal strain on BPDPKS, particularly in the context of declining palm oil export revenues. Consequently, government subsidies will be essential to sustain the competitiveness of biodiesel.

The policy for developing renewable energy power plants will undoubtedly increase the share of renewable energy and reduce emissions. Indeed, the advancement of renewable energy emerges as the most vital strategy for curtailing emissions. Table 5 shows the renewable energy share may reach 34 % by 2050 with potential emission reduction for 591 million tons of CO_{2e}. Various clean energy transition studies share the same recommendation: the need to increase the use of renewable energy [32,34,39]. However, the growth in capacity and production of renewable energy remains below the renewable energy targets in RUEN due to several economic, technical, institutional, and social challenges. Economic challenges are beginning to be resolved with the reduction in investment costs and the renewable energy procurement system using ceiling prices and tenders, making electricity prices from renewable energy competitive. The main technical challenge is the intermittent nature of renewable energy, which leads to institutional challenges, such as concerns from the State-owned Electricity Company about the stability of an electricity grid with a high share of renewable energy. Some solutions to these challenges include battery energy storage, expansion of the electricity grid system, and upgrades to smart control systems to manage the electricity grid [32,34].

The city gas network policy does not impact the capacity of renewable energy but reduce emissions, although not significantly, as shown in Table 5. This emission reduction is due to the lower emission factor of the city gas network compared to the LPG emission factor, resulting in a 11 % reduction or 218 g of CO_{2e} for every 1 m³ of gas [80]. Due to the minimal benefits of emission reductions, the primary goal of the urban gas network policy is to reduce LPG imports and subsidy. However, the urban gas network policy faces obstacles due to the high investment costs of building gas pipelines, resulting in the failure to meet the gas

pipeline development targets. Additionally, the non-renewable nature of natural gas poses a risk of these pipelines becoming stranded assets in the future. Therefore, reducing LPG imports could be more effectively achieved through policies that encourage the use of induction cookers to replace LPG stoves [7]).

6. Conclusions

This study highlights the crucial role of participatory modeling in advancing energy system analysis, particularly in addressing the common limitations of traditional models that focus primarily on energy supply. The development of the P/ESDM framework, which engages stakeholders from both academic and non-academic sectors, enhances the understanding of interdependencies between energy demand and supply. The participatory process played a key role in developing a robust energy model. The involvement of external modelers from non-energy sectors not only refined modeling techniques and algorithms but also demonstrated how an energy system dynamics model can be integrated with a low-carbon development system dynamics model encompassing multiple sectors beyond energy. Likewise, the participation of various ministries and NGOs was instrumental in prioritizing policies for analysis and validating simulation results. These contributions formed the foundation for refining both the model and its analysis, with the results subsequently reviewed by key stakeholders for further feedback. This approach not only strengthened modeling methodologies but also ensured that policy simulations aligned with real-world priorities, facilitating more effective energy planning and policy design. Furthermore, the model's adaptability allows for its application across different geopolitical contexts, providing policymakers with valuable insights into the demographic, economic, and environmental implications of various energy scenarios.

However, this study has certain limitations. Factors such as data availability, policy assumptions, and technological uncertainties may introduce potential inaccuracies in the model's outcomes. Additionally, while the study demonstrates the P/ESDM framework's ability to simulate eight policies under two contrasting scenarios, the analysis remains limited to individual policies. We encourage future studies to explore the simultaneous simulation of multiple policies for a more comprehensive assessment. More importantly, future participatory modeling studies should focus on decoupling GDP from carbon emissions by investigating innovative strategies, policies, and technologies that promote economic growth while simultaneously reducing carbon emissions. Furthermore, as the model is currently tailored to Indonesia, adjustments will be necessary to account for regional differences when applied in other contexts. Lastly, rapid advancements in renewable energy and storage technologies should be further integrated into future modeling efforts to enhance the model's relevance and accuracy. One limitation of this study's participatory process is the weak and unsystematic documentation procedures. For future research, we recommend establishing and retaining written records of input from every stakeholder. Additionally, future studies should promptly save Zoom meeting recordings in a secure, accessible working folder.

CRedit authorship contribution statement

Ariana Soemanto: Validation, Writing – original draft, Investigation. **Ervan Mohi:** Writing – original draft. **Joko Santosa:** Software, Writing – original draft, Methodology. **Muhammad Indra al Irsyad:** Methodology, Writing – original draft, Conceptualization. **Priyono:** Formal analysis. **Nurry Widya Hesty:** Writing – original draft, Writing – review & editing. **Aminuddin:** Writing – original draft, Writing – review & editing. **Hariyadi:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal

relationships which may be considered as potential competing interests:

Muhammad Indra al Irsyad reports financial support was provided by the United Nations Development Programme. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.erss.2025.104231>.

Data availability

The detailed P/ESDM specification is available as Supplementary Material and can be also accessed at <https://github.com/Alyarasya21/P-ESDM>.

References

- [1] IRENA, Global Energy Transformation: A Roadmap to 2050, International Renewable Energy Agency, 2018. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_Report_GET_2018.pdf?rev=7eca1eb7dd1d405a83efcb6ba5e3e3c.
- [2] S. Pye, O. Broad, C. Bataille, P. Brockway, H.E. Daly, R. Freeman, et al., Modelling net-zero emissions energy systems requires a change in approach, *Clim. Pol.* 21 (2021) 222–231, <https://doi.org/10.1080/14693062.2020.1824891>.
- [3] F.C. Krysiak, H. Weigt, The demand side in economic models of energy markets: the challenge of representing consumer behavior, *Front. Energy Res.* (2015) 3, <https://doi.org/10.3389/feeng.2015.00024>.
- [4] Ganiyu Bolawale Omotoye, Binaebi Gloria Bello, Sunday Tubokirifuruar Tula, Azeez Jason Kess-Momoh, Andrew Ifesinachi Daraojimba, Adedayo Adefemi, Navigating global energy markets: a review of economic and policy impacts, *International Journal of Science and Research Archive* 11 (2024) 195–203, <https://doi.org/10.30574/ijrsra.2024.11.1.0029>.
- [5] M.I. al Irsyad, A.B. Halog, R. Nepal, D.P. Koesrindartoto, Selecting tools for renewable energy analysis in developing countries: an expanded review, *Front Energy Res* (2017) 5, <https://doi.org/10.3389/feeng.2017.00034>.
- [6] S.C. Bhattacharyya, G.R. Timilsina, A review of energy system models, *International Journal of Energy Sector Management* 4 (2010) 494–518, <https://doi.org/10.1108/17506221011092742>.
- [7] T. Anggono, I. Ruslan, C. Anditya, D.G. Cendrawati, M.I. al Irsyad, Assessing the feasibility of migration policy from LPG stoves to induction stoves in Indonesia, *IOP Conf Ser Earth Environ Sci* 1041 (2022) 012039, <https://doi.org/10.1088/1755-1315/1041/1/012039>.
- [8] A. Sugiyono, I. Rahardjo, P.T. Wijaya, Dwijatmiko A. Aminuddin, E. Siregar, et al., Transitioning from coal to solar: a cost-benefit analysis for sustainable power generation in Indonesia, *AIMS Energy* 12 (2024) 152–166, <https://doi.org/10.3934/energy.2024007>.
- [9] A. Soemanto, E. Mohi, M.I. al Irsyad, Y. Gunawan, The role of oil fuels on the energy transition toward net zero emissions in Indonesia: a policy review, *Evergreen* 10 (2023) 2074–2083, <https://doi.org/10.5109/7160867>.
- [10] A. Afshar, E. Soleimani, H.A. Variani, M. Vahabzadeh, A. Molajou, The conceptual framework to determine interrelations and interactions for holistic water, energy, and food nexus, *Environ. Dev. Sustain.* 24 (2022) 10119–10140, <https://doi.org/10.1007/s10668-021-01858-3>.
- [11] B. Pranoto, I. Adilla, H. Soekarno, N.K. Supriatna, Adrian, L. Efiyanti, et al., Using satellite data of palm oil area for potential utilization in calculating palm oil trunk waste as cofiring fuel biomass, *Evergreen* 10 (2023) 1784–1791, <https://doi.org/10.5109/7151728>.
- [12] V. Nurliyanti, K. Ahadi, R. Muttaqin, B. Pranoto, G.P. Srikandi, al Irsyad M.I., Fostering rooftop solar PV investments toward smart cities through e-SMART PV, in: 2021 5th International Conference on Smart Grid and Smart Cities (ICSGSC), IEEE, 2021, pp. 146–150, <https://doi.org/10.1109/ICSGSC52434.2021.9490406>.
- [13] Aminuddin, B. Pranoto, M.I.A. Irsyad, A.L. Sihombing, V. Nurliyanti, Hybrid floating photovoltaic - hydropower potential utilization in Indonesia, *IOP Conf.*

- Ser. Earth Environ. Sci. 1105 (2022) 012004, <https://doi.org/10.1088/1755-1315/1105/1/012004>.
- [14] D.G. Cendrawati, N.W. Hesty, B. Pranoto, A. Aminuddin, A.H. Kuncoro, A. Fudholi, Short-term wind energy resource prediction using weather research forecasting model for a location in Indonesia, *International Journal of Technology* 14 (2023) 584, <https://doi.org/10.14716/ijtech.v14i3.5803>.
- [15] N.W. Hesty, D.G. Cendrawati, R. Nepal, M.I. Al Irsyad, Wind energy potential assessment based-on WRF four-dimensional data assimilation system and cross-calibrated multi-platform dataset, *IOP Conf. Ser. Earth Environ. Sci.* 897 (1) (2021) 012004, <https://doi.org/10.1088/1755-1315/897/1/012004>.
- [16] N.W. Hesty, D.G. Cendrawati, R. Nepal, M.I. al Irsyad, *Crawford School of Public Policy CAMA Centre for Applied Macroeconomic Analysis Energy Potential Assessments and Investment Opportunities for Wind Energy in Indonesia*, 2021.
- [17] B. Pranoto, H. Soekarno, D.G. Cendrawati, I.F. Akrom, M.I.A. Irsyad, N.W. Hesty, et al., Indonesian hydro energy potential map with run-off river system, *IOP Conf. Ser. Earth Environ. Sci.* 926 (2021) 012003, <https://doi.org/10.1088/1755-1315/926/1/012003>.
- [18] L. Putriyana, Y. Daud, M. Aziz, N.W. Hesty, Nasruddin, Evaluation and ranking of the CO2 storage potential in low to medium temperature geothermal fields in Indonesia, *Case Stud. Chem. Environ. Eng.* 8 (2023) 100406, <https://doi.org/10.1016/j.csee.2023.100406>.
- [19] H. Hidayat, Anam A. Fausiah, Destian E.F. Sudono, I. Noor, et al., Oil palm biomass ash removal for boiler fuel optimization: a case study, *Case Studies in Chemical and Environmental Engineering* 11 (2025) 101049, <https://doi.org/10.1016/j.csee.2024.101049>.
- [20] Nuramalia Putri Ayu, Amanda Sekar Ayu, Aminuddin, Helios Muhammad Penta, Arfiana, Tjahjono Endro Wahju, et al., Biomass fuel quality improvement using hydrogen peroxide and demineralized water pre-treatment and torrefaction, *Evergreen* 11 (2024) 2949–2958, <https://doi.org/10.5109/7326936>.
- [21] D. Mansur, A. Aminuddin, V.J. Wargadalam, Production of bio-hydrocarbon from refined-bleach-deodorized palm oil using Micro activity test reactor, *Reaktor* 20 (2020) 75–80, <https://doi.org/10.14710/reaktor.20.2.75-80>.
- [22] V.J. Wargadalam, Aminuddin, M.H.G. Syaefi, J. Enrico, Kinetic study of palm oil catalytic cracking over a zeolite-based catalyst, *J. Penelit. Has. Hutani.* 41 (2023), <https://doi.org/10.55981/jphh.2023.1000>.
- [23] L. Hauli, D. Mansur, Aminuddin Saepurahman, Insight into catalytic pyrolysis of palm fronds over MFI, BEA, and FAU framework types of zeolite extrudate, *Biomass Convers. Biorefinery* (2023), <https://doi.org/10.1007/s13399-023-04092-1>.
- [24] D. Mansur, Aminuddin., Chemical conversion of Calophyllum inophyllum oil into biohydrocarbons fuel over presulfided NiMo/Al2O3 catalyst, *Int. J. Energy Res.* 44 (2020) 7746–7760.
- [25] Dieni Mansur, Hari Setiaprja, Oni Fariza, Siti Yubaidah Aminuddin, Clean marine fuel: integration of co-pyrolysis oil with high-sulfur fuel oil, *Evergreen* 11 (2024) 2959–2968, <https://doi.org/10.5109/7326937>.
- [26] N.F. Hasanah, M.A. Darmawan, Aminuddin Muryanto, H. Bahua, H. Hidayat, et al., Oil palm trunks as raw material for bioethanol production: a study on the delignification efficiency of betaine-based natural deep eutectic solvents, *Waste Biomass Valoriz.* (2025), <https://doi.org/10.1007/s12649-025-02927-8>.
- [27] N.K. Supriatna, Aminuddin, A. Kismanto, I. Purawardi, R. Alamsyah, N.W. Hesty, et al., Economic feasibility study of syngas-derived garden waste biomass as liquified petroleum gas substitute in Indonesia: a case study for 1-megawatt updraft fixed bed gasifier, *Evergreen* 10 (2023) 1835–1846, <https://doi.org/10.5109/7151733>.
- [28] N.K. Supriatna, P. Zuldian, Aminuddin, I. Purawardi, N. Aprianti, Y. Gunawan, et al., Experimental investigation and performance evaluation of *Samanea saman* leaves and twigs gasification from urban residential garden waste as alternative future energy, *Bioresour. Technol. Rep.* (2024) 101950, <https://doi.org/10.1016/j.biteb.2024.101950>.
- [29] N.K. Supriatna, Zuldian P. Aminuddin, N.W. Hesty, N. Aprianti, H. Handayani, et al., Garden waste for sustainable development in Indonesia, *IOP Conf Ser Earth Environ Sci* 1344 (2024) 12009, <https://doi.org/10.1088/1755-1315/1344/1/012009>.
- [30] N.W. Hesty, Fauziah K. Aminuddin, T. Zaky, S.R. Fithri, M. Aman, et al., A comprehensive analysis of wind power integrated with solar and hydrogen storage systems: case study of Java's southern coast, *Int. J. Hydrog. Energy* (2024), <https://doi.org/10.1016/j.ijhydene.2024.10.185>.
- [31] N.W. Hesty, Aminuddin, N.K. Supriatna, D.G. Cendrawati, V. Nurliyanti, A. Nurrohm, et al., Unlocking development of green hydrogen production through techno-economic assessment of wind energy by considering wind resource variability: a case study, *Int. J. Hydrog. Energy* (2024), <https://doi.org/10.1016/j.ijhydene.2024.09.294>.
- [32] J. Langer, F. Lombardi, S. Pfenninger, H.P. Rahayu, Irsyad M.I. Al, K. Blok, The role of inter-island transmission in full decarbonisation scenarios for Indonesia's power sector, *Environmental Research: Energy* 1 (2024) 25006, <https://doi.org/10.1088/2753-3751/ad53cb>.
- [33] P. Paiboonsin, G. Oluleye, M. Howells, R. Yeganyan, C. Cannone, S. Patterson, Pathways to clean energy transition in Indonesia's electricity sector with open-source energy modelling system modelling (OSEMOSYS), *Energies* (Basel) 17 (2023) 75, <https://doi.org/10.3390/en17010075>.
- [34] al Irsyad M.I. Pramudya, H. Phoumin, R. Nepal, The Role of Battery Energy Storage Systems and Market Integration in Indonesia's Zero Emission Vision, 2024, pp. 121–143, https://doi.org/10.1007/978-981-99-8239-4_6.
- [35] A.H. Kuncoro, Wahid L.O.M.A. Pramudya, J. Santosa, Nurrohm A. Aminuddin, et al., Fuel demand analysis on the optimization of sustainable electricity system expansion planning 2021–2050 in West Kalimantan, *Evergreen* 10 (2023) 1683–1694, <https://doi.org/10.5109/7151717>.
- [36] A. Tampubolon, Rencana Umum Energi Nasional (RUEN): Existing Plan, Current Policies Implication, and Energy Transition Scenario, Institute for Essential Services Reform (IESR), Jakarta, Indonesia, 2020. Retrieved from, www.iesr.or.id.
- [37] S.R. Shakya, A.M. Nakarmi, A. Prajapati, B.B. Pradhan, U.S. Rajbhandari, M. Rupakheti, et al., Environmental, energy security, and energy equity (3E) benefits of net-zero emission strategy in a developing country: a case study of Nepal, *Energy Rep.* 9 (2023) 2359–2371, <https://doi.org/10.1016/j.egy.2023.01.055>.
- [38] C. Bataille, H. Waisman, Y. Briand, J. Svensson, A. Vogt-Schilb, M. Jaramillo, et al., Net-zero deep decarbonization pathways in Latin America: challenges and opportunities, *Energ. Strat. Rev.* 30 (2020) 100510, <https://doi.org/10.1016/j.esr.2020.100510>.
- [39] Irsyad MI Al, A. Halog, R. Nepal, Estimating the impacts of financing support policies towards photovoltaic market in Indonesia: a social-energy-economy-environment model simulation, *J. Environ. Manag.* 230 (2019) 464–473, <https://doi.org/10.1016/j.jenvman.2018.09.069>.
- [40] J.L. Castle, D.F. Hendry, *Econometrics for Modelling Climate Change*, Oxford Research Encyclopedia of Economics and Finance, Oxford University Press, 2022, <https://doi.org/10.1093/acrefore/9780190625979.013.675>.
- [41] J. Liu, Y. Zhou, H. Yang, H. Wu, Uncertainty energy planning of net-zero energy communities with peer-to-peer energy trading and green vehicle storage considering climate changes by 2050 with machine learning methods, *Appl. Energy* (2022) 321, <https://doi.org/10.1016/j.apenergy.2022.119394>.
- [42] B. Dangerfield, *System Dynamics*, Springer US, New York, NY, 2020, <https://doi.org/10.1007/978-1-4939-8790-0>.
- [43] T.A.P. Metzke, J. van den Broek, R. van Est, E.H.W.J. Cuppen, Participatory repertoires for aligning policy and society: an analysis of Dutch stakeholder views on deep geothermal energy, *Energy Res. Soc. Sci.* 98 (2023) 103019, <https://doi.org/10.1016/j.erss.2023.103019>.
- [44] K. Maczka, A. Lis-Plesińska, K. Iwińska, Epistemic justice impossible? Expert perceptions of the participatory monitoring of geo-energy projects in Poland, *Energy Res. Soc. Sci.* 102 (2023) 103154, <https://doi.org/10.1016/j.erss.2023.103154>.
- [45] E. Martinez-Hernandez, A. Castillo-Landero, D. Dominguito-Ramírez, M. A. Amezcua-Allieri, S. Morse, R. Murphy, et al., Priorities and relevance of bioenergy sustainability indicators: a participatory selection framework applied to community-based forestry in Mexico, *Energy Res. Soc. Sci.* 109 (2024) 103425, <https://doi.org/10.1016/j.erss.2024.103425>.
- [46] E.A. Moallemi, S. Malekpour, A participatory exploratory modelling approach for long-term planning in energy transitions, *Energy Res. Soc. Sci.* 35 (2018) 205–216, <https://doi.org/10.1016/j.erss.2017.10.022>.
- [47] G. Venturini, M. Hansen, P.D. Andersen, Linking narratives and energy system modelling in transport scenarios: a participatory perspective from Denmark, *Energy Res. Soc. Sci.* 52 (2019) 204–220, <https://doi.org/10.1016/j.erss.2019.01.019>.
- [48] K.M.G.K. Konara, A. Tokai, Integrated evaluation of energy system in Sri Lanka: a multidimensional sustainability perspective, *International Journal of Sustainable Energy* 41 (2022) 1193–1214, <https://doi.org/10.1080/14786451.2022.2039140>.
- [49] A. Dagne, J. Corfee-Morlot, A.M. Bassi, C. Elliott, G. Pallaske, M. Guzzetti, et al., Navigating climate-resilience: co-benefits and costs of a net zero development pathway in Ethiopia, *Clim. Pol.* (2024) 1–17, <https://doi.org/10.1080/14693062.2024.2438300>.
- [50] G. Bernardo, S. D'Alessandro, Societal implications of sustainable energy action plans: from energy modelling to stakeholder learning, *J. Environ. Plan. Manag.* 62 (2019) 399–423, <https://doi.org/10.1080/09640568.2018.1483905>.
- [51] Jean-Luc De Kok, Peter Viaene, Stijn Vranckx, Karolien Vermeiren, Guy Engelen, *Blueprint of a system dynamics model for Flanders*, in: 8th International Congress on Environmental Modelling and Software, IEMSS, Toulouse, France, 2016.
- [52] S. Eker, N. Zimmermann, S. Carnohan, M. Davies, Participatory system dynamics modelling for housing, energy and wellbeing interactions, *Build. Res. Inf.* 46 (2018) 738–754, <https://doi.org/10.1080/09613218.2017.1362919>.
- [53] L. Gallagher, B. Kopainsky, A.M. Bassi, A. Betancourt, C. Buth, P. Chan, et al., Supporting stakeholders to anticipate and respond to risks in a Mekong River water-energy-food nexus, *Ecol. Soc.* 25 (2020), <https://doi.org/10.5751/ES-11919-250429> art29.
- [54] A. González-Rosell, M. Blanco, I. Arfa, Integrating stakeholder views and system dynamics to assess the water–energy–food nexus in Andalusia, *Water* (Basel) 12 (2020) 3172, <https://doi.org/10.3390/w12113172>.
- [55] P. Martínez, M. Blanco, B. Castro-Campos, The water–energy–food nexus: a fuzzy-cognitive mapping approach to support nexus-compliant policies in Andalusia (Spain), *Water* 10 (2018) 664, <https://doi.org/10.3390/w10050664>.
- [56] L.K.S. Olabisi, A.R. Kapuscinski, K.A. Johnson, P.B. Reich, B. Stenquist, K. J. Draeger, Using scenario visioning and participatory system dynamics modeling to investigate the future: lessons from Minnesota 2050, *Sustainability* 2 (2010) 2686–2706, <https://doi.org/10.3390/su2082686>.
- [57] F. Salerno, G. Viviano, S. Thakuri, B. Flury, R.K. Maskey, S.N. Khanal, et al., Energy, forest, and indoor air pollution models for Sagarmatha National Park and Buffer Zone, Nepal, *Mt. Res. Dev.* 30 (2010) 113–126, <https://doi.org/10.1659/MRD-JOURNAL-D-10-00027.1>.
- [58] A. Shahmohammadi, K. Khoshbakht, H. Veisi, M.R. Nazari, Exploring dynamics of water, energy, and food systems in agricultural landscapes using mental modeling: a case of Varamin plain, Iran, *Environ. Manag.* 73 (2024) 34–50, <https://doi.org/10.1007/s00267-023-01875-0>.

- [59] J. Sušnik, C. Chew, X. Domingo, S. Mereu, A. Trabucco, B. Evans, et al., Multi-stakeholder development of a serious game to explore the water-energy-food-land-climate nexus: the SIM4NEXUS approach, *Water* 10 (2018) 139, <https://doi.org/10.3390/w10020139>.
- [60] J.W. Forrester, System dynamics, systems thinking, and soft OR, *Syst. Dyn. Rev.* 10 (1994) 245–256, <https://doi.org/10.1002/sdr.4260100211>.
- [61] J. Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World*, Irwin/McGraw-Hill, 2000.
- [62] W. Zhang, M. Zhang, S. Wu, F. Liu, A complex path model for low-carbon sustainable development of enterprise based on system dynamics, *J. Clean. Prod.* 321 (2021) 128934, <https://doi.org/10.1016/j.jclepro.2021.128934>.
- [63] B. Bush, D. Stright, J. Huggins, E. Newes, Simulation process and data flow for a large system dynamics model, *Simulation* 98 (2022) 823–833, <https://doi.org/10.1177/00375497221093381>.
- [64] MEMR, Tahun 2030, Target Lifting Minyak 1 Juta Barel Per Hari, 2020.
- [65] Ministry of Energy and Mineral Resources (MEMR), Ringkasan Renstra 2020–2024 (Summary of Strategic Plan 2020–2024), 2020.
- [66] S. Winzenried, D. Kohar, T. Watson, A. Lukito, P. Atma, F. Taner, Oil and Gas in Indonesia, 10th ed, PricewaterhouseCoopers (PwC) Indonesia, Jakarta, Indonesia, 2019. <https://www.pwc.com/id/en/energy-utilities-mining/assets/oil-and-gas/oil-gas-guide-2019.pdf>.
- [67] MEMR, in: MEMR, MoEaMR (Eds.), Ministerial Decree of Energy and Mineral Resources Number 16 of 2020 on the Strategic Plan of the Ministry and Mineral Resources, Ministry of Energy and Mineral Resources (MEMR), Jakarta, Indonesia, 2020. <https://www.esdm.go.id/assets/media/content/content-rencana-strategis-kesdm-2020-2024.pdf>.
- [68] MEMR, Kejar Target Jargas 4 Juta SR Tahun 2024, Pemerintah Dorong Skema KPBU. Ministry of Energy and Mineral Resources (MEMR), Jakarta, Indonesia, Retrieved from, <https://www.esdm.go.id/id/berita-unit/direktorat-jenderal-minyak-dan-gas-bumi/kejar-target-jargas-4-juta-sr-tahun-2024-pemerintah-dorong-ske-ma-kpbu>, 2020.
- [69] A.J. Purwanto, Jokowi galakkan mobil listrik, tapi riset tunjukkan 2 faktor bisa hambat efektivitasnya untuk turunkan emisi gas rumah kaca, *Lingkungan, The Conversation*, Jakarta, Indonesia, 2019. Retrieved from, <https://theconversation.com/jokowi-galakkan-mobil-listrik-tapi-riset-tunjukkan-2-faktor-bisa-hambat-efektivitasnya-untuk-turunkan-emisi-gas-rumah-kaca-121878>.
- [70] BPDPKS, PPKS Uji Coba B50, Tempuh Medan-Jakarta. Badan Pengelola Dana Perkebunan Kelapa Sawit (BPDPKS), Jakarta, Indonesia, Retrieved from, <https://www.bpdp.or.id/ppks-uji-coba-b50-tempuh-medan-jakarta>, 2019.
- [71] MEMR, Handbook of Energy & Economic Statistics of Indonesia 2020, in: (MEMR), MoEaMR (Ed.), Jakarta, Indonesia. Retrieved from, <https://www.esdm.go.id/en/publication/handbook-of-energy-economic-statistics-of-indonesia-heesi>, 2021.
- [72] Offshore Technology, Tuban Oil Refinery and Petrochemical Complex. <http://www.offshore-technology.com/projects/tuban-oil-refinery-and-petrochemical-complex/?cf-view>, 2020. (Accessed 18 February 2025).
- [73] MEMR, Hasilkan Bahan Bakar Ramah Lingkungan, Pembangunan Kilang Dipercepat, Ministry of Energy and Mineral Resources (MEMR), Jakarta, Indonesia, 2019.
- [74] MEMR, Handbook of Energy & Economic Statistics of Indonesia 2020, in: (MEMR), MoEaMR (Ed.), Jakarta, Indonesia, Retrieved from, <https://www.esdm.go.id/en/publication/handbook-of-energy-economic-statistics-of-indonesia-heesi>, 2021.
- [75] GOI, Presidential Decree Number 22 of 2017 on the National Energy General Plan Government of Indonesia (GOI), Jakarta, Indonesia. <https://jdih.esdm.go.id/peraturan/Perpres%2022%20Tahun%202017.pdf>, 2017.
- [76] BPS, Indonesia Population Projection 2015–2045 Result of SUPAS 2015 (Revised Edition), in: (BPS), C.B.o.S. (Ed.). Central Bureau of Statistics (BPS), Jakarta, Indonesia. <https://www.bps.go.id/publication/2018/10/19/78d24d9020026ad95c6b5965/proyeksi-penduduk-indonesia-2015-2045-hasil-supas-2015.html>, 2018.
- [77] Ismoyo., Energy Minister Apologizes After Woman Dies in 3-kg LPG Queue. JakartaGlobe.ID, Jakarta, Indonesia, Retrieved from, <https://jakartaglobe.id/news/energy-minister-apologizes-after-woman-dies-in-3kg-lpg-queue>, 2025.
- [78] I. Haryani, I.A. Aditya, A.H. Nuraini, S. Widiyanesti, A. Alamsyah, E. Nurhazidah, et al., Blockchain-based renewable energy certificate system in Indonesia, *Heliyon* 11 (2025) e42364, <https://doi.org/10.1016/j.heliyon.2025.e42364>.
- [79] Fitriyah, A.I. Suroso, L.M. Baga, The strategic architecture of “BPDPKS” – oil palm plantation fund management agency, *IOP Conf. Ser. Earth Environ. Sci.* (2024) 012023, <https://doi.org/10.1088/1755-1315/1379/1/012023>.
- [80] MEMR, Pembangunan Jaringan Gas Bumi untuk Rumah Tangga. Ministry of Energy and Mineral Resources (MEMR), Jakarta, Indonesia, Retrieved from, <http://migas.esdm.go.id/uploads/buku-jasrgas-isi.pdf>, 2013.