Accelerating net-zero emissions in Indonesia's energy sector: participatory energy planning and alternative energy scenarios

by

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Summary

This PhD thesis explores pathways to achieving a net-zero emissions (NZE) energy system in Indonesia by 2050, addressing critical gaps in energy planning, renewable energy (RE) integration and sector coupling. It focuses on key challenges, such as the country's dependence on fossil fuels, regulatory barriers and socio-economic differences. The research also highlights Indonesia's significant RE potential, including solar, bioenergy, hydro, and geothermal. These efforts are aligned with global goals like the Paris Agreement and the Sustainable Development Goals.

The research employs an integrated framework of different theories and methods to examine energy transitions. The choice awareness theory and the smart energy systems concept guide the work, ensuring the research addresses both technical solutions and practical challenges. Methods, such as multi-criteria decision analysis, are applied to rank energy sources based on cost, environmental impact and public acceptance. Energy system analysis tools, EnergyPLAN and MultiNode, are used to simulate energy systems and assess how various scenarios can reduce emissions and enhance efficiency.

The core findings are structured across three publications, each addressing a vital aspect of the energy transition. The first publication develops a participatory framework for ranking energy sources for sustainable electricity generation, highlighting solar energy as the most viable option due to its economic feasibility and public acceptance. The second publication explores how integrating electricity, transport and cooling systems can save energy and lower carbon emissions. The third publication outlines clear pathways for achieving NZE, showing the need for more renewables, better technology and firm policies.

This thesis provides valuable contributions to the academic and policy discourse on Indonesia's energy transition. It proposes a detailed framework that aligns technical feasibility with socio-economic realities. Policy recommendations derived from the research focus on enhancing RE adoption, fostering sectoral synergies and addressing institutional and infrastructural barriers. In conclusion, the research offers a transformative vision for Indonesia's energy future, underlining the critical role of renewable energy and stakeholder participation. By addressing the unique challenges of Indonesia's energy landscape, this thesis contributes to the global discourse on energy transitions, providing insights that can inform similar efforts in other developing economies.

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AHP	: Analytic Hierarchy Process
BAU	: Business-As-Usual
CEEP	: Critical Excess Electricity Production
CHP	: Combined Heat and Power Plant
CO_2	: Carbon Dioxide
DC	: District Cooling
EV	: Electric Vehicle
HE	: High Electrification
MCDA	: Multi-Criteria Decision Analysis
ME	: Moderate Electrification
NDC	: Nationally Determined Contribution
NZE	: Net-Zero Emissions
PES	: Primary Energy Supply
RE	: Renewable Energy
RQ	: Research Question
RUEN	: *Rencana Umum Energi Nasional* - National Energy Plan
RUPTL	: *Rencana Umum Pengusahaan Tenaga Listrik* - Electricity Supply Business Plan
SDG	: Sustainable Development Goal

Chapter 1. Introduction: Setting the stage for Indonesia's energy transition

The global energy transition marks a significant shift from using fossil fuels to adopting cleaner and more efficient ways of producing and using energy. For decades, energy systems have supported industrial growth and modern lifestyles, but their heavy reliance on polluting and limited resources has created serious challenges. Today, countries worldwide are looking for new ways to meet their energy needs while reducing environmental harm.

The need for a global energy transition arises from the growing challenges posed by current energy systems. Fossil fuels have long underpinned global energy production, but their widespread use has driven substantial environmental challenges, notably escalating carbon emissions and climate instability. These impacts threaten the environment and highlight the urgent need to rethink how energy is produced and used. Moreover, the limited availability of fossil fuels raises concerns about long-term energy security. Renewable energy (RE) offers a dependable and abundant alternative. Transitioning to such systems is not only about reducing environmental harm but also about ensuring a stable and adaptable energy supply for future generations. By shifting towards cleaner energy sources, the global community aims to address critical environmental challenges while laying the groundwork for a more reliable and resilient energy future.

Indonesia finds itself at a pivotal moment in its energy journey, with growing recognition of the need to reduce dependence on fossil fuels and adopt cleaner energy systems. The country's unique geography and abundant natural resources, such as geothermal, solar and bioenergy, present immense opportunities for this transition. However, using these resources fully requires clear goals and strong efforts to overcome existing challenges. Indonesia's energy transition is not merely a national endeavour; it represents a chance to contribute meaningfully to global efforts to reduce emissions and create a resilient energy future. This context sets the stage for exploring how Indonesia's energy transition can be shaped and how ideas and strategies can guide this transformation. This PhD thesis explores these dynamics by focussing on pathways to achieve a net-zero emissions (NZE) energy system in Indonesia.

Chapter 1 examines Indonesia's energy transition by contextualising its challenges and opportunities within global energy trends and examining the country's energy sector, policy frameworks and planning complexities. The chapter concludes with analyses of future energy scenarios and proposes a framework to guide Indonesia towards achieving a net-zero emissions system.

Section 1.1 provides a comprehensive background on energy transition's global and national significance, highlighting the interconnectedness of energy policies and climate change commitments. Section 1.2 discusses Indonesia's current energy planning strategies and future energy systems. Section 1.3 identifies key research gaps in energy planning and the integration of RE sources within the Indonesian context. Section 1.4, the heart of this chapter, outlines the research objectives, questions and contributions of the PhD thesis. It presents a framework for the country's transition to an NZE energy system, contributing to the Indonesian energy transition discourse. Finally, Section 1.5 describes the PhD thesis's structure, summarising each chapter's contents and focus to ensure a cohesive and structured research exploration.

1.1. Background: Contextualising global energy transition and Indonesian perspectives

Addressing global energy challenges and mitigating climate change relies heavily on the Sustainable Development Goals (SDGs), particularly SDG 7. This goal targets universal access to affordable, reliable, sustainable, and modern energy, acknowledging its significance for development and economic growth. This goal is closely related to the Paris Agreement, which aims to limit global temperature rise to well below 2°C above pre-industrial levels, aiming to cap it at 1.5°C [1]. Achieving these targets requires substantial reductions in greenhouse gas emissions, especially from the energy sector, the primary global emissions source [2].

As of 2022, energy production and consumption were responsible for roughly 89% of global carbon dioxide (CO_2) emissions [2]. The Paris Agreement offers a framework for countries to set and achieve ambitious climate targets through Nationally Determined Contributions, which are crucial for transitioning to a low-carbon economy [1]. This Agreement fosters international cooperation, stimulates technological progress and improves resilience to climate impacts. By committing to its goals, countries aim to replace fossil fuels with renewable energy sources, thus reducing environmental and health impacts. Moreover, the Agreement stimulates economic growth by creating green jobs [3] and attracting clean technology investments [4,5].

The shift in the global energy landscape towards more RE sources is gaining momentum. Driven by the urgent need to combat climate change and achieve NZE by 2050, this transition requires substantial investments in energy efficiency measures, renewable energy infrastructure and innovative technologies [1]. Renewable energy sources, such as solar, wind and hydropower, are becoming increasingly cost-effective and widely adopted, providing viable alternatives to fossil fuels. Countries must enhance their policy frameworks, promote international collaboration and mobilise financial resources to support this transition [6].

Indonesia, the world's fourth-largest population and seventh-largest economy (based on purchasing power parity), could play a pivotal role in the global energy transition, ensuring a sustainable and prosperous future for its citizens. Aligning its energy policies with global sustainability goals and commitments could improve Indonesia's energy security, diversify its energy sources and drive technological innovations that promote renewable energy growth.

1.2. Navigating Indonesia's energy sector: present realities and future directions

Indonesia's energy sector heavily depended on fossil fuels, which account for over 85% of its energy supply in 2022, predominantly used in the industry and transport sectors [7]. This trend, as shown in Fig. 1.1 and 1.2, has persisted for decades and presents significant challenges for transitioning to renewable energy sources. Despite efforts such as the 2014 National Energy Policy [8], which aims to elevate renewables to 23% by 2025 in the primary energy mix, progress has been minimal. As Southeast Asia's largest emitter of greenhouse gases, Indonesia's fossil fuel reliance has profound environmental implications, including significant contributions to global CO_2 emissions [9], air quality degradation in urban areas [10,11] and threats to biodiversity due to mining and land use changes.

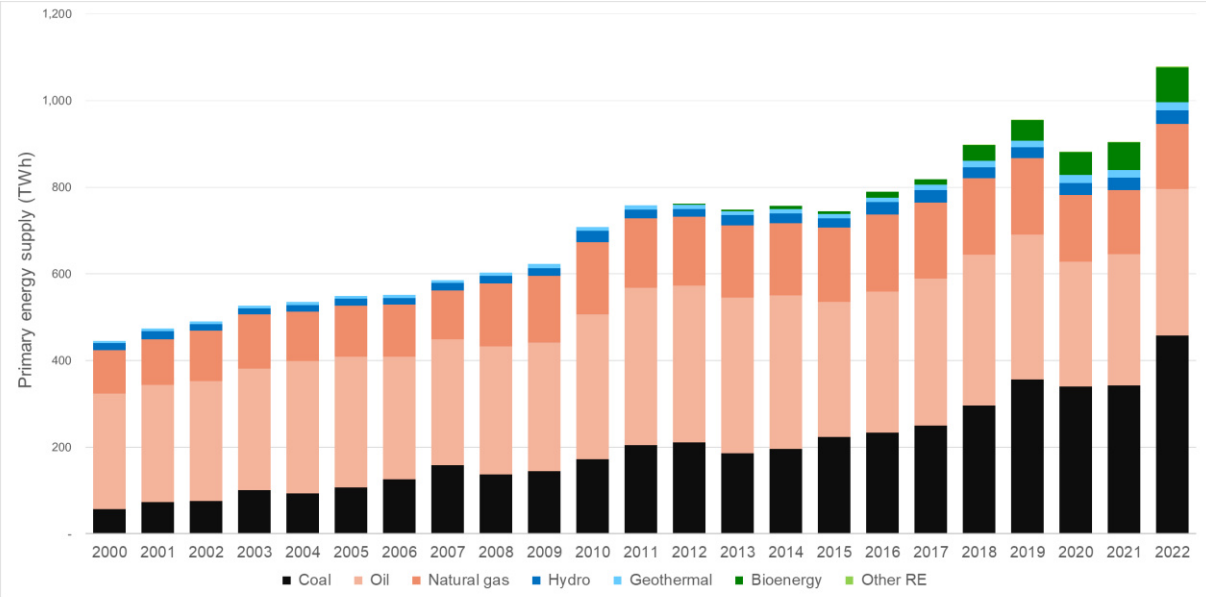

Fig. 1. 1. Total primary energy supply by sources in Indonesian from 2000 to 2022 [7,12]

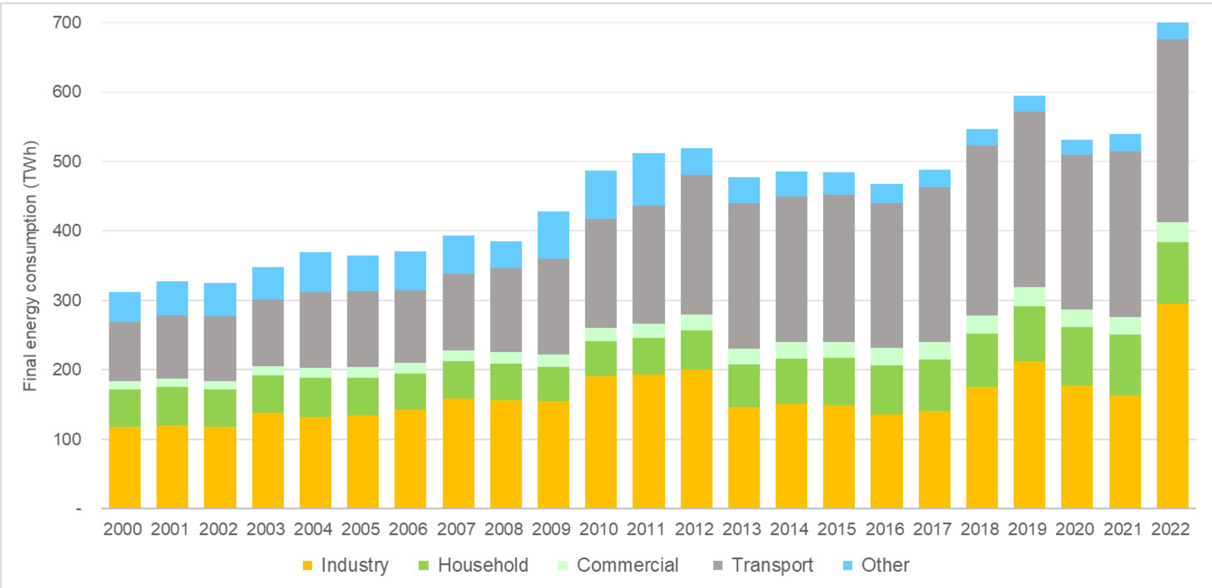

Fig. 1. 2. Total final energy consumption by sectors in Indonesian from 2000 to 2022 [7,12]

Significant policy and regulatory challenges impede Indonesia's transition to renewable energy. Inconsistent enforcement and bureaucratic hurdles have slowed progress. The complex and lengthy approval process for RE projects deters potential investors and delays implementation [12]. Local governments frequently lack the necessary resources and political commitment to effectively implement national energy policies, leading to a disconnect between national objectives and local execution [13]. The regulatory environment is further complicated by frequent changes in policy direction, which create uncertainty and discourage long-term investments in renewable energy [14]. Moreover, despite efforts to promote renewable energy, subsidies for fossil fuels persist, undermining initiatives to transition to renewables.

Indonesia possesses vast renewable energy potential that remains largely unexploited. With abundant natural resources, Indonesia has the capacity to harness solar, bioenergy, hydro, geothermal, and wind on a large scale. The archipelago's geographical characteristics offer substantial opportunities for solar power, particularly in regions with high insolation levels.

Bioenergy, derived from the country's vast agricultural and forestry residues, also offers considerable potential for energy production. The country’s numerous rivers and large volumes of rainfall make hydroelectric power a highly viable option for generating renewable energy. The country’s location along the Pacific Ring of Fire provides access to extensive geothermal resources, while its coastal areas and islands offer ideal conditions for wind energy development. However, challenges such as inadequate infrastructure, limited financing and insufficient policy support must be addressed to tap into this potential.

Technological innovation and infrastructure development are fundamental for Indonesia's transition to an NZE energy system. Modernising the existing energy infrastructure is critical to integrating RE sources effectively. Advancements in grid technology, such as smart electricity grids, can enhance the efficiency and reliability of electricity distribution, accommodating the intermittent nature of solar and wind power [15]. Moreover, investing in energy storage solutions like pumped hydro electricity storage is needed to ensure a stable and resilient energy supply. Developing comprehensive infrastructure for electric vehicles (EVs), including numerous charging stations, will support the growing use of EVs, thus reducing reliance on fossil fuels for transportation.

1.2.1. Assessing Indonesia's energy planning: status and insights

Indonesia's energy planning predominantly employs a top-down approach, exemplified by the 2017 National Energy Plan (RUEN) [16]. This centralised strategy aims to create a cohesive national energy policy, for instance, directing significant investments into major infrastructure projects, such as hydro and geothermal plants. Periodic Ministerial Decrees on Electricity Supply Business Plan (RUPTL) reinforces this strategy by setting specific development plans and timelines for state-owned and private electricity suppliers, ensuring alignment with national objectives. Furthermore, the RUEN requires each province to formulate its own regional energy plan, aligning with the national framework but tailored to regional conditions. However, this top-down approach often fails to account for the diverse regional needs and local contexts, leading to challenges in implementation at the sub-national level [13]. Bureaucratic inefficiencies and slow decentralisation could delay projects and reduce policy responsiveness to local conditions [17].

While Indonesia's top-down energy planning approach aims for cohesive national policies, it has notable drawbacks. This approach often results in short-sighted decisions prioritising immediate gains over long-term benefits for the population and the environment [18]. The focus on large-scale infrastructure projects frequently overlooks sustainable development aspects, leading to inefficient resource allocation and implementation issues. The planning process typically fails to consider long-term impacts on energy security and environmental sustainability, causing adverse outcomes like biodiversity loss and landscape degradation [19]. The lack of integration between energy planning and sustainable development goals shows the need for more simple financial metrics in addressing complex energy issues. Effective planning should evaluate alternative pathways and consider limitations like conflicting interests, economic constraints and technological challenges. Without considering a wide range of variables, including public acceptance and political risk, energy planning remain one-dimensional and inadequate for modern challenges [20].

Transparency and participative planning are notably lacking, exacerbating existing issues. In Indonesia, the energy planning processes are often opaque, limiting public access to critical information and excluding key stakeholders from significant participation [21]. The exclusion of local communities from the planning process erodes trust and generates resistance against projects perceived as imposed without considering local contexts and needs [22]. Participatory planning methods, proven to improve decision-making quality and public acceptance, remain underutilised. Addressing these issues requires implementing strong transparency measures and fostering participatory processes to create more effective and inclusive energy policies.

Critiquing Indonesia's top-down energy planning reveals the need for a balanced approach that integrates multidimensional analysis and active stakeholder participation. Multidimensional analysis simultaneously addresses economic, social, environmental, and technical factors to evaluate energy planning comprehensively. Previous studies have highlighted that traditional one-dimensional approaches are insufficient for addressing complex trade-offs and uncertainties inherent in energy systems. For example, integrating these dimensions enables more effective decision-making frameworks that consider both quantitative and qualitative factors, enhancing the relevance and sustainability of energy planning [23].

Effective energy planning must extend beyond simple financial metrics like net present value or cost-benefit analysis, which need to be revised for modern energy challenges because they fail to capture critical qualitative factors, such as societal acceptance and political feasibility. For instance, a renewable energy project might be economically viable in cost-benefit terms but face rejection due to public opposition or regulatory delays. Similarly, financial analyses may not adequately account for technological uncertainties, such as the future cost trajectory of renewable technologies or battery storage. Energy planning should incorporate qualitative and quantitative variables, such as technological advancements, resource availability and public acceptance.

The active involvement of stakeholders is equally important, as it brings diverse perspectives and local knowledge to the development of context-specific energy planning. This participatory approach enhances the legitimacy of decisions and fosters public trust and acceptance, which is vital for successful implementation. Moreover, robust scientific methodologies are needed to account for uncertainties in energy supply and demand while reconciling the often conflicting interests of various stakeholders [24].

1.2.2. Future energy systems: the need for pathways towards 2050

The Government of Indonesia has laid out comprehensive energy plans to achieve long-term sustainability and energy security through documents like the 2017 RUEN and the Ministerial Decree on RUPTL 2021–2030 [25]. The RUPTL targets 51.6% of the new power generation capacity from renewable energy sources. Meanwhile, the Long-Term Strategy for Low Carbon and Climate Resilience 2050 [26] aims to achieve NZE by 2060. Despite these ambitions, the plans have been criticised for their continued reliance on coal and natural gas, which hampers the development of renewable energy sources.

Indonesia's current energy plans have been criticised for relying too much on fossil fuels and slowly adopting renewable technologies [27], highlighting the need to explore alternative energy systems in the future. Studies have shown that Indonesia's dependency on coal undermines its climate goals and hinders economic efficiency due to overcapacity and the financial burdens associated with maintaining fossil fuel infrastructure [28]. Alternative energy systems modelled using various scenarios indicate that increasing the share of renewable energy sources can significantly reduce greenhouse gas emissions while being cost-effective [29,30].

Several key factors must be considered to ensure an effective transition in developing alternative energy systems for Indonesia. The country should maximise its diverse renewable resources, including solar, bioenergy, hydro, geothermal, and wind, to reduce fossil fuel reliance and improve energy security. This integration requires substantial investment in infrastructure like smart electricity grids and energy storage to manage renewable variability and ensure grid stability. Economic factors, such as the cost of renewable technologies and job creation potential [31,32] are critical in garnering public and political support for the transition. Social aspects, such as public participation and the acceptance of RE projects, are also important for the effective implementation of alternative energy systems [33].

To achieve the ambitious goal of NZE by 2050, Indonesia's current energy plans require significant acceleration guided by international and scientific imperatives. The Paris Agreement demands countries, including Indonesia, to advance their decarbonisation timelines. Furthermore, the scientific consensus from the Intergovernmental Panel on Climate Change emphasises the urgent need for rapid and comprehensive transitions in energy, land and infrastructure to avoid severe climate impacts [1]. These commitments require Indonesia to not only revise its energy plans but also to incorporate sustainability and equity into its development strategies.

1.3. Research gaps

Recent studies have identified substantial gaps in energy planning and the integration of renewable energy sources and strategies for achieving net-zero emissions, especially in Indonesia. These gaps highlight the need for thorough evaluations of energy sources, efficient approaches for integrating renewables across various sectors and practical pathways for transitioning to a RE-based system. Furthermore, in-depth research addressing Indonesia's unique socio-economic and environmental challenges is rare. Understanding and addressing these gaps will provide a more precise direction for future research and development initiatives in Indonesia’s energy sector.

A notable research gap exists in understanding how stakeholders perceive and prioritise available energy sources for sustainable electricity generation in Indonesia. Prior studies have often lacked a holistic approach that incorporates diverse stakeholder perspectives. This omission has led to an incomplete understanding of the sustainability of various energy sources when considering economic, social and environmental criteria. Moreover, the frequent oversight of balancing these criteria has hindered the development of comprehensive assessments.

In addition to gaps in energy source evaluation, there is a need for more comprehensive analyses on sector coupling, particularly the integration of electricity, transport and cooling sectors with high shares of renewable energy. Previous studies have rarely examined how such integration can boost RE penetration and enhance energy efficiency in Indonesia. Additionally, strategic pathways for achieving NZE by 2050 in Indonesia’s energy sector have so far been inadequately detailed. While earlier studies have highlighted the importance of reducing emissions, they typically fall short of providing actionable strategies tailored to Indonesia’s context. Filling these gaps, Indonesia can shape sound policies and smoothly transition to a net-zero emission energy system, outlining clear steps for enhancing energy efficiency, fast-tracking renewable energy uptake and transforming the national energy system.

1.4. Research objective, question and contribution

This PhD thesis aims to develop a comprehensive framework for Indonesia's transition to a net-zero emissions energy system. It addresses the significant research gaps in energy transitions in Indonesia and focuses on achieving NZE by 2050.

Utilising choice awareness theory and the smart energy systems concept, the research employs multi-criteria decision analysis (MCDA) to prioritise energy sources through a participatory approach. Advanced modelling tools, such as EnergyPLAN and MultiNode, simulate future energy scenarios, emphasising integrating different energy sectors across the entire Indonesian archipelago. The research evaluates various scenarios to identify pathways for reducing CO_2 emissions, enhancing energy efficiency and improving economic viability. The findings are synthesised into policy recommendations to guide Indonesia's energy planning and strategies. The ultimate goal is to provide a detailed, actionable pathway that leverages stakeholder-driven priorities, sector coupling and regional diversities to achieve a sustainable and economically feasible net-zero future.

This thesis combines theoretical frameworks and practical tools, ensuring that the transition to an NZE energy system is both scientifically grounded and practically feasible. This holistic approach directly addresses a main research question and three sub-research questions, guiding the exploration of prioritising energy sources and sector coupling to achieve a net-zero emissions energy system in Indonesia by 2050.

The main research question (RQ): How can Indonesia prioritise energy sources and apply sector coupling to achieve net-zero emissions in the energy sector by 2050?

Three sub-research questions (sub-RQs):

1. How can Indonesia prioritise energy sources for sustainable electricity generation in energy planning?

2. How can sector coupling impact Indonesia's energy system's efficiency and CO_2 emissions?

3. How can Indonesia achieve net-zero emissions in the energy sector by 2050?

Three specific chapters, called Publication 1, 2 and 3, were written to answer the three sub-RQs. Publication 1 addresses sub-RQ 1 by developing a framework for prioritising energy sources for sustainable electricity generation using participatory multi-criteria analysis. Publication 2 answers sub-RQ 2 by examining the impacts of sector coupling on different future energy systems. Publication 3 provides insights for sub-RQ 3 by exploring strategic pathways for achieving net-zero emissions by 2050 in Indonesia's energy sector.

The three publications have significantly contributed to energy planning, integration of renewable energy and pathways to achieving net-zero emissions in Indonesia. These research efforts address previously identified gaps, including the need for comprehensive evaluations of energy sources, practical methods for integrating renewable energy across different sectors and actionable pathways for transitioning to an NZE energy system. The contributions of these studies include the development of frameworks and policy recommendations that provide new insights and practical solutions for Indonesia's energy transition. All research contributions in this PhD thesis are grouped and summarised in Table 1.1.

Publication 1 introduces a participatory MCDA framework for evaluating and ranking energy sources for sustainable electricity generation in Indonesia. This publication makes substantial contributions by incorporating diverse stakeholder perspectives from government, academia, industry, and civil society to ensure a balanced and comprehensive assessment of energy sources. This approach not only improves the robustness of the evaluation but also enhances stakeholder engagement and buy-in. The research develops a comprehensive set of criteria, providing a more holistic understanding of sustainability in energy planning.

Publication 2 advances the field by addressing the integration of electricity, transport and cooling sectors with high shares of renewable energy, a concept known as sector coupling. One significant contribution of this research is the detailed analysis of how sector coupling can enhance renewable energy penetration and improve overall energy efficiency in Indonesia. The research provides a systemic perspective, identifying synergies and efficiencies that can be achieved through integrated planning and operation of these sectors. Furthermore, the research offers policy recommendations derived from its analysis, which provide practical guidelines for policymakers to support sector coupling and renewables integration.

Publication 3 contributes to understanding the pathways for achieving NZE by 2050 in Indonesia's energy sector. This research presents detailed scenarios that outline various pathways to NZE. These scenarios include electrification and renewable energy adoption levels, providing flexible and adaptable strategies. The research also highlights the importance of energy efficiency measures and technological innovations in achieving NZE. Moreover, it deepens the need for substantial investments in renewable energy infrastructure and supportive policy frameworks. These contributions provide a comprehensive framework for guiding Indonesia’s long-term energy strategy.

Table 1. 1. Research contributions by research topics in this thesis.

Research topic	Research contribution
Participatory energy planning	• Employing a multi-criteria decision analysis in ranking energy sources for sustainable electricity generation • Applying a participative approach, involving all relevant stakeholders in energy planning
Alternative energy scenario	• Conducting a sector coupling analysis comprising electricity, transport and cooling sectors and employing a bottom-up approach for transport and a geospatial analysis for cooling • Analysing future primary energy supply, critical excess electricity production, CO_2 emissions, and annual total costs in defining the most suitable future energy scenario • Developing future scenarios based on various assumptions on demand side • Analysing all entire energy sectors, consisting of electricity, transport and industry, in an integrated scenario development • Aggregating the future Indonesian energy system from five distinct regional energy systems

1.5. Structure of the PhD thesis

This PhD thesis is structured to analyse Indonesia's pathways towards a net-zero emissions energy system. The thesis is organised into six chapters, each addressing critical aspects of the research objectives. Publications 1, 2 and 3 are particularly placed in Chapters 3, 4 and 5, respectively. Below is an overview of the structure of this thesis.

Chapter 1. Introduction: Setting the stage for Indonesia's energy transition

This chapter sets the context for the research by discussing the global significance of climate change and the need for an international energy transition. It outlines the research questions, objectives and the importance of the study. By situating the research within the broader framework of global climate goals and national energy policies, this chapter highlights its relevance and contribution. It also defines the focus of the overarching research.

Chapter 2. Framework: Theoretical and methodological

Chapter 2 outlines the theoretical and methodological frameworks foundational to this PhD thesis. It introduces the choice awareness theory and the smart energy systems concept, which provide the underlying theories used in the research publications. Moreover, this chapter discusses the methods employed in the research, including multi-criteria decision analysis and energy system analysis, which inform the research and results presented in each publication. The framework presented in this chapter ensures a coherent application of the selected theoretical and methodological approaches, allowing for a focused examination that aligns with the defined objective of the research.

Chapter 3. Ranking of energy sources for sustainable electricity generation in Indonesia: A participatory multi-criteria analysis

Focussing on the first sub-research question, Chapter 3 introduces a participatory MCDA framework for evaluating and ranking energy sources for sustainable electricity generation. It integrates diverse stakeholder perspectives and develops comprehensive environmental, economic, social, and technical criteria. The chapter presents the findings and discusses their implications for energy policy development in Indonesia. This approach enhances the robustness of the evaluation process and fosters greater stakeholder engagement and consensus. The results provide a prioritised list of energy sources tailored to Indonesia's specific context.

Chapter 4. Sector coupling of electricity, transport and cooling with high share integration of renewables in Indonesia

Addressing the second sub-research question, Chapter 4 investigates the integration of electricity, transport and cooling sectors with high RE shares. It provides a detailed analysis of how sector coupling can enhance renewable energy penetration and improve overall energy efficiency in Indonesia. The chapter includes policy recommendations based on the parametric analysis, offering practical guidelines for advancing the country's energy transition. This chapter also explores technological and infrastructural requirements for effective sector coupling.

Chapter 5. Pathways towards net-zero emissions in Indonesia's energy sector

The final research chapter, Chapter 5, explores strategic pathways for achieving net-zero emissions in Indonesia's energy sector by 2050, focussing on the third sub-research question. It presents detailed scenarios outlining various pathways, highlighting the importance of energy efficiency measures, RE-based energy systems and technological innovations. The chapter emphasises the need for substantial investments in renewable energy infrastructure and supportive policy frameworks.

Chapter 6. Synthesis: Integrating research findings for Indonesia's energy future

The concluding chapter, Chapter 6, synthesises the research findings, summarising the contributions to Indonesia’s energy transition. It discusses the study's broader implications for policymakers. The chapter underlines the importance of continued efforts to achieve Indonesia's sustainable and economically feasible net-zero emissions energy system. By integrating insights from all previous chapters, this final chapter highlights the interconnectedness of the research findings and their collective impact on advancing Indonesia’s energy transition. It also proposes directions for future work, ensuring that the research remains relevant and continues to contribute to the global energy transition discourse.

This PhD thesis provides a comprehensive analysis of Indonesia's energy transition, exploring the global context, national strategies and specific methodologies for energy planning, as well as the net-zero emissions pathways. Fig. 1.3 illustrates the interconnected structure and relationships between the chapters.

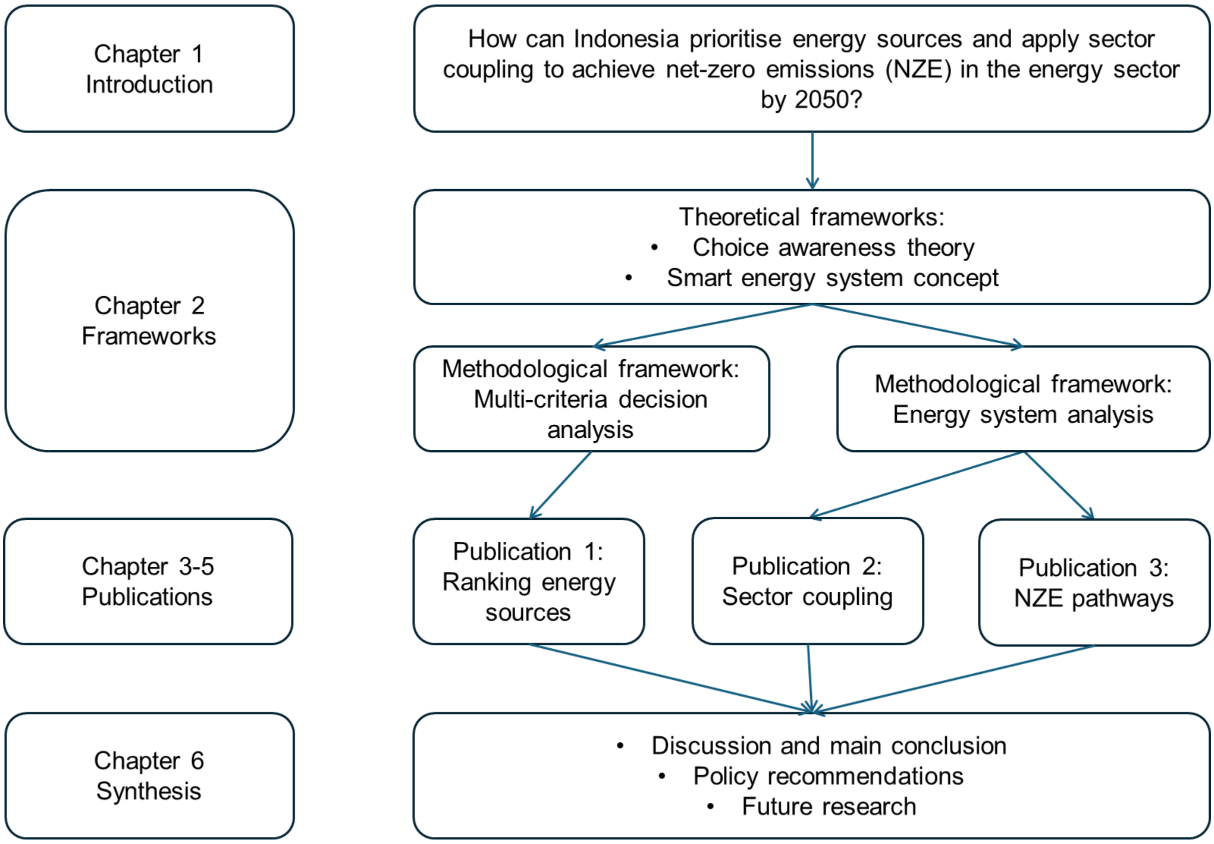

Fig. 1. 3. Structure and relation of chapters in this PhD thesis.

Chapter 2. Framework: Theoretical and methodological

This chapter outlines out the theoretical and methodological frameworks that form the foundation of this PhD thesis. These frameworks are essential for understanding and analysing the multifaceted ideas introduced in the first chapter. By offering a structured approach, the framework prepares the way for interpreting the analyses and conclusions in the following chapters. It ensures the consistent application of the selected theoretical and methodological approaches. It further serves as a key perspective through which the data are assessed, allowing for a focused examination that aligns with the research's defined objectives.

In addition, the framework ensures that the analysis remains relevant to the specific details of the situation under study, which enhances the validity and reliability of the findings. This framework also acts as a guiding tool that directs the scholarly inquiry and supports the overall research design.

Section 2.1 presents the choice awareness theory and the concept of smart energy systems. This theoretical framework proposes the underlying theories used in the research publications. Section 2.2 discusses the methods employed in the research: multi-criteria decision analysis and energy system analysis. This methodological framework shapes the analyses and findings presented in each publication.

2.1. Theoretical framework

The development of alternatives, such as energy sources for sustainable electricity generation or future energy scenarios, is the starting point of the research in this PhD thesis. The thesis discusses relevant theories that examine the technical and socio-political dimensions of transitioning away from fossil fuels. This thesis also explains several energy concepts that integrate all entire energy sectors as the theoretical framework to analyse the whole energy system.

The choice awareness theory provides a strong foundation for why developing and presenting alternatives is a key element in the process of energy transition in Indonesia. Further, the smart energy systems concept offers a complete analysis of all energy sectors with appropriate strategies and technologies.

2.1.1. Choice awareness theory

In addressing the complex challenges of energy transitions, it is important to draw from a diverse range of theoretical frameworks that highlight their suitability in guiding the energy transition process. The framework must not only evaluate the technical viability of renewable energy but also address the institutional, social and political barriers that hinder their progress. Such a framework should provide a comprehensive approach, ensuring that technological feasibility and socio-political acceptance are considered. Selecting a theory that promotes net-zero emissions pathways while involving various stakeholders and clarifying decision-making processes is, therefore, a crucial step in advancing the renewable energy development.

This PhD thesis explains and compares five theories: multi-level perspective, path dependency theory, transition management, technological innovation systems, and choice awareness theory. Each theory offers insights into how societies might shift from fossil fuels to renewable sources. Together, they provide different views on processes, barriers and drivers for change, each with unique relevance to the energy transition challenges facing countries like Indonesia. A comparative analysis of these theories helps to identify which framework is most suitable for addressing the specific institutional, technological and socio-political complexities of this transition.

The Multi-Level Perspective (MLP) on socio-technical transitions [34,35] is widely applied in energy transition studies. It conceptualises transitions as multi-layered processes, where innovations emerge at the niche level, challenge the dominant socio-technical regimes, and ultimately reshape the broader sociotechnical landscape. MLP is especially good at capturing the complexity of large-scale changes and showing how renewable technologies progress through interactions between different levels, niches, regimes and landscapes. However, while the MLP provides a comprehensive framework for understanding technological innovations, it places less emphasis on the decision-making processes that enable the perception of alternatives. This makes it less suitable for contexts such as Indonesia, where powerful stakeholders and status-quo institutions often prevent people from knowing about or using renewable energy options.

Path dependency theory [36,37] suggests another valuable perspective by focussing on how historical decisions and investments lock societies into certain technological pathways. This theory is particularly relevant in explaining why fossil fuel systems persist despite the growing availability of renewable alternatives. The concept of "lock-in" describes how economic, infrastructural and political forces create barriers to change, making it difficult to shift towards RE sources. While this theory effectively illustrates the challenges of breaking free from established systems, it does not provide actionable strategies for overcoming these barriers, particularly in cases where public awareness of alternatives is limited.

Transition management [38–40] provides a governance-oriented framework, emphasising the need for strategic, long-term planning to guide societal transitions towards sustainability. The theory encourages incremental, phased approaches with a strong focus on stakeholder involvement and policy coordination. Transition management is particularly useful in contexts where gradual, managed change is possible. However, its focus on incremental shifts may be less suited to situations requiring urgent, radical transformations, such as Indonesia's energy transition.

The Technological Innovation Systems (TIS) theory [41–43] examines how new technologies develop and spread within specific sectors, like renewable energy. TIS focuses on the innovation ecosystem, looking at how networks of actors, institutions and market forces influence the growth and adoption of new technologies. This theory is valuable for understanding how technological innovations are supported or hindered by systemic factors, such as regulations and financial incentives. However, like the path dependency theory, TIS does not fully address the socio-political dimensions that can limit the acceptance and use of renewable energy.

Choice awareness theory [44] offers a different perspective by focussing on the role of institutional and social dynamics in shaping energy transitions. While other theories address the technical and structural barriers to renewable energy adoption, they often overlook how the perception of available choices can be manipulated by influential stakeholders. In contexts where vested interests dominate, such as Indonesia [28], creating the illusion that no viable alternatives to fossil fuels can significantly hinder progress.

The choice awareness theory emphasises the importance of transparency, public engagement and informed decision-making in overcoming resistance from the established institutions. This theory is particularly relevant to Indonesia’s energy transition, where deeply fossil fuel-dominated systems persist despite the need for a radical change. In the context of Indonesia, this radical change means accelerating RE development in relatively short period of time. By focussing on expanding the public and institutional understanding of available energy options, the theory provides a structured framework well-suited to guiding Indonesia's shift towards a net-zero emissions energy system.

This theory developed by Lund [44] highlights the urgent need for implementing radical technological transformations to secure a sustainable future. Such transformations are needed to address the limitations and environmental impact of current traditional energy systems, which rely heavily on fossil and nuclear sources. Moving towards renewable technologies requires a broad approach, involving adjustments not only in energy production but also within organisational and institutional structures. Here, technologies are understood to include techniques, knowledge, organisational methods, and products. Transformations are seen as radical when they bring about large, simultaneous changes across these areas, reshaping how energy systems function and are managed.

In this choice awareness theory, the term "choice" is crucial, signifying the opportunity to select from multiple options after evaluating their merits and drawbacks. The theory distinguishes between "true choices," which involve genuine alternatives, and "false choices," which only appear to offer a selection but do not, in reality, offer meaningful options. "Awareness" in this context refers to the state of being conscious or aware though not necessarily understanding of a situation; thus, framing choice with awareness enhances decision-making by fostering a deeper understanding and evaluation of options.

This theory takes a broad view, involving many organisations and people, not just private companies. It draws on ideas from discourse theory, suggesting that energy change is shaped by shared social views. A key point is that established organisations often resist significant changes to keep their power and influence. This is especially relevant in Indonesia, where the energy sector is linked to deep-rooted political and economic interests [28]. This resistance slows down the move to renewable energy and delays policy updates.

The theory sets out two main ideas. First, it suggests that when a society aims for major technological changes, existing institutions and their influence can block new solutions and limit options, making it seem like maintaining current systems is the only choice. Second, it emphasises that raising awareness of alternative options enables informed decision-making, benefiting society as a whole. This awareness can be encouraged by clearly explaining new technological options in public discussions and highlighting the potential outcomes of these changes, such as how they could reshape economic or environmental policies. Public debate and thorough feasibility studies that include key political goals can help move society towards better, more informed choices.

The theory of choice awareness brings to light the conflict and gradual process inherent in decision-making. This involves identifying and evaluating different options, often marked by conflicts among various interests and influences, as established organisations try to hold onto their power. The process is gradual, requiring time to build societal practices for developing options, reliable methods for assessment and strong public regulation. The choice awareness theory outlines four steps to increase public understanding of energy choices and to support more active public participation in energy policy. These steps ensure that society considers diverse perspectives and solutions in energy planning and decision-making.

1. Design technical alternatives

This initial step promotes viable alternatives to the current status quo that support informed decision-making. To qualify as true choices, these alternatives must be practical, actionable, and distinct enough to present clear options beyond the status quo. Making sure the alternatives are true choices means understanding how different groups and public views shape them. These options should cover all parts of renewable energy systems to support a move away from fossil fuels. For instance, using a mix of solar and wind power with energy storage can make sure these options are not only possible but also flexible for changing demands. Aligning costs with the main plan and using strategies like demand management and gradual investments can help avoid issues like having too much capacity. Creating these alternatives often ties into political and economic goals, like boosting energy independence and supporting local jobs through renewable energy industries.

2. Conduct economic feasibility studies

This involves conducting socio-economic feasibility studies to gather critical information for identifying which alternatives best meet political goals. Traditional methods like cost-benefit analyses and macroeconomic equilibrium models are based on applied neoclassical economics that frequently fall short because they can overlook social and institutional factors, leading to incomplete assessments. To address this, approaches based on concrete institutional economics are recommended. Concrete institutional economics involves examining the broader social and institutional frameworks that impact economic decisions, focussing on how these structures shape the feasibility and success of implementing energy alternatives. This approach highlights the need to incorporate market and non-market factors, such as regulatory policies, social norms and stakeholder involvement, to create realistic and sustainable solutions. Furthermore, the socio-economic feasibility studies should explore opportunities to benefit both the environment and economy and help formulate institutional policies necessary for such implementations.

3. Identify market barriers and design public regulations

This step focuses on defining the contextual framework for implementing alternatives. It involves identifying market, economic, and institutional barriers that impede the implementation of socio-economically optimal solutions, which are alternatives that best fulfil political, energy policy and economic objectives. These barriers are distinguished through business economic feasibility studies, the results of which are compared with those from socio-economic studies. This step also includes proposing short-term public regulation measures, such as adjustments in taxes, subsidies and financing options, to facilitate the adoption of these alternatives.

4. Improve democratic infrastructure

The final step is to enhance public awareness by identifying and addressing broader institutional barriers, such as weaknesses in organisational structures or gaps in knowledge dissemination necessary for informed decision-making. This includes scrutinising additional barriers within institutions that hinder the provision of relevant information. The process concludes with proposing long-term institutional changes to improve organisations and the democratic infrastructure. Critical to this step is determining who should implement the necessary initiatives, using insights gained from different case studies.

The choice awareness theory is particularly suitable for Indonesia's energy transition context due to its complex socio-political landscape and multifaceted approach to energy governance. Indonesia's planning and policymaking processes are marked by significant involvement of various stakeholders, from government agencies and state-owned enterprises to local communities. However, existing frameworks often struggle with addressing deep-seated institutional barriers and the integration of public input into decision-making. To adapt the choice awareness theory for Indonesia, it is important to focus on including more stakeholders in the decision-making process and sharing information openly. This helps address issues like strong political interests and the heavy influence of fossil fuel companies.

The application of the four steps, as proposed by the choice awareness theory, is evident in the publications of this PhD thesis. The design of technical alternatives is addressed in Publications 1, 2 and 3, while economic feasibility studies are detailed in Publications 2 and 3. Less emphasis is placed on identifying market barriers and designing public regulations. Nevertheless, the last step to improve democratic infrastructure is beyond the focus of the PhD research. Table 2.1 shows the application of the proposed theory steps in the PhD publications.

Table 2. 1. Applied proposed steps of the choice awareness theory in PhD publications.

Publication	Proposed steps	Part of the publication
Publication 1	Step 1: Design technical alternatives	Providing an alternative by developing an approach to rank energy sources for sustainable electricity generation based on sustainable development aspects
Publication 2	Step 1: Design technical alternatives	Developing alternative sector coupling scenarios by including large-scale RE integration into future energy systems
	Step 2: Conduct economic feasibility studies	Calculating total costs of future energy systems that apply a social discount rate
Publication 3	Step 1: Design technical alternatives	Designing alternatives of the accelerated net-zero emissions pathway in the entire energy sector
	Step 2: Conduct economic feasibility studies	Applying a carbon tax scheme in calculating the total costs of future energy systems

Publications 1, 2 and 3 present concrete technical alternatives. Publication 1 offers an extensive approach to ranking energy sources for sustainable electricity generation, covering all energy sources beyond the conventional fossil fuel-dominated options. All alternatives are evaluated systematically and equitably. Publications 2 and 3 provide several options that challenge the business-as-usual approach, favouring the existing fossil fuel industry. The simulated energy scenarios in these publications are shown to outperform the BAU scenario in terms of primary energy supply, CO_2 emissions and total annual costs.

Further, broader economic feasibility studies based on evaluating the social, environmental and financial costs are conducted in Publications 2 and 3. These publications apply a low interest rate aligned with the social discount rate [45] to maximise intertemporal social welfare. Lastly, Publication 3 introduces a carbon price to account for the real externality costs of fossil fuels. The findings confirm that these alternatives support a more cost-effective energy system than the traditional fossil fuel-based system.

2.1.2. Smart energy systems concept

Achieving net-zero emissions across Indonesia's energy sector demands a comprehensive theoretical framework that integrates diverse energy components. Concepts like Energy Hubs, Multi-Energy Systems (MES) and Energy System Integration (ESI) provide structured methods for linking various energy carriers and infrastructures. Energy hubs [46] facilitate the intake, conversion and distribution of electricity, natural gas, and heat, enhancing local flexibility and optimising resource allocation. MES [47] go further by coordinating the operations of electricity, heating, cooling, fuels, and transportation sectors, which boosts overall system efficiency and sustainability. In contrast, ESI [48,49] expands this integration, linking energy carriers with communication networks and water systems to create a resilient, optimised network. While valuable, these concepts tend to face limitations when applied to large-scale renewable transitions, particularly within a complex and geographically diverse context like Indonesia.

Building upon the choice awareness theory [44] the thesis applies the concept of smart energy systems to integrate the whole energy sector. It is linked to the choice awareness steps for designing and comparing alternatives and conducting economic feasibility studies. This concept views integrated energy systems as a holistic approach, incorporating solutions that connect multiple energy sectors, including electricity, transport and cooling. It addresses all components of an energy system, encompassing infrastructure design and operational strategies for future systems. A smart energy system specifies that it should be set up to accommodate renewable-based energy systems.

A “Smart energy system is defined as an approach in which smart electricity, thermal and gas grids are combined and coordinated to identify synergies between them to achieve an optimal solution for each individual sector as well as the overall energy system” [50]. The infrastructure of a smart energy system comprises three interconnected grid systems:

1. Smart electricity grids. These grids are designed to integrate flexible electricity demands like heat pumps and electric vehicles with RE sources, such as wind and solar. This interconnectedness helps manage the intermittent nature of renewables, improving energy reliability and efficiency. These grids use bi-directional communication and power flow to enhance the stability and resilience of energy systems, enabling demand-response strategies and better consumer participation.

   Mathiesen et al. [51] emphasise that smart electricity grids should not operate in isolation; instead, they should be integrated with other energy sectors, such as heating and transport, to form a cohesive smart energy system. This approach maximises the utilisation of renewable energy by creating synergies between sectors, which is essential for achieving high renewable penetration. A review paper by Li et al. [52] further highlights the importance of flexibility in residential energy demand, demonstrating how advanced demand-side management can reduce peak loads and increase the grid's ability to absorb variable renewable energy sources. The system enhances overall grid stability and resilience by leveraging technologies like smart appliances and EV integration.

2. Smart thermal grids (district heating and cooling). The grids connect the electricity and heating sectors, providing significant flexibility by using thermal storage systems. This integration allows for recycling heat losses from industrial processes or energy generation, supporting efficient use of renewable sources and reducing reliance on electricity storage. Thermal grids also enhance grid stability by balancing heat demand and supply, especially when coupled with low-temperature networks optimised for RE sources like solar.

   Yang et al. [53] investigate how solar heating and thermal storage improve efficiency when combined in district heating networks. By using both large seasonal storage and smaller local storage, these grids cut down on heat loss and reduce energy consumption. Flexibility is further enhanced when buildings are equipped with heat pumps and thermal storage, as shown by Zhang et al. [54]. This setup allows buildings to adjust their heat and electricity use based on grid needs, helping maintain grid stability. The setup allows buildings to support the grid with real-time responses actively.

3. Smart gas grids. They link electricity, heating and transport sectors, allowing gas storage utilisation and converting electricity into gas (e.g., hydrogen) to create flexibility. This storage can later be refined into liquid fuels, enhancing the potential for flexible energy use and decarbonising various sectors. These grids contribute to the overall resilience and adaptability of the energy system by offering a more sustainable option compared to direct electricity storage.

   In particular, Martínez Ceseña and Mancarella [55] research how integrating gas storage with electricity and heat in smart districts can provide flexibility to meet varying demands across sectors. By optimising energy flows across these networks, they show that smart gas grids can effectively balance out uncertainties in energy demand and supply. Moreover, Brosig et al. [56] demonstrate the economic potential of gas grids as a balancing resource. They discuss a benchmark network model, which shows that incorporating renewable gas, such as hydrogen, can help stabilise the gas grid and support fluctuating renewable sources. This approach improves the reliability of the gas infrastructure and adds flexibility, especially during peak periods.

   The interconnectivity of these grids forms the core infrastructure of a smart energy system. Synergies between energy sectors, i.e. cooling, heating, electricity, transport, and industry, enable more effective and least-cost solutions to add flexibility to RE-based energy systems. Fig. 2.1 illustrates simplified energy flows from different energy sectors in the smart energy systems concept.

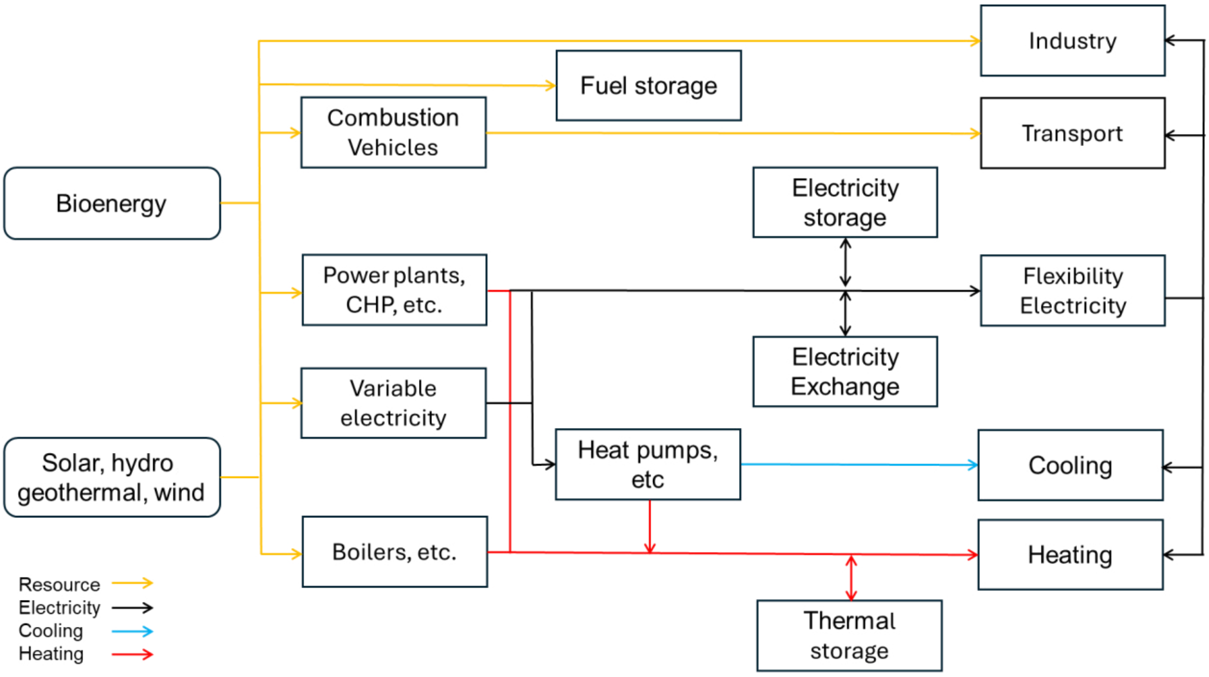

Fig. 2. 1. A simplified model of energy flows in the smart energy systems concept.

Several synergies can be achieved by taking a coherent approach to the complete smart energy systems rather than focussing on individual sectors in isolation. This approach aims to find the best solution for the overall system and seeks the best possible outcomes for each sector. In economic terms, this goal aligns with the concept of a Pareto optimum, where resources are shared to benefit the whole system without negatively impacting any part. By adopting this approach, the smart energy systems concept can be viewed as a balanced arrangement where each sector operates at peak efficiency, contributing to overall system performance.

These synergies, achieved through the coherent approach to the entire system rather than isolated sectors, include [50]:

- Heat utilisation: Excess heat from industrial processes and electricity production can be redirected to heat and cool buildings via district heating or cooling systems.
- Storage solutions: Instead of electricity storage, heat storage can be utilised for heating purposes, offering a more cost-effective and efficient solution. This also enhances the flexibility of combined heat and power (CHP) production.
- Versatile heat pumps: Heat pumps employed for heating can also provide cooling within district cooling networks and vice versa, maximising their utility.
- Biomass conversion: The conversion of biomass to gas and liquid fuels, which requires steam, can leverage the low-temperature heat produced by CHP plants. This heat can then be utilised within district heating and cooling grids.
- Vehicle energy integration: Electricity can replace traditional fuels in vehicles, balancing electricity needs within the system.

Smart energy systems require the use of information and communication technology to coordinate different parts of the energy system. These systems generally prioritise electricity as the main energy carrier, especially from variable RE, and integrate it with thermal systems to meet heating and cooling needs. In colder climates, this integration is essential as heating demand is high, making technologies like heat pumps and electric boilers critical connection points. However, in a tropical country like Indonesia, where heating demand is naturally low, the system's focus shifts more heavily toward cooling needs, which requires a different configuration of resources.

In Indonesia's context, where cooling demand dominates, there is a higher reliance on cooling technologies, such as advanced air conditioning systems that can be linked to the grid and adjusted to match renewable energy availability [57]. Moreover, lower heat demand reduces the need for fuel storage and thermal buffers typically used in colder regions, which can simplify the energy system.

The smart energy systems concept transforms the traditional linear approach of fuel conversion for end-use, a characteristic of current energy systems, into a more integrated and cohesive strategy. By linking energy sectors, the resultant flexibility compensates for the variability of renewable energy sources [58–62]. This integration is crucial for incorporating a high share of renewable energy into the system.

This concept has been applied in the research presented in Publications 2 and 3. Publication 2 investigates the sector coupling of electricity, transport and cooling, focussing on the large-scale integration of renewable energy and electric vehicle penetration into future energy systems. It also explores the utilisation of waste heat from CHPs for cooling. Publication 3 connects and simulates the entire energy sector towards a net-zero emissions energy system. The future energy systems in the two publications are also equipped with flexibility synergies, such as the district cooling network combined with thermal storage and vehicles-to-grid. More detailed applications of the smart energy systems concept in these publications are shown in Table 2.2.

Table 2. 2. Applications of the smart energy systems concept in Publication 2 and 3.

Publication	Smart energy system concept applied in the publication
Publication 2	• Sector coupling of electricity, transport and cooling • Large-scale RE penetration from solar • Waste heat from CHPs used to meet cooling demand • High electric vehicle deployment in road transport
Publication 3	• Reduced energy demand by implementing energy efficiency measures • All energy sectors, electricity, transport and industry are connected and synergised with electricity as the backbone • Net-zero emissions energy system • Flexibility strategies, such as vehicles-to-grid • High electric vehicle deployment in transport

2.2. Methodological framework

Expanding on the theoretical framework outlined in the preceding section, this section details the methodologies employed to achieve the research objectives of the PhD thesis. To comprehensively understand the energy transition in Indonesia, this thesis adopts a mixed-methods approach, gathering and combining both qualitative and quantitative data. This approach uses the strengths of each data type while reducing their limitations, making it well-suited to the complex field of energy studies. Using mixed methods allows for a more in-depth examination of the research objectives by drawing insights from both types of data. Specifically, this thesis applies two primary methodologies: multi-criteria decision analysis and energy system analysis.

2.2.1. Multi-criteria decision analysis

Multi-Criteria Decision Analysis (MCDA) is a subset of operations research methods designed to address complex problems. It is particularly suited for contexts involving high uncertainty, diverse data types, and varied stakeholder interests and perspectives. These methods are designed to facilitate decision-making in scenarios with multiple competing objectives, where solutions often hinge on stakeholder preferences and typically require a compromise.

Generally, all MCDA methods follow four main stages: formulation of alternatives and selection criteria, weighting criteria, evaluation, and final treatment and aggregation of results. Initially, alternatives for the decision-making problem are formulated from a set of selected criteria, and the original data of these criteria are normalised. Secondly, weights are assigned to the criteria to reflect their relative importance in the MCDA methods. Subsequently, acceptable alternatives are ranked using MCDA methods that apply these criteria weights. Finally, the alternatives are ordered based on their ranking. However, if preferences change, the weights and evaluations might need updating to match the new priorities, as MCDA outcomes can be sensitive to such changes [63]. In cases where these changes alter the rankings, re-aggregation of results ensures that the final choice aligns with the latest stakeholder preferences.

Numerous methods exist in MCDA, each involving distinct protocols for eliciting inputs, structures for representing these inputs, algorithms for combining them, and processes for interpreting and utilising the results in accurate decision-making or advisory contexts. The review literature details further grouping and classification of MCDA methods [20,23,64–67]. The most used methods are explained below.

- Multi-Attribute Value Theory (MAVT) and its variant, Multi-Attribute Utility Theory (MAUT), assign a numerical value to each alternative under evaluation. MAVT constructs a preference order of alternatives based on the stakeholders' value judgments, typically using an additive value function [20]. In this context, a value function is a mathematical tool that assigns scores to each attribute of an alternative, reflecting the relative importance of each attribute to the stakeholders. These individual scores, or partial value functions, are then combined to create an overall score for each alternative, helping to clearly rank options in line with stakeholders' preferences.
- Analytic Hierarchy Process (AHP) features a hierarchical structure encompassing goals, criteria and alternatives. This structure is divided into three levels: the goal at the top, the main criteria and sub-criteria in the middle and alternatives at the bottom. Pairwise comparison matrices are created based on stakeholder evaluations for criteria and alternatives using precise numbers of the AHP method. The alternative with the highest weight, calculated through mathematical operations, is selected as the most suitable. AHP is the most used method for energy decision-making research [20,64–66].
- Analytic Network Process (ANP), an extension of AHP, considers dependencies and feedback within the decision-making process and utilises a supermatrix approach to systematically examine all forms of dependencies and feedback. Additionally, it allows for input and interactions both between and within clusters [64].

- Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) identifies the best alternative by measuring the distances of alternatives to positive and negative ideal solutions. It calculates a closeness index, gauging similarity to the positive ideal solution and distance from the negative ideal solution, with the highest closeness value indicating the preferred alternative. TOPSIS assumes that each attribute exhibits a utility that consistently increases or decreases, facilitating the determination of both ideal and least desirable solutions [64,65].
- The Elimination and Choice Translating Reality (ELECTRE) method, suitable for handling both quantitative and qualitative discrete criteria, focuses on dominance relations among alternatives. It explores outranking relations using pairwise comparisons under each criterion, emphasising concordance in outranking relations, allowing for comparative assessments of alternatives [64,65].
- The preference ranking organisation method for enrichment evaluation (PROMETHEE) employs the outranking principle to simplify and clarify decision-making. It is particularly effective in scenarios with a finite number of alternatives and multiple, sometimes conflicting criteria, constructing a valued outranking relation to rank alternatives based on their incoming and outgoing flows [64,65].

In the context of energy research, especially energy planning, MCDA methods offer solutions to increasingly complex problems. At any level, energy planning seeks to determine the optimal supply mix to satisfy demand. Unlike outdated approaches guided solely by technical and economic criteria, modern energy planning acknowledges the multifaceted nature of the problem, requiring attention to both quantitative (economic, technical and environmental) and qualitative (social) criteria. MCDA provides a structured evaluation framework to address environmental, socio-economic, technical, and institutional challenges in energy planning. Developing these criteria that reliably assess sustainability is essential for selecting the best alternative, identifying unsustainable energy supply systems, informing stakeholders about the integrated performance of alternatives and monitoring impacts on the social environment.

Over the past decades, energy planning methodologies have evolved from simple, single-objective systems to complex frameworks due to the inclusion of multiple metrics, stakeholders and conflicting aims. MCDA methods enhance participant involvement in decision-making processes, facilitate compromise and collective decisions, and provide a platform for understanding the perceptions of models and analysts in realistic scenarios. These methods could empower stakeholders to consider all criteria comprehensively and make well-informed decisions based on established priorities. Since multiple dimensions govern ideal designs, a relevant stakeholder may need to identify criteria, such as technical or economic, that are amenable to compromise. MCDA assists the stakeholders by quantifying specific criteria in the presence of competing objectives and facilitates negotiating, quantifying and communicating priorities.

Recent publications have highlighted the growing use of MCDA methods to tackle complex issues, particularly in long-term energy planning and energy source prioritisation [20,68–70]. These methods offer a comprehensive alternative to traditional single-dimensional approaches and are increasingly utilised by a wide range of stakeholders, such as consumers, investors, policymakers, academics, and environmental groups, who often face conflicting objectives in the energy sector. MCDA enables stakeholders to access detailed information and justify diverse approaches, even amidst data uncertainties. Moreover, exploring technical alternatives requires a deep understanding of social expectations, linking social acceptability not only to direct benefits but also to the underlying decision values and potential environmental impacts. MCDA facilitates engaging stakeholders in defining, estimating and prioritising social impacts and their management. Participatory MCDA methods, which integrate stakeholder input throughout the decision-making process via structured surveys, assign weights to these inputs. This process enhances transparency in subjective value judgments, fostering social learning, consensus building, and resolving acceptability issues amongst stakeholders.

Against this background, planning for sustainable electricity generation was conducted using participatory multi-criteria decision analysis in this PhD thesis. The method encompasses multidimensional aspects of ranking energy sources for electricity in Indonesia. It involves the active participation of relevant stakeholders from the energy industry, capturing a participatory energy planning process during the energy transition. This proposed process provides concrete technical alternatives to the country's dominant fossil fuel-based electricity generation.

The AHP method was employed in Publication 1 to rank nine energy sources for sustainable electricity generation, considering four main criteria and twelve sub-criteria. AHP was chosen over other methods for its unique ability to integrate both quantitative and qualitative data within a structured hierarchical framework. This approach facilitates the relevant stakeholders to weigh criteria based on both objective metrics and their own judgments.

AHP's simplicity in mathematical processing makes it more transparent and accessible for stakeholders, encouraging engagement without requiring advanced technical knowledge, which is key to fostering trust and acceptance of the results [71]. Furthermore, a key feature of AHP is its consistency check, which identifies and adjusts any conflicting judgements, ensuring the inputs are reliable. This feature is particularly helpful when opinions vary, as it helps maintain the credibility of the final rankings. The choice of AHP was also influenced by initial discussions with Indonesian stakeholders, who expressed familiarity with the method from previous studies. This familiarity eased the process of stakeholder engagement, facilitating smoother participation and constructive input, and further supported the choice of AHP as the most fitting method for this analysis.

2.2.2. Energy system analysis

Designing and analysing future energy systems requires a robust methodology due to the inherent complexity of these systems. A robust methodology refers to an approach that can handle uncertainties and variations in critical factors without compromising the reliability of the results. In transitioning to renewable energy systems, the methodology must account for various interdependent technologies, evolving demand patterns and the variability of RE sources, such as wind and solar. This ensures that analyses remain accurate even when faced with unexpected system input or configuration changes. The move towards renewable energy introduces complexities due to the integration of new energy carriers, such as hydrogen and biofuels, which require advanced storage and distribution systems. The RE-based systems must be adaptable to fluctuating supply and demand while managing resource constraints like in solar irradiance.

This thesis aims to provide concrete technical alternatives that cover all aspects of future energy systems. To achieve this, it is imperative to employ an energy system analysis tool that can effectively identify and quantify the impacts of various alternatives. An ideal tool for this purpose should encompass the entire energy system, including electricity, heating, cooling, transport, and industry sectors. It should offer temporally modelling capabilities to handle the complexities of variable renewables and quantify impacts using environmental and economic parameters. In addition, the tool should accommodate all potential technologies involved in radical technological transformations and facilitate the integration of multiple energy systems.

In this thesis, a simulation tool is preferred over an optimisation tool. Simulation tools are designed to replicate the performance of an energy system under specific conditions, typically used with an alternative assessment approach, allowing users to explore diverse scenarios and outcomes. The primary distinction is that simulation tools predict system performance based on predefined assumptions, while optimisation tools seek the best operational or design outcome for a given system by minimising or maximising objectives [72].

One of the key benefits of simulation is its suitability for back-casting, an approach that foresees a desired future outcome and works backwards to identify necessary steps to achieve it. Back-casting is particularly valuable in transition management because it enables stakeholders to envision transformative goals without being restricted by current system constraints [73], an approach highlighted in public policy for managing complex transitions such as energy transitions [39].

Optimisation tools are less appropriate for long-term decision-making in democratic contexts, as they focus on economically optimal solutions rather than accommodating a range of stakeholder-driven scenarios [72]. In democratic settings, energy transitions typically require pathways that address environmental, social, and political goals beyond pure economic efficiency. The preferred simulation tool also aligns with the MCDA methods used in this thesis, as it allows for exploring different energy pathways that provide a spectrum of possible choices.

The EnergyPLAN tool possesses all the necessary features for conducting a thorough analysis in this PhD research. EnergyPLAN's high temporal resolution and integrated approach to energy system modelling make it suitable for assessing scenarios with radical technological transformations. Unlike econometric models, which focus primarily on economic relationships and often lack the sectoral detail needed for comprehensive energy analysis, EnergyPLAN is specifically designed to simulate an entire energy system in one cohesive framework.

This capability distinguishes EnergyPLAN from other tools that may not fully capture the interactions and dependencies across energy sectors. For example, TIMES and MESSAGE are optimisation-based models that seek cost-effective solutions but often require a stable input environment, which may not suit long-term, scenario-based explorations involving diverse technologies. While these tools are highly effective for determining economic feasibility within set constraints, they are less flexible for exploratory analyses of future energy pathways that integrate high shares of renewable sources and new technologies [74]. In contrast, EnergyPLAN's simulation-based design allows for varied technological inputs without needing an optimised baseline, providing robust support for analysing diverse transition scenarios.

EnergyPLAN is designed to model the hourly operation of all energy sectors over one year, including the electricity, heating, cooling, transport, and industry sectors shown in Fig. 2.2. It uses deterministic modelling, meaning it produces the same results each time for a given set of inputs. This reliability makes it ideal for planning energy systems with high shares of renewable energy sources, where consistent scenarios help policymakers understand potential pathways. Deterministic models like EnergyPLAN are particularly useful in scenario planning because they provide stable outcomes, allowing for straightforward comparisons between different energy system setups based on fixed assumptions, such as power capacities and production.

In contrast, stochastic models add randomness to input factors to account for uncertainties, such as changes in renewable energy supply or demand. While this type of model is suitable for capturing risks and variations, it requires a lot of computing power and produces a wide range of results, which can make it harder to interpret for long-term energy planning [75]. For example, stochastic models can explore uncertain factors through various scenarios, but this complexity may not be ideal when clear, repeatable outcomes are needed for policy decisions [76]. EnergyPLAN's deterministic approach fits well with the objectives of this thesis, as it supports the evaluation of specific energy scenarios under fixed conditions, providing a stable basis for assessing the technical feasibility and policy analysis of different options.

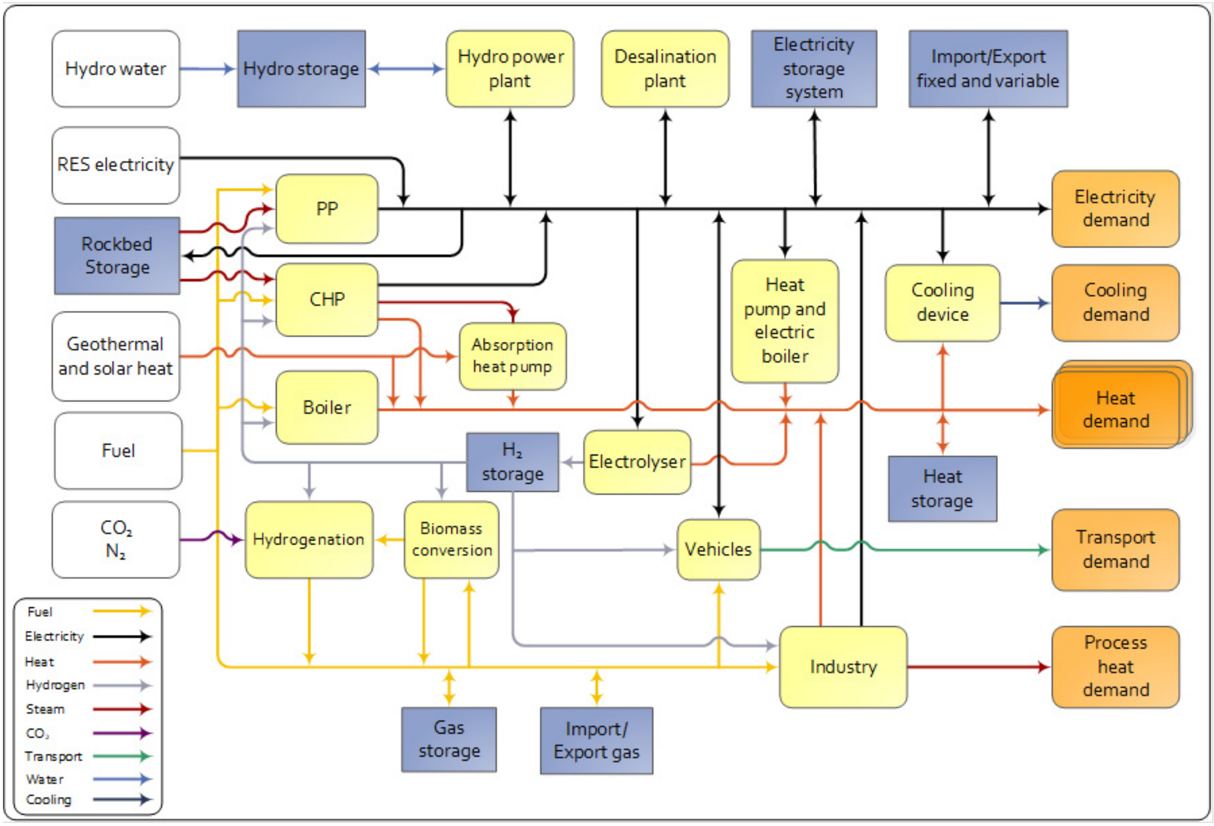

Fig. 2. 2. The overall energy sources, technologies and flows in EnergyPLAN [78].

The design of EnergyPLAN reflects the theoretical concept of smart energy systems, emphasising a holistic view of the energy system. This perspective considers, for example, the integration of variable RE-based power into the electricity grid using smart grids, not as an isolated challenge but as part of broader energy system strategies [77]. Guided by the choice awareness theory, EnergyPLAN fosters the exploration of multiple scenarios through efficient analytical programming, supporting the evaluation of technological transformations in short computational times. The purpose of using EnergyPLAN is not to prescribe or predict a single future energy configuration. Instead, it serves as a tool to openly consider different ways forward, giving stakeholders a wide range of choices.

This flexibility matches with MCDA, which focuses on offering multiple options instead of finding one 'optimal' solution. There is no single solution for creating RE-based energy systems, as stakeholders may have different goals, such as economic growth, environmental sustainability and social acceptability. By presenting a range of alternative scenarios, EnergyPLAN helps decision-makers look at other options based on many criteria, allowing them to make choices that best suit their goals.

Within EnergyPLAN, renewable energy sources are transformed into various energy carriers beyond electricity through different power-to-x technologies, including heat, hydrogen, e-gases, and electrofuels. It also models renewable energy systems incorporating energy conservation and efficiency improvements, such as CHP and fuel cells, which can potentially displace fossil fuels or enhance fuel efficiency [50]. However, EnergyPLAN is not designed to link specific regional energy systems or assess the benefits of such interconnected systems. This particular feature is essential for evaluating the potential benefits of interconnecting Indonesia's regional energy systems. The regional separation in Indonesia's energy infrastructure creates both technical and economic challenges, particularly in balancing RE supply and demand across the country. Therefore, this PhD thesis employed MultiNode to evaluate the advantages of system interconnectivity. By linking regional systems, MultiNode permits sharing surplus electricity generated from renewables, such as solar and hydropower, between regions with different energy needs and availability.

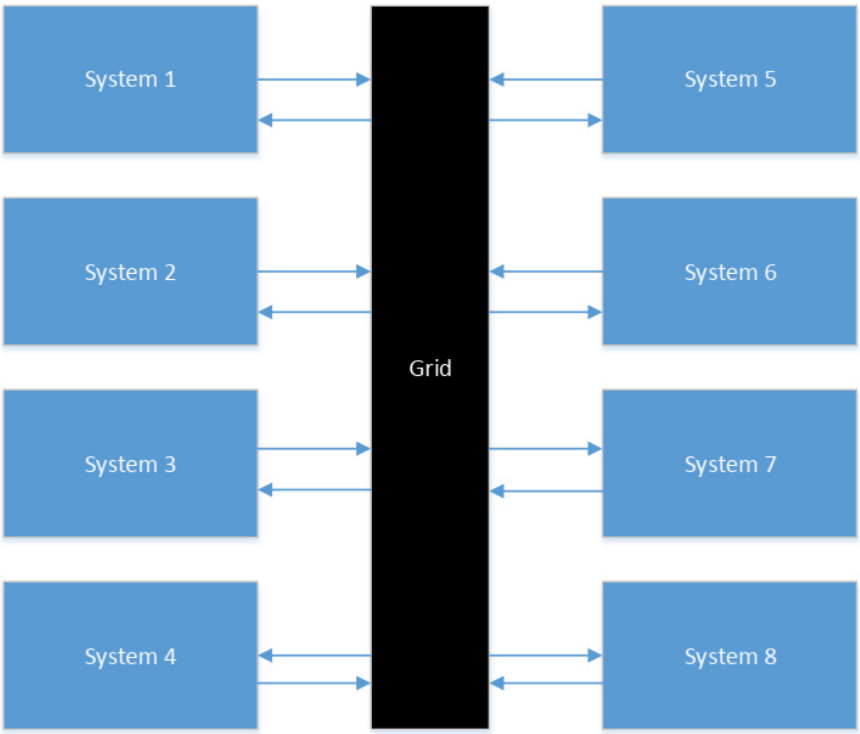

Fig. 2. 3. Principle of the MultiNode add-on tool for EnergyPLAN [79].

MultiNode is an additional tool for EnergyPLAN specifically developed to analyse the integration and development of several energy systems' plans. This add-on enables EnergyPLAN to evaluate interactions between different energy systems, allowing users to identify impacts on total resource use and electricity exchange. MultiNode assesses each energy system's production of excess electricity and potential for imports that reduce overall fuel use [78] shown in Fig. 2.3. The tool investigates every hour of operation in the energy systems and identifies import or export potentials. It facilitates the export of electricity from one system to another when excess electricity coincides with import potential, thereby reducing fuel consumption in the receiving system. Conversely, the tool only permits imports during hours of excess production in a neighbouring region, primarily from variable renewable sources, ensuring that one system does not activate power production in another.

The application of EnergyPLAN and MultiNode throughout this PhD thesis is detailed in Publications 2 and 3, each with distinct objectives and differentiated variables shown in Table 2.3.

Table 2. 3. The application of EnergyPLAN and MultiNode in Publications 2 and 3.

Variable	Publication 2	Publication 3
Tool used	EnergyPLAN	EnergyPLAN and MultiNode
Main objective	Investigating sector coupling of electricity, transport, and cooling	Exploring potential pathways towards a net-zero emissions energy system
Covered sector	Electricity, transport, cooling	All energy sectors
Covered area	Java-Bali system, focussing on Jakarta for district cooling analysis	All of Indonesia, connecting five regional energy systems
Time horizon	2040	2030; 2040; 2050
Carbon price	Not applied	Applied, USD 30 in 2030; USD 40 in 2040; USD 50 in 2050

Chapter 3. Ranking of energy sources for sustainable electricity generation in Indonesia: A participatory multi-criteria analysis

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Ranking of energy sources for sustainable electricity generation in Indonesia: A participatory multi-criteria analysis

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ABSTRACT

An evaluation of energy sources for electricity generation should consider manifold aspects of the sustainable development concept. The evaluation also needs active participation from all involved stakeholders. The objective of this paper is to rank energy sources for sustainable electricity generation in Indonesia. A multi-criteria decision analysis using the analytic hierarchy process method was applied to deal with multiple aspects of the sustainable development in the ranking of selected energy sources. Four criteria, twelve sub-criteria and nine energy source alternatives (three fossil fuels and six renewables) were defined. Relevant Indonesian energy stakeholders from government institutions, universities, think tanks, the energy industry, civil society and international organisations participated in this research. They gave judgements on pair-wise comparisons of the criteria and sub-criteria and a performance evaluation of the alternatives against four sub-criteria. The performance of the alternatives against the other eight sub-criteria was evaluated using data from relevant literature. This paper indicates that solar is the top ranked alternative for sustainable electricity generation in Indonesia, followed by hydro and oil as the top three. To fulfil the solar energy potential, the Indonesian government should consider policies that focus on the strengths of solar in the economic and social criteria.

Keywords

Sustainable energy systems;
Sustainable energy planning;
Sustainable electricity generation;
Analytic hierarchy process;
Energy stakeholder participation;

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1. Introduction

The sustainable development concept has emerged over the past three decades and now plays a vital role in our daily life. Introduced in 1987 by the World Commission on Environment and Development, sustainable development is defined as "a development which meets the needs of current generations without compromising the ability of future generations to meet their own needs" [1]. In 2015, the United Nations adopted 17 Sustainable Development Goals (SDGs) as a global plan of action for people, the environment, and economy. SDG 7, a goal for the energy sector, aims to ensure access to affordable, reliable, sustainable, and modern energy for all [2]. This can only be achieved by promoting energy efficiency, reducing the use of fossil fuels that produce harmful emissions to people and the environment, and at the same time by increasing renewable energy penetration into energy systems. Renewable energy is not only better for people and the environment than fossil fuels but also good for the global economy. The International Renewable Energy Agency concludes that a renewables-based energy system will, on average, increase global GDP growth until 2050 [3].

Formulating energy plans that consider the sustainable development concept has become a main concern for all governments in the world. Negative impacts of energy projects, such as health problems and land-use change, are becoming increasingly important in energy planning. Maulidia et al. [4] believe that Indonesian energy planning is short-sighted and does not consider long-term benefits to people and the environment, such as

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energy security and environmental sustainability. Moreover, energy planning in Indonesia lacks transparency and inclusiveness. The Indonesian government needs to apply a thorough analysis and participatory process in energy planning. Against this background, the present research selected Indonesia as the case study focusing on energy planning in the electricity sector.

Since the early 2000s, electricity generation has increased substantially in Indonesia. Between 2010 and 2020, it almost doubled from 156 TWh to 291 TWh [5], as shown in Figure 1. The rise corresponds to an average GDP growth of 4.74 % over that period. Nevertheless, the electricity consumption per capita was still only 1,090 kWh in 2020 [6], significantly below the national target of 2,500 kWh by 2025 [7]. Current official Indonesian documents [8–10] predict an accelerating trend of electricity generation and consumption. Several international institutions have made similar projections [11,12]. The Asia-Pacific Economic Cooperation estimates that Indonesian electricity generation will be approximately 1,050 TWh in 2050 [13].

Fossil fuel–based sources have dominated Indonesia's electricity generation over the past two decades, as shown in Figure 1, and they are expected to remain the main sources. Coal, oil and natural gas–fired power plants accounted for almost 85.5% of the total installed capacity in 2020 [5]. The latest Indonesian electricity supply business plan [10] sets the share of coal, natural gas and oil in the total installed capacity by 2030 at 45%, 23% and 4%, respectively. Coal-fired power plants will continue to dominate electricity generation in Indonesia.

Renewables development in the electricity sector has experienced slow progress in Indonesia. From 2000 to 2020, the share of renewables in the country's total electricity generation increased by just 2% [5,14]. In 2020, the installed capacity from renewables was approximately 10.5 GW or 14.5% of the total installed capacity [5]. Hydro, geothermal and biomass contributed 6.1 GW, 2.1 GW and 1.8 GW, respectively. Other renewables solar, wind and biogas only accounted for around 0.5 GW [5]. The current increase seems contradictory, considering that Indonesia has abundant renewable energy potential in various forms [14–21], and numerous Indonesian studies [23–26] conclude that renewables can compete technically and economically with fossil-based sources.

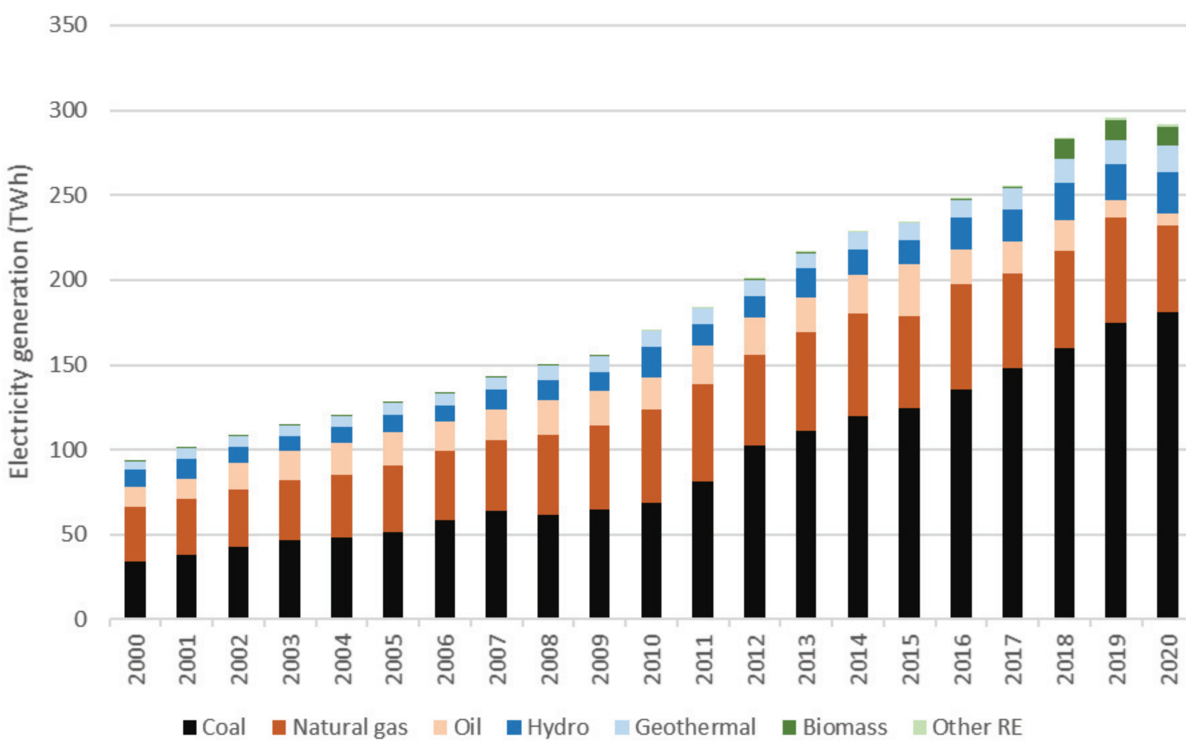

Figure 1: Total electricity generation in Indonesia from 2000 to 2020 [5,14]

An evaluation of energy sources for electricity generation in energy planning should be based on the sustainable development concept. Social, economic, and environmental aspects should be simultaneously assessed when prioritising alternative sources of energy [27]. The evaluation should also include various limitations, such as conflicting interests, economic constraints and technological challenges [28]. Multi-criteria decision analysis (MCDA) methods are suitable in dealing with these limitations and the manifold aspects of sustainable development in the energy sector. The MCDA methods can accommodate opposing interests and objectives from diverse backgrounds of stakeholders in the energy sector.

Various MCDA methods have been applied in Indonesian sustainable energy studies. Tasri and Susilawati [29] employed an MCDA method to select the most appropriate renewable energy sources for electricity generation. Miraj and Berawi [30] utilised two MCDA methods to evaluate the best solar PV alternative for electricity access on Tomia island. A combination of spatial analysis and MCDA methods was employed by Ruiz et al. [31] to select the optimal location of solar plants. However, it is believed that an evaluation using MCDA methods to rank all energy sources for electricity generation in Indonesia has not been conducted. This evaluation could be an alternative approach that is needed to consider multiple aspects of sustainable development concept in energy planning. This paper attempts to fill this literature gap by combining the use of MCDA and the active participation of relevant energy stakeholders for an evaluation of sustainable electricity generation in the country. It could benefit policymakers, planners and other relevant energy stakeholders in the development of sustainable energy plans, particularly in the electricity sector.

This paper suggests an approach for the ranking of energy sources for electricity generation in energy planning in Indonesia. The aim of the paper is to rank energy sources for sustainable electricity generation in the country. This paper applies MCDA employing the analytic hierarchy process method. A total of 23 Indonesian energy stakeholders from five different groups representing various interests and objectives participated in the present research. Four criteria and twelve sub-criteria were developed to rank the energy sources. This research evaluated a selection of all existing energy sources, both fossil fuels and renewables, which could be used in energy planning in Indonesia.

The paper lays out a research hypothesis that renewable energy sources have higher ranks than fossil fuels to generate sustainable electricity generation in Indonesia. The proposed approach that combines qualitative and quantitative data analyses could capture renewables' competitiveness in generating electricity against fossil-based power plants.

2. Methods and data

This section explains the multi-criteria decision analysis applications in energy planning, and the analytic hierarchy process method and the associated data used in this research.

2.1. Multi-criteria decision analysis in energy planning

Energy planning is a multi-dimensional process that has to deal with a broad range of qualitative and quantitative variables. A one-dimensional process that only uses quantitative variables, such as net present value or cost-benefit analysis, cannot comprehensively solve current energy planning issues. Qualitative variables, such as public acceptance and political risk, have been found to play a vital function in energy planning [32]. Competing interests and purposes amongst energy stakeholders should be captured in an analysis process that accommodates all involved variables. Multi-criteria decision analysis (MCDA) is well suited for this as it can be applied to determine trade-offs, co-benefits, and consensus results of complicated planning problems [33]. MCDA can increase the quality of decisions by creating them more explicitly, efficiently and rationally [34]. Stakeholders, such as government institutions, industry associations and civil society organisations, who actively engage in the energy planning process, need a structured framework, and this is possible with the MCDA method.

MCDA methods have been used globally as an alternative to traditional one-dimensional evaluation as they can handle many issues in energy planning, such as the ranking of energy sources or energy technologies for electricity generation. Some MCDA methods that are widely used in sustainable energy studies are Elimination and Choice Translating Reality (ELECTRE), Preference Ranking Organization Methods for Enrichment Evaluation (PROMETHEE), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Analytic Hierarchy Process (AHP). The ELECTRE method was utilised by Martínez-García et al. [35] to select the most sustainable technology for electricity generation in the United Kingdom. Seddiki et al. [36] utilised PROMETHEE to rank renewable energy technologies for electricity generation in a residential building. Alidrisi and Al-Sasi [37] employed TOPSIS to rank the G20 countries with respect to their energy selection for electricity generation. The AHP method was adopted by Shaaban et al. [38] to rank electricity generation technologies in Egypt. Al Garni et al. [39] and Ahmad and Tahar [40] utilised the AHP method for the ranking of renewables in the electricity sector in Saudi Arabia and Malaysia, respectively. Several extensive literature reviews [41–43] on MCDA applications in the sustainable energy field found that the analytic hierarchy process is the most used method.

2.2. Analytic hierarchy process for ranking alternative energy sources

The AHP method was introduced by Thomas L. Saaty in the 1970s and has been used to structure and model complex problems [44,45]. This method provides a thorough and logical framework for constructing a decision problem and solving it. The AHP method enables the ranking of different alternatives by offering a framework that can manage interests and provide solutions for conflicting aims. It transforms the decision problem into a hierarchy tree of a goal, criteria (and if needed, sub-criteria and further lower levels of sub-criteria) and alternatives. The alternatives are a group of options to be ranked based on the given criteria and sub-criteria. Figure 2 depicts the hierarchy tree for this research. The AHP method permits decision analysis processes to integrate quantitative data and qualitative judgements. This method matches a need to consider multifold aspects in the sustainable development concept. Another advantage of the AHP method is that it does not require complicated mathematical calculations [46]. Users can follow simple formulas and compute them. Figure 3 illustrates the main steps to rank energy sources for sustainable electricity generation in Indonesia using the AHP method.

A broad range of Indonesian energy stakeholders from the Indonesian government, universities, think tanks, the fossil fuel and renewable industry, civil society and international organisations participated in this research. These groups of stakeholders were chosen to reflect diverse interests in the Indonesian energy sector. A total of 52 stakeholders (Indonesian government: 9 stakeholders; universities and think tanks: 13; fossil

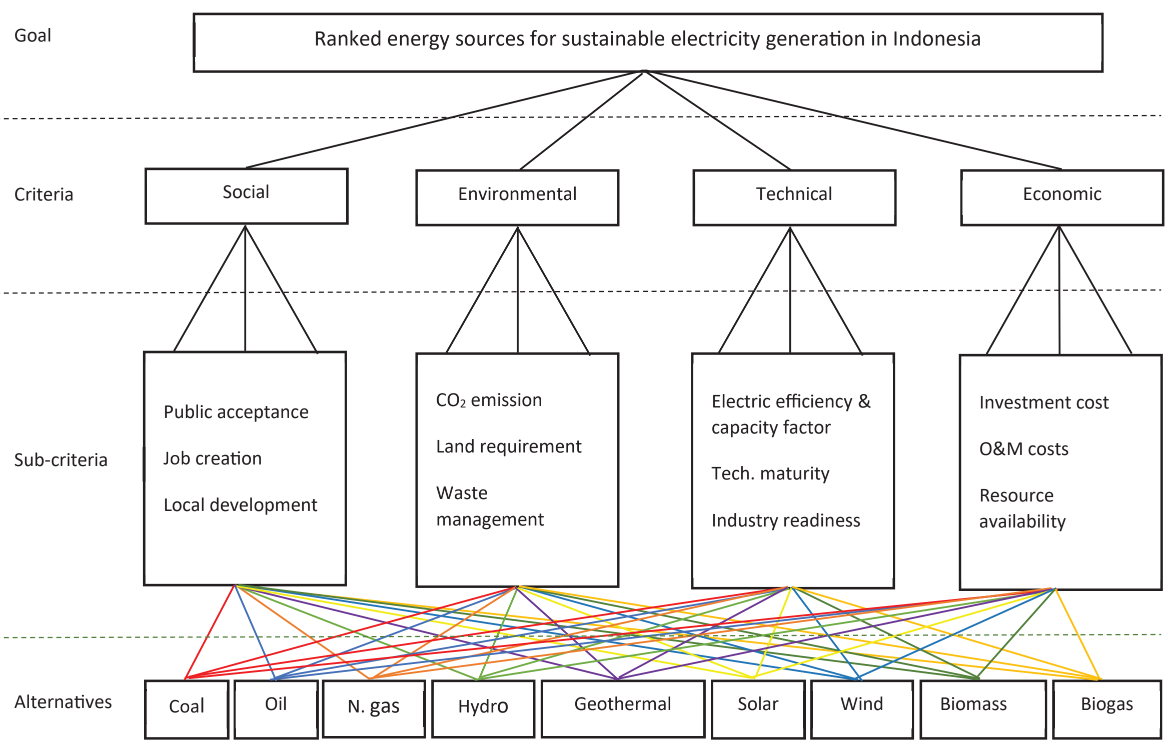

Figure 2: Hierarchy tree for ranking energy sources for sustainable electricity generation in Indonesia

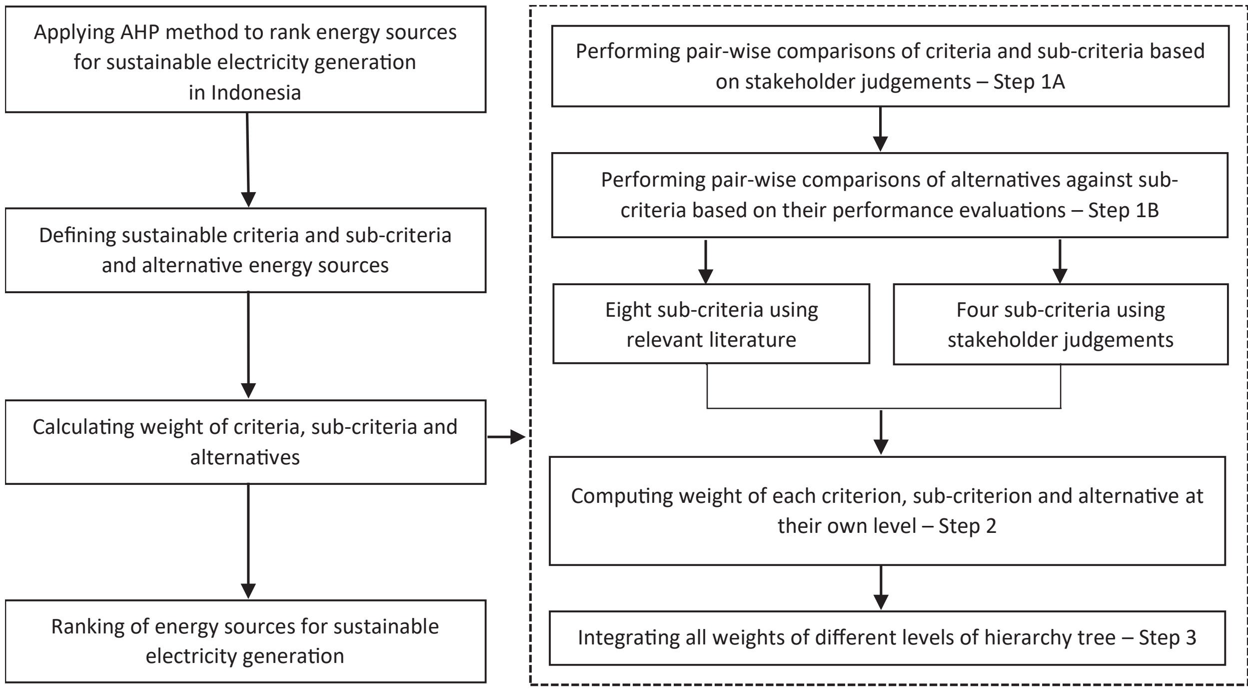

Figure 3: Main steps to rank energy sources for sustainable electricity generation in Indonesia using the AHP method

fuel industry: 7 and renewable industry: 7; civil society and international organisations: 16) were invited to participate in the research. Twenty-three stakeholders (details in Appendix 1) replied to the invitation. Data collection from the stakeholders took place between July and August 2021.

The 23 Indonesian energy stakeholders gave their judgements in two different questionnaires. The first questionnaire (Appendix 2) requested pair-wise comparisons of the criteria and sub-criteria, using Saaty's nine-integer importance scale, as shown in Table 1. The second questionnaire (Appendix 3) determined the performance of alternatives against four qualitative sub-criteria. Stakeholders evaluated the performance of each alternative on a 1-9 performance scale, as shown in Table 2. The two questionnaires in Indonesian were provided online and sent via email. The stakeholders had the opportunity to ask their own questions or clarify questions in the questionnaires.

2.3. Defining criteria, sub-criteria and alternatives

The ranking of energy sources for sustainable electricity generation requires a comprehensive process of defining selected criteria and sub-criteria, which should accommodate the sustainable development aspects. An extensive literature review was undertaken to obtain a list of possible criteria and sub-criteria. The list was modified to provide the most suitable ones in the context of the Indonesian electricity sector. Literature reviews by [32,41,42,47,48] on MCDA applications in the sustainable energy field found that social, environmental, technical and economic criteria were commonly used in these applications. Sub-criteria, such as job creation, CO_2 emission, electric efficiency, and investment cost, were also found to be commonly used. Table 3 summarises the most common criteria and sub-criteria used in sustainable energy research. This present research applied a subjectivity method based on own opinion in selecting and classifying criteria and sub-criteria. This method depends on preferences of people who are responsible for conducting the research and the goals set in the research design [48].

The criteria selected in this research are social, environmental, technical, and economic. Each of these four criteria has three sub-criteria. The social criterion covers social dimensions of the development of a power plant in a specific location and contains the sub-criteria public acceptance, job creation and local development. The environmental criterion considers environmental impacts of a power plant on the environment and people and contains the sub-criteria CO_2 emission, land requirement and waste management. The technical

Table 1: Importance scale for pair-wise comparison [44]

Intensity of importance (Variable A to Variable B)	Definition
1	Variable A and Variable B are equally important
3	Variable A is weakly more important than Variable B
5	Variable A is strongly more important than Variable B
7	Variable A is very strongly more important than Variable B
9	Variable A is absolutely more important than Variable B
2, 4, 6, 8	Intermediate intensities

Table 2: Performance scale for an alternative against qualitative sub-criteria

Performance score	Definition
1	Worst performance
3	Bad performance
5	Adequate performance
7	Good performance
9	Best performance
2, 4, 6, 8	Intermediate performances

Table 3: Popular criteria and sub-criteria used in sustainable energy research

Criterion	Sub-criterion	Source
Social	Public acceptance	[29,39,40,49–51]
	Job creation	[29,40,50–54]
	Local development	[49,52,53,55,56]
	Health impact	[49,52,56]
	Political acceptance	[39,57,58]
Environmental	CO_2 emission	[29,39,49,50,52–54]
	Land requirement	[29,39,49,50,52,53]
	Waste management	[29,49,54,57,59]
	Ecological impact	[49,51,53]
	Particles emission	[60–62]
Technical	Electric efficiency	[38,39,50,53,54,63,64]
	Capacity factor	[49,50,52,53,63]
	Technology maturity	[39,40,53,64]
	Industry readiness	[29,49,53,54]
	Flexibility	[49,50,52]
Economic	Investment cost	[29,39,49,51,53,54,63]
	O&M costs	[39,49,51,53,63,64]
	Resource availability	[39,40,49,52,55]
	Fuel cost	[49,63]
	Payback period	[65,66]

criterion considers the main technical aspects of a power plant and its technological development and contains the sub-criteria electric efficiency and capacity factor, technology maturity and industry readiness. Finally, the economic criterion discusses economic factors concerning power plant construction and operation, and energy source availability for electricity generation. This criterion has investment cost, operation and maintenance (O&M) costs and resource availability as its sub-criteria.

The current research considered all of the energy sources currently being used in the Indonesian electricity sector as alternatives. These include the fossil fuels coal, natural gas, and oil, and the renewable energy sources hydro, geothermal, solar, wind, biomass (including sources from waste), and biogas. Several official energy plan documents [8–10] also use the same selection of energy sources in relation to energy planning in Indonesia. These nine energy source alternatives capture the current status of the Indonesian electricity sector and the plans for the ranking of energy sources in the future. The selection of alternatives excluded sources, such as nuclear, tidal and wave energy, as they are not used commercially in Indonesia at present.

All of the alternatives were evaluated with respect to the sub-criteria. Energy stakeholders gave their judgements on the performance of alternatives against the qualitative sub-criteria public acceptance, local development, waste management, and industry readiness. These alternative performances were ranked based on the geometric mean of all stakeholder judgements in each sub-criterion. The technology maturity sub-criterion used qualitative information from literature. The remaining sub-criteria of job creation, CO_2 emission, land requirement, electric efficiency and capacity factor, investment cost, O&M costs, and resource availability are quantitative and based on relevant literature. The source selection for these sub-criteria was carried out for their reliability and applicability, i.e., Indonesian government publications or peer-reviewed articles. It is important to note that each quantitative sub-criterion used only one source except for resource availability, which used three sources. The decision to use one source per sub-criterion provided a uniform methodology for evaluating nine different energy sources against each sub-criterion. Table 4 presents the data sources for each sub-criterion.

The following sub-sections provide detailed definitions and explain the sources used for each sub-criterion in this research.

Public acceptance. This indicates the satisfaction level of the general public for the development of a new power plant. Public acceptance directly and indirectly affects the progress of power plant development. The performance of each alternative for this sub-criterion was evaluated qualitatively by stakeholders. The best performance indicates the public's most welcomed energy source for a new power plant. Stakeholders indicated that coal is the least welcome alternative and that solar is the most welcome one. The complete evaluation for this sub-criterion can be seen in Table 5.

Table 4: Sub-criteria in this research and the sources of relevant data

Sub-criterion	Source
Public acceptance	Stakeholder judgement
Job creation	[67]
Local development	Stakeholder judgement
CO_2 emission	[68]
Land requirement	[69]
Waste management	Stakeholder judgement
Electric efficiency and capacity factor	[69]
Technology maturity	[69]
Industry readiness	Stakeholder judgement
Investment cost	[69]
Operation and maintenance (O&M) costs	[69]
Resource availability	[5,9,12]

Table 5: Performance of the alternatives for selected sub-criteria

Alternative	Public Accept-ance	Job creation		Local develop-ment	CO_2 emission (ton/GJ)	Land require-ment (1000 m^2/MW)	Waste manage-ment
		C&I stage (Job-years/MW)	O&M stage (Jobs/MW)				
Coal	1	24.64	0.31	2	0.096	0.04	1
Natural gas	3	2.86	0.31	5	0.056	0.02	3
Oil	2	2.86	0.46	1	0.074	0.05	2
Hydro	8	16.28	0.44	9	0	62	9
Geothermal	7	14.96	0.88	7	0	30	6
Solar	9	28.6	1.54	8	0	14	8
Wind	6	7.04	0.66	4	0	14	7
Biomass	5	30.8	3.30	6	0	35	4
Biogas	4	30.8	4.95	3	0	70	5

Job creation. This sub-criterion indicates the opportunities for creating new jobs by building a new power plant. Jobs can be associated with direct employment during the stages of both construction and operation. This primarily generates development and prosperity in local communities. Job creation is the most used sub-criterion in the social criterion [32]. For this sub-criterion, the performance of the alternatives is taken from a recent study by Ram et al. [46], which investigated the number of jobs created by all types of power plants across the globe. Until now, no such comprehensive study has been carried out in Indonesia. Ram et al. [67] specify job creation factors for different regions. The current research applied the job creation factor of the Southeast Asia region. The job creation sub-criterion contains two different performances, which were evaluated for the stages of building a power plant. First, there is the construction and installation (C&I) stage with the unit job-years/MW. Second, it is the operation and maintenance (O&M) stage with the unit jobs/MW. These two performances equally evaluated alternatives and are listed in Table 5.

Local development. This expresses social progress in a region where a power plant has been built. In the Indonesian context, the power plant could affect either one or several cities and regencies, or at a broader level, provinces. Quantifying the full indirect impact of a new power plant is extremely difficult. This research used qualitative judgements of stakeholders to rank the performance of alternatives for this sub-criterion. Hydro is ranked as having the highest impact on local development, and oil is ranked as having the lowest impact. Table 5 shows the full evaluation for this sub-criterion.

CO_2 emission. This sub-criterion evaluates the direct impact of alternatives on the environment by assessing the volume of CO_2 emitted into the air in the process of generating electricity. The sub-criterion is taken from quantitative data, in the unit CO_2 ton/GJ, from the Indonesian GHG Inventory Data for Energy Sector [68]. Only fossil fuel sources are assumed to be CO_2 emitters. Renewable energy sources do not produce CO_2 in electricity generation. This assumption also applies in Indonesian energy planning documents [8–10]. Table 5 shows the performance of alternatives with regard to the CO_2 emission sub-criterion.

Land requirement. This requirement quantifies the area of land needed to build a power plant and its supporting facilities. It is a quantitative sub-criterion with data taken from the newest Technological Data Catalogue for Power Sector in Indonesia [69]. It is worth mentioning that the catalogue is predominantly based on power plant projects in Indonesia. This can ensure the country-specific nature of land requirement for each energy source. The land requirement for each alternative is shown in Table 5.

Waste management. This sub-criterion assesses all processes of waste disposal from the construction phase to the decommissioning of a power plant. The sub-criterion indicates that every energy source needs specific waste treatment, which can be harmful to people and the environment if not managed properly. Each performance of the alternatives against this sub-criterion was evaluated qualitatively by stakeholders. The best performance is associated with the alternative that requires the least effort to manage its waste. The worst performance of an alternative is associated with the greatest effort required. Stakeholders ranked hydro as the best alternative and coal as the worst in this sub-criterion. The complete ranking is shown in Table 5.

Electric efficiency and capacity factor. This sub-criterion provides data on two separate performances: electric efficiency and capacity factor and shares an equal portion in the evaluation of alternative performance. The performance of electric efficiency is the ratio between the total amount of electricity delivered to the grid and fuel consumption. The capacity factor is the ratio of the average net annual electricity generation to its theoretical annual generation if the power plant were operating at full capacity all year round. This quantitative sub-criterion used electric efficiency and capacity factor data from the Indonesian Technological Data Catalogue for Power Sector [69]. Data for this sub-criterion are shown in Table 6.

Technology maturity. This sub-criterion evaluates the maturity of the technology used for each alternative. It also reflects its commercial viability at national and international levels. The performance of each alternative for this sub-criterion was evaluated qualitatively, referring to the Technological Data Catalogue for Power Sector in Indonesia [69]. The nine energy source alternatives were grouped into two category levels: Level 3 (moderate deployment) and Level 4 (large deployment). Level 3 indicates that the maturity level of the technology is well known, and that it is likely that there will be major improvements in the technology in the future. Level 4 indicates that there is a high level of maturity and that only incremental improvements are likely. Technology maturity for each alternative is shown in Table 6.

Industry readiness. This sub-criterion assesses the readiness of Indonesian industry to actively develop the power plant technology of each alternative. The sub-criterion also indicates the availability of national and local workforce to produce and install the equipment and to operate and maintain the power plant facilities. The performance for each alternative was evaluated qualitatively using stakeholder judgements. The best performance indicates the most established industry associated with an energy source in Indonesia. Oil has the highest performance, and wind energy the lowest. Table 6 shows the full evaluation for this sub-criterion.

Investment cost. This sub-criterion consists of mechanical and plant equipment costs, and installation costs. The former expenditure covers all physical equipment costs, while the latter contains equipment installation, building construction and grid connection expenses. Investment cost is the most commonly used sub-criterion in the economic criterion [42]. This sub-criterion used data from the Indonesian Technology Catalogue for Power Sector [69]. The full list of investment costs for each alternative is provided in Table 6.

Operation and maintenance (O&M) costs. Both fixed and variable costs of operating a power plant are included in this sub-criterion. The fixed costs include payments for administration, salaries, service and network charges, property tax, and insurance. The variable costs comprise auxiliary material costs, such as lubricant and fuel additives, waste treatment costs, spare part expenses, and output-related repair and maintenance costs. These fixed and variable costs share equal weighting in the evaluation of the performance of the alternatives. The fuel cost for thermal power plants is not part of the O&M costs. This quantitative sub-criterion used data from the Indonesian Technological Data Catalogue for Power Sector [69]. The stated O&M

Table 6: Performance of the alternatives for selected sub-criteria

Alternative	Electric efficiency (%)	Capacity factor (%)	Technology maturity (Level)	Industry readiness	Investment cost (million USD/MW)	O&M costs		Resource Availability
						Fix cost (USD/ MW/ year)	Variable cost (USD/MWh)	
Coal	42	87	4	8	1.52	56,600	0.11	972 EJ
Natural gas	56	90	4	6	0.69	23,500	2.30	66 EJ
Oil	45	98	4	9	0.80	8,000	6.40	24 EJ
Hydro	95	36	4	7	2.08	37,700	0.65	94.3 GW
Geothermal	15	80	3	4	4.00	50,000	0.25	28.5 GW
Solar	100	19	3	5	0.79	14,400	0	207.8 GW
Wind	100	34	3	1	1.50	60,000	0	9.3 GW
Biomass	31	88	3	3	2.00	47,600	3.00	32.3 GW
Biogas	34	90	3	2	2.15	97,000	0.11	0.5 GW

costs in this data catalogue are the average O&M costs during the whole lifetime of a power plant. O&M costs for each alternative are shown in Table 6.

Resource availability. This indicates how much of each energy source is available to generate electricity in Indonesia. Because of their infinite characteristics, all six renewable energy sources were prioritised first before fossil fuels. Resource availability for renewables represents their theoretical potential for producing electricity in a GW unit. The renewables data were drawn from two sources: [9] and [12]. For fossil fuels, resource availability refers to the total energy reserves in a unit exa joule (EJ) based on the Indonesian annual statistics of energy and economic data [5]. Table 6 provides the performance of the alternatives for the resource availability sub-criterion.

2.4. Calculating criteria, sub-criteria and alternative weights

To calculate the weights of the criteria, sub-criteria and alternatives, the current research used the AHP method in three steps (see Figure 3). In the first step, pair-wise comparisons for all variables in each level of the hierarchy tree were made using Saaty's nine-integer value of importance scale, as shown in Table 1. At the criteria and sub-criteria level, the pair-wise comparisons were performed by stakeholders, who gave their judgements on the importance intensity of one variable to another. At the alternatives level, pair-wise comparisons were made based on the performance of alternatives against each sub-criterion, using rank number of alternatives as suggested by Garni et al. [39].

In the second step, the maximum eigenvalue, consistency index, consistency ratio and normalised eigenvector were computed to obtain the weight of each criterion, sub-criterion and alternative at their own level. A consistency check of pair-wise comparisons was performed in this step. Because the pair-wise comparisons are subjective, the AHP method utilises a consistency ratio (CR) to check for inconsistent judgements by stakeholders. The CR checking can be calculated using following equations:

$$CI = (\lambda_{max} - n) / (n - 1) \quad (1)$$

Where, CI is the consistency index, λ_{max} is the maximum eigenvalue of a pair-wise comparison and n is the number of variables used in a pair-wise comparison.

$$CR = CI / RI \quad (2)$$

Where, RI is the random consistency index, a given value suggested by Saaty [44] depending on the size of n.

The CR attribute is considered to be an advantage of the method. Saaty [44] suggests that the CR value should be less than 0.1. All calculations in this step were performed using an online AHP calculator tool [70].

In the third step, all of the weights were integrated over different levels of the hierarchy tree. [70] was also employed in this step. This step determines the weight of each criterion, sub-criterion and alternative with respect to the goal. The ranking of the energy sources for sustainable electricity generation in Indonesia is defined by each alternative weight with respect to the goal.

3. Results and discussion

The result of the criteria weight with respect to the goal in this research is depicted in Figure 4. The economic criterion has the highest weight at this level. Technical comes the second, followed by environmental and social. As the economic criterion constitutes almost one-third of the total criteria weight, it is evident that it is the most important aspect to be considered for sustainable electricity generation in Indonesia. The ranking of the energy sources mainly depends on their performances in this criterion. The social criterion, however, with the lowest weight, receives a lower importance level from the Indonesian energy stakeholders than of the other criteria.

Figure 5 shows the weights of sub-criteria with respect to the goal. The top three sub-criteria represent the most weighted sub-criteria in the economic, technical and environmental criteria. Resource availability from the economic criterion is the highest weighted sub-criterion, indicating a primary priority to use the most readily-available energy source in Indonesia for electricity generation. From the technical criterion, industry readiness comes as the second most weighted sub-criterion, which could imply a high importance to prioritise the national industry for electricity generation. Waste management, as the third most weighted sub-criterion, is considered the most important aspect of the environmental criterion. It is notable that all social sub-criteria have similar low weightings. It could be interpreted that each sub-criterion has equal importance in the social criterion.

Based on the criteria and sub-criteria weights, alternative weights with respect to the goal were computed, and the results are shown in Table 7. The CR

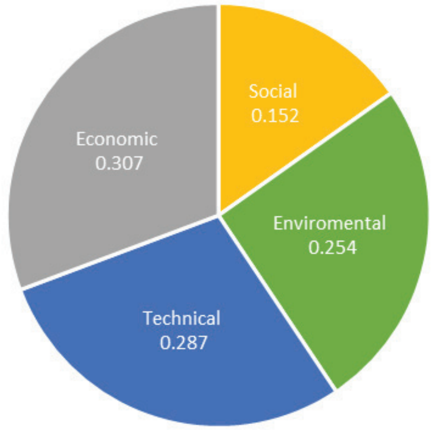

Figure 4: Weights of the criteria with respect to the goal

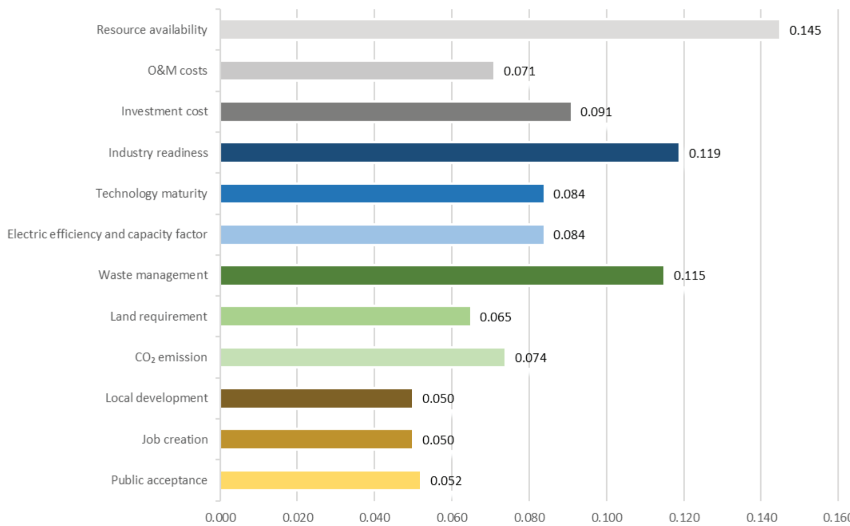

Figure 5: Weights of the sub-criteria with respect to the goal

of conducted pair-wise comparisons at all levels was less than 0.1. Detailed CR values from pair-wise comparisons made by stakeholders are in Appendix 4. This research concludes that solar is the highest ranking alternative, which should be prioritised as the energy source for sustainable electricity generation in Indonesia. Hydro is ranked second followed by oil. It should be noted that the weight for solar is much higher than other energy alternatives. Solar has a wide gap weight with hydro as the second rank (0.0475, the biggest one between two consecutive ranks, e.g. second and third rank or third and fourth rank) that emphasises a paramount priority to use this alternative for electricity generation in the country. The rankings of the remaining alternatives in high-low rank order are natural gas, wind, coal, biogas, geothermal, and biomass. This ranking result supports the stated research hypothesis that overall, renewable energy sources have higher ranks than fossil fuels. Top three and top five ranks are dominated by the renewables.

There is not an alternative which completely dominates each criterion. Solar performs as the best alternative in the social and economic criteria but not in the environmental and technical criteria, as can be seen in Figure 6. Hydro has the highest weight in the environmental criterion but not in the other three criteria. Oil has the lowest weight in the social criterion but the highest weight in the technical criterion. The remaining

Table 7: Weight and rank of alternative energy sources

Alternative	Weight	Rank
Coal	0.0912	6
Natural gas	0.1013	4
Oil	0.1184	3
Hydro	0.1519	2
Geothermal	0.0815	8
Solar	0.1994	1
Wind	0.0949	5
Biomass	0.0775	9
Biogas	0.0840	7

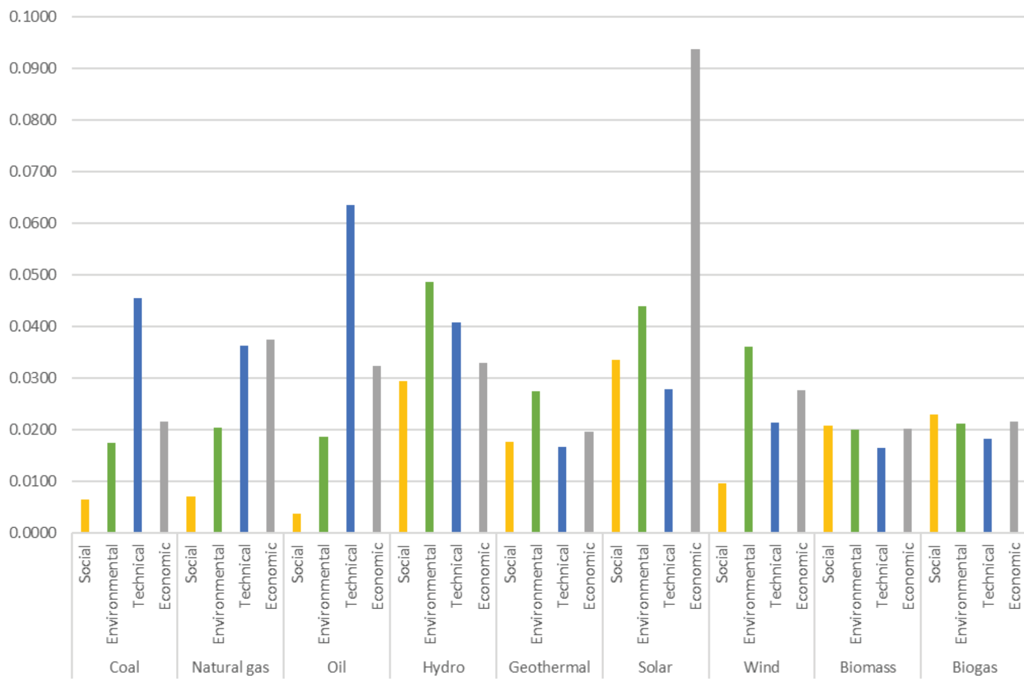

Figure 6: Alternative weights for each criterion with respect to the goal

six alternatives have a range of relatively low and high weights in one or more criteria. This could be explained by the fact that each alternative has its own strong and weak criteria. A combination of solar, hydro and oil as the top three alternatives for all four criteria appears to be the optimal mix for sustainable electricity generation in Indonesia. However, more work needs to be done, particularly with respect to technical and economic aspects of integrating different energy sources into the grid before finally concluding the optimal mix.

Another significant result is that coal is only ranked sixth as an energy source for sustainable electricity generation in Indonesia (see Table 7), although the current electricity generation is mainly from this alternative and this will continue to remain the case in the future. The present research raises the possibility of revisiting the existing planning process in the Indonesian electricity sector that puts coal as the primary energy source for electricity generation. Even though coal has a high weight (the second highest) for the technical criterion, its weights for the social and environmental criteria are low, the second lowest and lowest, respectively (see Figure 6). Sourcing coal as the primary source for electricity generation would not be sustainable. Indonesia needs a transition in its sustainable electricity generation planning, which reduces its dependency on coal. If Indonesia's dependence on coal continues for years to come, it would put its sustainable development at risk.

Stakeholder judgements make subjective evaluations based on their interests and objectives. These subjective evaluations could change the criteria and sub-criteria weights and subsequently alter the ranking of alternatives. Performing various sensitivity analyses could help to better understand the ranking results. This research conducted a sensitivity analysis based on the groups of stakeholders that they represent. The results of the criteria weight in this sensitivity analysis are shown in Table 8, and their rankings are provided in Table 9. Solar is ranked the highest by the five groups of stakeholders. The results confirm this alternative as the top ranked energy source across the different backgrounds of the stakeholders. Overall, these sensitivity analysis results indicate a similar order for the different groups with solar, hydro and oil as the top alternatives.

One interesting result in Table 9 is that oil is ranked in second place by the government stakeholder group. At the criteria level, government stakeholders give a much higher importance to the technical criterion (see Table 8). As a result, fossil-based alternatives generally have a higher weight than renewables in the technical criterion (see Figure 6) and are ranked higher by the government group than others. This might be explained by the fact that all government stakeholders are from technical institutions. It makes sense that their institutions' interest is reflected in their preference for the technical criterion. Furthermore, as they have strong technical expertise, they put the technical criterion at a higher level of importance than other criteria.

Another interesting result from Table 9 is that fossil fuels are ranked low (oil is ranked fifth; natural gas, eighth; and coal, ninth) in the fossil fuel industry group. A possible explanation for this is that the stakeholder in this group prefers to give a proportional weight for all criteria (see Table 8). As a result, fossil fuel alternatives that have lower weights for the social and environmental criteria (see Figure 6) have lower total weights when these two criteria have a bigger portion. The fossil fuel industry stakeholder might believe that the same weight for the four criteria could reflect the fossil fuel industry's interests.

Table 8: Criteria weight with respect to the goal based on stakeholder group

Criterion	Stakeholder group					
	All groups	Government	Fossil fuel industry	Renewable industry	University-Think tank	Civil society-International organisation
Social	0.152	0.092	0.250	0.145	0.182	0.186
Environmental	0.254	0.162	0.250	0.244	0.297	0.314
Technical	0.287	0.500	0.250	0.210	0.260	0.172
Economic	0.307	0.246	0.250	0.402	0.260	0.329

Table 9: Ranking of alternatives based on stakeholder group

Alternative	Stakeholder group					
	All groups	Government	Fossil fuel industry	Renewable industry	University-Think tank	Civil society-International Organisation
Coal	6	4	9	6	6	7
Natural gas	4	5	8	4	5	4
Oil	3	2	5	3	3	3
Hydro	2	3	2	2	2	2
Geothermal	8	8	6	8	8	6
Solar	1	1	1	1	1	1
Wind	5	6	4	5	4	5
Biomass	9	9	7	9	9	9
Biogas	7	7	3	7	7	8

4. Conclusion

The MCDA method enables a thorough analysis that considers multiple aspects and is a participatory process that involves various stakeholders. The method is ideal for use in energy planning in Indonesia. First, it can consider multifold aspects simultaneously in the design of energy plans. Second, by involving different groups of stakeholders in the energy sector, the credibility and acceptability of the planning results can be increased.

The use of the analytic hierarchy process in the MCDA method has been used here for the first time to rank nine energy sources for sustainable electricity generation in Indonesia. Solar is found to be highest ranked alternative. The sensitivity analysis results show solar to be the highest ranked alternative for all groups of stakeholders. This analysis also shows that different groups of stakeholders put different level of importance to the four criteria and in doing so represent their group's interests.

It is suggested that the Indonesian government should consider policies that can optimise the strength of solar in the economic and social criteria. For example, policies to maximise its resource availability can be implemented by promoting roof-top solar panels in big cities or by utilising reservoir dams as locations for solar farms. The latest ministerial regulation on roof-top solar utilisation [71] is a good starting point in accelerating solar use in the Indonesian electricity sector. To obtain a significant deployment of new roof-top solar users, the implementation of the regulation should be supported by the promotion of benefits to all electricity end-users [72].

Future work in the ranking of energy sources for sustainable electricity generation in Indonesia can be conducted in different ways, based on spatial and temporal research. Considering that Indonesia has a vast land area, specifying research locations and tailoring their criteria and sub-criteria accordingly could be one approach in future spatially-orientated research. Conducting a number of sensitivity analyses based on the forecasted performance of alternatives against sub-criteria could be a temporally-orientated future study.

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Appendix 1 Details of participated stakeholders

Table A1: List of participated stakeholders

Stakeholder	Job title	Age (years)
Government 01	Electricity programme analyst	34
Government 02	Policy analyst	43
Government 03	Policy analyst	42
Government 04	Renewable energy cooperation analyst	36
Government 05	Renewable energy programme analyst	33
Government 06	Director	51
Government 07	Senior researcher	61
Fossil fuel industry 01	-NA-	53
Renewables industry 01	Vice chairman - Independent consultant	58
Renewables industry 02	Technical manager	59
Renewables industry 03	Executive director	55
Renewables industry 04	Group head corporate affair	46
University – Think tank 01	Executive director	42
University – Think tank 02	Professor - Senior lecturer	69

Stakeholder	Job title	Age (years)
University – Think tank 03	Chairperson	41
University – Think tank 04	Deputy programme director	-NA-
University – Think tank 05	Professor - Senior lecturer	61
Civil society – International organisation 01	Executive director	48
Civil society – International organisation 02	Team eader	34
Civil society – International organisation 03	Manager	38
Civil society – International organisation 04	Researcher	30
Civil society – International organisation 05	Programme manager	36
Civil society – International organisation 06	Executive board member	52

Appendix 2 First questionnaire example

Please rate the importance intensity of the below four criteria with respect to the goal of ranking energy sources for sustainable electricity generation in Indonesia.

Table A2: Pair-wise comparison amongst criteria

Criterion	Importance scale of 1-9	Criterion
Social		Environmental
Social		Technical
Social		Economic
Environmental		Technical
Environmental		Economic
Technical		Economic

Please rate the importance intensity of the below three sub-criteria with respect to the social criterion.

Table A3: Pair-wise comparison amongst social criterion

Sub-criterion	Importance scale of 1-9	Sub-criterion
Public acceptance		Job creation
Public acceptance		Local development
Job creation		Local development

Appendix 3 Second questionnaire example

Please rate the performance score of the below alternatives against the qualitative sub-criteria.

Table A4: Alternative performance scoring against qualitative sub-criteria

Alternative	Public acceptance	Local development	Waste management	Industry readiness
	Performance score of 1-9			
Coal				
Natural gas				
Oil				
Hydro				
Geothermal				
Solar				
Wind				
Biomass				
Biogas				

Appendix 4 CR values of pair-wise comparisons made by all stakeholders

Table A5: CR values from pair-wise comparisons by stakeholders

Stakeholder	Amongst four criteria	Amongst social criterion	Amongst environmental criterion	Amongst technical criterion	Amongst economic criterion
Stakeholder 01	0.086	0.080	0.098	0.098	0.080
Stakeholder 02	0.073	0.080	0.080	0.090	0.090
Stakeholder 03	0.090	0.080	0.000	0.098	0.000
Stakeholder 04	0.000	0.030	0.000	0.000	0.000
Stakeholder 05	0.087	0.056	0.077	0.090	0.090
Stakeholder 06	0.076	0.077	0.000	0.000	0.000
Stakeholder 07	0.089	0.090	0.080	0.000	0.056
Stakeholder 08	0.043	0.056	0.040	0.056	0.000
Stakeholder 09	0.064	0.098	0.098	0.056	0.098
Stakeholder 10	0.000	0.098	0.000	0.074	0.056
Stakeholder 11	0.023	0.098	0.026	0.034	0.090
Stakeholder 12	0.066	0.098	0.010	0.000	0.004
Stakeholder 13	0.000	0.000	0.084	0.000	0.019
Stakeholder 14	0.099	0.019	0.019	0.056	0.056
Stakeholder 15	0.057	0.056	0.000	0.000	0.000
Stakeholder 16	0.057	0.000	0.000	0.000	0.056
Stakeholder 17	0.098	0.084	0.039	0.000	0.084
Stakeholder 18	0.000	0.056	0.089	0.000	0.056
Stakeholder 19	0.099	0.080	0.074	0.098	0.000
Stakeholder 20	0.000	0.056	0.000	0.056	0.098
Stakeholder 21	0.093	0.098	0.098	0.098	0.000
Stakeholder 22	0.057	0.019	0.056	0.000	0.000
Stakeholder 23	0.002	0.000	0.056	0.000	0.068

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Chapter 4. Sector coupling of electricity, transport and cooling with high share integration of renewables in Indonesia

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Sector coupling of electricity, transport and cooling with high share integration of renewables in Indonesia

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Energy system modelling

A B S T R A C T

Sector coupling improves energy system efficiency by maximising potential synergies among energy sectors. This paper aims to assess the sector coupling of electricity, transport, and cooling on the Java and Bali islands, Indonesia. Future energy systems in 2040, focussing on decarbonised electricity sector with high electric vehicles deployment and district cooling penetration, were simulated using EnergyPLAN. A bottom-up calculation approach was applied to determine demand in the transport sector. In the cooling sector, geospatial analysis was employed to quantify cooling demand and locate potential district cooling networks in Jakarta. Six scenarios were explored based on their energy demand and supply characteristics. Modelling results show that the sector coupling of three sectors could reduce primary energy supply (PES), CO_2 emissions and annual costs. The most suitable scenario has about 8% lower PES, 14% lower CO_2 emissions and 2% less annual costs compared to the business-as-usual scenario. Results also show that transport electrification could only effectively and significantly decrease CO_2 emissions if its electricity demand is produced from renewables. Transport electrification with large scale integration of renewables could also lower the annual costs by decreasing fossil fuel costs in the transport and electricity sectors.

1. Introduction

1.1. Background

Decarbonisation of the global energy sector is required to combat climate change. CO_2 emissions from the energy sector accounted for more than 75% of the world's CO_2 emissions in 2019 [1]. The challenge to reduce CO_2 emissions in the energy sector requires combined efforts on the demand and supply sides, such as increased energy efficiency, electrification of end-use sectors and large-scale integration of renewable energy (RE) sources [2].

Globally, the electricity and transport sectors produced almost two-thirds of the total CO_2 emissions from the energy sector in 2019 [3]. In that year, the electricity sector relied heavily on coal use, while oil derivatives, such as diesel and petrol, dominated energy consumption in the transport sector [3]. Sector coupling of electricity and transport through transport electrification offers optimism that fossil fuel dependency can be reduced. Transport electrification will play a major role in the decarbonisation of future energy systems in two ways [4]. First, sector coupling with high shares of RE sources enables more of the electricity generated from renewables to be utilised to charge electric vehicles (EVs). Second, electric motors can operate as the replacement for internal combustion engines to eliminate exhaust emissions. Consequently, decarbonisation in the electricity and transport sectors will substantially decrease CO_2 emissions.

Indonesia, which has the largest economy in the Southeast Asia region, consumes much of the energy it needs from fossil fuels. In 2019, coal, natural gas and oil was used to produce 247 TWh of electricity, which equates to 84% of the total electricity production [5]. The remaining 16% was derived mainly from hydropower and geothermal sources [5]. In 2019, in terms of power capacities, coal-fired power plants dominated with their production of 30.37 GW, followed by natural gas (19.51 GW) and oil (3.57 GW) [6]. In the same year, all renewables accounted for 9.217 GW in total [6]. In the transport sector, almost 100% of the energy demand (705.21 TWh) was supplied by oil derivatives in 2019 [5].

1.2. Existing research on sector coupling

Sector coupling has become an integral part of efforts to decarbonise

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the global energy sector. In the concept of smart energy systems [7,8], sector coupling could improve energy system efficiency by maximising potential synergies among energy sectors, while increasing the share of renewable energy. This concept involves all sectors in the entire energy system and enables the selection of appropriate energy infrastructure designs and operating strategies.

The use of sector coupling in future energy systems has been assessed in different geographic scales and focus areas. Transport electrification has been researched at country level in Portugal [9], Italy [10] and Germany [4,11] and at island and city level [12–14]. A number of transport electrification studies have been conducted with a particular focus, such as interregional and charging mode strategies [15] and the combination of energy efficiency measures and the production of electro fuels in the transport sector [16]. Sector coupling studies involving the cooling sector are also often identified as an essential element of decarbonisation. While numerous studies in this area have been conducted in sub-tropical countries [17–19], sector coupling research involving tropical countries, such Indonesia, is still rare. Studies on coupling of different energy sectors, particularly involving cooling sector in tropics can enrich the understanding of the dynamics of sector coupling. Review of sector coupling studies on transport electrification and cooling sector can be seen in Table 1.

Studies of the future Indonesia energy system mainly address individual energy sectors. The electricity and transport sectors have been frequently explored. Handayani et al. [20] assessed power plant expansion plans based on the nexus of climate change mitigation and adaptation. Reyseliani and Purwanto [21] focus on obtaining a 100% share of renewables in the electricity sector. Ordonez et al. [22] studied the least-cost optimisation of coal versus renewable energy for future power plants. Al Hasibi [23] performed the multi-objective analysis of sustainable generation expansion planning based on the renewable energy potential. In the transport sector, most studies are in the sub-sector of road transport. Deendarlianto et al. [24] conducted scenario analyses of an optimal energy mix in this sub-sector. A study by Chandra Setiawan et al. proposes a model that could enable a quantitative projection of oil demand and CO_2 emissions in the automotive industry [25]. Until now, there is a lack of studies on future energy systems in the cooling sector in Indonesia. The limited scope of cooling studies is reported in Refs. [26,27]. A sector coupling study of electricity and transport in Indonesia has been conducted by Li and Chang [28]. It appears that there is, however, no study of sector coupling of electricity, transport and cooling in Indonesia.

1.3. Research objective and contribution

The objective of this paper is to investigate sector coupling of electricity, transport, and cooling in Indonesia's future energy system, by focussing on the islands of Java and Bali, the two most populated islands in the country, which have an isolated power system. This paper also aims to examine the impact of sector coupling of different future energy scenarios and to select the most suitable one.

Six explorative scenarios of sector coupling on the Java-Bali islands were simulated using EnergyPLAN. All energy scenarios are characterised by their differences in demand and supply. The modelling results are discussed and used to draw two policy recommendations.

This paper offers two contributions. First, it fills the literature gap on energy sector coupling in Indonesia. It is believed that the present research is the first attempt to couple electricity, transport and cooling sectors, employing a bottom-up calculation approach and geospatial analysis. Second, a parametric analysis of primary energy supply (PES), critical excess electricity production (CEEP), CO_2 emissions and annual costs of the explorative scenarios offer comprehensive insights of future energy systems in Indonesia. These energy systems provide a decarbonised electricity sector with high EV deployment and district cooling (DC) network penetration, which is relevant to the ongoing discussion about the Indonesian energy system. Policy makers and other energy

Table 1
Review of sector coupling studies on transport electrification and cooling sector.

Reference	Geographic	Study focus
Figueiredo et al. [9]	Portugal	This study investigates sector coupling of all energy sectors: electricity, transport, heating, and industry. Transport electrification covers light passenger and freight vehicles. The study is focussed on decarbonised power system by exploring the impact of climate variability on electricity production from variable renewable energy sources.
Bellocchi et al. [10]	Italy	This study discusses all energy sectors focussing on the transport and heating sectors. It investigates how much renewables capacity is needed to fulfil growing shares of electric vehicles in private transport and heat pumps in individual heating.
Bellocchi et al. [4]	Italy and Germany	This study compares the roles of transport electrification towards decarbonised energy systems in Italy and Germany. The study discusses all energy sectors. A 100% electrification in the transport sector only covers private vehicles.
Ahmed and Nguyen [12]	Växjö Municipality, Sweden	This study investigates a carbon-neutral society covering all energy sectors at the city level of Växjö, Sweden. Transport electrification includes all types of vehicles in the transport sector. A carbon-neutral city is projected to be supplied by local and national energy sources
Gils and Simon [13]	Canary Islands, Spain	This study investigates a 100% renewables system covering all energy sectors on the Canary Islands. To achieve the 100% RE system, it will need about 50% of land transport demand from electricity.
Pfeifer et al. [14]	Islands of Vis, Korcula, Lastovo, and Mljet, Croatia	This study explores the interconnections of four neighbouring islands in Croatia by integrating locally available renewables. It focusses on the integration dynamic of variable RE sources and electrical vehicles. EVs are used as a demand response technology to store electricity produced by variable renewables.
Yuan et al. [15]	Cities of Beijing, Tianjin and Hebei, China	This study focusses on the coupling of the deployment of electric vehicles and a decarbonised power system. It explores different planning strategies and vehicle charging modes in a cross-sector and cross-region energy system of three cities of Beijing, Tianjin and Hebei. Transport electrification covers the road sub-sector.
Kany et al. [16]	Denmark	This study aims to fully decarbonise the Danish transport sector. A number of measures in all sub-sectors of transport, such as shifting modal shifts and extensive electrification, are explored to achieve the complete decarbonisation of the transport sector. Transport electrification measure plays a vital role in reducing GHG emissions.
Bonati et al. [17]	Pompeii Municipality, Italy	This study defines a 100% RE smart energy system by analysing the energy system from an exergetic point of view considering the exergy of the whole energy system and its

(*continued on next page*)

Table 1 (*continued*)

Reference	Geographic	Study focus
		components. To meet the future cooling demand of Pompeii in a sustainable way, the study suggests to have a district cooling grid integrated into the electricity grid and supplied by solar PV, solar thermal and combined heat and power plants.
Wang et al. [18]	Finland and Italy	This study analyses the high share integration of renewables towards sustainable energy transitions. The cooling sector is compared in both countries by analysing their electricity demand. In this study, cooling demand is supplied by air conditioning systems and district cooling networks from absorption heat pumps.
Matak et al. [19]	Zagreb, Croatia	This study investigates an integration of combined heat and power plant waste incineration technologies into the existing district heating system. An introduction of a district cooling system supplied by energy-from-waste is simulated. The cold storage option is also explored to meet differences in short-term cooling consumption and production.

stakeholders might benefit from these insights.

2. Methods and data

An overview of the methodology applied in this research is shown in Fig. 1. There are three main steps: 1) collection and input of energy demand and supply data in the electricity, transport and cooling sectors; 2) modelling of the energy system using EnergyPLAN, covering the aforementioned sectors and simulating six demand and supply-driven scenarios; and 3) analysis of future energy systems, focussing on energy system and cost analyses.

2.1. Energy system modelling using EnergyPLAN

In the current research, sector coupling in an integrated energy system with high renewables deployment was assessed using EnergyPLAN. This advanced energy system simulation tool offers hourly energy demand and supply balance data, and the ability to integrate all energy-related sectors into the energy system [29], as shown in Fig. 2. Furthermore, the tool offers various storage options to maximise the synergy potential within energy sectors [29]. EnergyPLAN can cope with fluctuations of variable renewables in energy systems that have a high degree of RE integration [30].

EnergyPLAN offers two types of simulation: technical and market economic [29]. The technical simulation determines the least fossil fuel–consuming energy system, while the market economic one determines the least-cost energy system involving the electricity market to fulfil energy balances throughout a year. This present research selected the technical simulation. To run this simulation, EnergyPLAN requires data inputs of energy demand and supply, such as fuel demand; electricity demand and its hourly distribution profile; power plant capacity and efficiency; and investment and operation and maintenance (O&M) costs of different technologies.

Since the early 2000s, EnergyPLAN has been used in a large number of peer-reviewed articles to analyse a wide range of energy systems. It was employed to model high RE-based energy systems in Denmark [31], China [32], Mexico [33] and Nicaragua [34]. A recent review article by Østergaard et al. [35] compiles the use of EnergyPLAN to model various energy systems in different regions, such as Southeast Europe and the Iberian Peninsula; countries, such as Australia and Brazil; and cities, such as Cuenca, Ecuador and Beijing, China.

2.2. Bottom-up calculation approach for the transport sector

A bottom-up approach was used to calculate the energy demand in the transport sector adopting the approach by Deendarlianto et al. [24]. The approach has been verified in other studies [25,36]. The transport demand only covers the road sub-sector.

Road vehicles in this research were grouped into four types: motor-

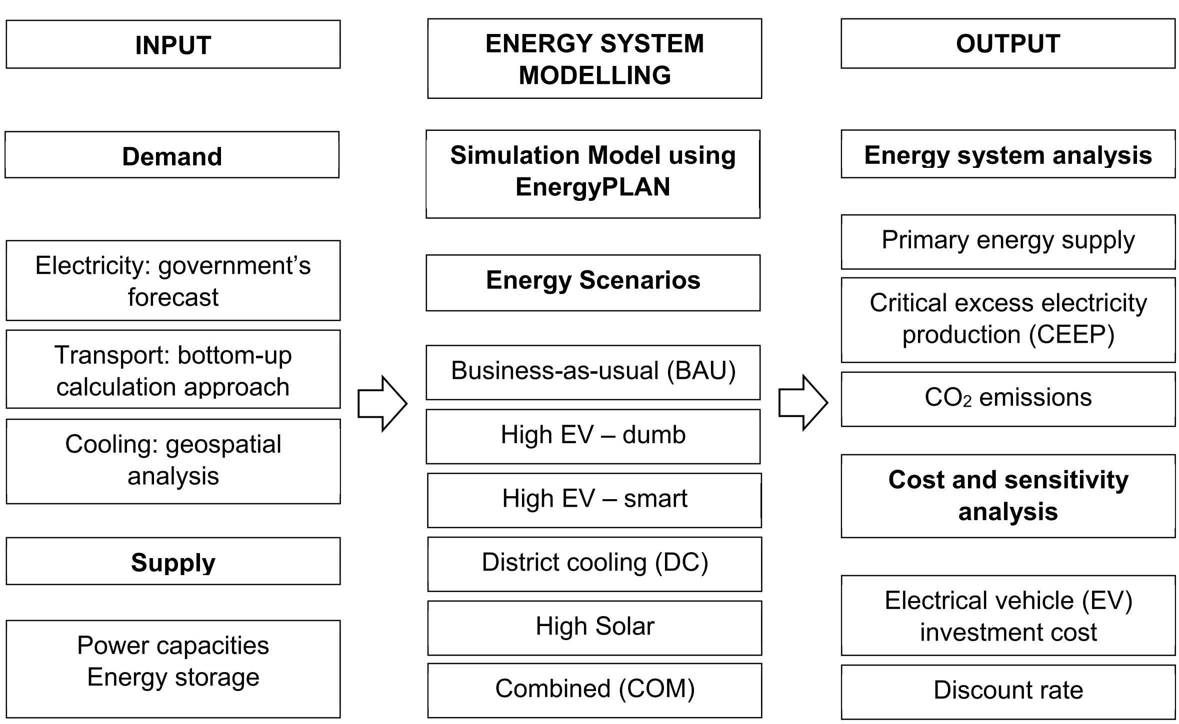


Fig. 1. Methodological flowchart for this research.

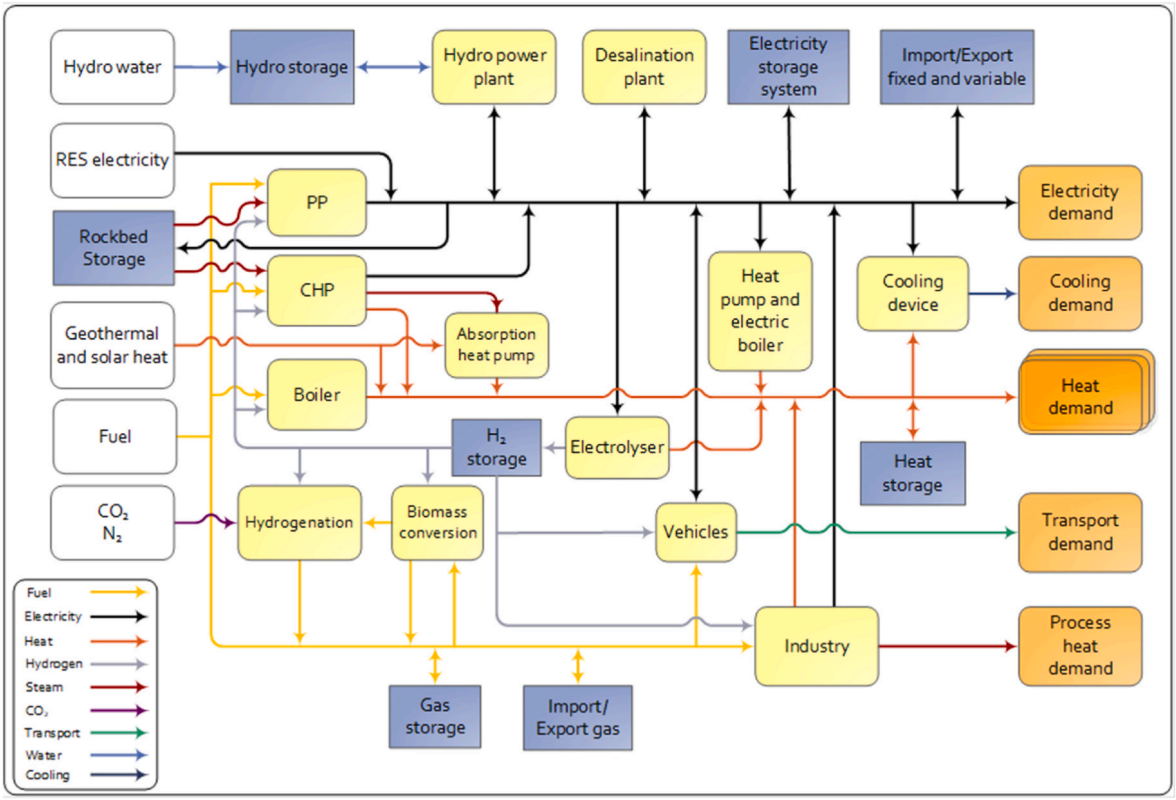


Fig. 2. Energy flows from different sectors and sources in EnergyPLAN [29].

bike, passenger car, bus, and truck. Vehicle stock determination uses unit-in operation (UIO) data rather than registration data. UIO data reflect the more realistic energy demand of road vehicles. Three fuels, diesel, petrol, and electricity, were used as energy demand inputs in EnergyPLAN. The annual energy demand of each fuel type, ED_f, was calculated using Equation (1).

$$ED_f = \sum_v VS_v \text{ x } VP_{v,f} \text{ x } FE_{v,f} \text{ x } TD_v \quad (1)$$

where f denotes the fuel types; VS_v is the vehicle stock of each type; v is the vehicle type; $VP_{v,f}$ is the proportion of vehicle type v using fuel f; $FE_{v,f}$ is the fuel economy of vehicle type v using fuel f; and TD_v is the annual travel distance of vehicle type v.

The majority of data used are from official documents and country-specific peer-reviewed studies. Vehicle stock data are based on historical and forecasted GDP per capita and UIO data from Refs. [25,37–41]. Specifically for forecasting the motorbike vehicle stock, this research adopted quantitative targets in the official document [42]. It is worth noting that the research does not consider any modal shift that could reduce the rate of vehicle stock over the years. Fuel economy and annual travel distance of each vehicle type were obtained from Refs. [25,28,36] and are shown in Table A1 in the supplementary material.

2.3. Geospatial analysis for the cooling sector

The demand for cooling services depends on climatic, socio-economic and behavioural factors. While climatic factors of specific locations include outside temperature and humidity, these can be expressed as cooling degree–days for a given reference temperature. Socio-economic and behavioural factors contain a wide range of aspects, all of which express the extent to which physical cooling demands are met, such as the ability to pay for cooling services, cultural norms, energy access, and also the construction of buildings and their use [43].

The appraisal of the physical cooling needs of a building requires in-depth knowledge of the building's construction and its layout, the heat transmission properties of surfaces of the building, and the building volumes and their ventilation rates. When attempting to assess the physical cooling needs of buildings on a large scale, it becomes obvious that the lack of data in the form of building registers, standardised building typologies and detailed studies of the energy performance of building types renders a cooling needs assessment impossible.

For the present research, an assessment of building volumes was made, using assumed specific cooling needs. Jakarta, the largest city on the Java-Bali islands and of Indonesia with a total population of approximately 10.5 million in 2019 [38], was selected as for this assessment. Buildings volumes can be modelled using high resolution digital elevation models, such as the Copernicus 1 arc-second digital surface model. This has an approximate grid size of 30 m [44] and includes the heights of buildings and trees. Using machine learning, [45] has removed the heights of buildings and trees in order to arrive at a global digital terrain model. For a given location, the difference between surface and terrain results in an approximate height of buildings and trees, averaged for each 30 m grid cell. Using this information, the volume in m^3 was calculated from height and cell size and the volume data were aggregated to a uniform 100 m grid.

For specific cooling needs, a physical cooling demand of a typical house in Jakarta was modelled by Andarini et al. [46] and found to be 35 kWh/m^3 annually. This value was used in this research as a benchmark independent of user preferences or socio-economic influence as better data are not available. A typical real cooling demand in Jakarta will lie below this value. To supply this cooling demand, in this present research, waste heat from two existing natural gas-fired power plants, Muara Karang and Tanjung Priok, were assessed for its use for district cooling (DC) networks around Jakarta city. These power plants will require modification to combined heat and power plants (CHPs) in order to achieve this. The feasibility of CHPs as the source for cooling in a DC network has been discussed by Refs. [47–49].

In order to determine which areas have cooling demands that are sufficiently high to justify the establishment of DC networks, the urban area of Jakarta has been classified by average building footprint size in each of the 100 m cells. The thesis is that larger buildings are much more likely to be connected to a DC network, and that in an urban area such as Jakarta three basic types of built-up areas prevail: areas with predominantly small buildings, where air conditioning (AC) is the exception; areas with 3–5 storey buildings attached to blocks, where air conditioning is more frequent, but cooling demand density is too low to make DC infrastructure feasible; and finally areas with a few large buildings, which are generally business districts and other areas with dense and compact building tissue, where DC may be feasible.

2.4. Reference energy system

A reference energy system covering electricity, transport and cooling sectors was defined in this present research with the reference year of 2019. Simulation model results from this energy system were validated using national statistics data (see Table B1 in the supplementary material). Validation for the bottom-up calculation approach in the transport sector is provided in Table B2 in the supplementary material.

2.4.1. Energy demand

EnergyPLAN allows for the inputs of electricity, transport and cooling demands. For this research, electricity input was obtained from national statistics and transport sector inputs were from the bottom-up calculation.

The total electricity production on the Java-Bali islands was 201.85 TWh in 2019 [6]. The electricity demand peaked mostly in late afternoon and early evening on both weekdays and weekends. The hourly demand input used the electricity demand profile from Ref. [50].

In 2019, the total UIO of vehicles on the Java-Bali islands was about 59.5 million. Motorbikes accounted for almost 80% of this value, as shown in Table 2. A total of 331.85 TWh of oil derivatives, consisting of diesel (32.28%) and petrol (67.72%) was consumed in 2019. More than 70% of the total fuels was used by passenger cars. Since 2004, Indonesia has been a net importer of oil, and most of it has been used to meet the transport demand [51]. This research assumes that there was no electricity demand in the transport sector in 2019.

By applying the geospatial analysis method described in section 2.3, it was found that Jakarta can be classified into three areas, as shown in Table 3. For this purpose, the number of buildings and the building footprint area per hectare were summarised from Open Streetmap building polygons by converting them to point features, which were joined spatially to a generic grid with a 100 m cell size. Dividing the sum of the building footprint area per hectare by the number of buildings per hectare results in an average building footprint size, which was used as an indicator to decide whether the area has potential for a DC network. It was found that only high-density areas have sufficient cooling demand for a DC network.

Fig. 3 shows the resulting grid containing the potential cooling demand in potential areas for the development of district cooling networks. The cold demands in the reference year 2019 were allocated to two existing power plants on the basis of straight-line distance, and this is shown in Table 4. In 2019, the total capacity of these power plants was 4,132 MW [41]. In the reference energy system, all cooling demand was assumed to be part of the electricity demand. In the future energy system of Java-Bali, this demand is simulated in the cooling sector in some scenarios. Adopting some assumptions from Ref. [52], cooling degree-days were used to generate the Jakarta cooling demand profile (Fig. C1 in the supplementary material).

Table 2
Vehicle stock in 2019 and 2040 on the Java-Bali islands using the bottom-up calculation approach. Source: own calculation.

Vehicle type	Vehicle stock in Unit In-Operation (UIO) (1000)	
	2019	2040
Motorbike	47,415	137,789
Passenger car	11,131	33,050
Bus	69	202
Truck	893	2,630

Table 3
Characteristics of built-up areas in Jakarta. Source: own elaboration and assumption.

Area type	Characteristics	Average building footprint size	Assumed air conditioning and district cooling characteristics
Low and small buildings in urban villages	Many small buildings of low rise, separated. Mix of formal and informal settlements.	<100m^2	No AC, no DC
Semi-dense urban areas	Compact urban areas in blocks	100–200 m^2	AC, but no DC
High-density areas	Blocks and towers	>200m^2	AC and DC

2.4.2. Energy supply

Inputs for the supply side were derived mainly from national statistics and a government report. In EnergyPLAN, these inputs can be divided into two main sources: fossil fuels and renewables. In 2019, fossil fuels produced almost 90% of the total electricity generation in the Java-Bali power system [6].

The Java-Bali power system had around 36.1 GW of fossil-fired power capacities in 2019 [6]. Coal-based power plant was approximately 62% of the total capacity, followed by natural gas-fired power plant (37%) and oil-based generators (less than 1%) [6]. The CO_2 emissions data are from Ref. [53].

Hydropower and geothermal were the main RE sources for electricity production on the Java-Bali islands in 2019 with dammed hydropower providing 2,560 MW, river hydropower providing 131 MW and geothermal sources providing 1,193 MW [6]. The renewables distribution profile used data from Ref. [50].

Based on the maximum potential capacity from Ref. [54], utilisation rate of dammed hydropower, river hydropower and geothermal were still 60%, 4% and 17%, respectively in 2019. Until that year, there was no such solar PV utility scale on the Java-Bali islands. While in total, the potential capacity of solar energy can be up to 7,000 GW across Indonesia [55].

2.5. Future energy scenarios

This research developed six scenarios to assess energy sector coupling (see Table 5). Explorative scenarios (*what can happen?*) were used here, rather than predictive (*what will happen?*) or normative scenarios (*how can a specific target be reached?*), as the research intends to investigate what can happen if different energy sectors are coupled in a future energy system. All explorative scenarios target future energy systems in 2040. The first scenario, business-as-usual (BAU), assumes existing energy plans and regulations will be continued without delay and there is no development of new plans and regulations. The second and third scenarios, High EV – dumb and High EV – smart respectively, are based on a more ambitious electric vehicle (EV) deployment than that in the government's plans. The fourth scenario, district cooling (DC), examines the establishment of DC networks in Jakarta. The fifth scenario, high solar PV integration (High Solar), explores the high integration of renewables by focussing on a substantial increase of solar PV installation into the electricity sector. The sixth scenario, combined (COM), combines some main assumptions of the previously discussed scenarios.

These six scenarios can be differentiated by their characteristics on

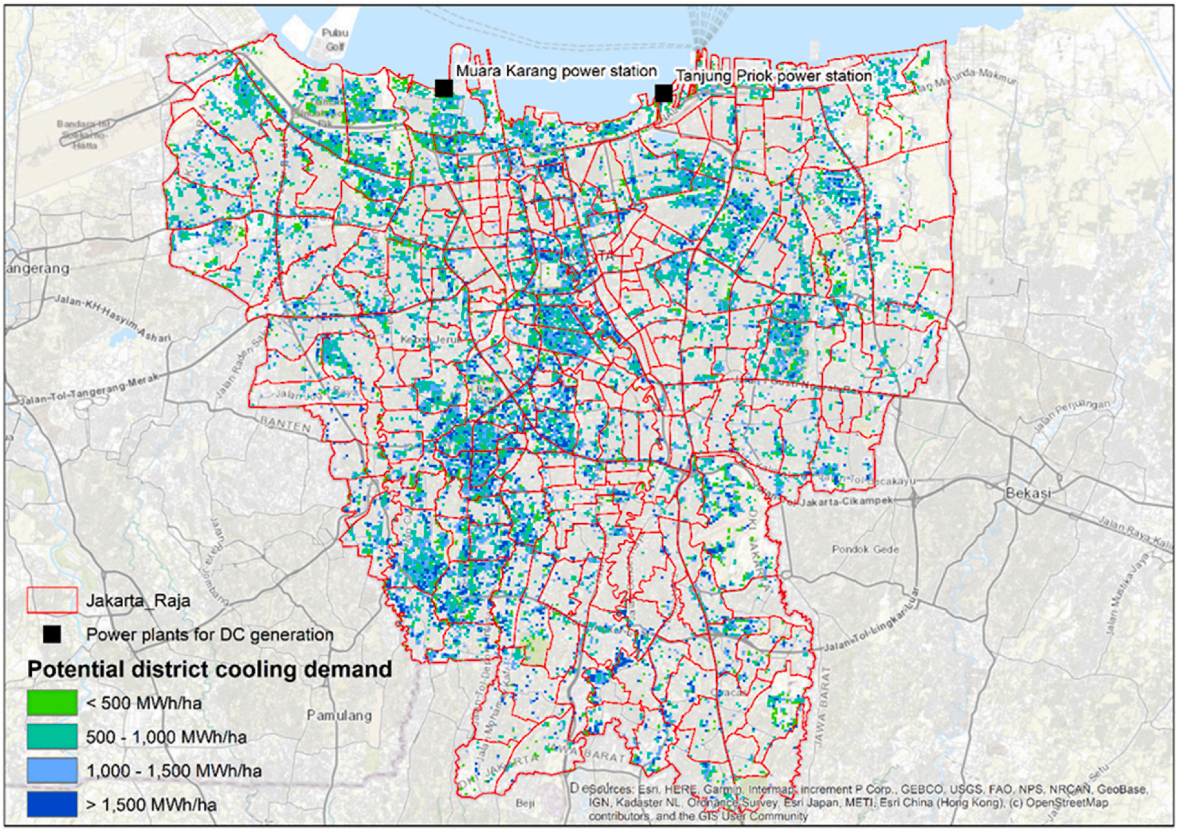


Fig. 3. Jakarta's cooling demand in areas found suitable for district cooling and the locations of two power plants for the supply of district cooling.

Table 4
Jakarta's cold demand allocated to existing power plants by distance. Source: own calculation.

Cold demand in areas deemed suitable for DC (GWh/year)	<1 km	1–2 km	2–5 km	5–10 km	10–20 km	>20 km	Total
Muara Karang power plant	116.5	254.7	1,223	2,386	4,058	848.4	8,887
Tanjung Priok power plant	56.21	78.87	964.5	2,740	3,426	1,368	8,634
Total	172.8	333.5	2,188	5,125	7,484	2,216	17,520

how the demand and/or supply side are being modelled.

2.5.1. *Business-as-usual (BAU) scenario*

Electricity demand in the BAU scenario is based on the Indonesian government's forecast [40,41]. Using these forecast data, the total electricity demand for the Java-Bali power system is calculated to be 514.4 TWh in 2040. This figure includes some measures of energy efficiency stated in the National Electricity General Plan [40]. Based on the total UIO of vehicles in 2040 (see Table 2), the BAU scenario assumes an additional 20% of vehicle stock in the period 2020 to 2040 from EVs, adopting targets from Ref. [42]. EVs are assumed to use fully battery-based vehicles. This scenario also assumes that mandatory biofuel regulations [56] will be implemented.

Existing electricity plans [40,41] were used in this research to project

Table 5
Characteristics on energy demand and supply of six scenarios.

Scenario characteristics	BAU	High EV – dumb	High EV –smart	DC	High Solar	COM
Demand						
Electricity (TWh)	514.14	514.14	514.14	507.36	514.14	507.36
Transport						
Diesel (TWh)	175.98	149.16	149.16	175.98	175.98	162.76
Petrol (TWh)	422.38	358.07	358.07	422.38	422.38	399.89
Electricity (TWh)	34.72	71.97	71.97	34.72	34.72	50.25
Cooling (TWh)	–	–	–	14.08	–	14.08
Supply						
Fossil fuels (MW)	69,576	69,576	69,576	66,580	66,000	66,000
CHP	–	–	–	4,332	–	4,332
Renewables (MW)	20,663	51,900	51,900	20,663	91,075	62,900
Storage						
PHES (GWh)	180	705	705	180	1420	910
Cold storage (GWh)	–	–	–	28	–	20
EV charging mode	dumb	dumb	smart	dumb	dumb	smart

power capacities for fossil fuels and renewables in 2040. It is calculated that fossil-fired power plant will have a total capacity of 69,576 MW, hydropower, geothermal and solar PV will have a combined capacity of 20,663 MW in 2040. Pumped hydro energy storage (PHES) is explored based on the government's plan [41]. PHES options are also used in the other five scenarios.

2.5.2. High EV penetration (High EV) scenario: dumb and smart

Electricity demand in these two scenarios is the same as for the BAU scenario. 40% of the additional UIO of EVs in 2040 is assumed in the High EV scenarios. This is double the figure in the BAU scenario and results in an increase in electricity demand in the transport sector to 71.97 TWh from 34.72 TWh. The increase in EV use will reduce the demand for diesel and petrol. The dumb and smart charge modes employed in EnergyPLAN are based on [57]. The dumb charge mode means that most EVs are charged overnight and in the early morning at their home owners or public charge stations. On the other hand, the smart charge mode means that most EVs are charged during the whole day e.g., in the late morning or daytime, depending on the electric vehicle owners' need. This mode can shift the peak of electricity demand.

The additional electricity demand in the transport sector is entirely covered by added capacities from renewable energy. Hydropower and geothermal capacities are optimised to their maximum potential capacity based on [54]. The total capacity of solar will be 38 GW in 2040.

2.5.3. District cooling (DC) scenario

The energy demand in the transport sector in this scenario is the same as that in the BAU scenario. From the total cooling demand in areas deemed feasible for DC networks in Jakarta (see Table 4), the cooling demand of 14.08 TWh will be provided by DC networks in this scenario. In the BAU scenario, all cooling demand is assumed to be met by chillers, air conditioning and other home appliances that consume electricity. Thus, the total electricity demand is reduced from 514.14 TWh in the BAU scenario to 507.36 TWh in the DC scenario.

DC networks in Jakarta are supplied by the waste heat from two natural gas-fired power plants, Muara Karang and Tanjung Priok, which are to be modified to operate in combined heat and power mode. In 2040, their total capacity will be 4,332 MW. The DC scenario also explores cold storage to meet the peak cooling demand. A reduced total electricity demand requires a lower fossil-fired power plant capacity compared to the BAU scenario.

2.5.4. High solar PV integration (High Solar) scenario

All demands in the electricity and transport sectors are the same in the High Solar and BAU scenarios.

Electricity demand will still be met by mainly fossil-fuelled power plants. However, their total capacity will be less than that in the BAU scenario. The total renewables capacity will be approximately 91 GW in 2040. Of that total, 77.17 GW will be from solar PV [58]. was used to generate the hourly solar production profile (Fig. C2 in the supplementary material). This scenario focusses on much higher solar energy integration as hydropower and geothermal reach their ultimate potential capacities. A recent study by Ref. [59], which applied a participatory multi-criteria analysis to rank nine energy sources, concluded that solar energy is the highest rank energy for sustainable electricity generation in Indonesia.

2.5.5. Combined (COM) scenario

In this scenario, 30% of the additional vehicle stock in 2040 is assumed to be from EVs. This will increase electricity demand and reduce fossil fuel demand in the transport sector, relative to the BAU scenario. This scenario only applies the smart charge mode. Cooling demand is the same as that in the DC scenario.

Fossil-fired power plants will still supply the majority of the electricity demand in the COM scenario. Total renewables capacity is higher than for the BAU scenario but not as high as in the High Solar scenario. Centralised chillers using electricity are added to meet the peak cooling demand.

Some detailed characteristics of each scenario are provided in Table 5.

2.6. Cost structure and data

EnergyPLAN produces the annual levelised cost of each technology by calculating their investment cost, O&M costs, technical lifetime, and discount rate. The tool also calculates annual fuel costs. Cost data of modelled technologies (see Table D1 in the supplementary material) were obtained from the Indonesian technological catalogue [60], Silalahi et al. [61], and the Heat Roadmap Europe database [62]. [63] was used as the single source for DC infrastructure costs. References for vehicle costs (see Table D2) are Yuan et al. [15] and ADB's report on electric motorbike roadmap for Indonesia [64]. It is important to note that in this present research, annual investment and O&M costs incurred in the transport sector only account for the cost of the total number of EVs needed, and the investment cost only represents the gap in purchasing price between internal combustion engine vehicles (ICEVs) and electric vehicles (EVs). This research set a discount rate of 4%. Forecasted fuel costs in 2040 (see Table D3) refer to price projections of the US Energy Information Administration [65].

3. Results and discussion

3.1. Energy system analysis

The primary energy supply (PES) of six scenarios for individual sources and sectors is shown in Fig. 4. Energy supply heavily relies on the fossil fuels coal, oil, and natural gas in all scenarios. Coal accounts for 45–54% in these scenarios. In terms of the sectors, the electricity sector seizes the lion's share, at least 66% in the High Solar scenario and up to 73% in the High EV – dumb scenario. The cooling sector indicated by DC penetration in the DC and COM scenarios only needs a small fraction of PES.

By coupling the electricity, transport and cooling sectors, the COM scenario consumes the lowest PES, approximately 1,736 TWh in 2040. This scenario combines higher EV penetration on the demand side and higher renewables integration on the supply side than the BAU scenario. The BAU scenario has the highest PES of approximately 1,883 TWh. The COM scenario shows that sector coupling reduces the total energy consumed to run the future energy system of the Java-Bali islands.

A high share of variable renewables in an energy system could produce more electricity than the system needs at certain times. In this context, EnergyPLAN has a unique feature called critical excess electricity production (CEEP) to capture such event. CEEP is the quantity of electricity produced which cannot be utilised due to a lack of demand. Fig. 5 shows CEEP in absolute and relative values for all scenarios.

All scenarios have CEEP significantly below 5% of the total electricity production. Dominković et al. [47] suggest that an energy system is technically sound, and variable RE is successfully integrated into that system if CEEP does not surpass 5% of the system's total electricity production. This indicates that all future energy systems developed in this research can successfully integrate high quantities of variable RE sources. Even the DC and COM scenarios (other than the BAU scenario) have zero CEEP. The use of CHPs in these two scenarios maximises electricity production from variable renewables. Mathiesen and Lund [66] suggest that the first step to integrate variable RE is to use CHP plants with storage and activate the plants when low production from renewables occurs.

A closer analysis should be paid to the High Solar, High EV – dumb and smart charge scenarios that have CEEP in the range of 3.0–3.6%. An explanation why the High Solar scenario has the highest CEEP is that this scenario has the highest amount of renewables with a total capacity of 77,175 MW solar PV. High quantities of variable renewables can be effectively integrated into the entire energy system as a result of transport electrification and the utilisation of pump hydro energy storage.

Further analysis of the High EV – dumb and smart charge scenarios shows that smart charging has a slightly lower CEEP both in absolute and relative values. This charging mode reduces CEEP to a higher degree

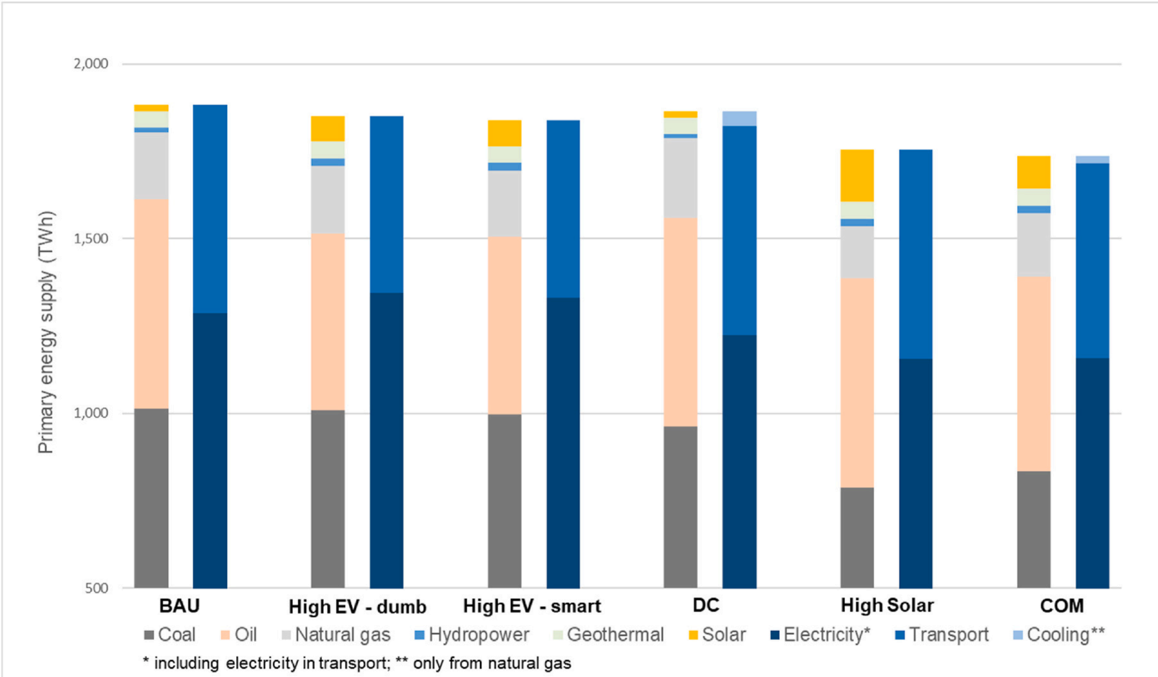


Fig. 4. Primary energy supply for individual sources and sectors in all scenarios.

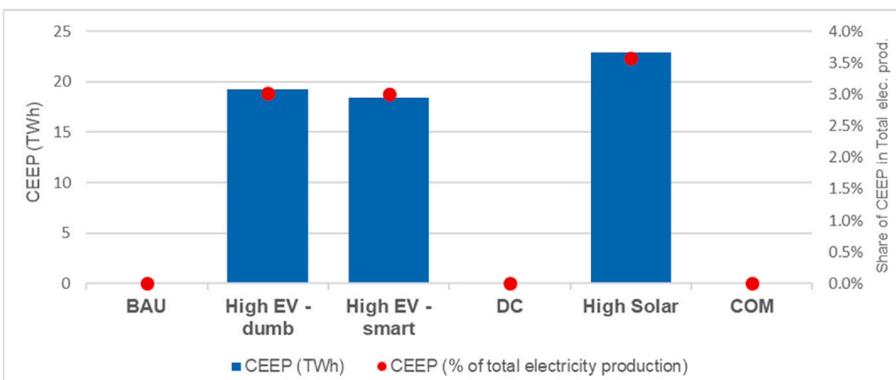


Fig. 5. CEEP in absolute and relative values in all scenarios.

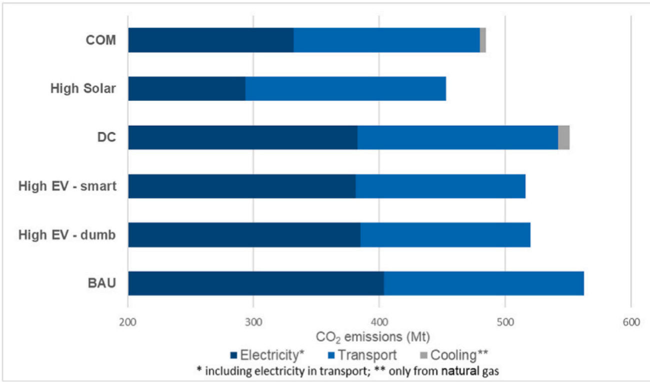
by offering more flexible electricity demand in the transport sector. The absolute difference of CEEP between the High EV dumb and smart charge scenarios is relatively low, about 0.83 TWh. This can be explained that electricity produced by renewables predominantly by solar PV is evenly distributed throughout the day. The differences of EVs charging time have a low effect on CEEP. However, in a bigger picture of these two scenario comparison, the High EV smart scenario can save up to 13.27 TWh in PES (see Fig. 4.).

Fig. 6 (a) shows CO_2 emissions for the electricity, transport and cooling sectors. As the electricity sector contributes the highest share of the PES, it also contributes the highest share of CO_2 emissions by sector. The BAU scenario, which is predominantly supplied by fossil fuels in PES emits the highest CO_2 emissions and the High Solar scenario, which has the highest renewables integration, produces the lowest CO_2 emissions. Another interesting result is that the DC scenario produces 11.6 million tons less CO_2 emissions than the BAU scenario. This is because the DC scenario successfully optimises existing natural gas-fired power plants as CHPs by maximising waste heat to produce cold in Jakarta. On a wider scale, this result opens promising opportunities to explore DC potential in other big cities on the Java-Bali islands.

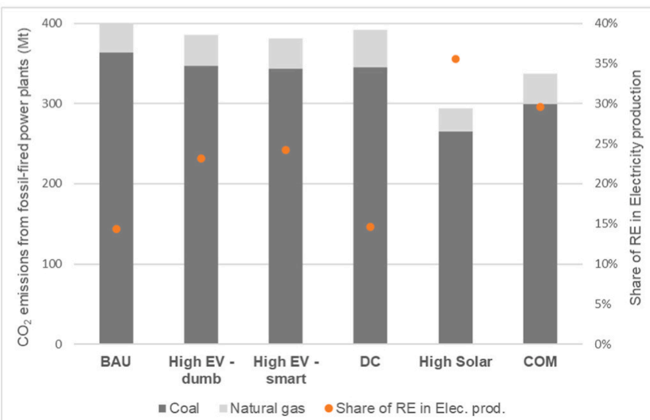
Fig. 6 (b) provides information about CO_2 emissions from fossil-fired power plants as well as the share of renewable energy in electricity production. Unsurprisingly, coal is the biggest CO_2 emitter in all scenarios. This result supports a broader consensus to phase out coal-fired power plants to reduce CO_2 emissions effectively and significantly in an entire energy system. Fig. 6 (b) also indicates that increased shares of renewables in the High Solar and COM scenarios lowers CO_2 emissions. This result confirms the effectiveness of high renewables integration in lowering CO_2 emissions from the electricity sector.

Fig. 7 shows the sector coupling of transport and electricity with renewables integration in the BAU, High EV – smart and COM scenarios. These three scenarios were selected to analyse the impact of different degrees of EV penetration in the future energy system.

A higher EV penetration does not automatically reduce CO_2 emissions more. This important result can be clearly seen when comparing CO_2 emissions in the High EV – smart and COM scenarios. The High EV – smart scenario with an EV deployment of 40% has 31 Mt CO_2 emissions more than the COM scenario with its EV penetration of 30%. This is because the High EV scenario requires a more carbon-intensive energy system. Although there is a reduced fossil fuel demand in the transport



(a)



(b)

Fig. 6. (a) CO_2 emissions by sector in all scenarios and (b) CO_2 emissions from fossil-based power plants and the share of RE in electricity production in all scenarios.

sector in the High EV – smart scenario, the electricity requirement is met by fossil fuel–based power plants. The COM scenario, however, with its relatively lower fossil-fired power capacity and the highest share of renewables, has lower CO_2 emissions. This emphasises the need for a complete understanding of the linkage between the transport and electricity sectors and further underlines the effort needed to increase EV penetration in line with the decarbonisation of the electricity sector.

3.2. Cost analysis

Defining the most suitable future energy scenario does not only need parametric analyses of technical and environmental factors but also requires a cost analysis of all scenarios. This analysis was performed by looking at the details of annual costs calculated by EnergyPLAN. An annual costs breakdown of all scenarios and their shares of variable cost are shown in Fig. 8.

Of the six scenarios, the COM scenario needs the least annual costs. The COM scenario is not only the most cost-effective one; it also consumes the lowest PES of the six scenarios. It is clear that the most suitable explorative scenario is the COM scenario.

An interesting result from Fig. 8 is that variable cost account for the major share of annual costs in all scenarios. It varies by 66–80% of the total annual costs. Variable costs are the highest for fossil fuels, which are needed in the transport, electricity and cooling sectors. This reflects the resilience of an energy system that could be impacted by the fluctuations in fossil fuel price. The High EV – dumb and smart scenarios have the lowest variable costs, and this indicates that a high EV deployment of up to 40% additional vehicle stock can reduce the share of variable costs even though there is a requirement for extra investment and fixed costs for additional EVs and renewables power capacities in these energy systems. The COM scenario has the second lowest variable costs and achieves this by using electricity rather than oil derivatives in the transport sector. The COM scenario also integrates a high level of renewables in the electricity sector. As a result, the overall annual costs for the COM scenario are lower than that of the High EV – dumb and smart scenarios.

To conduct a further cost analysis, the COM scenario was chosen to compare with the BAU scenario. This comparison gives sensitivity analyses based on EV investment cost and discount rate.

Given the likelihood of future decreases in EV investment cost due to technological advancement, a sensitivity analysis was conducted to examine the changes in EV investment cost on total annual costs. A comparison of annual costs of five variations of the COM scenario based on assumed EV investment cost and the BAU scenario is shown in Fig. 9. The variation of COM (0%) means 0% reduction in the investment cost between ICEVs and EVs. There is not a reduction in the EV investment cost in this variation. The COM (100%) variation is the 100% reduction in the investment cost between ICEVs and EVs. This variation indicates that there is no investment cost needed for road vehicles. The COM (25%) to COM (75%) variations correspond to their percentage reduction. The COM (100%) variation has annual costs that are USD 5.1 billion less than for the BAU scenario or USD 4 billion less than COM (0%) variation. The Indonesian future energy system in the COM (100%) scenario would need fewer total annual costs if the investment cost of ICEVs and EVs was the same. This opens further discussions on what the Indonesian government can do to reduce the gap in this investment cost.

To calculate annual costs in EnergyPLAN, this present research used a discount rate of 4%. This figure is very low compared to the power plant project document used by the state-owned electricity company

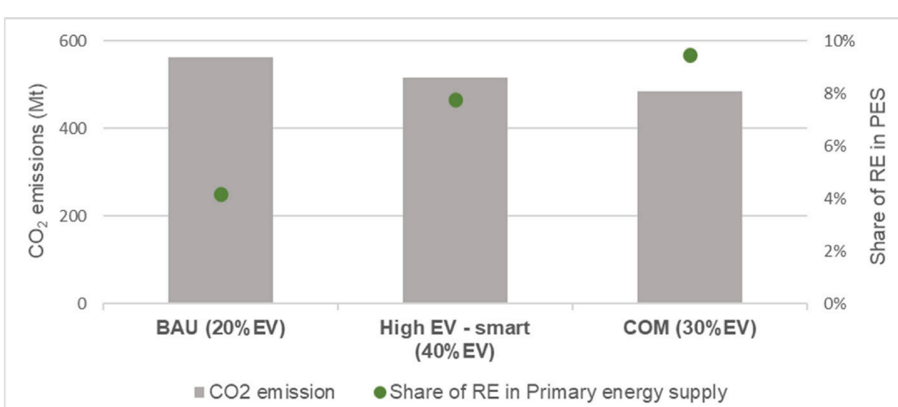


Fig. 7. CO_2 emissions and RE share in PES in the BAU, High EV – smart and COM scenarios.

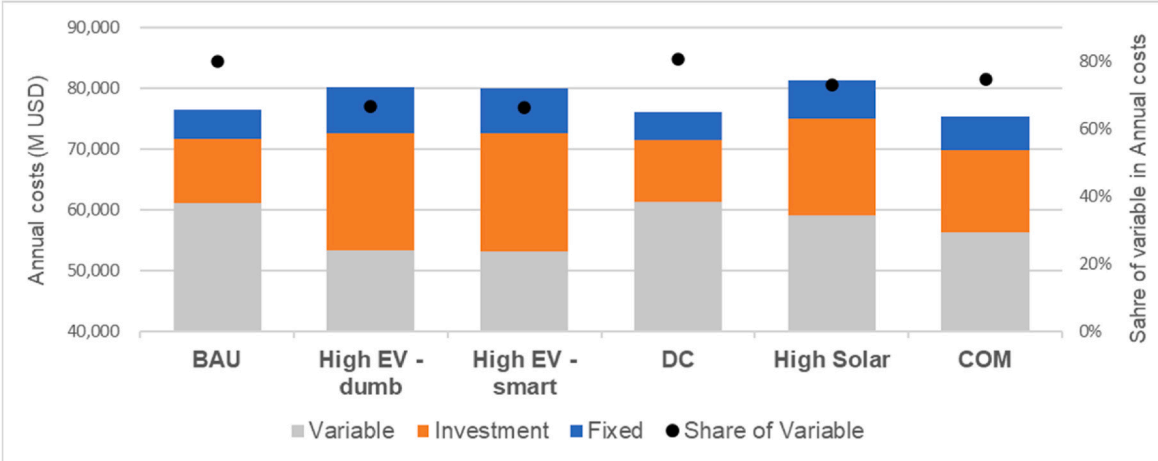


Fig. 8. Annual costs breakdown and variable cost share in all scenarios.

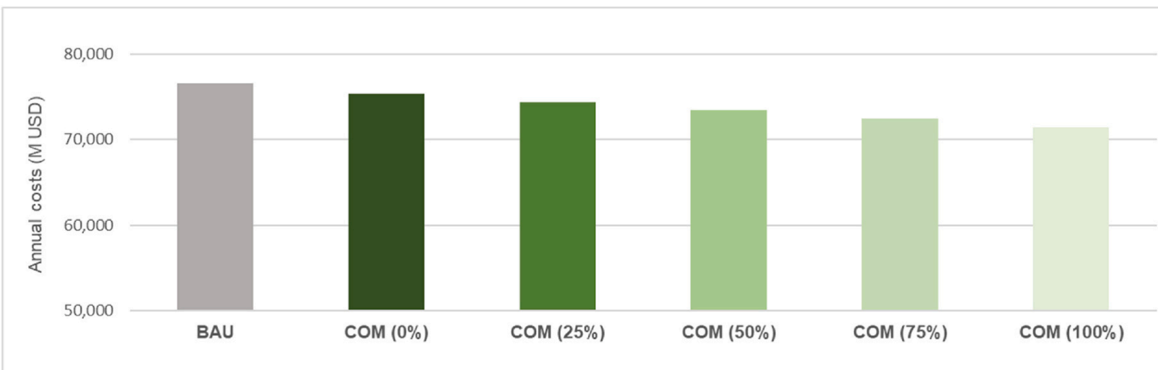


Fig. 9. Sensitivity analysis on EV investment cost in the BAU and COM variation scenarios.

[67] which sets a 12% discount rate, or several Indonesian studies [20–22] focussing on energy modelling in the electricity sector, which use a discount rate in the range of 8–12%.

Theoretically, there are two different discount rates, the private discount rate and the social discount rate [68]. The private discount rate is used to model investment decisions by private companies, which select business options, such as a particular technology for a power plant, in order to maximise their own profits. The social discount rate is the rate that is used to determine socially optimal solutions, such as climate change mitigation investments, by maximising intertemporal social welfare. From these discount rate definitions, it can be said that high discount rates set by Indonesian studies reflect the use of a private discount rate instead of a social one. This interpretation is confirmed by Steffen [68], who found that private discount rates used for renewable power plant projects in developing countries are in the range of 7–10%. Dietz et al. [69] suggest that social discount rates can be close to 1% for

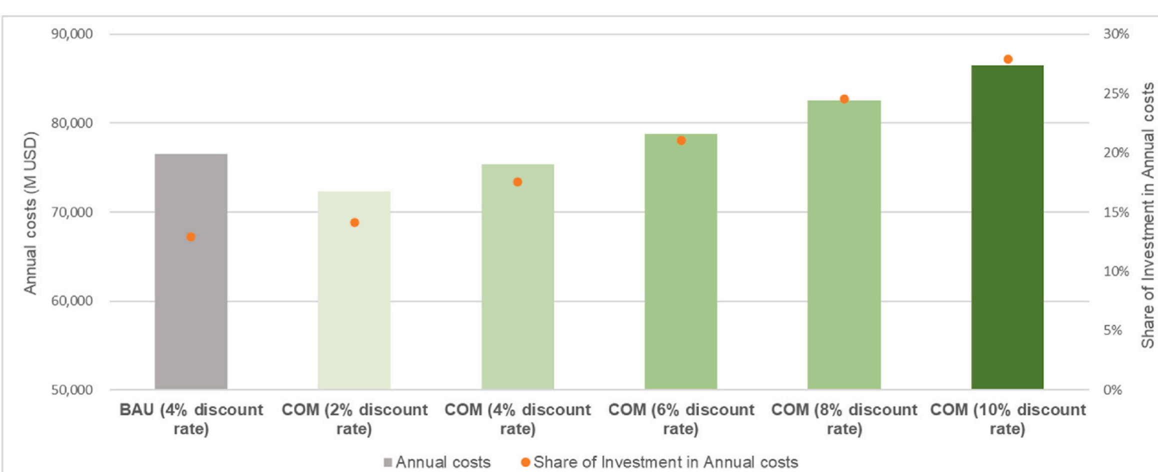


Fig. 10. Sensitivity analysis on discount rate in the BAU and COM scenarios.

climate change mitigation projects.

A sensitivity analysis of the annual costs at discount rates of 2–10% was conducted to capture the use of social and private discount rates and is shown in Fig. 10. An increase of 2% in the discount rate in the COM (6% discount rate) scenario results in higher annual costs than for the BAU scenario. This indicates that for this range of discount rates it is not possible for other scenarios to compete with the BAU scenario in the annual costs parameter. The increased annual costs will reach USD 86.5 billion in the COM (10% discount rate) scenario. This is 13% greater than the BAU scenario and 14.8% higher than the COM (4% discount rate) scenario. In contrast, with a discount rate of 2% the annual costs for the COM scenario could be USD 4.2 billion lower than for the BAU scenario. A closer inspection of Fig. 10 shows that an increased interest rate is in line with an increase of investment share in total annual costs. This confirms that the investment cost is sensitive with the discount rate, especially when investing in an energy system with large scale integration of renewables.

4. Conclusion

This paper has presented the benefits of sector coupling in future energy systems. Transport electrification could reduce primary energy supply (PES) and CO_2 emissions with a large scale of renewable energy integration. District cooling (DC) network penetration could also decrease emitted CO_2. In the costs analysis, sector coupling could lower annual costs.

Six explorative scenarios based on different characteristics of their energy demand and supply were developed to investigate sector coupling of the Java-Bali energy system in 2040. This present research employed methods of bottom-up calculation in the transport sector and geospatial analysis in the cooling sector. Future energy systems were simulated using EnergyPLAN. The most suitable scenario is the combined (COM) scenario concerning its PES and annual costs. It has been shown that transport electrification can only effectively reduce CO_2 emissions if its electricity demand is generated from RE sources.

This paper suggests two policy recommendations based on the analysed and discussed results:

1. The transport electrification programme in Indonesia guided by Presidential Regulation [70] should be in line with increasing the share of renewables in the electricity sector. There are two benefits from this recommendation: i) it can effectively reduce CO_2 emissions from the transport and electricity sectors, and ii) it can significantly decrease energy subsidies by lowering fossil fuel consumption in both the transport and electricity sectors.
2. One way to accelerate electric vehicles (EVs) penetration for the Indonesian government is to support the purchase of EVs. This can be by direct subsidies to buyers, tax breaks and tax holidays, duty exemptions and other non-financial supports. The main point of this suggested policy is to reduce the gap in the investment cost between internal combustion engine vehicles and electric vehicles.

Future energy simulation work could be done by assessing energy sectors and focus areas and improving methods, data, and analysis. Research on energy sector coupling could include industry and other transport sub-sectors, such as waterways and rail transport. Sector coupling research could also be expanded to include other parts of Indonesia. Specifically, in the cooling sector, it is worth exploring the potential of DC networks in other big cities, such as Surabaya, Bandung, and Denpasar. Future cooling demands might be modelled using local population forecasts, projections of GDP development, anticipated temperature, and humidity, as well as assumptions for energy efficiency improvements in building stock. Cost and sensitivity analyses could be enriched by applying carbon tax as this could capture more comprehensively the ongoing debate of fossil fuels versus renewables.

CRediT authorship contribution statement

Yudha Irmansyah Siregar: Conceptualisation, Methodology, Validation, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Visualisation. Bernd Möller: Formal analysis: geospatial assessment of cooling demand and supply, Writing - Review & Editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.segy.2023.100102.

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Chapter 5. Pathways towards net-zero emissions in Indonesia's energy sector

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Pathways towards net-zero emissions in Indonesia's energy sector

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ABSTRACT

This research provides a comprehensive analysis of the transition pathways towards net-zero emissions in Indonesia's energy sector by 2050, focussing on overcoming the country's fossil fuel dependency. Utilising EnergyPLAN and MultiNode simulations across three scenarios: Nationally Determined Contribution, High Electrification and Moderate Electrification, the paper presents thorough scenario development and cross-sectoral analysis to capture future energy systems from both supply and demand sides. It contributes notably by detailing scenario-specific energy demands, such as industry sector energy efficiency and electric vehicle penetration and introducing a novel modelling approach that segments the Indonesian energy system into five regional systems. Modelling results indicate the necessity of transitioning towards 100 % renewable energy, emphasising the central role of electricity in future energy systems and the importance of regional connectivity in achieving net-zero emissions. Results also reveal that the Moderate Electrification scenario offers a cost-effective route to net-zero emissions by reducing energy demand and fully exploiting renewable energy sources. The paper concludes with policy recommendations to boost energy efficiency, accelerate electrification, initiate interconnected regional energy systems, and leverage carbon capture and storage as a supplementary measure.

1. Introduction

The persistent reliance on fossil fuels has culminated in a marked increase in carbon emissions, contributing to pronounced changes in global climate and environmental degradation. The Paris Agreement, established during COP21, marks a pivotal advancement in international efforts to combat climate change, setting an ambitious goal to cap the increase in global temperature to below 2 °C while striving to limit the temperature rise to 1.5 °C above pre-industrial levels by the year 2100. Achieving a limit of 1.5 °C in global warming necessitates a reduction of approximately 45 % in global net anthropogenic carbon dioxide (CO_2) emissions from the levels recorded in 2010 by 2030, progressing towards achieving net-zero emissions (NZE) by 2050 [1].

Reducing CO_2 emissions from the energy sector is identified as a critical strategy in addressing climate change. As of 2022, this sector was responsible for 89 % of worldwide CO_2 emissions [2]. The ongoing dependency on coal, natural gas, and oil has significantly contributed to the sector's carbon footprint. A transition within the energy sector requires substantial efforts to decrease the use of fossil fuels, promote energy efficiency and accelerate the adoption of renewable energy (RE) sources. There is a global consensus on the necessity of implementing actions that support the energy transition towards NZE as a means to tackle climate change effectively.

Indonesia has pledged to reduce its total emissions, as detailed in its Updated Nationally Determined Contribution document [3]. Furthermore, the country has articulated a vision for deep decarbonisation in its recent long-term strategy [4], aiming for CO_2 emissions to peak by 2030 and achieve net-zero emissions by 2060 or sooner. Despite these ambitious targets, Indonesia faces significant hurdles in transitioning from fossil fuel dependence in its entire energy sector. In 2019, coal, natural gas and oil accounted for approximately 84 % of the total electricity generation [5]. That year, fossil fuels almost entirely powered the transport sector [6]. In industries, renewables contributed to about 13 % of the total energy use in the same year [6]. Currently, renewable energy sources remain largely untapped in Indonesia despite the country's vast potential for such resources.

1.1. Existing research on net-zero emissions in the energy sector

In recent years, a growing interest has been in modelling research focused on achieving NZE in future energy systems at national and regional levels by 2050. Dominković et al. [7] demonstrated Southeast Europe's potential for a zero-carbon system through biomass, renewable energy harmonisation and enhanced energy efficiency. Pradhan et al. [8] discussed Thailand's NZE transition, emphasising energy demand reduction, renewable energy and green hydrogen, explicitly excluding

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carbon capture and storage (CCS). The research by Parrado-Hernando et al. [9] presented Spain's RE pathway, with a specific focus on transitioning towards electrification and moving away from the use of nuclear and combined heat and power (CHP) units. Vats and Mathur [10] explored India's NZE achievement via renewable integration and energy efficiency. The paper by Raycheva et al. [11] introduces a novel approach for risk-informed coordinated generation and transmission system expansion planning, focussing on Switzerland within a European net-zero emissions context. It integrates cost-based and risk-based planning models to ensure cost-effective, secure, and reliable power supply amidst transitioning energy systems. Chang et al. [12] outlined Chile's renewable shift, integrating multiple sectors and applying marginal abatement cost curves for optimal carbon strategies. These discussed papers emphasise the diversity of approaches and strategies adopted by different countries to achieve net-zero emissions based on their specific resources, technological capabilities, and policy preferences.

Research on NZE by 2050 extends to localised contexts, including islands, cities, and provinces, illustrating the adaptability of strategies to specific geographic and socio-economic conditions. Zhou et al. [13] explored NZE policies for Hinnøya Island, Norway, advocating for the ban on combustion engine cars and implementing carbon taxes to reduce transport emissions. In examining Växjö Municipality, Sweden, Ahmed and Nguyen [14] focused on developing a carbon-neutral energy system. They underlined the critical role of integrating renewables and bioenergy from both local and national levels with carbon capture and storage (BECCS). Luo et al. [15] developed a decarbonisation strategy for Sichuan, China, proposing a mix of imported electricity, biomass, natural gas, and CCS technologies for achieving NZE. These studies highlight the necessity of tailored approaches to NZE, considering each location's distinct challenges and opportunities, particularly on the connectivity of renewables-based energy systems.

Within the Indonesian context, grey literature and scholarly articles have explored pathways to achieve net-zero emissions in the country's energy system by 2050. The International Energy Agency [16] presents a roadmap highlighting renewables expansion, energy efficiency, and electrification as key to reducing emissions, promoting economic growth and enhancing energy security. Similarly, the Institute for Essential Services Reform [17] suggests Indonesia can reach NZE through significant decarbonisation, focussing on RE adoption, increased electrification, and reduced fossil fuel use. Both pieces of grey literature also explore the connectivity of regional energy systems towards a carbon-neutral energy system.

Recent scholarly articles have examined Indonesia's pathways to achieving an NZE energy system by 2050 as a country and within a group of studied countries. Reyseliani et al. [18] compared Indonesia's current policy trajectory by applying the TIMES model and concluding that significant investment increases and technological shifts towards renewables and CCS are essential to achieve net-zero emissions by 2050. Their research highlights policy gaps and the need for ambitious targets, cleaner technologies, and market reforms to support the decarbonisation of Indonesia's electricity sector. Using OSeMOSYS, Paiboonsin et al. [19] examined energy transition strategies, advocating for large-scale renewable energy adoption and coal phase-out as cost-effective methods to lower CO_2 emissions towards carbon neutrality by 2050. The study highlights that delaying the net-zero target to 2060 leads to higher cumulative emissions, despite similar RE shares.

Other studies employ Low Emissions Analysis Platform (LEAP) in projecting NZE in Indonesia's electricity sector by 2050. Kanugrahan et al. [20] focused on the techno-economic aspects of expanding power generation. The study models four scenarios: Business As Usual (BAU), Cost Optimisation (CO), National Plan (NP), and Zero-Carbon (ZC), evaluating their costs and feasibility in meeting renewable energy targets. The ZC scenario aims for 100 % RE by 2050 by adopting significant advancements in technology and additional renewable energy sources. Further, Handayani et al. [21] included Indonesia in the regional study of Southeast Asian countries on NZE targets. Their study highlights the necessity of capitalising on the region's vast RE resources and the cost-effectiveness of renewable and energy storage technologies over CCS to achieve long-term goals. It reveals that the region's greenhouse gas (GHG) emissions will peak in 2029 and then decline to zero by 2050, with the net-zero pathway costing an estimated 12 USD per ton of CO_2 equivalent abatement. However, there is a noticeable absence of scholarly literature investigating net-zero emissions pathways from both demand and supply sides across Indonesia's entire energy sector by the year 2050. A review of the existing Indonesian energy modelling research discussed is summarised in Table 1.

1.2. Research objective and contribution

The objective of this paper is to explore potential pathways for Indonesia to achieve a net-zero emissions energy system by the year 2050. It will construct alternative scenarios for the years 2030, 2040, and 2050, each designed to illustrate varying future energy systems from both the demand and supply sides. This paper also seeks to examine the interconnectivity between various regional energy systems within the country, aiming to provide a comprehensive understanding of how these systems can be integrated to facilitate the transition to NZE. A further objective involves analysing the total annual costs associated with different NZE pathways.

This paper makes three significant contributions to the academic

Table 1
Review of Indonesian energy modelling research on net-zero emissions energy system by 2050.

Reference	Covered sector	Covered area	Research focus and methods
Reyseliani et al. [18]	Electricity	Indonesia as one energy system	This study analyses Indonesia's electricity transition to 2050, using the TIMES model across three scenarios: Reference, Current Policy, and Paris Agreement, focussing on technology, investment, and emissions, employing perfect foresight, linear programming, and detailed temporal analysis.
Paiboonsin et al. [19]	Electricity	Indonesia as one energy system	This research uses OSeMOSYS to model six scenarios for Indonesia's low-carbon electricity sector, which aims to achieve net-zero emissions by 2050. It focuses on investments, CO_2 emissions, and generation costs and is grounded in real-world data adaptation.
Kanugrahan et al. [20]	Electricity	Indonesia as one energy system	This study employs the LEAP model to explore four scenarios for Indonesia's power generation expansion towards 2050, emphasising renewable targets, energy security and cost minimisation.
Handayani et al. [21]	Electricity	Southeast Asia region, assuming Indonesia as one energy system	This research uses LEAP and NEMO to model the region's electricity sector to achieve net-zero emissions by 2050. It explores various scenarios, including renewable energy targets, generation mix, GHG, and the costs associated with integration.

Table 2
Energy demand by sector and sub-sector in Indonesia in 2019. Source: own calculations from Refs. [5,6,38,43,44].

Sector	Regional energy system					Indonesia
	Java-Bali	Sumatera	MPN	Kalimantan	Sulawesi	
Electricity (GWh)	203,586	45,428	6355	10,872	12,312	278,553
Transport (GWh)						
Road	337,014	107,612	13,853	35,410	32,707	526,595
Rail	38,157	3,721	–	–	–	41,878
Air	26,052	8,678	4,718	4,851	4,063	48,362
Water	12,803	19,387	13,935	2,612	13,627	62,364
Total transport	414,024	139,398	32,506	42,874	50,397	679,199
Industry (GWh)						
Iron and steel	43,666	9,514	649	–	16,719	70,550
Chemical and petrochemical	56,070	9,314	5271	21,222	2,200	94,078
Non-metallic minerals	92,506	17,475	567	4,581	42,284	157,414
Pulp and paper	33,423	4,222	46	2,235	471	40,396
Others	107,556	44,376	4,352	9,395	11,694	177,373
Various	98,165	36,147	12,878	10,190	12,921	170,301
Total industry	431,388	121,049	23,763	47,624	86,290	710,112

discourse on energy transitions, particularly within the Indonesian context, by utilising EnergyPLAN and MultiNode simulations across three scenarios encompassing the electricity, transport and industry sectors. These contributions are as follows:

1. The paper advances the existing body of literature by offering detailed scenario development that includes various assumptions of future energy demand, such as applying energy efficiency measures in the industry sector and high electric vehicle (EV) penetration in transportation. This addresses a notable gap in the literature concerning Indonesia, enabling a more thorough understanding of potential future energy systems within the country.
2. Through an extensive cross-sectoral analysis covering all energy sectors and their sub-sectors, the paper provides deeper insights into the operational dynamics of the future energy landscape. This analysis is particularly crucial as it underlines the central role of electricity as the backbone of future energy systems that will have direct connections with the transport and industry sectors. It is believed that this current research is the first attempt to analyse these sectors in the context of a net-zero emissions energy system in Indonesia.
3. The present research introduces a main modelling assumption that mirrors real-world complexities better by segmenting the Indonesian energy system into five distinct regional systems. This separation enables a more detailed and context-specific energy system analysis, providing a clearer picture of how regional variations and interconnections will play a critical role in Indonesia's transition to a net-zero emissions energy system by 2050.

2. Methods and research design

This section explains the tools used, the structure of reference and future energy systems and the cost structure applied in this research.

2.1. Smart energy systems using EnergyPLAN and MultiNode

This research adopted the smart energy systems concept [22,23] using EnergyPLAN. Smart energy systems aim to find the most effective and least-cost solutions by integrating all energy sectors and their sub-sectors of the energy infrastructure to harness synergies and identify appropriate storage and infrastructure designs. EnergyPLAN is a freeware tool aimed at helping design national energy planning strategies by conducting technical and economic assessments to analyse the outcomes of various choices and investments [24]. The tool employs analytical programming, utilising pre-defined procedures for modelling freely dispatchable unit operations in a purely deterministic framework without stochastic elements. It simulates user-customised systems without endogenous system optimisation. This tool allows users to apply various optimisation criteria in simulations, such as total system costs, renewable energy shares, maximum CO_2 emissions, and other factors in exogenous system optimisation during scenario design.

EnergyPLAN generates hourly data on energy demand and supply balance data, along with the capability to incorporate all sectors related to energy into the system, as shown in Fig. 1. To do that, this advanced energy system simulation tool differentiates itself by requiring exogenously defined demands and productions articulated through hourly time series data. This requirement is pivotal for capturing the inherent intermittencies associated with renewable energy sources, facilitating a more accurate and comprehensive integration of these resources into the energy system [24]. Unlike some scenario tools that work annually or optimisation tools using time slicing, EnergyPLAN's hourly simulation level offers insights into hourly, daily, weekly, and seasonal variations, such as in electricity demand and hydropower production.

EnergyPLAN can be run in two distinct simulation modes: technical and market economic [24]. The technical simulation focuses on identifying the energy system that minimises fossil fuel consumption, whereas the market economic simulation aims to find the least-cost energy system by incorporating the electricity market to maintain energy balances annually. The technical simulation was chosen for this current research. To execute this simulation mode, EnergyPLAN necessitates input data on energy demand and supply, including parameters such as fuel demand, power plant capacity and efficiency, and costs associated with various technologies.

EnergyPLAN has been utilised in numerous academic papers to model future energy systems based on a high share of renewable energy sources for more than 20 years. The role of bioenergy in the energy system was studied by Kwon & Østergaard [25] and Lund and Mathiesen [26]. A number of studies investigated the impact of high penetration of wind and solar PV generation on the power system [27–30]. Refs. [7,13,15,31] employed EnergyPLAN to explore pathways towards net-zero emissions by 2050 in their respective research areas. A recent review paper authored by Østergaard et al. [32] summarises the application of this simulation tool in modelling various types of energy systems at different levels of geographical scope: region, country, city, and island.

Further, MultiNode was applied to simulate an interconnection of regional energy systems in this present research. MultiNode is an add-on tool for EnergyPLAN to examine the excess electricity production of individual energy systems and their import capacity to minimise overall fuel consumption within the whole energy system [33]. This add-on tool investigates hourly energy system operations to pinpoint import or

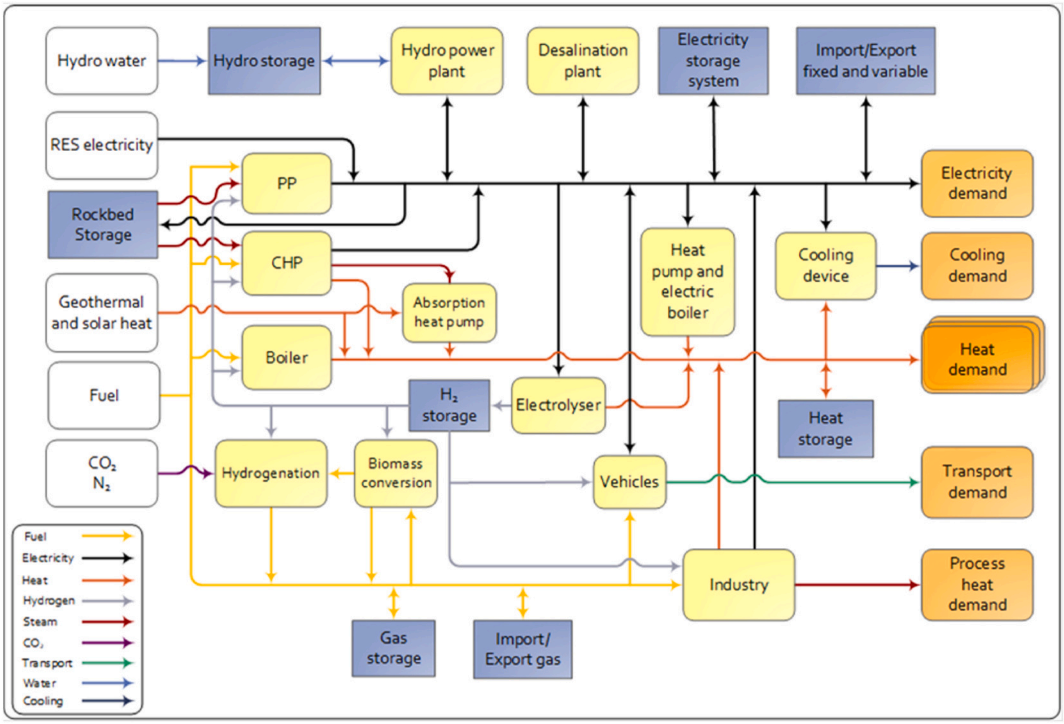

Fig. 1. Energy flows from different sectors and sources in EnergyPLAN [24].

export opportunities, enabling the transfer of surplus electricity from one system to another if it aligns with an import opportunity. It facilitates imports during hours of power plant production or capacity shortage, permitting importation solely when excess electricity production is accessible in the interconnected energy systems, thus preventing one system from initiating power generation from another system's plant; conversely, it allows exportation only if another system can substitute its production [33].

This add-on tool should be considered within the EnergyPLAN framework. Its primary characteristic is focussed on the technical aspects of transmission, specifically utilising excess electricity production. Nonetheless, MultiNode does not have the capability to generate additional excess electricity, which presents a limitation [33]. It cannot prioritise one power plant over another across different systems. Consequently, the analysis adopts a technical simulation to EnergyPLAN scenarios to reduce fuel consumption.

MultiNode was used in Refs. [33–37] to evaluate the advantages of connectivity across energy systems. These articles collectively advocate for a comprehensive approach to the design of renewable energy systems, emphasising the importance of cross-border and cross-sectoral connectivity. They support the development of smart energy systems capable of adapting to and utilising renewable sources' intrinsic variability.

2.2. Reference energy system

A reference energy system covering electricity, transport and industry sectors was defined in the reference year 2019. The structure of the 2019 Indonesian energy system was used as a reference model for future energy systems. Energy demand in the three energy sectors—electricity, transport, and industry (including other fuel consumption, which is called various)—was calculated and used as the main input for EnergyPLAN. A combination of industry and various was used to match the demand inputs in the EnergyPLAN structure. On the supply side, data inputs of fossil fuels and renewables were based on government statistics and relevant literature.

2.2.1. Energy demand

The demand within the electricity sector encompasses all electricity requirements from households, as well as commercial and industrial sectors. Data were sourced from Refs. [5,6,38,39] to establish the reference energy system. In the transport sector, the demand is divided into four sub-sectors: road, rail, air, and water, and it is quantified in the form of petrol, diesel, electricity, and jet fuel. A bottom-up approach was employed to calculate the road transport demand, aligning with methodologies adopted in prior studies [40–42]. For the remaining transport sub-sectors, energy demand data were derived from the government report [6]. The industry sector's demand includes all requirements from industrial activities that do not directly involve electricity consumption, such as fossil fuels and biomass. These demands include non-industrial (household and commercial) consumption, for instance liquid petroleum gas, collectively categorised under various. The industry sector is divided into five sub-sectors: iron and steel, chemical and petrochemical, non-metallic minerals, pulp and paper and others, consuming fuel types of coal, oil, natural gas, and biomass. The others sub-sector covers the main remaining industries, such as food and beverages, textiles and wearing apparel, rubber and plastic products, computer and electrical equipment and machinery and transport equipment. Given the lack of publicly accessible data on the demand specifics of these industry sub-sectors, assumptions and calculations were conducted to fill this gap. These calculations leveraged national statistics [38] and more detailed industrial statistics [43] to estimate the energy demand within each sub-sector.

2.2.2. Energy supply

The inputs for the supply side of the energy model, such as power plant capacities and their efficiencies, were sourced from government reports [5,6,44]. This data set contains many fossil fuel power plants, which utilise coal, natural gas, and oil. Alongside these, renewable power plants, which derive energy from geothermal, hydropower, biomass, solar, and wind sources, were also included in the model. Hourly distributions of variable renewables were generated from Refs. [39,45] and are visualised in Figs. S1A–J (Supplementary Material - SM).

2.2.3. Five regional energy systems

The Indonesian energy system was segmented into five isolated regional energy systems for the year 2019: Java-Bali, Sumatera, Maluku-Papua-Nusa Tenggara (MPN), Kalimantan, and Sulawesi, as shown in Fig. 2. The results were manually aggregated to represent the entire Indonesian energy system due to the distinct modelling of each regional system. In situations where regional-specific data were scarce or absent, this research relied on national statistics [38]. For the electricity demand, each regional demand was from statistics by the own-state utility company [44] and the annual ministry report [5]. Using the total transport demand in the annual energy and economy statistics [6], the national statistics [38] was used to determine the details of road, rail, air and water transport demand in each region. For industries, the total demand was calculated from Refs. [6,43]. The national statistics [38] was also used to determine the sub-sector industry demands in five regional energy systems.

All energy demands and detailed calculations for the road transport demand in 2019 are shown in Table 2 and Table S1 (SM), respectively. Notably, the Java-Bali energy system emerged as the most significant, accounting for up to 63 % of Indonesia's total energy demand in 2019. Additionally, the total primary energy supply for the same year, as derived from EnergyPLAN, is shown in Table S2 (SM), which also serves as model validation.

2.3. Future energy system

This section discusses all future energy systems in 2030, 2040 and 2050. It describes main features in each developed scenario.

2.3.1. Net-zero emissions by 2050

The future energy systems of Indonesia were developed for the years 2030, 2040 and 2050, charting a course towards achieving NZE by the year 2050. These pathways are driven by the recent government report, the Long-term Strategy for Low Carbon and Climate Resilience 2050 [4], mandated by the Paris Agreement. However, it is essential to note that the most ambitious scenario presented within the report does not explicitly target achieving NZE in the energy sector by 2050 but rather sets a goal for 2060 or sooner. This scenario, referred to in this present research as the nationally determined contribution (NDC) scenario, forms the basis for the future energy system developments examined in the research, with an in-depth discussion in Section 2.3.4.

In addition to adhering to the NDC scenario, this research developed two alternative scenarios aiming for NZE in the energy sector by 2050, distinguished by varying levels of electrification. The detailed characteristics and main assumptions of these alternative scenarios are thoroughly discussed in Section 2.3.4. The design and development of these NZE pathways were guided by the back-casting methodology outlined by Rotmans et al. [46]. This methodological approach involves identifying a desirable future state—in this case, NZE by 2050—and then working backwards to establish the steps and interventions required to achieve that state from the current situation.

2.3.2. Future energy demand

The NDC scenario serves as the baseline for projecting future energy demand, with identical electricity demand forecasts for household and commercial sectors across all scenarios. Electricity consumption for industry is differentiated based on the future industry structure in each scenario. Future road transport demand was estimated using a bottom-up approach, incorporating GDP and population projections [4,47]. Transport sub-sectors and industry sector demands were determined through a top-down approach.

2.3.3. Future energy supply

Coal and natural gas will remain the primary sources in the NDC scenario. On the other hand, bioenergy and solar energy will be the main sources of supply for NZE of future energy systems in alternative scenarios. Other renewables, such as hydropower, geothermal, and wind energy, will complement each other proportionally by utilising their maximum potential in each regional energy system. Renewables potential refers to Refs. [48,49]. All future power plant capacities were determined to meet electricity demand in each future scenario.

2.3.4. Future scenarios

Three future energy scenarios were developed based on different characteristics of demand, supply and the connectivity of regional energy systems. On the demand side, the main differences in the scenarios are the level of direct electrification in the industry sector and the share of electric vehicles in the transport sector. Regarding supply, the contribution of primary renewable sources, namely bioenergy and solar, to the overall energy mix exhibits variation across the simulated scenarios. The carbon capture and storage (CCS) deployment level also differentiates one scenario from another. The main assumptions used to develop future scenarios are shown in Table S3 (SM).

2.3.4.1. Nationally determined contribution (NDC) scenario. As explained earlier, the NDC scenario is the most progressive mitigation scenario in Indonesia's LTS LCCR 2050 report [4]. The model results of the NDC scenario in this research mirror the results in the report. Using available information in it, this present research deconstructed and restructured the Indonesian energy system following the EnergyPLAN's input structure. A quantifiable cross-scenario comparison of the EnergyPLAN results and the LTS LCCR report can be seen in Table S4 (SM).

The NDC scenario projects an average annual increase in electricity demand of 5.5 % from 2019 to 2050 for the residential and commercial sectors, reflecting anticipated economic growth and the adoption of energy efficiency initiatives. This upward trend is largely due to a shift in preference towards electric energy systems over combustion-based alternatives among end-users, coupled with an increased dependency on electricity within the commercial sub-sector for its energy needs. In the transport sector, a significant shift towards public transit is anticipated,

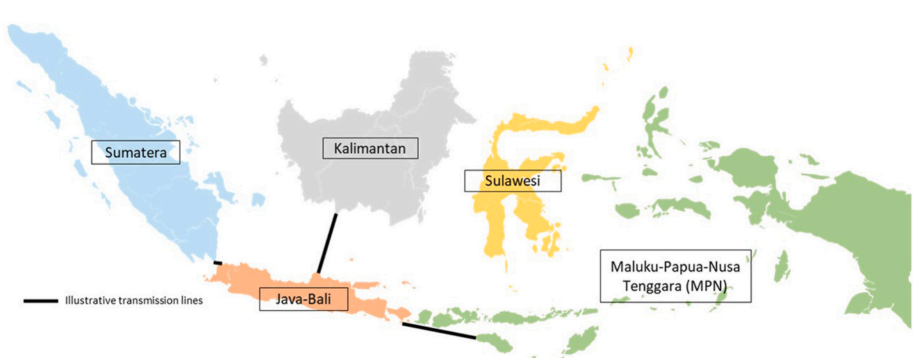

Fig. 2. Indonesia's regional energy systems and its illustrative transmission lines in 2050.

especially in major urban areas, to mitigate the challenges posed by the excessive use of private vehicles and resulting traffic congestion. For smaller cities, inter-city connectivity is expected to be achieved through trains and large buses, whereas air travel will serve as the primary mode of connecting major cities and islands, complemented by ships and ferries for inter-island journeys. Demand is predicted to follow a business-as-usual trajectory within the industrial sector, with no specific interventions envisaged to curb its growth.

From 2030 to 2050, the electricity sector is expected to be primarily supplied by coal and natural gas, alongside the widespread adoption of carbon capture and storage (CCS) in most coal power plants. Decarbonisation efforts in this scenario will be driven by deploying renewables, such as hydropower, geothermal, solar, wind, and biomass. Furthermore, biomass-coal cofiring power plants connected to biomass energy with carbon capture and storage (BECCS) systems are expected to contribute to this decarbonisation effort. Biofuels, oil fuels and electricity are the main sources in the transport sector. The crude palm oil (CPO)-based biofuel initiative is deemed effective and will persist until 2050 by delivering biofuel with increased biodiesel proportions. The energy supply for industries will shift from predominantly coal and oil fuels to natural gas, renewables and electricity. The adoption of CCS technology is also assumed in the industry sector, particularly industries that consume natural gas in their processing plants.

Indonesia's LTS LCCR 2050 report lacks details regarding the interconnectivity of regional energy systems. This current research proceeds on the premise that, within the NDC scenario, regional energy systems operate independently, with each regional system functioning in isolation across all considered time horizons. The model results of the entire Indonesian energy system were aggregated manually.

2.3.4.2. Alternative scenarios towards NZE by 2050. In developing alternative scenarios, the main guideline was to initially focus on minimising energy demand through the increased integration of electric vehicles and implementing energy efficiency measures within industrial activities. This principal guideline was implemented by referring to recent relevant research and putting the Indonesian economy and energy context into scenario development. On the supply side, pathways towards NZE by 2050 are explored by simulating future energy scenarios with 100 % renewable energy-based electricity as the main backbone of the energy system. Electricity will replace the majority use of fossil fuels. Bioenergy will substitute the remaining fossil fuels and compensate unabated fossil energy with BECSS. Two alternative scenarios, high electrification (HE) and moderate electrification (ME), were developed to capture different NZE pathways.

2.3.4.3. High electrification (HE) scenario. This scenario was developed to investigate a pathway characterised by extensive electricity penetration across the entire energy system, predicated on the deployment of advanced technologies. The HE scenario applied methods developed by Johannsen et al. [50] for integrating energy efficiency measures and transitioning to a 100 % RE-based by 2050 in the industry sector. Demand reductions will be observed across various industrial sub-sectors; for instance, in 2050, it will decrease up to 24 % in the non-metallic minerals sub-sector relative to projections under the NDC scenario. About 60 % of the energy demand in the industry sector in 2050 will be from electricity. The HE scenario draws on the work of Næss et al. [51] to determine the electrification rate in non-road transport sub-sectors. By 2050, it is expected that nearly 90 % of the energy demand in the transport sector will be met by electricity, leading to an electricity demand roughly twice that of the NDC scenario. The adoption of green hydrogen technology is anticipated to replace the use of natural gas in industrial applications and oil derivatives in transportation. Given its maximisation of renewable energy potential, the Java-Bali energy system will require electricity imports from adjacent regions to meet its needs.

2.3.4.4. Moderate electrification (ME) scenario. The ME scenario was designed to provide a distinctive pathway towards NZE by 2050 by lowering electricity demand in the industry and transport sectors. Reduced energy demand in industries will be similar to the HE scenario. The main difference is that hydrogen energy is not an option in the ME scenario. This will substantially reduce the electricity needed to produce green hydrogen. This assumption also extends to the transport sector, where a lesser penetration of electric vehicles mirrors a more moderate approach to the adoption of electricity.

A qualitative comparison of energy demand across the three scenarios in the simulated years is shown in Table 3. At the same time, Table S5 (SM) offers a detailed quantitative breakdown of energy demands by each sector.

2.4. Cost structure and carbon price

EnergyPLAN determines the annual levelised cost for each technology by assessing their investment costs, operations and maintenance (O&M) expenses, technical lifespan, and the applied discount rate. This includes the costs associated with road vehicles and transmission in a connected energy system. Moreover, EnergyPLAN computes the yearly expenses associated with fuel consumption, such as coal for thermal power plants or oil derivatives for combustion-based cars. Detailed information on the costs of the modelled technologies is available in Tables S6–7 (SM), with projected fuel costs presented in Table S8 (SM). The current research set a discount rate of 4 % and applied a CO_2 pricing scheme of USD 30, USD 40 and USD 50 per ton for the years 2030, 2040 and 2050, respectively.

3. Results and discussion

This section discusses this research's main results and its limitations and uncertainties.

3.1. Pathways towards net-zero emissions (NZE)

Amongst the three scenarios analysed, the NDC scenario projects the highest primary energy supply in 2030, 2040 and 2050, as shown in Fig. 3. This is attributable to the scenario's demand-side assumptions, which lead to increased energy consumption relative to the alternative scenarios. The NDC scenario continues to depend on fossil fuels to meet the energy system's needs from 2030 to 2050, with the absolute shares of coal, oil and natural gas rising over the simulation period. The share of coal, oil and natural gas will increase in absolute terms over the simulated years. The utilisation of CCS and BECCS in this scenario can only reduce about 30 % of emitted CO_2 in 2050 compared to the 2040 CO_2 emissions.

In contrast, in the alternative scenarios aimed at achieving NZE, the future energy systems will predominantly rely on bioenergy and solar energy. Due to reduced energy demands, these scenarios will utilise fewer energy sources than the NDC scenario. CO_2 emissions in these alternative scenarios are anticipated to peak in 2030, decrease significantly by 2040, and reach net-zero by 2050, when electricity production will be entirely renewable. Geothermal, hydropower, and wind energy potentials will be fully exploited, with BECCS compensating for the remaining oil usage in transportation.

A key distinction between the NDC and the alternative scenarios is the assumed reduction of energy demand in the transport and industrial sectors in the alternative scenarios. By 2050, the overall energy demand in the industry is expected to decrease by up to 15 %, a relatively moderate figure compared to European energy research, which suggests potential reductions of up to 40 % from its baseline scenario [50]. This moderation reflects Indonesia's industrial sector's lower complexity and maturity, especially in energy-intensive sub-sectors, such as non-metallic minerals, chemicals, petrochemicals and iron and steel. Applying high recycling measures, best available technologies and

Table 3
Energy demand comparison of three scenarios in 2030, 2040 and 2050.

Energy demand	2030 scenario			2040 scenario			2050 scenario		
	Nationally Determined Contribution (NDC)	High electrification (HE)	Moderate electrification (ME)	NDC	HE	ME	NDC	HE	ME
Electricity	in line with economy and population growth; EE measures in household and commercial sub-sectors implemented								
Transport	very limited penetration of electric vehicle (EV)	moderate penetration of EV	low penetration of EV	moderate penetration of EV; high share of biofuels	high penetration of EV	moderate penetration of EV	moderate penetration of EV; high share of biofuels	very high penetration of EV; hydrogen adoption	high penetration of EV
Industry	no specific energy efficiency (EE) measures implemented	low EE measures implemented	low EE measures implemented	no specific EE measures implemented	moderate EE measures implemented; hydrogen adoption	moderate EE measures implemented	no specific energy efficiency measures implemented	high EE measures implemented; hydrogen adoption	high EE measures implemented

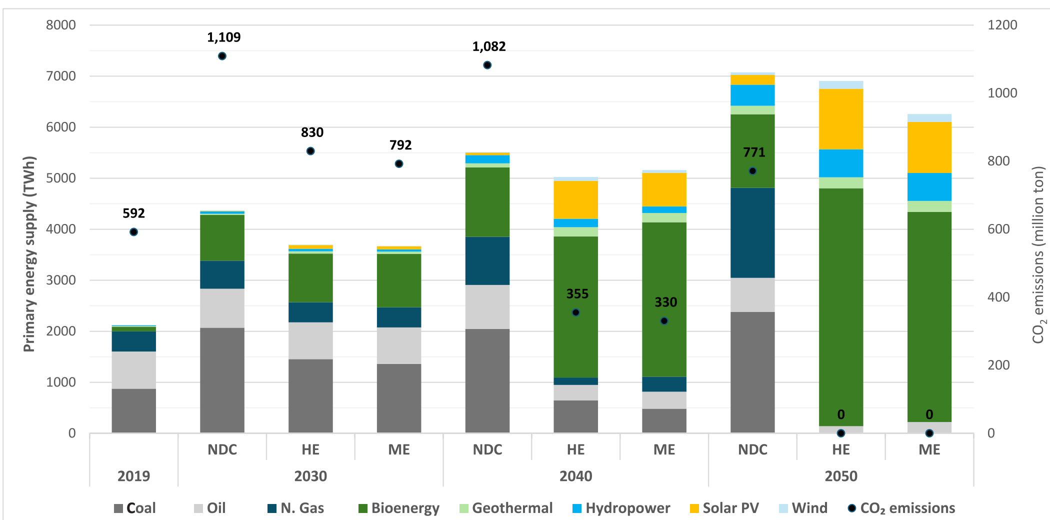

Fig. 3. Primary energy supply by sources and CO_2 emissions from all scenarios in 2030, 2040 and 2050.

innovative measures [50] in the non-metallic minerals sub-sector, the demand will decrease up to 24 % in 2050 compared to the NDC scenario. In the iron and steel sub-sector, the reduced demand will be up to 26 % in the same targeted year. Similar principles apply in the transport sector, where electrification will lead to a 20 % reduction in energy demand by 2050 compared to the NDC scenario.

In the HE and ME scenarios, renewable energy sources will increasingly penetrate the future energy system up to 2050. Bioenergy will be the primary renewable source across 2030, 2040, and 2050, supporting the electricity baseload in regions with high energy demand. Bioenergy, through biofuels in transportation and biomass in industry, will also contribute to the NZE objectives in both scenarios. A substantial increase in solar PV will occur from 2030 to 2040. The high growth in electricity demand will drive this rapid development of solar PV.

CO_2 emissions are projected to decrease across all scenarios over time, as shown in Fig. 3. Despite an increase in fossil fuel usage, the NDC scenario's CO_2 emissions are expected to decline through extensive CCS and BECCS implementation in power plants and heavy industry processing plants. While both alternative scenarios are set to achieve zero CO_2 emissions by 2050, differences are noted in 2030 and 2040, with the HE scenario emitting approximately 3 % more CO_2 in 2030 and 7 % more in 2040 compared to the ME scenario due to higher coal consumption in industries within the HE scenario. This coal usage will be replaced by biomass in the ME scenario, particularly by 2040.

Thus, the HE and ME scenarios delineate pathways toward NZE by 2050 through a reduction in energy demand across the transport and industrial sectors and by sourcing the entire energy system predominantly from renewable energy. This reduced energy demand will improve the resilience of energy independency from the context of energy security. The dependence on oil imports for transport and industrial sectors will be completely shifted to domestic energy from renewables. By 2050, the ME scenario will achieve the lowest primary energy supply by implementing a relatively lower degree of electrification in the entire energy system compared to the HE scenario.

Further examination of the electricity sector reveals a completely different picture of future energy systems envisioned by the NDC scenario versus the alternative scenarios, as shown in Fig. 4. From 2040 to 2050, the total primary energy supply within the electricity sector is substantially higher in the HE and ME scenarios compared to the NDC scenario. In the NDC scenario, the proportion of the primary energy supply allocated to electricity relative to all sectors is estimated to be approximately 45 % in 2040, increasing to 52 % in 2050. This ratio is projected to rise significantly in the alternative scenarios, reaching up to 66 % in 2040 and 75 % in 2050 in the ME scenario, with even higher percentages in the HE scenario. Notably, the HE scenario exhibits a greater demand for electricity in the transport and industry sectors than the ME scenario, with the difference expected to widen to 254 TWh in 2050.

Regarding energy sources, the NDC scenario will continue to primarily rely on coal-fired power plants equipped with CCS for electricity generation. On the other hand, starting in 2040, renewables will almost entirely supply the electricity sector in the HE and ME scenarios.

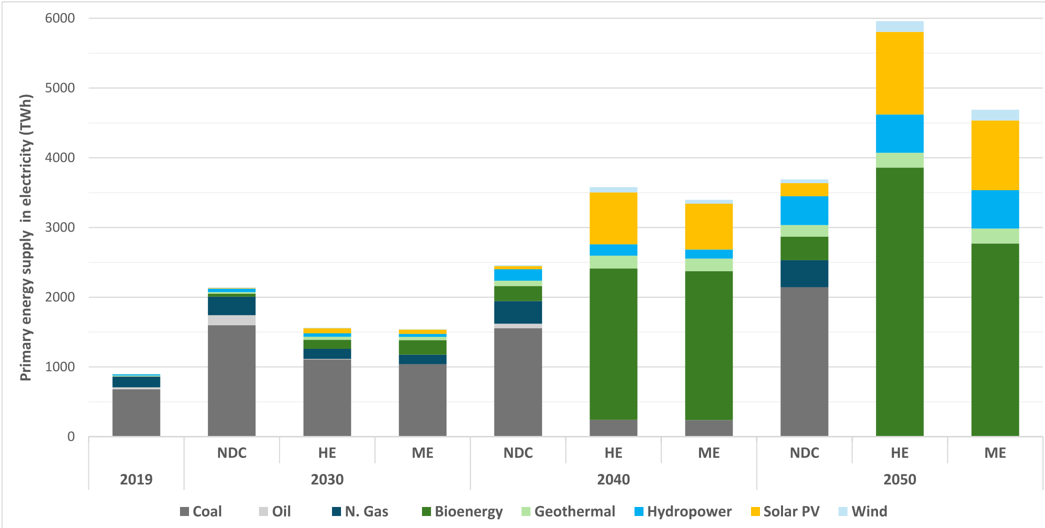

Fig. 4. Primary energy supply by sources in the electricity sector in all scenarios in 2030, 2040 and 2050.

Biomass power plants are anticipated to serve as the main electricity producers, especially designed to satisfy the electricity needs of the largest regional energy consumers: Java-Bali, Sumatera and Sulawesi. The full exploitation of hydropower, geothermal, and wind energy potential, alongside the integration of pumped hydro electricity storage (PHES) and extensive solar PV deployment, will address the electricity required in these regions. In regions with abundant renewable energy potential and relatively lower electricity demands, such as Maluku-Papua-Nusa Tenggara (MPN) and Kalimantan, the energy systems will fully capitalise on solar PV, hydropower, geothermal, and wind energy, complemented by PHES, to meet their 2050 electricity demands.

3.2. Interconnected regional energy systems

A fundamental assumption underpinning the NZE energy system within the HE and ME scenarios is the interlinking of regional energy systems. Simulation results of interconnected several energy systems are shown in Fig. 5. By 2050, the Java-Bali energy system is anticipated to establish connections with the energy systems of Sumatera, Maluku-Papua-Nusa Tenggara (MPN) and Kalimantan. As the primary regional energy consumer having maximised its RE potential: hydropower, geothermal, wind, and solar energy, Java-Bali will not pursue the development of additional biomass power plants to satisfy its electricity needs in the event of an electricity surplus from adjacent regions. The establishment of new transmission lines to facilitate these connections is depicted in Fig. 2, with each line drawn to represent the shortest feasible distance between systems. The assumptions for the transmission lines include direct links between Java-Bali and Sumatera, as well as Java-Bali and Kalimantan. For the Java-Bali to MPN line, a simplified assumption of a 400 km distance accommodates the complexity of connecting across MPN's medium to large islands, in contrast to the more straightforward connections with Sumatera and Kalimantan. Sulawesi will be simulated in an isolated energy system in the HE and ME scenarios 2050.

The energy systems of Sumatera, MPN, and Kalimantan are expected to generate surplus electricity, mainly from hydropower, geothermal, wind, and solar PV, with the potential of hydropower, geothermal and wind energy reaching their maximum capacity by 2050. A critical assumption for the NZE pathways in the HE and ME scenarios is the maximisation of renewable energy sources, especially solar energy, in Sumatera, MPN, and Kalimantan for electricity exports to the Java-Bali system. The ME scenario anticipates a reduced total transmission

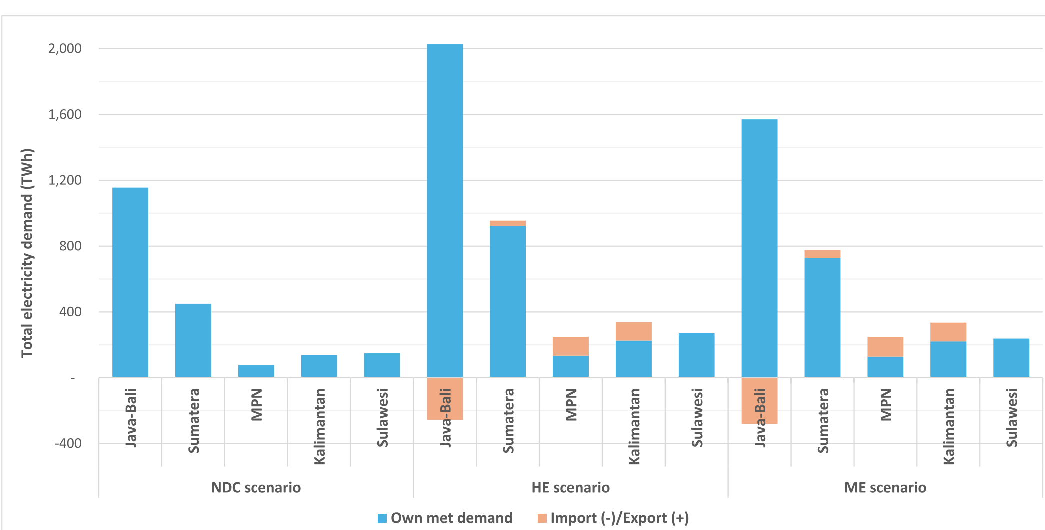

Fig. 5. Electricity demand, including import and export, in all regional energy systems from all scenarios in 2050.

capacity requirement compared to the HE scenario, which is attributed to the ME scenario's relatively moderate level of electrification across the entire energy system.

An interconnected energy system relying on 100 % RE-based electricity as the primary end-use of energy systems will open more connectivity between regions in Indonesia. This transformation is poised to reshape the Indonesian energy landscape and, by extension, potentially influence the future economic structure of the country. To further extent, this interconnection of five energy systems could also transform socio-economic aspects in Indonesia. The dependency on electricity import-export in the country would create a new dimension of daily life in the future. Given this current research's assumption of no significant economic structural changes—wherein Java-Bali remains the largest regional energy consumer from 2030 to 2050—the interplay between an interconnected energy system and future economic structure emerges as a pivotal area for future research.

3.3. Total annual costs

Fig. 6 shows the breakdown of the total annual costs from all scenarios in 2030, 2040 and 2050. The NDC scenario incurs higher total yearly costs than the other two scenarios, predominantly driven by a significant percentage of variable costs along the simulated time. The variable costs ratio against the total annual costs in the NDC scenario—rising from 65 % in 2030 to over 70 % by 2050—reflects a systemic dependence on fossil fuels. Consequently, the CO_2 cost component within this scenario's annual costs forms a substantial burden. While substantial, the investment costs of this scenario are lower relative to the higher spent HE and ME scenarios. The NDC scenario's escalating costs, driven by its high variable costs, such as coal and natural gas for power plants and oil for transport, and CO_2 cost component, signal the economic vulnerabilities of a pathway tethered to high fossil energy consumption.

Meanwhile, the HE and ME scenarios demonstrate a marked increase in investment costs over the time horizons, indicative of the capital required for a higher degree of electrification, such as electric vehicles and large-scale PV farms. However, the variable costs are much lower in these two scenarios compared to the NDC scenario. The alternative scenarios will not spend any fossil fuel costs for power plants and combustion engine cars. Over the years, the HE scenario appears to bear the highest costs, particularly in investment, such as the adoption of green hydrogen in 2050. By 2050, the ME scenario emerges as a compromise, with its total costs constituting about 63 % of the NDC scenario and 79 % of the HE scenario. This scenario's comparatively lower investment costs suggest a more balanced approach to moderate electrification and the flexible expansion of renewable energy, resulting in the lowest total annual costs in 2030, 2040 and 2050 among the scenarios.

In stark contrast with the NDC scenario, both the HE and ME scenarios exhibit a complete absence of CO_2 cost in 2050, a direct consequence of their successful transition to net-zero emissions. The extended analysis of total annual costs across 2030, 2040 and 2050 underscores the environmental and economic viability of the HE and ME scenarios over the NDC scenario. The two alternative scenarios demonstrate that substantial upfront investments in electrification and renewable energy can significantly reduce long-term variable and fixed operation costs, offering environmentally and economically sound pathways for Indonesia's energy sector.

Further analysis of the CO_2 cost under the HE and ME scenarios relative to the NDC scenario reveals more effective pathways to net-zero emissions despite necessitating higher initial investments. The simulation results indicate that the widespread adoption of CCS technologies in most coal-fired power plants within the NDC scenario by 2050 will not only fail to mitigate CO_2 emissions significantly but also escalate the total annual costs. Specifically, the incremental costs associated with CCS implementation are projected to increase the total annual costs by approximately 6 % or about USD 19.3 billion.

3.4. Limitation and uncertainties

Despite yielding significant results and thorough discussions, this present research has several limitations. One limitation involves dividing Indonesia into five regional energy systems. Regions with numerous large and medium-sized islands, such as Sumatra, MNP and Sulawesi, could be segmented into more than one individual energy system. Another limitation is the simplified top-down approach used to estimate energy demand in the industrial sector. Although recent studies have employed this approach, this current research was constrained by the lack of detailed Indonesian data within industry sub-sectors. Regarding the tools used, two additional limitations are noteworthy. In EnergyPLAN, thermal power plants are aggregated into a single large-capacity plant, requiring proportional distribution of fuel shares if multiple fuel types are used. In MultiNode, the excess electricity production can only be utilised for export if it is from variable renewables. Produced electricity from thermal power plants, such as from coal and biomass, cannot be exported.

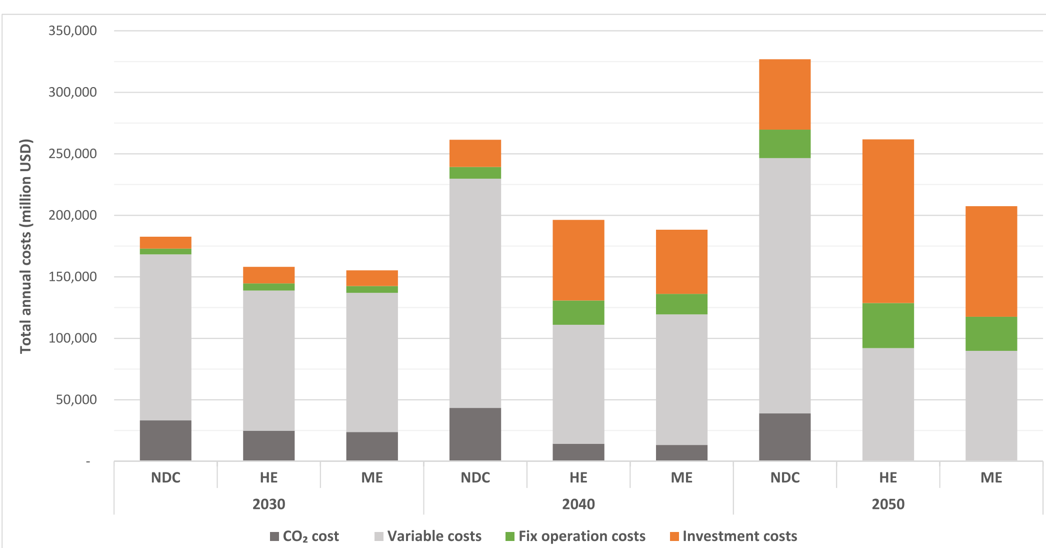

Fig. 6. Total annual costs breakdown from all scenarios in 2030, 2040 and 2050.

One important result of the research is the necessity for a substantial increase in bioenergy consumption to achieve an NZE system. For instance, in the 2050 Java-Bali system under the ME scenario, approximately 75 % of the total primary energy supply is projected to come from bioenergy. Bioenergy is prioritised only after all other renewable sources have reached their maximum potential. Referring to the global sustainable bioenergy consumption per capita at 10–129 GJ in 2050 [52], this current research estimates a value within that range, specifically 31–45 GJ per capita by 2050. It is worth noting that there is a lack of literature projecting the potential of various types of bioenergy, such as wood crops, wood processing residues, animal waste, and biofuels, in Indonesia for 2050. This research's scope was limited in terms of assessing detailed sustainability criteria, such as land requirements, to meet the projected per capita bioenergy consumption. Consequently, there is uncertainty regarding the potential of bioenergy. It is crucial to have reliable estimates of future bioenergy potentials in Indonesia.

All foundational assumptions employed in this research are subject to uncertainties that could significantly alter the structure of the Indonesian economy and, hence, the pathways of its energy system. For instance, the projection of a 5.5 % average annual growth in electricity demand from 2019 to 2050 needs careful consideration. While this estimate may seem optimistic, it is grounded in governmental forecasts [4]. Another example is that the variability of renewable energy sources, such as solar and wind, represents another critical assumption affecting energy supply. The uncertain future electricity output from these renewables could impact not only the mix of the primary energy supply but also modify demand dynamics in response to fluctuations in electricity availability.

4. Conclusion and policy recommendation

This paper has presented two potential pathways towards net-zero emissions (NZE) in Indonesia's energy sector by 2050. Pathways from the High Electrification (HE) and Moderate Electrification (ME) scenarios could achieve NZE in 2050 by reducing energy demand and supplying 100 % renewable energy in the electricity and industry sectors. The connectivity of several regional energy systems could maximise renewable energy potential. The analysis of total annual costs reveals that the ME scenario offers a cost-effective route to the NZE energy system. Furthermore, to accelerate net-zero emissions in Indonesia's energy sector ahead of the timeline set forth by the government's plan [4], this paper proposes four policy recommendations as follows:

1. Boosting implementation of energy efficiency measures, particularly in the electricity and industry sectors. Strategic investments in energy-saving technologies and best practices are crucial for reducing energy demand and facilitating a smoother transition to an NZE energy system.
2. Accelerating electrification, especially in the transport sector, is the first step to significantly reducing primary energy supply and CO_2 emissions. Prioritising renewable energy in the short term sets a solid foundation for achieving a 100 % renewables-based electricity sector by 2050.
3. Initiating the interconnection of regional energy systems by planning detailed cross-region transmission infrastructure across the country. It could start from the Java-Bali system to neighbouring regions, i.e. Sumatera and Maluku-Papua-Nusa Tenggara (MPN) energy systems. The interconnection plan could maximise renewable energy's potential at an earlier stage.
4. Emphasising the role of carbon capture and storage (CCS) technologies as a complementary measure rather than a primary strategy. While CCS technologies hold the potential for reducing CO_2 emissions, their application can only be applied to compensate for hard-to-abate emitted CO_2, such as from long-distance trucks or the aviation industry.

Future research will focus on detailed energy simulations of industry sectors and sub-sectors. This could include applying a bottom-up approach to define future energy demand in each sub-sector. The research could also be underpinned by a more thorough assessment of the 100 % renewable energy-based industry sector. Additionally, the connectivity of sub-regional energy systems, particularly in areas with unique geographical conditions and consisting of many islands like the MPN energy system, warrants closer examination. Such studies will enhance an understanding of the operational dynamics and potential of Indonesia's diverse energy landscape.

CRediT authorship contribution statement

Yudha Irmansyah Siregar: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2024.133014.

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Chapter 6. Synthesis: Integrating research findings for Indonesia's energy future

This chapter synthesises the key findings from previous research, highlighting Indonesia's potential pathways towards a net-zero emissions (NZE) energy system. It explores prioritising renewable energy (RE) sources, the impact of sector coupling on efficiency and emissions and strategic pathways to achieving NZE by 2050. The following sections provide a detailed examination of these themes, presenting insights for policy development and identifying avenues for future research.

Section 6.1 provides a summary and discussion of the research findings. Section 6.2 identifies the scientific contributions of the research findings. Section 6.3 presents the main conclusions drawn from these findings, emphasising the importance of renewable energy development, sector coupling and effective policy frameworks. Section 6.4 offers detailed policy recommendations to accelerate Indonesia's energy transition, focussing on short-term, medium-term and long-term strategies. Finally, Section 6.5 identifies the limitations of the current research and suggests areas for future work to enhance further Indonesia's pathways to an NZE energy system.

6.1. Summary and discussion of research findings

This section integrates the research findings, demonstrating how prioritising renewable energy sources, particularly solar, can significantly enhance Indonesia's sustainable electricity generation (sub-research question 1 – sub-RQ 1). It highlights the critical role of sector coupling in improving the energy system's efficiency and reducing carbon dioxide (CO_2) emissions (sub-RQ 2). It outlines the pathways necessary to achieve net-zero emissions by 2050 through high and moderate electrification scenarios (sub-RQ 3). Each sub-research question is addressed methodically, summarising the findings, discussing the implications, including their challenges in the context of Indonesia's energy transition, and connecting to the recent literature.

Sub-RQ 1: How can Indonesia prioritise energy sources for sustainable electricity generation in energy planning?

Publication 1 used a participatory multi-criteria analysis (MCDA) to rank various energy sources, handling multiple sustainability criteria and involving stakeholders from diverse groups. This approach ensures the energy planning process is comprehensive and considers various perspectives, making it highly relevant to Indonesia's energy policy development.

The research employed the Analytic Hierarchy Process (AHP) to structure the decision-making process into a hierarchy of criteria and sub-criteria. The criteria considered include economic, technical, environmental, and social aspects, each with its sub-criteria. Stakeholders from government institutions, universities, think tanks, the energy industry, civil society, and international organisations contributed to this research by providing judgments on pair-wise comparisons of these criteria and sub-criteria. The performance of nine energy sources against these criteria was evaluated using stakeholder inputs and relevant literature data.

The analysis reveals that solar energy is Indonesia's top-ranked alternative for sustainable electricity generation. Solar's high ranking is attributed to its economic benefits, such as low investment costs, and its social advantages, including high public acceptance. The results indicate that focussing on policies that leverage solar energy's economic and social strengths could significantly enhance Indonesia's sustainable electricity generation.

The results highlight the significant role of solar energy in Indonesia's energy planning. The research suggests that the Indonesian government should consider policies that maximise solar energy utilisation. The significant ranking gap between solar and other energy sources emphasises its paramount importance. Furthermore, the sensitivity analysis confirms that solar remains the top priority across different stakeholder groups, highlighting its broad acceptability.

The findings have several implications for energy planning in Indonesia. First, there is a clear need to transition away from coal, which ranked lower due to its environmental and social drawbacks despite its technical advantages. Second, enhancing the deployment of solar energy requires supportive policies, infrastructure development and possibly incentives for adoption. The research's participatory approach ensures that the recommended strategies are well-rounded and considerate of various stakeholder perspectives.

Given its favourable economic profile and high public acceptance, these findings highlight the strategic potential of prioritising solar energy within Indonesia’s electricity generation planning. However, practical implementation entails substantial challenges. Solar deployment depends heavily on land availability and geographic conditions, which may limit scalability in densely populated areas like Java and Bali islands, where the cost and scarcity of open land pose barriers [18]. Moreover, ecologically sensitive regions, particularly in Kalimantan and Sumatera islands, raise environmental concerns regarding the placement of large solar farms, where development may disrupt local ecosystems [79]. Compounding these challenges, the current domestic solar industry faces limitations in technological readiness, demanding substantial policy support and targeted investment to build the infrastructure and expertise necessary for effective integration. Overcoming these challenges is essential to harness solar’s potential fully.

Sub-RQ2: How can sector coupling impact Indonesia's energy system's efficiency and CO_2 emissions?

Publication 2 addresses the question by examining the integration of electricity, transport and cooling sectors within Indonesia's future energy system. This study focuses on the Java and Bali islands, which have isolated energy systems. The study aims to explore how sector coupling can enhance a more efficient energy system and reduce CO_2 emissions.

The methodology involves using EnergyPLAN to model and simulate various future energy scenarios. The scenarios include business-as-usual (BAU), high electric vehicle (EV) penetration, district cooling (DC) networks, high solar integration, and combined scenarios. Data collection included energy demand and supply inputs for electricity, transport and cooling sectors. A bottom-up calculation approach was used for the transport sector, while geospatial analysis was employed to assess cooling demand and identify potential DC networks in Jakarta. The scenarios were evaluated based on primary energy supply (PES), critical excess electricity production (CEEP), CO_2 emissions and annual costs.

The results indicate that sector coupling can significantly reduce PES, CO_2 emissions and annual costs. The combined (COM) scenario, which integrates higher EV penetration and increased renewables, is the most efficient. This scenario shows about 8% lower PES, 14% lower CO_2 emissions and 2% lower annual costs than the BAU scenario. Transport electrification is the most effective in reducing CO_2 emissions when paired with renewable energy sources. The DC scenario also shows promise by optimising waste heat from natural gas-fired power plants to provide cooling, reducing CO_2 emissions by 11.6 million tons compared to the BAU scenario.

The findings emphasise the importance of integrating high shares of renewables in the electricity sector to maximise the benefits of transport electrification. The research shows that higher penetration of EVs alone does not automatically result in lower CO_2 emissions unless renewable sources meet the electricity demand for EVs. The COM scenario demonstrates the potential for substantial reductions in PES and CO_2 emissions by combining smart EV charging, high renewable integration and district cooling networks. The research also highlights the role of smart charging in reducing CEEP, further enhancing energy system efficiency.

This transformative potential of sector coupling in Indonesia’s energy system also reveals some challenges. With high penetration of variable renewable sources, such as wind and solar, balancing supply and demand becomes complex, particularly as EV charging demand surges. Studies in other high-renewable systems suggest that without advanced grid management solutions, including demand-side response and energy storage, such integration can lead to grid instability and even frequency imbalances [15]. Further, the current Java-Bali grid, for instance, has limited capacity to balance supply and demand, and the addition of substantial EV charging could exacerbate this imbalance, leading to potential grid instability [80]. Moreover, Indonesia's current EV charging infrastructure is underdeveloped, which hinders the effective implementation of vehicles-to-grid technologies that are essential for enhancing grid flexibility. Lastly, a coordinated approach to sector coupling would require robust data on real-time energy demand across sectors, which Indonesia’s current data and monitoring systems might not yet support. Such data are critical for implementing integrated energy management systems and optimising energy flows across electricity, transport and cooling. Addressing these challenges will require policy support focused on modernising grid infrastructure, expanding EV infrastructure and establishing comprehensive energy data systems to make sector coupling both feasible and effective.

Recent studies underpin the findings of this research on the benefits and challenges of sector coupling in Indonesia’s energy system. Zahari and McLellan [81] highlight the importance of well-designed policies, such as carbon pricing and a fossil fuel depletion premium, to accelerate the transition in the electricity sector. Their analysis suggests that while these policies can drive renewable energy growth, they may also bring economic challenges to Indonesia's fossil-fuel-dependent economy, making balanced policy design essential. In the transport sector, Fitriana et al. [82] examine EVs as a key strategy for improving energy efficiency. Their modelling work indicates that EV adoption could significantly cut fossil fuel use and emissions in the long term. However, they note that realising these benefits requires a parallel increase in renewable energy share in electricity generation. These studies support the need for coordinated policies across sectors to effectively achieve Indonesia’s energy transition goals.

Sub-RQ 3: How can Indonesia achieve net-zero emissions in the energy sector by 2050?

Publication 3 examines the question by analysing transition pathways integrating all energy sectors. The research presents an in-depth exploration of the challenges and strategies for Indonesia to transition away from its reliance on fossil fuels, emphasising the role of electricity in future energy systems and the significance of regional connectivity.

The methodology employed in this research includes using EnergyPLAN and MultiNode simulations to model and simulate future energy scenarios. The research developed three scenarios: Nationally Determined Contribution (NDC), High Electrification (HE) and Moderate Electrification (ME). Each scenario considers different levels of electrification, energy efficiency measures and RE integration. The scenarios were designed to capture the future energy demands and the potential for renewable energy utilisation across the entire energy sector. The energy system is segmented into five regional systems to provide a detailed and context-specific analysis.

The findings highlight that both HE and ME scenarios are viable pathways to achieving NZE by 2050, with distinct advantages in terms of energy efficiency and CO_2 reduction. The HE scenario suggests an aggressive shift towards renewable energy and high electrification, significantly lowering CO_2 emissions and energy demand, especially in the transport and industrial sectors. Conversely, the ME scenario provides a more cost-effective approach with moderate electrification. It focuses heavily on maximising the use of bioenergy and solar, balancing technological feasibility and financial sustainability.

The research concludes that Indonesia can achieve NZE by 2050 through high and moderate electrification strategies that leverage renewable energy and innovative technologies. The findings provide a framework for policymakers, suggesting that strategic investments in renewable energy and technology can significantly shift Indonesia's energy paradigm from heavily relying on a fossil-based energy system. Interconnected regional energy systems are central to this transition, highlighting the need for coordinated efforts across different sectors and regions to realise the full potential of RE sources and electrification.

While the research presents a clear framework for achieving NZE by 2050 through electrification and renewable integration, it also identifies challenges for implementation. The shift to high and moderate electrification scenarios demands substantial upgrades in grid infrastructure to manage the intermittency of renewable energy sources like solar and wind [83]. Without enhanced storage solutions and demand-response strategies, there is a risk of grid instability, especially as the demand from sectors like transport and industry grows [84]. Moreover, Indonesia's geographic diversity requires a coordinated inter-regional energy system to fully utilise renewable sources across its regions, which involves complex set-up, logistical and financial investments [85,86]. Meeting these challenges require strategic policy support and investments in both advanced grid technologies and energy storage.

Recent literature strongly supports this research's focus on Indonesia's pathways to net-zero emissions, emphasising the need for infrastructure and technology to enable full decarbonisation. Langer et al. [87] and Resosudarmo et al. [88] both illustrate how advanced energy infrastructure is essential for Indonesia's net-zero goals. Langer et al. explore how inter-island transmission lines could balance renewables supply across regions by linking resource-rich areas to those with high demand. In a different study focus, Resosudarmo et al. examine the financial and technical challenges of shifting from coal to renewable energy, stressing that substantial investment and new technologies will effectively expand RE capacity. Together, these studies confirm the importance of targeted infrastructure investment and technological progress, supporting this research’s conclusion that pathways towards an NZE system require both physical upgrades and economic commitment.

6.2. Scientific contributions

Building on the synthesis of research findings, this section discusses the scientific contributions of this thesis. This research suggests a structured framework for achieving NZE by 2050 by addressing critical gaps in theoretical understanding, methodological approaches and analytical insights. Specifically, the thesis makes three key contributions: advancing theoretical frameworks for RE integration, refining methodologies for energy system modelling and delivering actionable analytical insights.

Theoretical contributions

Theoretical contributions focus on advancing the understanding of energy transition dynamics, particularly regarding RE integration and socio-economic development. By bridging policy, technology and socio-economic considerations, this thesis provides a conceptual foundation for addressing Indonesia’s unique challenges in transitioning to NZE.

Framework for RE prioritisation: This thesis introduces a prioritisation framework that aligns renewable energy development with Indonesia's socio-economic goals. A structured evaluation of various renewables, such as solar, wind and hydro, provides insights into developing resource deployment strategies. The framework considers, among others, local economic conditions, industry readiness and resource availability, offering a replicable model for other countries or areas with similar challenges.

Energy system resilience: The research develops a theoretical understanding of energy system resilience by examining how a diverse mix of RE sources can contribute to grid stability while addressing regional disparities. It argues that decentralisation and resource diversity enhance system adaptability to fluctuations in demand and supply. These findings form the foundation for strategies to ensure a reliable energy transition.

Methodological contributions

The methodological contributions involve developing and refining tools and processes to model energy systems and evaluate RE development strategies. By leveraging established tools and novel adaptations, this research enhances the capacity for precise and context-specific energy system analyses.

EnergyPLAN and MultiNode integration: The thesis refines EnergyPLAN to simulate Indonesia’s energy system under varying RE adoption alternatives, incorporating local constraints, such as resource distribution and demand patterns. Complementing this, MultiNode models decentralised systems, offering insights into region-specific challenges and opportunities like Indonesia.

Analytical contributions

The analytical contributions provide detailed, data-driven insights into NZE pathways and their implications for Indonesia's energy transition. These analyses inform policymakers and stakeholders about the most effective pathways for achieving NZE goals.

Sector coupling strategies: The thesis highlights the benefits of sector coupling, such as electrifying transportation. Using scenario analyses, it demonstrates how sectoral integration enhances system-wide efficiency while reducing CO_2 emissions.

Policy-driven impact modelling: This thesis provides actionable insights into emissions reductions and system adjustments needed to meet NZE targets by simulating the impact of coal phase-out policies and other energy strategies. Further, it evaluates policy scenarios, offering a roadmap for aligning national energy strategies with long-term objectives.

6.3. Main conclusions

Publication 1 highlights Indonesia's substantial potential for RE development, strategically focussing on enhancing sustainable electricity generation. The research identifies solar energy as a leading option due to its economic benefits and high public acceptance. A focus on solar energy could substantially enhance RE development in the country by promoting the widespread adoption of solar technologies to capitalise on its advantages.

In Publication 2, sector coupling, which integrates electricity, transport and cooling sectors, emerges as a pivotal strategy for enhancing energy efficiency and reducing CO_2 emissions. The research highlights the benefits of high EV penetration and RE integration, which can optimise energy use and improve system resilience. Strategies, such as implementing smart charging infrastructure and developing district cooling networks, are crucial for maximising these benefits.

The transition pathways to NZE by 2050 offer comprehensive insights into achieving Indonesia's climate goals in Publication 3. The scenarios modelled in this research reveal that both high and moderate electrification pathways present viable routes, each with distinct advantages. High electrification emphasises aggressive renewable energy adoption, significantly lowering emissions and energy demand, while moderate electrification balances technological feasibility with economic sustainability. These pathways provide policymakers with a clear framework for implementing energy efficiency measures and integrating renewables.

Effective policy frameworks are essential for realising Indonesia's energy transition. The research provides key recommendations, such as subsidies, tax incentives, and regulatory frameworks to promote renewable energy and sector integration. Emphasising supportive measures, the research points out the importance of overcoming financial and regulatory barriers to facilitate the large-scale deployment of renewables. Developing an integrated regional energy system is also crucial for optimising electricity distribution and utilisation, ensuring a balanced and resilient energy supply across diverse regions.

Stakeholder engagement and public participation play a crucial role in the energy transition process. Decision-making processes involving government agencies, the private sector, and local communities are key to the successful implementation of energy policies. The research stresses the importance of transparent communication in fostering public support and ensuring equitable distribution of benefits.

Overall, this PhD thesis provides a comprehensive framework for Indonesia to achieve net-zero emissions in the energy sector by 2050. The research offers a holistic energy planning and policymaking approach by integrating technical, economic, environmental, and social dimensions. The findings and recommendations serve as a strategic guide for policymakers, researchers and industry stakeholders.

The extensive analysis and robust methodological framework highlight the feasibility and necessity of coordinated efforts to transition to renewable energy. Leveraging insights from this PhD thesis, Indonesia can implement effective strategies that address current energy challenges and pave the way for a better future. Emphasising sector coupling, renewable energy prioritisation and stakeholder engagement provides a thorough perspective on the multifaceted nature of energy transitions. This thesis contributes to the academic discourse on energy policy and offers practical solutions for pressing energy challenges.

6.4. Policy recommendations

This PhD thesis provides valuable perspectives on Indonesia's energy transition, highlighting the importance of early adoption of renewable energy technologies, enhancing stakeholder engagement and integrating various sectors to achieve an NZE energy system by 2050. The research findings underscore the necessity for substantial policy interventions, including a participatory approach to energy planning, implementing energy efficiency measures in household, commercial, and industrial sectors, and maximising solar energy potential. Defining these interventions across three main time frames allows for a structured and phased approach, ensuring immediate actions align with long-term strategic goals shown in Table 6.1.

In the short term (1-3 years), it is crucial to accelerate the sector coupling of electricity and transportation and adopt a more participative energy planning approach. Medium-term (3-5 years) strategies could focus on boosting RE development and planning for the early retirement of fossil-based power plants. Long-term (beyond five years) goals include the integration of electricity with remaining sectors and initiating the interconnectivity of regional energy systems. The subsequent sections will provide detailed policy recommendations to accelerate the energy transition.

6.4.1. Short-term (1-3 years)

Applying a more participatory approach to energy planning

This recommendation actively involves diverse stakeholders to create a more effective planning strategy. This strategy ensures that environmental, social, economic, and technical aspects are comprehensively addressed by engaging various stakeholders. The planning process can capture diverse perspectives and expertise by involving various stakeholders, leading to more acceptable energy plans. This approach promotes transparency and fosters public trust. Engaging stakeholders in MCDA facilitates a balanced evaluation of energy sources and strategies. For instance, this comprehensive participatory approach can be effectively integrated into the existing frameworks of the Regional Energy Plan and the Electricity Supply Business Plan.

Implementing energy efficiency measures in household and commercial sub-sectors

Adopting these measures in the household and commercial sub-sectors is vital to reducing energy use. Significant energy savings can be achieved by focussing on these sub-sectors in the immediate future. Key measures include upgrading to energy-efficient appliances, such as refrigerators, air conditioners and lighting systems, which can significantly reduce energy consumption. Improving building insulation and implementing energy-efficient architectural designs can minimise the need for cooling. Encouraging the adoption of energy-efficient practices, such as turning off unused appliances and optimising energy use during off-peak hours, can also make a substantial difference. Public awareness campaigns and educational programmes can inform consumers about the advantages of energy efficiency and the implementation of these measures. Financial incentives, such as rebates and tax credits, can motivate households and businesses to invest in energy-efficient technologies and practices. This comprehensive approach ensures that energy efficiency becomes integral to the country's energy strategy.

Maximising solar energy potential

To accelerate renewable energy development in Indonesia, tapping into the country's vast solar energy potential is essential. With high solar irradiance levels, Indonesia is ideally suited for extensive solar energy deployment. Efforts could focus on expanding utility-scale solar farms and promoting rooftop installations on residential and commercial buildings, significantly boosting solar capacity. Financial incentives, such as subsidies and tax benefits, can drive investment in solar technologies. Streamlining regulatory processes to enable faster project approvals and reduce administrative barriers is equally important. Promoting public awareness and education about the benefits of solar energy can foster broader community support and participation.

Accelerating transport electrification

Transforming Indonesia's transportation sector through electrification is a key pillar in the country's broader energy transition. This can be achieved by promoting the adoption of EVs and developing the necessary infrastructure, such as widespread charging stations. Financial incentives for EV purchases, including subsidies and tax rebates, can stimulate consumer interest and market growth. Moreover, investing in research and development to enhance battery technology and vehicle efficiency is essential. Simplifying regulatory frameworks to support the rapid rollout of charging infrastructure will further facilitate this transition. Public awareness campaigns highlighting EVs' environmental and economic benefits can drive acceptance and accelerate adoption.

6.4.2. Medium-term (3-5 years)

Implementing energy efficiency measures in the industry sector

As a major energy consumer, the industrial sector offers vast potential for efficiency improvements that can significantly reduce energy consumption and CO_2 emissions. Key measures include adopting the best available technologies, such as high-efficiency boilers, advanced manufacturing processes and cutting-edge heat recovery systems designed to optimise energy consumption and reduce environmental impact. For instance, enhancing material efficiency through better recycling processes can lead to substantial reductions in energy demand and emissions [89]. Adopting innovative energy management systems equipped with digital tools and smart technologies enables real-time monitoring and optimisation of energy use. These systems provide valuable insights into consumption patterns, enabling further efficiency gains. Financial incentives, like tax breaks or subsidies for energy-efficient upgrades, can motivate industries to invest in these advanced technologies. Prioritising these strategies allows Indonesia to achieve significant energy savings, reduce reliance on fossil fuels, and align its industrial sector with broader renewable energy targets.

Boosting RE development and planning for early retirement of fossil-based power plants

The energy transition depends on scaling up renewable energy deployment while systematically phasing out fossil fuel power plants. Removing administrative barriers and streamlining RE project approval processes is essential to accelerate progress. At the same time, a strategic plan for the early retirement of fossil-based power plants is necessary to reduce CO_2 emissions. This plan should consider plant closures' economic and social consequences and include support measures for affected workers, such as retraining programmes and job placement services. Reconfiguring existing coal-fired power plants to co-firing with biomass can serve as an interim solution, reducing emissions while maintaining energy stability. This approach utilises existing infrastructure to facilitate a smoother shift towards full renewable energy integration. These strategies will help scale up RE capacity while gradually reducing the country's dependence on fossil fuels.

6.4.3. Long-term (beyond five years)

Integration of electricity with the remaining sectors

Achieving net-zero emissions in Indonesia’s energy sector by 2050 depends on the seamless integration of electricity with other sectors. Shifting industrial processes from conventional energy sources to electrified systems is a key strategy for reducing emissions. Financial incentives, such as grants, tax breaks and low-interest loans, can encourage industries to adopt electric heating and integrated cooling systems. Introducing stringent energy efficiency standards and conducting regular energy audits can further ensure ongoing improvements in industrial energy use. Another key application involves using renewable electricity to produce green hydrogen, which can serve as a clean fuel for hard-to-abate industries, such as chemicals and steel, addressing the challenges of direct electrification. Establishing hydrogen production facilities and creating a supportive regulatory framework can stimulate private sector participation and investment. Furthermore, integrating energy storage solutions is vital for balancing supply and demand across sectors. Supporting the deployment of pumped hydro electricity storage, advanced battery storage systems and other innovative storage technologies can enhance grid stability and reliability.

Initiating the interconnectivity of regional energy systems

Enhancing the country’s energy infrastructure depends on linking regional energy systems for better reliability and efficiency. By connecting regional grids, Indonesia can optimise the distribution of renewable energy sources, ensuring a more balanced and resilient power supply. This interconnectivity allows regions with surplus renewable energy, such as solar or wind energy, to supply those with deficits. Implementing this policy involves developing a reliable transmission infrastructure to handle the increased load and variability of renewable energy sources. Establishing a regulatory framework that facilitates cooperation between regional energy authorities is an important milestone. This framework should address the technical and administrative challenges of integrating different regional systems, including standardising grid codes and operational protocols. With increased regional collaboration and investment in grid infrastructure, Indonesia could create a more cohesive and efficient energy network.

Table 6. 1. Transformative policy recommendations for NZE energy sector in Indonesia.

Time frame	Policy recommendation
Short-term (1-3 years)	• Applying a more participatory approach that includes all energy aspects in energy planning • Implementing energy efficiency measures in household and commercial sub-sectors • Maximising solar energy potential for acceleration of RE development • Accelerating sector coupling of electricity and transportation
Medium-term (3-5 years)	• Implementing energy efficiency measures in the industry sector • Boosting RE development; planning for early retirement of fossil-based power plants
Long-term (> 5 years)	• Integration of electricity with the remaining sectors • Initiating the interconnectivity of regional energy systems

6.5. Limitations and future research

This section proposes several key research areas to address the outlined limitations and guide future efforts. Table 6.2 highlights these proposed research topics. Targeting these research efforts aims to develop tailored strategies that enhance the effectiveness and inclusiveness of Indonesia’s transition towards a net-zero emissions energy system.

In Publication 1, the analysis excludes other potential renewable energy sources, such as tidal and wave energy, which might contribute to the diversity of the energy mix. This analysis exclusively examines the current performance of the assessed energy sources without considering future advancements in renewable technologies. This static approach might not fully capture the potential long-term benefits and enhancements expected from renewables. Future research could address these gaps by incorporating a more comprehensive range of renewable sources and considering their anticipated advancements. Another limitation is the broad application of criteria and sub-criteria without tailoring them to specific regional contexts. Tailoring the evaluation criteria to specific regions could provide more localised and relevant insights. Implementing a more participatory energy planning, especially in fossil-dependent regions, can enhance the effectiveness and acceptance of the agreed plans.

Publication 2's analysis of sector coupling for electricity, transport and cooling in Indonesia presents several limitations. The cooling demand is based solely on 2019 data, not accounting for future changes up to 2040, potentially underestimating future cooling needs. The proposed district cooling network is limited to Jakarta, which restricts the study's applicability to other urban areas that could benefit from similar interventions. Future research could incorporate updated and projected cooling demands to accurately reflect potential changes up to 2040 and beyond. Expanding the geographical scope to include other major cities in Java-Bali or different regional energy systems in Indonesia could provide a broader understanding of the proposed solutions' applicability and effectiveness.

A few limitations are evident in Publication 3. A top-down approach for predicting future demand in non-road transport and industry sectors might not capture detailed sector-specific nuances. Moreover, the research does not include renewable energy sources, such as tidal, wave, and offshore wind, nor does it consider advanced technologies like electrofuels. To overcome these limitations, future research could adopt a bottom-up approach to understand the mentioned sectors' specific demands better. It is essential to perform detailed regional simulations that focus on highly renewable energy potential areas and regions with significant future demand, such as large cities, the new capital of Nusantara and industrial zones. Assessing the possible integration of electrofuels within Indonesia’s energy framework could provide critical insights into their practicality and advantages. Furthermore, assessing the socio-economic impacts of renewable energy transitions, such as job creation, community acceptance, and economic resilience, will offer a comprehensive perspective. These research efforts will help develop strategies tailored to regional energy requirements, optimise renewable resource utilisation and support Indonesia's economic and social goals in transitioning to an NZE energy system.

Future research must explore the integration of a just energy transition, building on the comprehensive analysis of RE sources, sector coupling and net-zero pathways presented in this chapter. While it is outside the current research focus, pursuing this area is essential and relevant. It would give a more precise lens for the multi-criteria decision analysis and energy system analysis to approach the just energy transition.

Indonesia is highly dependent on fossil fuels and is among the world's largest coal producers. In 2022, coal constituted approximately 60% of the country’s electricity mix, serving as the primary energy source for power generation [7]. A just energy transition emphasises the equitable distribution of benefits and burdens associated with the shift from fossil fuels to renewable energy, ensuring that all societal groups, particularly marginalised communities, are included in and benefit from the transition [90]. This focus aligns with the participatory multi-criteria analysis by addressing social equity alongside economic and environmental criteria. Moreover, considering a just energy transition in pathways to NZE ensures that the transition is socially sustainable, balancing technological feasibility with the socio-economic needs of the impacted communities. This approach not only supports Indonesia's climate goals but also fosters social resilience and inclusive economic growth [91].

To expand the emphasis on equitable benefits distribution and socio-economic considerations on the just energy transition, future research could explore two promising topics. First, integrated socio-economic models: developing comprehensive models that integrate economic, social and environmental variables to predict the outcomes of various energy transition interventions on job markets and local economies. Such models can provide policymakers with robust tools to balance growth and equity effectively. South Kalimantan, East Kalimantan and South Sumatera provinces would be the focus of research locations. Second, longitudinal employment and economic studies: implementing longitudinal studies to track economic and employment trends over time is essential for assessing energy transitions' sustainability and real-world impacts. These initial ideas will offer deeper insights into policies' long-term impacts and adaptability.

Table 6. 2. Proposed further research areas for advancing Indonesia’s energy transition.

Research area	Topic focus	Spatial focus
Energy planning	Dynamic performance of alternatives; Need for advanced technologies supporting energy transition	Specify more research locations with tailored criteria and sub-criteria, especially in fossil-dependent regions
Energy scenario	Updated baseline and projection data; Applying bottom-up approach in broader energy sectors; Incorporating more advanced technologies	High RE potential, such as solar, hydro and geothermal; High future energy demand
Just energy transition	Socio-economic aspects of fossil phase-out from an energy system analysis perspective	Coal mining regions and fossil-based power plant locations

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