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Research Article

Renewable energy in sustainable cities: Challenges and opportunities by the case study of Nusantara Capital City (IKN)

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Abstract. This study explores strategies for optimizing energy consumption in Indonesia's New Capital City (IKN) to achieve net zero emissions by 2045, focusing on energy efficiency, sustainable mobility, and renewable energy through the Low Emissions Analysis Platform (LEAP) model. Sustainable cars, such as renewable-energy-powered electric and green hydrogen-powered vehicles, can reduce energy consumption by 43% in 2045 and 33% in 2060, respectively, compared to BAU. GHG emissions per capita will drop 70% in 2045 and 63% in 2060. In NZE scenario, IKN can reach 100% green energy by 2045 with a 4.4 GW solar power plant, a 0.92 GWh BESS, and a full load hour capability of 4 hours. By 2045, 1.1 GW of hydropower and 143 MW of wind power are expected to be utilized. In 2060, hydropower will be 2.8 GW, wind power will be 184 MW, and solar power will be 8 GW with 1.6 GWh of BESS. Lack of legislation, technical expertise, high prices, inadequate grid infrastructure, and renewables shortfalls restrict Indonesia's BESS. Solar installation criteria, subsidies, and off-grid project incentives can all help ease BESS use. Forecasts predict 0.53 GW of rooftop solar PV capacity by 2045 and 3.35 GW by 2060. Net metering and solar tariffs boost rooftop solar system profitability. One ton of green hydrogen production requires 55.7 MWh from a solar power plant. Solar power plant capacity will rise to 0.49 GW by 2045, producing 19,359 tons of green hydrogen, and almost quintuple to 89,594 tons by 2060. Hydrogen generation, storage, transit, and distribution require specific infrastructure due to high capital costs and a lack of networks, yet interest in them is growing.

Keywords: Sustainability; BESS; Rooftop PV; Green Hydrogen.

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1. Introduction

Under Law No. 3 of 2022, Indonesia will officially establish the city of Nusantara (IKN) as its national capital in 2024 (GoI, 2022b). IKN envisions a progressive metropolis that reduces emissions while promoting environmentally responsible economic growth, social inclusion, climate resilience, and equity. The IKN Authority (2023) commits to achieving net zero emissions by 2045, surpassing the national goal of 2060 or sooner.

According to Suparman (2023), the government aims to accelerate the nation's economic transition toward more Indonesian-centered development by launching the IKN New Capital. The new capital will be located in East Kalimantan, encompassing the districts of Kutai Kartanegara and North Penajam Paser, with the cities of Samarinda and Balikpapan serving as its main urban centers. IKN covers an area of 256,142 hectares of land and 68,189 hectares of water, including sections of the picturesque Makassar Strait (Raharjo *et al.*, 2022).

The complete construction and occupation of IKN could serve as a model for Indonesia's climate-resilient, sustainable, and low-carbon development. To prevent the climate crisis from worsening, it is essential to transition from a carbon-intensive economy, as seen in Indonesia, to sustainable and renewable development. Once IKN achieves full smart city functionality, it will be a vibrant and desirable place to live (IKN Authority, 2023).

One of the most critical components of a smart city is its energy system, which plays a key role in making urban areas more environmentally friendly (Hoang *et al.*, 2021). To be considered smart, a city must be green, sustainable, and eco-friendly (Toh, 2022). Furthermore, studies have shown that utilizing renewable energy sources significantly reduces pollution, thereby enhancing the overall quality of life on our planet (Hoang *et al.*, 2021). Lowering carbon emissions on a global scale requires the integration of various low-carbon technologies, each tailored to a country's specific needs, energy sector capabilities, and policy and technological objectives (CDP, 2022).

Activities and urban structures that define cities, including transportation, industrial and commercial operations, residential and commercial buildings, and infrastructure, rely on a constant energy supply (Krstić – Furundžić *et al.*, 2020). Urban areas have a substantial demand for electricity. From a global

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perspective, cities consume a significant amount of electrical energy and contribute to the emission of greenhouse gases, particularly carbon dioxide. This leads to substantial environmental pollution and contributes to climate change. Residential and commercial buildings account for significant global electricity usage (Krstić – Furundžić *et al.*, 2020). To tackle climate change and its impact, the European Commission's Clean Energy Package encourages local communities to participate in the energy transition through Energy Communities (ECs) (Losada-Puente *et al.*, 2023). Greece has reduced greenhouse gas emissions by 38% between 1996 and 2020 (Tsepi, E., Sebos, I., & Kyriakopoulos, 2024), thanks to efforts such as the National Renewable Energy Action Plan and participation in the EU emissions trading scheme (I. Sebos *et al.*, 2016).

To address global warming, smart city sustainable development requires carefully planning the future urban energy system. Transitioning to low-carbon energy will bring significant changes to the energy grid. Experts and NGOs are exploring the feasibility of achieving a 100% renewable energy mix (Yao *et al.*, 2022). Experts anticipate that wind and solar power will significantly influence the future energy system. However, incorporating huge-scale variable renewable energy (VRE) into metropolitan power systems presents challenges, including power balancing, VRE power quality, and connections between the central infrastructure and VRE generators (Yao *et al.*, 2022).

Cities around the world are increasingly adopting clean energy policies that include energy equity, smart communities, green buildings, and net-zero regulations. The use of 100% renewable energy is becoming more prevalent, with hundreds of locations worldwide pledging to achieve this goal. Specifically, 180 cities in the US, 100 in the UK, 140 in Germany, and 140 in France have committed to transitioning to renewable energy. Moreover, over 100 communities now derive at least 70% of their energy from renewable sources, reflecting significant progress toward sustainability targets (Kunkel *et al.*, 2022).

The IKN Strategic Plan calls for rooftop solar panels, farms, and power plants to provide 100% of the city's yearly electricity demands (GoI, 2022a). Beginning in 2024 with 50 megawatts (MW), solar energy will fulfill all electricity needs between 2030 and 2045 (IKN Authority, 2023). IKN will connect to the Kalimantan electricity system to accommodate demand and anticipate inconsistent solar power supplies. Kalimantan's electricity system is expected to provide power to IKN under low irradiation conditions. During peak days, excess solar energy can be stored and exported to Kalimantan. Energy storage options, such as batteries and hydrogen, are considered (GoI, 2022a).

Meanwhile, the IKN urban transportation system, based on an innovative public transportation network, promotes fuel-efficient and environmentally friendly vehicles, including those powered by hydrogen and electricity (Kalalinggi *et al.*, 2023; GoI, 2022a). When powered by renewable energy sources, electric mobility in transportation becomes more cost-competitive and reduces air pollution (IRENA, 2016). Presidential Regulation 55/2019 of Indonesia encourages the adoption of electric vehicles (EVs) (GoI, 2019). The EV regulation underlies future derivative legislation. The percentage of electric vehicles is greater than 5% in Norway, Iceland, Sweden, and the Netherlands. In some Chinese and American cities, the EV market share surpasses 20%. Indonesia could achieve this by applying best practices and lessons learned to its unique circumstances (Adiatma & Marciano, 2020).

Hydrogen is a promising technology, although it is still in the early stages of deployment (IRENA, 2016). Hydrogen-powered energy offers many impressive advantages, including wide availability, affordability, the ability to diversify the energy supply, and potential applications in emergency response situations. Hydrogen-related technologies, such as fuel cells and fuel cell vehicles, significantly enhance energy efficiency across various sectors, including transportation, residential, commercial, and industrial. Additionally, hydrogen is an exceptionally attractive sustainable energy source because it can store substantial amounts of energy for long durations (Toh, 2022).

In addition to renewable energy and sustainable transportation, IKN is also developing green industrial areas. The green industry encompasses various sectors that focus on clean technology and low-carbon energy, including solar panel assembly, two-wheel electric vehicle production, and biofuel and synthetic fuel manufacturing. Additionally, the pharmaceutical and chemical industries are involved in producing pharmaceuticals and conducting research and development on chemicals and their derivatives (GoI, 2022a).

This groundbreaking study aims to explore how Indonesia's New Capital City (IKN) can optimize its energy consumption and supply to become a sustainable city, achieving net zero emissions by 2045. To reach this innovative goal, advanced technologies were leveraged to implement a 100% renewable energy-based electricity system, the first of its kind in Indonesia. Starting with 2023 as the baseline, energy consumption was forecasted across various sectors, including the adoption of electric vehicles, green hydrogen for transportation, and induction stoves for residential use. By maximizing the integration of renewable energy sources and striving for a 100% renewable energy mix (GoI, 2022b), the primary energy supply required to transition to low-carbon alternatives was estimated. The study also tracked CO_2 emissions over time. This research used the Low Emissions Analysis Platform (LEAP), which applies IPCC Tier 1 emission factors (Indrawan *et al.*, 2017). It has helped Cambodia, Laos, Myanmar, Nigeria, and Pakistan model energy transitions and construct renewable energy systems that meet their needs (Handayani *et al.*, 2023; Emodi *et al.*, 2017; Mirjat *et al.*, 2018). More than 190 countries and thousands of organizations have implemented LEAP, and over 70 peer-reviewed publications and 85 UNFCCC country reports include it (Handayani *et al.*, 2022).

2. Materials and Methods

2.1 Research Framework

For this research, the LEAP program was used to model IKN's energy sector. To calculate the least-cost optimization, the Next Energy Modeling System for Optimization (NEMO), which is closely linked to LEAP, was also utilized (Heaps, 2021; Charles Heaps, Eric Kemp-Benedict, 2021; Ordonez *et al.*, 2022; Yudiartono *et al.*, 2023).

The main advantage of using LEAP is that it only requires basic knowledge and accurate statistical information for the base year (Connolly *et al.*, 2010). LEAP helps with regional trading and analysis for energy system scenarios (Santosa *et al.*, 2023), like those for IKN. However, users often struggle to integrate inaccurate information when high-quality data is unavailable, which makes the modeling process more complex. This study applied a multi-scenario methodology to address the

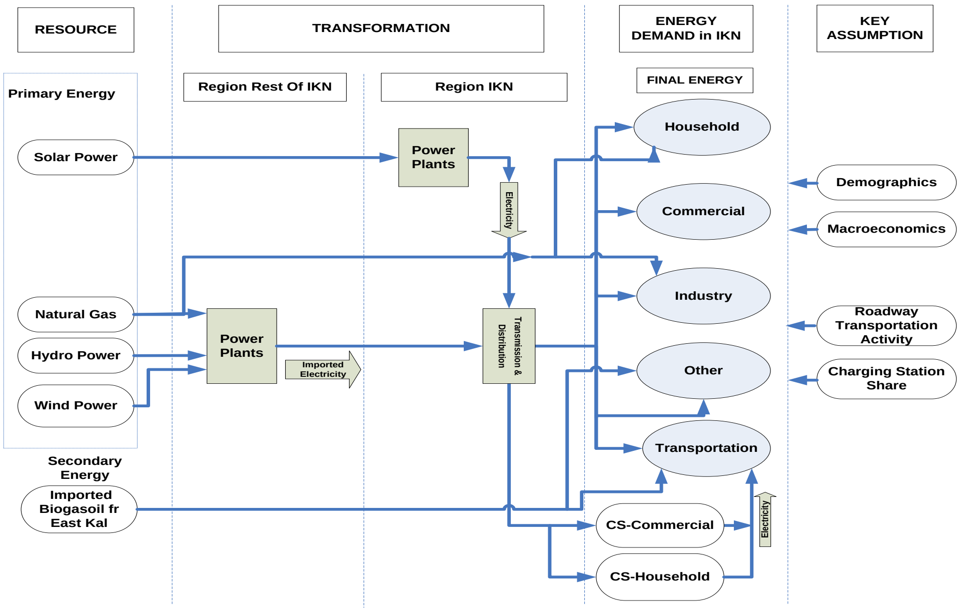

Fig. 1 Framework of IKN Energy System with LEAP Model

uncertainties in LEAP modeling caused by insufficient data. To validate the limited local data, secondary sources, such as data from organizations like the IEA and the World Bank, are incorporated. Historical data is used for extrapolation and calibrated based on previous periods to improve accuracy and align the model with local contexts. This calibration to real conditions helps minimize the risk of overestimation or underestimation.

Meanwhile, several researchers have added technology to LEAP to increase estimation accuracy. Sadri *et al.* (2014) predicted light-duty vehicle activity and energy intensities for the LEAP model using GM (Grey Model) and ANN (Artificial Neural Network) approaches. Kale and Pohekar (2014) used LEAP to forecast electricity supply and demand scenarios and ARIMA (Auto-Regressive Integrated Moving Average) to estimate industry economic growth. Chen *et al.* (2019) proposed a hybrid LEAP model to enhance energy demand forecasting in Hunan Province, China, and assessed forecast uncertainty using the Monte Carlo method.

The LEAP data entry set comprises several components: essential assumptions, demand, transformation, and resources (Fig. 1). The module's main considerations include Gross Domestic Product (GDP) per capita, total population, population growth, and roadway transportation activities. To accurately predict energy demand, the demand module is divided into five sectors: household, industrial, transportation, commercial, and others. These sectors are influenced by demographics and socioeconomic variables (Heaps, 2021; Mirjat *et al.*, 2018; Hong *et al.*, 2019). The industrial sector is divided into three sub-sectors: the chemicals and pharmacy industry, the clean technology industry, and others. The transportation sector is divided into two subsectors: road and rail. The household sector primarily resides in urban regions, while the commercial sector exclusively concentrates on the energy needs of electrical equipment. The other sector includes two sub-sectors: sustainable agriculture and construction.

The transformation module focuses on modeling the energy supply and conversion sectors, specifically power generation. Each module includes one or more processes, each using a different technology, such as a specific power plant, to produce one or more fuels. Processes comprise power plants with the same output fuel (Heaps, 2021). As mentioned earlier, we can use LEAP, supported by optimization tools called the Next Energy Modeling System for Optimization (NEMO), to perform least-cost optimization in the power sector. The goal of least-cost optimization is to minimize the present value total cost of a power generation system to meet a given electricity demand (Santosa *et al.*, 2023; Heaps, 2021; Charles Heaps, Eric Kemp-Benedict, 2021). Moreover, we divide the transformation module into two regions: the rest of the IKN region, encompassing South Kalimantan, East Kalimantan, and North Kalimantan, and the IKN region, featuring a solar power plant and energy storage. In the rest of the IKN region, there are gas-fired power plants, hydropower plants, and wind power plants.

The Resources section is the final component of LEAP. The Tree Resources section automatically displays the corresponding branches when the tree demands or transformations reference a specific type of energy (Heaps, 2021). Resources are classified into two distinct types: natural gas and energy from renewable sources. The study's assessment primarily focuses on hydro, solar, and wind energy as examples of green energy sources (Hong *et al.*, 2019).

In terms of the role of charging station (CS) infrastructure in pushing up electric vehicle (EV) penetration, it is assumed that there are two types of CS: CS commercial as public charging infrastructure and CS household for EV charging at home. The assumed share of EVs using CS is outlined in the key assumptions.

2.2 Scenario

The potential effects of a scenario, a collection of assumptions used to execute the model, on the overall energy system are assessed. This paper contrasted the "business as usual" (BAU) scenario with the "net zero emissions" (NZE) scenario. For both scenarios, GDP per capita and IKN population projections were assumed to be the same. The assumption of electric vehicle projection was also considered the same.

The BAU scenario outlines the low adoption rate of rooftop PV. However, it does not account for the adoption of hydrogen-powered vehicles and hydrogen for industry in the target sectors by the specified year. Gas-fired power plants would

Table 1
Assumed GRDP per capita and proportion of the IKN population in 2024

Proportion of the IKN Population		Unit	GRDP per capita at 2010 Constant Market Prices	
			2022	2024
Kutai Kartanegara Regency	8,450	people	$ 2,647.15	$ 2,588.21
Penajam Paser Utara Regency	37,000	people	$ 2,697.65	$ 2,719.78
Civil Servant	16,500	people	$ 1,257.92	$ 1,335.18
Total	61,950	people	$ 6,602.72	$ 6,643.17

Sources : (GoI, 2022a);(Badan Pusat Statistik Kabupaten Kutai Kartanegara, 2023);(Badan Pusat Statistik Kabupaten Penajam Paser Utara, 2023);
(Badan Pusat Statistik Kabupaten Penajam Paser Utara, 2022);
(Badan Pusat Statistik Indonesia, 2023b)

Table 2
Assumptions on GRDP per capita and population 2024–2060

Macro Assumptions		Years of study			
		2024	2025	2045	2060
Population	Thousand people	61.95	395	2,112	4,126.54
GRDP/ Capita	Thousand US$ (constant 2010)	6.64	6.98	18.51	38.48
GRDP/ Capita	Millions Rupiahs	59.73	62.72	166.40	345.94
GRDP	Trillions Rupiahs	3.70	24.77	351.44	1,427.53

remain under consideration until 2060 as a means of supplying electricity to the IKN.

The NZE scenario involves a moderate adoption rate of hydrogen-powered vehicles and rooftop PV in the target sectors by the year it is aimed at. However, gas power plants are only being considered until 2029. From 2030 to 2060, the IKN electricity system is expected to rely completely on renewable energy, which refers to hydropower, solar, and wind power plants.

2.3 Macro Assumptions

Forecasting energy consumption for a new capital city like IKN can be challenging when no historical data is available. However, various methods exist to develop estimates, such as identifying energy drivers by determining the main factors affecting energy consumption in the surrounding areas (Penajam Paser Utara and Kutai Kartanegara districts). These factors may include population growth, economic activity, industrial production, transportation patterns, and the energy sector's adoption rate of low-carbon technologies. Tables 1 and 2 describe the assumptions for GRDP per capita and population in the IKN area, respectively. Table 3 outlines the targets for achieving low-carbon technology.

The Nusantara capital city, or IKN, will initially be populated by residents from Kutai Kartanegara (Kukar) and Penajam Paser Utara (PPU) regencies, as well as civil servants. The Gross Regional Domestic Product (GRDP) of IKN was estimated using the GRDP per capita values from these regions, while the national GDP per capita was used to represent civil servants. For the 2024 projections, the GRDP per capita growth for each region was calculated using compounding, considering the time value of money. These values were then multiplied by the expected population in IKN, with the total GRDP estimated as the sum of these calculations. Table 1 shows the estimated GRDP per capita of IKN for 2024, which is $6,643.17.

The Indonesian provinces that have experienced the highest growth in GDP per capita, ranging from 4.27% to 9.36%, over the past 13 years are DKI Jakarta, South Sulawesi, Central Sulawesi, and North Maluku (Badan Pusat Statistik Indonesia, 2023a). These provinces' GDP per capita growth was a benchmark for predicting IKN GDP per capita growth. Apart from that, according to the principles and main performance indicators of IKN (GoI, 2022a), IKN's GRDP per capita of IKN is classified as a high-income country. Therefore, GRDP's per capita growth over the next 36 years was assumed to be 5%.

In 2060, GDP per capita is estimated to reach US$ 38,480, or Rp. 345.94 million. Taking into account the projected IKN

Table 3
Targets set for low-carbon technology increase in the energy sector for BAU & NZE scenarios.

Sectors	Technology	Level of low-carbon technology adoption	
		BAU	NZE
Household Sector	Rooftop PV	Low	Moderate
	Electric Stoves	High	High
Industrial Sector	Rooftop PV	Low	Moderate
	Green Hydrogen	Low	High
Transportation Sector	Electric Cars	High	High
	Green Hydrogen Cars	Low	Moderate
	Biofuel Cars	High	Low
Commercial Sector	Rooftop PV	Low	Moderate

population in 2060, the IKN GRDP is expected to reach Rp. 1,427.53 trillion.

Table 3 displays the target for low-carbon technology adoption in the energy sector. The target is separated into three categories based on the level of adoption (GoI, 2022a; Dewi *et al.*, 2023; Ashour *et al.*, 2021):

1. Low adoption rate: 0%-29%
2. Moderate adoption rate: 30%-69%
3. High adoption rate: 70%-100%

In the BAU scenario, the utilization of rooftop PV technology in households, industries, and commercial sectors is low. On the other hand, in the NZE scenario, rooftop PV technology is moderately adopted. Electric vehicles have been widely adopted for sedans, motorbikes, and buses in the transportation sector. However, their adoption of trucks is only moderate. Additionally, as per the NZE scenario, the adoption of hydrogen vehicle technology in sedans and trucks is moderate, while it is low for buses.

3. Empirical Results and Discussions

3.1 Final Energy Demand Projection

The base year for this study is 2023, which is considered the post-pandemic year. During this time, the pandemic did not affect the supply or use of new IKN energy, but global energy demand shifted due to disruptions in work and school. Telecommuting and online learning increased, leading to reduced traffic and greenhouse gas emissions (Papadogiannaki *et al.*, 2023). In April 2020, Le Quéré *et al.* (2020) reported a 17% drop in global CO_2 emissions from 2019, while Liu *et al.* (2020) noted a 9% decline in the first half of 2020. Meanwhile, significant reductions in air pollutant emissions in Athens due to decreased air, road, and marine traffic ranged from 20 to 90% (A. G. Progiou *et al.*, 2022). These reductions highlight the potential for shaping a more sustainable energy policy (Yassine & Sebos, 2024). Furthermore, transitions to sustainable energy consumption and demand reduction can be achieved by improving energy efficiency, utilizing the most energy-efficient appliances and equipment, and enabling end-use electrification (GoI, 2023; United Nations, 2023). According to GoI (2023), downstream energy management is defined as energy supply and consumption in transportation, industry, residences, and buildings. Downstream management implements and advances more efficient and environmentally friendly energy technologies to improve energy efficiency. This study applies the principle of sustainable energy consumption to the household sector (appliances and lighting), the industrial sector (lighting, air conditioning, refrigeration technology, and motors), and the transportation sector (electric vehicles and hydrogen vehicles).

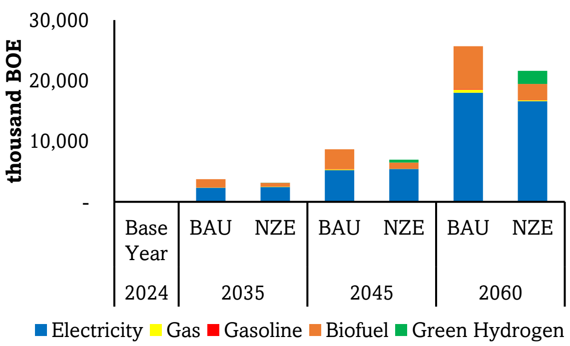

Fig. 2 Projection of final energy demand by type

Furthermore, the study's findings show that the estimated total energy demand in 2024 in the new capital, Nusantara (IKN), is around 99 thousand BOE, 55% electricity, 44% biofuel, and the remainder gas and gasoline. Over 36 years, energy demand would grow by 16.7% in the BAU scenario and 16.1% in the NZE scenario. To establish a society devoid of carbon emissions, it is imperative to improve energy consumption efficiency by implementing energy-efficient devices (Toh, 2022) such as electric stoves, which have a high adoption rate in the residential sector. Similarly, increasing the adoption of electric-powered vehicles in the transportation sector is important. Low- and moderate-adoption hydrogen-powered cars can also significantly contribute to achieving a carbon-free civilization. In 2045, total energy demand is projected to be 8,676 thousand BOE under the BAU scenario, compared to 6,948 thousand BOE under the NZE scenario—a decrease of 1,728 thousand BOE, or 20%. By 2060, the NZE scenario predicts a further decline in total energy demand, reaching 16% below the BAU projection because of the adoption of energy-efficient appliances. Hydrogen is expected to meet 7% of energy needs in 2045 and 10% in 2060, with the remaining energy supplied by electricity, biofuels, and a small portion of gas.

On a mass basis, hydrogen has a higher energy density than diesel, roughly 2.7 times greater (Zheng *et al.*, 2024), so hydrogen fuel cell trucks can carry fewer batteries, enabling them to travel longer distances and cope with heavier payloads (Han *et al.*, 2023; Willmer, 2022). Moreover, estimates suggest that the energy demand for hydrogen trucks would reach approximately 379 thousand BOE by 2045 and 1,780 thousand BOE by 2060, significantly surpassing that of hydrogen cars and buses, which typically range from 0.7 thousand BOE to 140 thousand BOE. Therefore, it can be stated that hydrogen-powered vehicles have larger driving ranges than battery-electric cars, making them ideal for long-distance travel and heavy-duty trucks. In 2045 and 2060, the projected energy needs for hydrogen-fueled trucks would be around 20% and 40% of total road transportation energy needs.

From the end user's perspective, it is predicted that in 2045 and 2060, the industrial and transportation sectors will dominate energy use in IKN, accounting for a share in the range of 29% to 35%. Significant strides towards a more sustainable future can be made by adopting eco-friendly and energy-saving technology. In the transportation and industrial sectors, for instance, the NZE scenario promises to make energy demand 43% and 7% more efficient by 2045, respectively, compared to the BAU scenario. Moreover, by 2060, energy demand in these sectors is projected to be 33% and 13% more efficient than in the BAU scenario, thanks to the continued implementation of eco-friendly measures.

3.2 Forecasting the demand for electrical energy by sector

The study projects that IKN's electricity demand would rise by 17% annually until 2060. Under the BAU scenario, this development would increase demand from 87 GWh (1,406 KWh/capita) in 2024 to 8,448 GWh (4000 KWh/capita) in 2045, and then to 29,090 GWh (7,049 KWh/capita) in 2060. According to the NZE scenario, IKN's total energy demand would decrease by 8%, reaching 26,835 GWh (6,503 KWh/capita) in 2060. The increased use of efficient electrical equipment in the household and industrial sectors is responsible for this decrease.

In 2024, the household sector will require the most electricity, accounting for around 65% of the total demand. However, this proportion would decrease over time due to the industrial, commercial, and transportation sectors taking on a larger share of the demand. The industrial sector's electricity

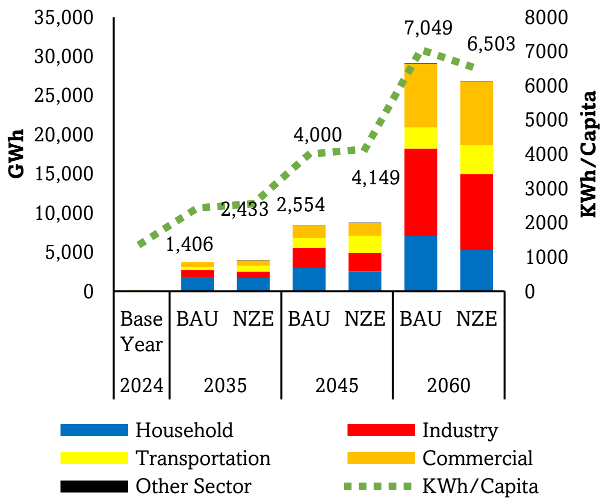

Fig. 3 Projection of electrical energy demand by sector

demand is expected to grow at a rate of approximately 15% per year, significantly increasing its share from 14% at the start of the study to 38% in the BAU scenario and 36% in the NZE scenario by 2060. The industries contributing to this growth include chemical and pharmaceutical industries, industrial clean technology, and low-carbon energy industries (GoI, 2022a). Both scenarios predict an approximate 18.7% annual growth in commercial electricity demand. Its share would grow from around 18% at the start of the study to 30% by 2060.

A swift increase in the transportation sector's electricity requirements is anticipated due to the growing demand for electric vehicles, including mass transportation. Under the BAU scenario, the growth rate in this sector is estimated to reach 15.8% per year, while the NZE scenario projects it to reach 16.9% per year. This study focuses on four types of road transportation: electric cars, electric motorcycles, electric trucks, and electric buses. Except for electric trucks, which aim for a moderate adoption rate, the objective is to achieve a high technology penetration rate for all vehicle types (GoI, 2022a). Finally, the demand for electricity in other sectors, such as sustainable agriculture, is predicted to be relatively small, accounting for no more than 0.2% of total demand. Sustainable agriculture development is expected to occur in IKN on up to 25 thousand hectares of land.

Two types of electric vehicle (EV) charging stations are assumed at IKN: home charging stations (H-CS) and commercial charging stations (C-CS). Electric car and motorcycle owners use H-CS to charge their vehicles at home, typically outside of peak load times. On the other hand, C-CS are public EV chargers commonly found in hotels, restaurants, apartments, workplaces, and malls. Electric cars, motorcycles, buses, and trucks use these stations (Edi Hilmawan *et al.*, 2021). In 2024, the two types of charging stations are predicted to require 16.87 GWh of electrical power, with C-CS accounting for 56% and H-CS for the remainder. In 2045 and 2060, the electricity demand for charging stations in the NZE scenario is expected to reach 2,658 GWh and 4,577 GWh, respectively, 81% and 39% higher than in the BAU scenario. A rise in hydrogen-fueled vehicles is anticipated in 2060, which will reduce the electricity required for charging stations.

3.3 Projection of power generation capacity within and outside IKN areas

In the context of urban development, the energy transition is profoundly significant. A wise future society necessitates a renewable energy system that enables a city to emit virtually zero greenhouse gases (Yuan *et al.*, 2018). Renewable energy sources, like solar and wind power, have gained significant popularity because of their positive impact on the environment and economy. These sources are considered a crucial solution for meeting our energy needs by reducing greenhouse gas emissions, mitigating climate variability, and promoting energy independence. However, when connected to the grid, the sporadic nature of these sources presents a significant issue. To address this challenge, we utilize a battery storage power station to effectively manage the fluctuating solar and wind energy resources (Nkounga *et al.*, 2022).

Solar power plants equipped with battery energy storage systems (BESS) are the only sources of electricity in the IKN area. Outside the IKN area are gas-fired, hydropower, and wind power plants. Gas-fired power plants play a significant role in the BAU scenario but not in the NZE scenario. In the NZE scenario, the power plants that play a role are solar power plants with BESS, hydropower plants, and wind power plants (PT.PLN (Persero), 2021; IKN Authority, 2023).

North Kalimantan has the largest hydropower potential on Kalimantan Island, with a capacity of 22.107 GW, according to the draft National Electricity Master Plan (RUKN) 2023–2060 (Ministry of Energy and Mineral Resources, 2023). However, the 2021–2030 Business Plan for Electricity Provision specifies that North Kalimantan will develop hydropower plants with a total capacity of 8.977 GW (PT.PLN (Persero), 2021). South Kalimantan, on the other hand, will only develop 0.07 GW of wind power plants (PT.PLN (Persero), 2021), despite its potential capacity reaching 8.455 GW (Ministry of Energy and Mineral Resources, 2023). Solar power has the largest renewable energy potential in Kalimantan, with 432 GW, of which 101 GW is located in East Kalimantan (Ministry of Energy and Mineral Resources, 2023).

In the future energy grid, power derived from wind and solar sources is expected to play a pivotal role, facilitating the achievement of a 100% renewable energy mix and enabling a complete transition to low-carbon energy (Yao *et al.*, 2022). The NZE scenario forecasts that IKN will reach 100% green energy

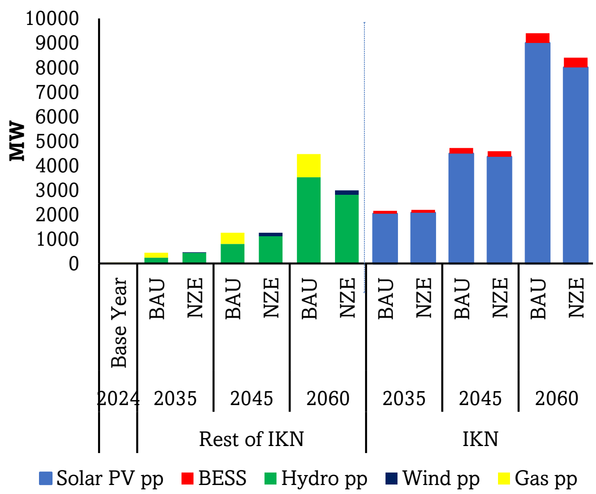

Fig. 4 Types of power plant projections within and outside of IKN areas.

by 2045, featuring a 4.4 GW solar power plant complemented by a BESS with a capacity of 0.92 GWh and a four-hour full load capability. That same year, the energy mix will also include 1.1 GW from hydropower plants and 0.143 GW from wind power plants. By 2060, solar power capacity is projected to increase to 8 GW, with a corresponding BESS capacity of 1.6 GWh. Additionally, hydropower capacity is expected to reach 2.8 GW, while wind power will contribute 0.184 GW.. Rooftop solar photovoltaic (PV) systems play a vital role in supplying power to residential, industrial, and commercial sectors. The total capacity of rooftop solar PV is projected to reach 0.53 GW by 2045 and is expected to increase more than sixfold, rising to 3.35 GW by 2060. Gas-fired power plants play a vital role in the BAU scenario, continuing to operate until 2030 in the NZE scenario and still providing energy generation outside the IKN area..

3.4 Electricity Demand and Supply in the IKN Region

To create a reliable, sustainable, and resilient energy infrastructure for its residents and businesses, the new capital city (IKN) region can implement several key strategies. These strategies include assessing projected electricity demand, adopting energy efficiency measures across all sectors (GoI, 2023; USAID, 2017), incorporating a variety of renewable energy sources such as solar, wind, and hydro, and deploying energy storage systems to address the intermittency issues associated with solar and wind power (Yao *et al.*, 2022). By following these measures, the IKN region can effectively manage electricity demand and supply.

The study projects an 8% reduction in electricity demand in the NZE scenario compared to the BAU scenario. The end-use sector's adoption of efficient and environmentally friendly electrical equipment is responsible for this reduction. To meet the projected demand, plans include the development of solar power plants with battery storage systems, rooftop solar photovoltaic (PV) installations, and electricity imports from outside the IKN region (GoI, 2022b).

In both scenarios, electricity production in the IKN area will primarily depend on solar power plants and BESS. The BAU scenario is projected to generate 5.38 thousand GWh of electricity by 2045, increasing to 15.43 thousand GWh by 2060. In contrast, the NZE scenario forecasts production levels of 6.2 thousand GWh in 2045 and 14.09 thousand GWh by 2060. Additionally, rooftop photovoltaic (PV) systems are expected to contribute 0.49 thousand GWh and 2.86 thousand GWh in the BAU scenario, while in the NZE scenario, contributions are projected to be 1.16 thousand GWh and 7.33 thousand GWh for the same years. The adoption of rooftop PV technology varies among households, industries, and commercial sectors: in the BAU scenario, acceptance remains low, whereas in the NZE scenario, it reaches moderate levels across all sectors.

The BAU scenario anticipates that the IKN region will import 3.64 and 13.62 thousand GWh of electricity in 2045 and 2060, respectively, while the NZE scenario predicts 2.57 and 7.8 thousand GWh. Electricity imports will be reduced by approximately 43% in the NZE scenario, as the electricity generated from rooftop PV in the IKN region will more than double. The BAU scenario relies on electricity imports from hydropower and gas plants, whereas the NZE scenario will rely on imports from hydropower and wind power plants.

3.5 Green Hydrogen Production

Green hydrogen generation has been rising in recent years, especially in nations like Indonesia, which has plenty of renewable energy sources. Renewable energy sources such as solar, wind, or hydropower use electricity to break water molecules into hydrogen and oxygen, resulting in the production of green hydrogen (Hassan, Sameen, *et al.*, 2023; Hassan, Abbas, *et al.*, 2023). Green hydrogen production is environmentally friendly, unlike the production of grey and blue

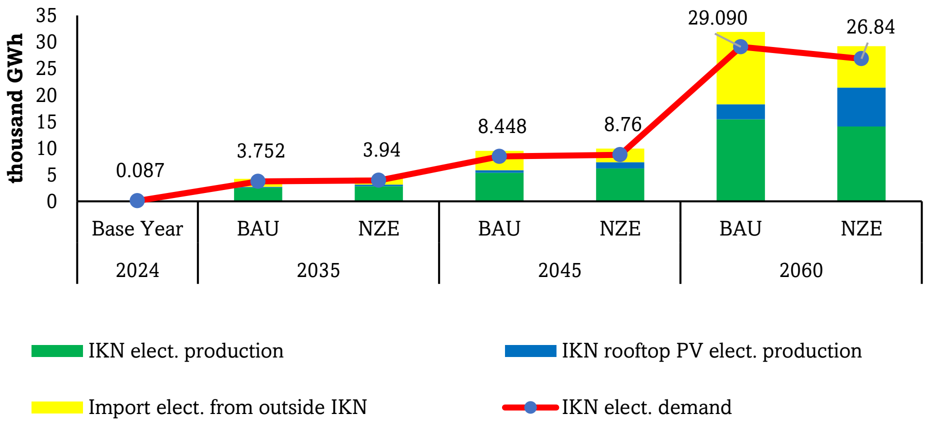

Fig. 5 Projection of Electricity Demand and Supply in the IKN Region for the BAU and NZE Scenario

Table 4
Green hydrogen production projections

Years	Solar power plants to produce clean and sustainable green hydrogen		
	Solar Power Capacity	Hydrogen Production	Electricity Production
	GW	Tons	GWh
2035	0.0325	1,278.74	71.2
2045	0.4925	19,359.62	1,078.60
2060	2.2793	89,594.05	4,991.70

hydrogen, which emits carbon dioxide. The steam methane reforming process generates grey hydrogen by reacting natural gas with steam to produce hydrogen and carbon dioxide. Conversely, the blue hydrogen process employs carbon capture and storage (CCS) technology to absorb the carbon dioxide emissions generated during hydrogen generation (Hassan, Sameen, *et al.*, 2023).

Producing green hydrogen transforms a significant portion, around 70–80%, of the electrical energy into chemical energy, specifically hydrogen gas. The energy needed to create 1 kilogram of hydrogen is around 50 to 55 kilowatt-hours (kWh). Over the past decade, the production cost of green hydrogen has decreased by 60%, typically ranging from €3.6 to €5.3/kg (Kurrer, 2020).

This study determines that the production of one ton of green hydrogen requires a solar power plant to generate 55.7 MWh of electrical energy. The demand for solar power generation capacity is projected to reach 0.49 GW by 2045, which will enable the production of 1,079 GWh of electricity. Furthermore, projections indicate that the need for solar power generation capacity will increase to 2.28 GW by 2060, resulting in the production of 4,992 GWh of electricity. Additionally, projections indicate that green hydrogen production will increase from 19,359 tons in 2045 to 89,594 tons by 2060.

3.6 Greenhouse Gas (GHG) Emissions in the IKN Area

The LEAP software uses emission estimates consistent with the IPCC's 2006 Guidelines for National Greenhouse Gas (GHG) Inventories. It accomplishes this by computing energy consumption using emission factors and contaminants (Malka *et al.*, 2023). Using the same methodology, Yassine *et al.* (2024) conducted a study to quantify GHG emissions in Oman's fishing industry, highlighting the significance of applying mitigation strategies to lower carbon intensity. These emissions are computed using the amount and type of fuel burned and its carbon content. In contrast, MITICA improves model accuracy using IPCC nomenclature and UNFCCC inventories. It investigates greenhouse gas emissions and the absorption of policy activities, focusing on emission sources and standardizing methodologies for more accurate country-level evaluations (Martín-Ortega *et al.*, 2024). Then, Akkermans *et al.* (2023) present a new five-step backcasting method for investigating ways to reach carbon neutrality in Tajikistan by 2050. It provides an initial assessment and foundation for long-term low greenhouse gas emission strategies (LT-LEDS) while being consistent with the country's nationally determined contributions (NDC) and greenhouse gas inventory. This can help inform climate policies and activities.

The relationship between climate change and air pollution is profound, and efforts to reduce greenhouse gases and air pollutants can yield substantial combined benefits (Pinho-Gomes *et al.*, 2023). IKN, a newly developed city, aims to rely entirely on renewable energy sources. While this study focuses on greenhouse gases, it does not specifically address air pollution. Road traffic and the household sector in Europe have primarily contributed to air quality limit violations (A. Progiou *et al.*, 2023). Moreover, urban areas are crucial in creating and enforcing climate policy. To achieve climate neutrality, a city needs to take steps to reduce greenhouse gas emissions from all sectors and sources within its borders. There are various technological options available for significantly reducing greenhouse gas emissions. One approach is transitioning from traditional technology to alternatives that do not produce carbon dioxide or are carbon neutral, such as electric vehicles, hydrogen, and fuel cells. However, ensuring that the energy used to generate electricity or other fuels has a minimal carbon footprint is important (Christidis *et al.*, 2024).

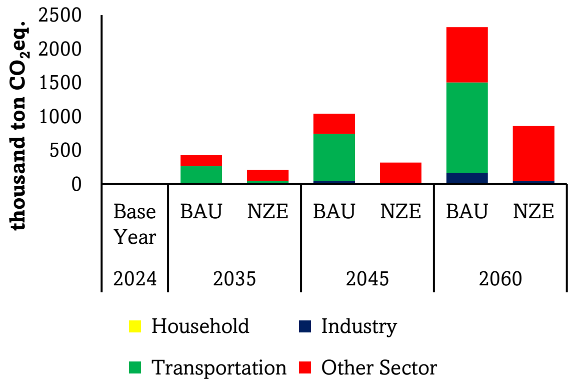

Fig. 6 Projection of GHG Emissions Per Sector in the IKN Region

The NZE scenario forecasts that total greenhouse gas (GHG) emissions will reach 317 thousand tons of CO_2eq by 2045 and 858 thousand tons of CO_2eq by 2060. This indicates a substantial reduction of 70% and 63%, respectively, compared to the BAU scenario. The adoption of energy-efficient technologies, the use of renewable energy sources, and the promotion of sustainable transportation primarily drive the decrease. In addition, for the transportation sector, greenhouse gas emissions are expected to decrease by 99% in 2045 and by 100% in 2060. The increased adoption of hydrogen and electric vehicles is responsible for this dramatic decline.

The BAU scenario anticipates that the industrial sector will produce 36 thousand tons of CO_2eq in 2045 and 156 thousand tons of CO_2eq in 2060, accounting for 4% to 7% of the total GHG emissions expected in those years. In contrast, the NZE scenario forecasts a significant reduction in industrial emissions, with nearly an 80% decrease compared to the BAU scenario. This reduction is attributed to the adoption of more efficient and environmentally friendly industrial equipment. However, both scenarios predict that GHG emissions in other sectors, such as construction and sustainable agriculture, will remain constant, at 299 thousand tons of CO_2eq in 2045 and 817 thousand tons of CO_2eq in 2060. This stability is largely due to the continued reliance on biogasoil (B30) fuel in the construction sector rather than other energy sources.

3.7 GHG emissions per Gross Regional Domestic Product (GRDP) and GHG emissions per capita

The BAU scenario projects a continuous decrease in GHG emissions per gross regional domestic product (GRDP) after 2045. The estimated amount of GHG emissions per GRDP will drop by 45%, from 2.96 tons of CO_2 eq in 2045 to 1.63 tons of CO_2 eq in 2060. The NZE scenario predicts a significant 33% decrease in GHG emissions per GRDP from 2045 to 2060, following the same trend.

The intensity of greenhouse gas (GHG) emissions per capita tends to increase in IKN as it is still developing into a capital city equivalent to a developed country. This development requires much energy for economic activities. As people's income increases, commercial energy consumption grows, leading to a further increase in GHG emissions.

Compared to the BAU scenario, the NZE scenario predicts a 70% reduction in greenhouse gas emissions per capita in 2045 and a 63% decrease in 2060. The increasing popularity of electric vehicles with renewable electricity and green hydrogen-

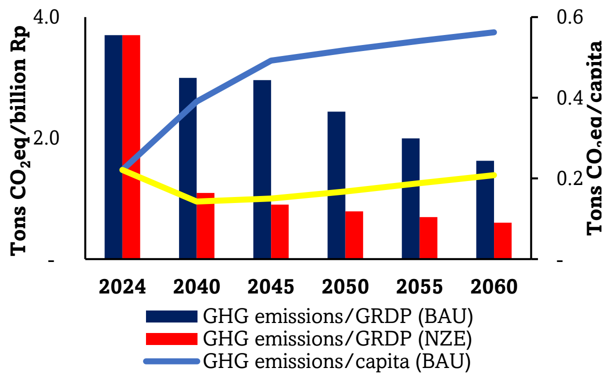

Fig. 7 GHG emissions per GRDP and GHG emissions per capita

fueled vehicles, which emit fewer greenhouse gases than conventional vehicles, is responsible for this reduction. Additionally, implementing electricity-based public transportation is considered a strategy to mitigate climate change. This method is crucial for attaining many sustainable development objectives, such as SDGs-13 for mitigating climate change, SDGs-8 for fostering economic expansion, SDGs-7 for ensuring accessible and clean energy, and SDGs-3 for promoting excellent health and well-being (Montoya-Torres *et al.*, 2023; Bhat & Farzaneh, 2022).

4. Policy Implications

Indonesia's new capital, Nusantara, aims to achieve net zero emissions by 2045, aligning with the country's 2060 climate goals. The Nusantara Capital Authority collaborates with stakeholders to create a plan that tackles local challenges and reduces emissions, supporting Indonesia's climate commitments (IKN Authority, 2023; GoI, 2022b). Effective stakeholder engagement is essential for fostering innovation, trust, and collaboration, though it can be difficult to assess across sectors (Ioanna *et al.*, 2022). Understanding stakeholder perceptions and addressing knowledge gaps is key to developing effective climate policies, as a study from Greece highlights the need for improved communication among scientists, stakeholders, and policymakers (Ioannis Sebos *et al.*, 2023).

The research focuses on optimizing energy needs and supply in Nusantara, a city committed to sustainability and environmental goals. To achieve net zero emissions, the city plans to electrify transportation, introduce hydrogen-powered vehicles, boost energy efficiency, and generate 100% renewable electricity (GoI, 2022b). These efforts will lay the foundation for reducing long-term energy consumption and production of carbon emissions.

The IKN Master Plan (GoI, 2022a) envisions that IKN will rely exclusively on renewable energy by 2045. To ensure reliability and energy security, IKN must also work toward establishing a diverse mix of renewable energy sources. Potential options for renewable power plants include photovoltaic power stations, wind, and hydropower plants.

By 2040, experts anticipate that solar power will contribute significantly to increased generating capacity and enhanced energy security. Factors such as decreasing costs, improved efficiency, and greater installation flexibility are driving this shift (Namin *et al.*, 2023; IEA, 2017). Consequently, substantial growth in the capacity of solar PV power plants is expected. However, the fluctuating nature of solar power can lead to grid instability. To address this , a rapid-response energy storage system is required to create a buffer. Suri *et al.* (2023) suggest that implementing a battery-powered energy storage system is generally effective in achieving this goal.

Battery storage devices have become more popular in recent years. The energy storage market share for lithium-ion batteries (LiBs) is the second-highest globally. Between 2010 and 2016, the price of LiB packs dropped by 73%. Experts expect a 93% drop by 2030, primarily due to the increasing sales of electric cars (Yao *et al.*, 2022; Mirzaei Omrani & Jannesari, 2019). Experts predict battery storage solutions will become more affordable in 5 to 6 years (Yao *et al.*, 2022; Martinez-Bolanos *et al.*, 2020).

Problems plaguing Indonesia's battery energy storage system (BESS) industry include a lack of regulation, insufficient technical knowledge, high prices, a shaky grid infrastructure, a small percentage of renewable power, and cheap fossil fuels. Policy recommendations to hasten its implementation include BESS subsidies, solar energy installation mandates, off-grid project incentives (such as solar plus BESS in FiT schemes and RPS), and the establishment of a value chain for BESS in Indonesia (Yoo & Ha, 2024).

Setting up solar PV panels on roofs and making electricity is important for saving energy and protecting the environment (Ashour *et al.*, 2021). Rooftop PV systems can significantly contribute to energy production without greenhouse gas emissions. Small PV systems on roofs hold significant potential, prompting further research on their quality and performance. By the end of 2018, Germany had installed more than 1.5 million rooftop systems (te Heesen *et al.*, 2019). A group of researchers also looked into whether it would be possible to put solar PV modules on the roofs of Saudi Arabian university buildings. They found that installations on roofs could provide about 30% of the power homes need. However, policy changes and increased awareness of the issues are necessary to achieve this (Ashour *et al.*, 2021).

The survey results show that government policies play a significant role in promoting the growth of rooftop solar panels. Two key measures that enhance the adoption of solar rooftops and provide substantial financial benefits are the establishment of feed-in tariffs and net metering schemes. The net metering scheme enables solar owners to sell any excess electricity generated by their rooftop solar systems back to the grid (Ashour *et al.*, 2021).

The Ministry of Energy and Mineral Resources (MEMR) in Indonesia has just implemented MEMR Regulation No. 2/2024, which abolishes the practice of net metering for rooftop solar installations (GoI, 2024). The absence of net metering increases the cost of investing in rooftop solar PV. IESR expresses disappointment that this regulation favors PLN's interests, potentially impeding consumer participation in the government's efforts to accelerate Indonesia's energy transition (IESR, 2024).

In light of the challenges associated with transitioning to a future with renewable energy sources, green hydrogen, an emerging technology, has gained increasing attention in the past few years (Hassan *et al.*, 2024; Hassan, Abdulateef, *et al.*, 2023). By decarbonizing several sectors, such as transportation, manufacturing, and power generation, green hydrogen offers a significant chance to reduce carbon emissions and fight climate change (Hassan *et al.*, 2024).

The significant capital investment required and the absence of dedicated networks for green hydrogen necessitate the development of a specialized infrastructure for its production, storage, transportation, and distribution. Because green hydrogen has a lower energy density per volume than traditional fuels, its long-range transportation is more complex and less cost-effective (Hassan *et al.*, 2024).

To fully utilize green hydrogen as a critical component of sustainable energy, it is essential to overcome existing challenges and accelerate the adoption of this technology. This can be achieved by allocating funds for research and development, expanding infrastructure, strengthening regulatory frameworks, fostering government-business collaborations, enhancing international cooperation, developing the workforce, and increasing public awareness (Hassan *et al.*, 2024).

5. Conclusion

East Kalimantan is in the process of constructing IKN, a sustainable metropolis for future generations. The community prioritizes energy-efficient technologies, renewable energy, and sustainable transportation for environmental and economic sustainability. By 2045 and 2060, energy-efficient technologies are projected to reduce energy consumption in the household sector by 15% and 25%, respectively, and in the industrial sector by 7 and 13%. Meanwhile, electric vehicles and green hydrogen-powered vehicles are expected to decrease energy use by 43% and 33%, respectively.

To achieve 100% renewable energy-based electricity in the NZE scenario, IKN must embrace a range of renewable energy technologies. This includes implementing solar power within IKN and harnessing wind and hydropower resources in surrounding areas. By 2045 and 2060, rooftop and ground-mounted solar PV are expected to generate 7.36 GWh and 21.42 GWh of electricity, reflecting increases of 25% and 17%, respectively, compared to the BAU scenario. However, the NZE scenario predicts a decline in Wind and hydropower production outside IKN, primarily due to the moderate adoption of rooftop solar PV. To enhance the effectiveness of solar rooftops, implementing feed-in tariffs and net-metering schemes is essential. Additionally, to manage fluctuating solar and wind energy supplies, Indonesia will implement a battery energy storage system (BESS) with a capacity of 919 MWh in 2045, which will nearly double to 1600 MWh in 2060. In Indonesia, factors such as low renewable energy, cheap fossil fuels, inadequate regulations, high costs, unstable grid infrastructure, and insufficient government support impact the BESS business. Implementing BESS subsidies, solar panel installation laws and off-grid project incentives can help address these challenges.

Implementing electric vehicles (EVs) and green hydrogen fuel vehicles (GHVs) is vital for advancing sustainable transportation in IKN. Clean energy sources like solar or wind can power EVs, while renewable energy produces green hydrogen. Both approaches contribute to reducing greenhouse gas emissions. The NZE scenario anticipates a 43% and 33% more efficient energy demand in the transportation sector by 2045 and 2060, respectively, compared to the BAU scenario. Since EVs and GHVs generate no emissions during operation, the NZE scenario is projected to reduce greenhouse gas (GHG) emissions in the transportation sector by nearly 99% in 2045 and achieve complete elimination by 2060. By 2045, a solar power plant with a capacity of 0.49 GW will need to generate 1,079 GWh to produce 19,359 tons of green hydrogen. Twenty years later, in 2065, the production of green hydrogen is expected to reach 89,594 tons, requiring solar power plants with a total capacity of 2.28 GW and an electricity output of 4,992 GWh. IKN must develop comprehensive strategies for hydrogen-filling facilities and electric vehicle charging infrastructure to promote the widespread adoption of environmentally friendly vehicles. Residential charging facilities, workplace charging stations, and public charging stations are all required for electric vehicle operation. Developing a suitable and easily accessible charging infrastructure is critical to widespread adoption. Nevertheless, the construction of hydrogen refueling facilities is laborious and costly. In contrast to electric vehicle charging stations, constructing hydrogen refueling stations requires specialized equipment and distribution networks. Therefore, IKN must invest in the construction of a network of accessible and dependable hydrogen refueling stations throughout the city. IKN can transition to sustainable mobility as part of the worldwide effort to reduce greenhouse gas emissions.

Future studies should focus on examining the potential effects of green hydrogen-powered vehicles on demand. On the supply side, research could investigate how Battery Energy Storage System (BESS) technology can facilitate the integration of intermittent renewable energy sources, such as solar and wind power, into IKN grid operations.

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