100% Renewable Electricity in Indonesia

Subjects: Green & Sustainable Science & Technology | Energy & Fuels
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Researchers investigate an Indonesian energy decarbonization pathway using mostly solar photovoltaics. An hourly energy balance analysis using ten years of meteorological data was performed for a hypothetical solar-dominated Indonesian electricity system for the consumption of 3, 6 and 10 megawatt-hours (MWh) per capita per year (compared with current consumption of 1 MWh per capita per year). This research showed that Indonesia's vast solar potential combined with its vast capacity for off-river pumped hydro energy storage could readily achieve 100% renewable electricity at low cost. The levelized cost of electricity (LCOE) for a balanced solar-dominated system in Indonesia was found to be in the range of 77–102 USD/MWh.

levelized cost of electricity | renewable electricity | solar energy

1. Introduction

Indonesia is a rapidly developing country in Southeast Asia with a population of approximately 280 million people [1], which is the world's fourth largest. Indonesia's population is projected to reach 335 million in 2050 [2]. Indonesia is projected to have the fourth-largest economy in the world by 2045 [3].

The current electricity consumption of one megawatt-hour (MWh) per capita per year is expected to eventually approach Singapore's current 9 MWh per capita per year [4][5]. Further, as Indonesia electrifies most energy functions—transport, heating, and industry—its electricity demand could increase to 10–20 MWh per capita per year.

Transitioning to clean energy [6] is essential for Indonesia to fulfill its international climate commitment of net zero emissions by 2060 [7], which is ten years in advance of the previous plan [8]. Indonesia's energy is primarily supplied by fossil energy. Gas and coal account for 83% of the electricity mix [9]. Indonesia is the tenth-largest global greenhouse gas emitter. If Indonesia continues to meet its energy demand by relying on fossil fuels, then the current carbon emissions of 2.3 tonnes of CO_2-equivalent per person [10] will rise significantly. Elimination of carbon emissions from the energy sector is essential [11].

The technology of solar photovoltaics (PVs) is a low emission energy technology that is vastly available in Indonesia [12]. Wind energy is available in some areas but at a modest level due to Indonesia's tropical location. In 2022, solar power constituted more than half [13] of global new generation capacity additions, which is compelling market-based evidence that solar is cost-competitive with fossil, nuclear, wind, hydro and other renewable generation technologies.

Hydroelectricity is being deployed globally at rates that are ten times smaller than those of solar PV [14]. Hydro is fundamentally limited by the availability of rivers to dam, and it often encounters social and environmental opposition.

The global nuclear capacity has been static at about 400 gigawatts (GW) since 2010 [15]. Nuclear energy has not been deployed in Indonesia. It is difficult to see how Indonesia could credibly rely on nuclear energy to decarbonize by 2060. Firstly, Indonesia would start from a very low knowledge and skill base. Secondly, the absence of growth of the global nuclear industry contrasts sharply with the rapid growth of the global solar industry (191 GW of new solar in 2022, according to IRENA [14]), which is compelling market-based evidence that solar energy is cheaper than nuclear energy.

One challenge of the reliance on variable solar and wind energy in an electricity system is balancing supply and demand to maintain the reliability and security of the system. Many techniques are available to solve this challenge, including energy storage (e.g., pumped hydro storage, batteries), flexible generation (e.g., legacy fossil fuel, hydro, bioenergy), transmission interconnections over large areas to smooth out local weather and demand and demand-side management. Many papers have investigated electricity or energy systems supplied by 100% renewable resources.

Off-river pumped hydro is identified as a vastly available, off-the-shelf, market dominant and cost-effective energy storage technology that can provide overnight storage for a solar-dominated Indonesian energy system. The effect of small amounts of backup fuel (for example, hydrogen or synthetic methane) in place of some long term (rarely used) storage is investigated. Battery storage could a substitute for pumped hydro but is neglected in this study because it is still expensive compared with pumped hydro for overnight storage. If battery costs eventually fall below the cost of pumped hydro, then the cost of balancing a 100% renewable energy grid will be lower than modelled in this research.

2. Modelling assumptions

The Indonesian archipelago is modelled at a high resolution (hourly) over 10 years for five separate regions and also as a combined supergrid, allowing for a direct comparison. Updated cost estimates for solar generation and pumped hydro are utilized. Extrapolations from current technology are avoided.

The hourly energy supply and demand over ten years was simulated for the whole of Indonesia to model an optimized electricity system configuration and system costs. The following assumptions and scenarios were applied in the modelling:

- Electricity demands of 3, 6 and 10 MWh per capita per year were modelled, compared with current demand of 1 MWh per capita per year. These demand levels were approximately mapped to 2030, 2040 and 2050–2060, respectively. The modelling was primarily dependent on per capita demand and was largely independent of the date (except for a weak dependence on a slowly growing population).

- The current Java–Bali hourly load pattern was scaled up to represent the demand pattern for electricity demands of 3 and 6 MWh per capita per year. For an electricity demand of 10 MWh per capita per year, Singapore's hourly load pattern was adopted to represent Indonesia's future electricity demand pattern when it reaches parity with advanced economies.
- Ten years of historical hourly meteorological data from 2010 to 2019 for 34 Indonesian cities were used as a representation of future meteorological data. Each future energy demand scenario was tested against each of the 10 years of historical data.
- Solar (one-axis tracking) farms were assumed. To include local transmission costs, solar farms were assumed to be at a distance of 10 km from the grid infrastructure.
- Existing hydroelectric and geothermal generation was assumed to continue in operation indefinitely. Planned expansion of hydro and geothermal up until 2030 was constructed, but no new facilities were completed past 2030. The hydro capacities in 2020 and 2030 were 17 GW and 20 GW, and the geothermal capacities in 2020 and 2030 were 2 GW and 5 GW, respectively.
- Existing hydroelectricity capacity: some (2 GW) operates as a run-of-river that generates a constant output 24/7; the others (15 GW) have dams, which allow flexible outputs that could be reserved for critical times.
- Existing coal generation was assumed to continue unchanged for electricity demands of 3 and 6 MWh per capita per year. For an electricity demand of 10 MWh per capita per year, all coal generators were assumed to have retired, and gas turbines were replaced with new models that utilize hydrogen as their primary fuel source.
- Within each of the 5 modelled regions, high-voltage AC connection was assumed to gather and distribute electricity. Between each of these regions, high-voltage DC connection is available in some scenarios ("Supergrid") and not in others (5 independent regions).
- Energy storage was primarily modelled by means of off-river pumped hydro.
- Small amounts (several percent) of generation from "green" hydrogen (or synthetic methane) were included in some scenarios. These gases could be generated using surplus electricity during sunny days. The purpose of the hydrogen is to reduce the need for some of the pumped hydro storage that is only used to ride through rare extended periods of cloudy weather. It might be cheaper to burn hydrogen in a turbine to ride through such periods. The cost of such a measure is a small fraction of the total. Other methods to accomplish this aim might also become available.

3. Key findings and conclusions

This research explored a future 100% renewable Indonesian electricity system generated mostly by solar PV and complemented by existing geothermal power and hydroelectricity and balanced by off-river pumped hydro energy storage and transmission.

The key findings of this study were as follows:

- Indonesia has vast availability of solar power that can be harvested from rooftops, defunct mine sites, in combination with agriculture and floating on inland water bodies and calm equatorial seas.
- Off-river PHES is a vastly available, mature, low-cost method of storage that allows for an upper-bound cost of balancing the high penetration of solar energy in Indonesia. The required energy storage for a solar-dominant system in Indonesia (10 TWh) was only small fraction (3%) of the available PHES potential.
- Interconnecting Indonesia into a supergrid reduced the required storage and PV capacity. However, the system cost was found to be slightly higher than keeping the independent regions isolated. This contrasts with findings for countries at a higher latitude, which have a winter season with a low solar availability.
- The LCOE of the five independent Indonesian regions were in the range of 65–101 USD/MWh (3 MWh per capita scenario), 71–102 USD/MWh (6 MWh per capita) and 77–102 USD/MWh (10 MWh per capita). The higher LCOE at higher consumption was because of the dilution of existing (sunk-cost) generators.
- The incorporation of small amounts of hydrogen or synthetic methane (in the range of 1% of annual generation) combusted via gas peakers decreased the cost of electricity by around 10% by reducing the requirement for storage and excess solar generation capacity to ride through prolonged cloudy periods.
- Reduced sunlight over a long duration can be caused by natural and human factors. Researchers observed solar power output anomalies during the dry season in 2012, 2013 and 2014, which were most likely related to forest and peat fires. Given these findings, the Indonesian government would have a strong incentive to prevent forest fires when relying on a solar-dominated electricity grid.

This research shows that Indonesia could rely on solar PV combined with off-river PHES for its clean energy transition. The fossil fuel dependency in the current Indonesian electricity system can be replaced with affordable, reliable, and emissions-free electricity in different stages of economic development. The increasing electricity demand can be met by using renewable energy sources as the gradual phase-out of existing fossil fuels takes place. In the future, this research can be expanded to investigate the electrification of transport, heat and industry in Indonesia and its impact on the electricity grid once these energy domains attain maturity for a reliable estimation of the scales of these sectors to be presented.

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