



Article 100% Renewable Electricity in Indonesia

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Abstract: The rapid fall in the cost of solar photovoltaics and wind energy offers a pathway to the deep decarbonization of energy at an affordable price. Off-river pumped hydro energy storage and batteries provide mature and large-scale storage to balance variable generation and demand while minimizing environmental and social impacts. High-voltage inter-regional interconnection and dispatchable capacity (existing hydro and geothermal) can help balance supply and demand. This work investigates 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 solardominated 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). Pumped hydro provides overnight and longer storage. Strong interconnection between islands was found to be unnecessary for Indonesia, contrary to findings from similar modelling in countries at higher latitudes. Storage requirements for power and energy were found to be smaller than three kilowatts and 30-45 kilowatt-hours per person, respectively. Introducing gas turbines (burning hydrogen or synthetic methane) contributing around 1% of annual generation reduced the levelized cost of electricity (LCOE) by 14% and halved the storage requirements by allowing the system to ride through prolonged cloudy periods at lower cost. This work 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 LCOE for a balanced solar-dominated system in Indonesia was found to be in the range of 77-102 USD/megawatt-hour.

Keywords: levelized cost of electricity; renewable electricity; solar energy; pumped hydro energy storage

1. Introduction

This paper is concerned with the pathways to zero energy-related emissions of greenhouse gasses in Indonesia, taking into account a growing population and affluence and the electrification of transport, heating and industry. 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 present electricity consumption of one megawatt-hour (MWh) per capita per year is expected to eventually approach Singapore's current consumption of 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].



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). 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 marketbased evidence that solar is cost-competitive with fossil, nuclear, wind, hydro and other renewable generation technologies.

This study explores high-renewable-electricity scenarios for Indonesia, with the goal of achieving zero carbon emissions in the energy sector. The focus is on the mass deployment of new solar energy, supplemented with existing hydro and geothermal energy. Global solar deployment reached 1000 gigawatts (GW) in 2022 [14], which is several orders of magnitude larger than solar thermal, geothermal, bio and ocean energy generation. Extravagant growth rates would be required for alternative low-emissions technology to catch solar PV before the middle of the century, especially considering the sustained rapid growth of solar PV.

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 base of knowledge and skill. Secondly, the absence of growth of the global nuclear industry contrasts sharply with 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.

The scenarios explored in this study rely on domestic resources to both supply and balance electricity demand and include an analysis of regional interconnection and the potential for an "Indonesian super grid". This study highlights the potential for achieving a low levelized cost of electricity with high solar penetration in Indonesia's electricity system. We modelled Indonesia's electricity system using an hourly resolution of supply and demand using a chronological modelling of the energy supply–demand balance introduced by Lu et al. that has previously been used to assess 100% renewable electricity/energy scenarios for Australia, Southeast Asia, Japan and Bolivia [16–20].

The subsequent sections of this document are organized in the following manner. Previous studies of 100% renewable energy systems are presented in Section 2. The modelling and assumptions used in this study are given in Section 3. Then, different scenarios and the modelling results are discussed in Section 4. Finally, the overall study is concluded in Section 5.

2. Literature Review

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.

A study by the Lappeenranta-Lahti University of Technology (LUT) and Energy Watch Group in 2019 suggested that a global transition to 100% renewable energy across all sectors—power, heat, transport and desalination—is not only technically feasible but also economically viable, with the global energy system being able to meet the energy demand by 2050 through a mix of solar, wind, hydropower and bioenergy [21].

Jacobson et al. [22] concluded that transitioning to 100% renewable energy powered by wind, water and sunlight by 2050 is possible for 139 countries with low-cost and stable grid solutions. Sustainable energy systems with a 100% renewable energy are feasible worldwide

at a low cost with solar energy and wind power being the central pillars [23]. Brown et al. provided a good summary of 100% renewable energy system investigations [24].

There are several studies on 100% renewable energy for Indonesia. Bin et al. [25] studied a low-cost and low-emission future for Southeast Asian countries that included Indonesia with energy supplied mainly from solar PV supported by pumped hydro energy storage. Vidinopoulos et al. [26] concluded that the potential renewable resources of Southeast Asian countries including Indonesia are sufficient to achieve 100% renewable energy. Guenther [27], Simaremare et al. [28] and Tambunan et al. [29], studied the challenge and opportunities of a 100% renewable energy scenario for the Java–Bali grid. They concluded that the scenario is possible but requires a large storage capacity to balance the supply and demand. The potential and cost-effectiveness of grid-connected PV systems at Indonesia's provincial level has been assessed by Veldhuis and Reinders [30]. Sani et al. investigated the reduction in greenhouse gas (GHG) emissions in Sumatera's power sector [31]. Stocks [32] concluded that solar PV is likely to be cheaper than new coal generation and can be rapidly deployed throughout Indonesia.

Reyseliani and Purwanto [33] studied a pathway for a 100% renewable energy Indonesian power system. Their study was a least-cost optimization using the TIMES model comprising 27 power plants and three energy storage technologies and using a 24-hourly demand and supply operational profile representing each assessed year. Indonesia's electricity consumption in 2050 was projected to reach 1361 terawatt-hours (TWh) (4.3 MWh per capita) for a base case and 2565 TWh (7.9 MWh per capita) in a high-demand scenario. The study proposed that nuclear and solar PV will play an essential role with up to 16% and 70% of the total electricity production, respectively, in 2050.

A joint study by Lappeenranta University of Technology (LUT) and the Institute for Essential Services Reform and Agora Energiewende [34] assessed deep decarbonization in Indonesia. The LUT Energy System Transition model [35] treated Indonesia as eight electricity system nodes interconnected with a supply of 100% renewables assuming an increase in electricity consumption to 8.5 MWh/capita by 2050. Solar PV will dominate the source of electricity generation with a generation mix at 88% (1492 GW), followed by hydropower at 6%, geothermal at 5% and other renewables at 1%.

Our study differs from previous work in multiple important aspects. Solar energy is identified as a vastly available, zero-emissions and cost-effective energy source that will dominate the future Indonesian energy supply. Negligible reliance on wind energy and hydroelectricity is assumed because of the small resources compared with solar. Negligible reliance on other renewables, CCS or nuclear is assumed because they have a negligible role in annual global capacity additions.

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 paper.

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.

3. Modelling Input and Assumptions

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. This section describes the data input, modelling scenarios and cost assumptions. In our previous works [12,36], we showed that Indonesia has enormous practical potential for solar generation (Section 3.1) and pumped hydro energy storage (Section 3.3). To put this potential in perspective, we note that the per-capita electricity consumption in advanced economies (European Union, USA, Australia, Japan, Singapore) is in the range 6–12 TWh per million people per year [37]. Allowing for a doubling or tripling of electricity consumption caused by the future electrification of transport, heating and industry and the production of chemicals and synthetic aviation fuels [20], the future electricity demand in decarbonized advanced economies may reach 20 TWh per million people per year.

Thus, an affluent Indonesian population of 335 million people in the middle of the century with a fully decarbonized energy system may require about 7000 TWh of electricity per year. In this study, we model an electricity consumption of 3, 6 and 10 TWh per million people per year. The modelling results from consumptions of 10 and 20 TWh per million people per year would look similar (apart from scale) because both would be dominated by solar generation, with existing hydro and geothermal generation being heavily diluted.

3.1. Solar PV Availability

Solar PV constituted more than half of the new global generation capacity in 2022 [13]. This is compelling market-based evidence that solar PV is the cheapest method of electricity generation in most places. In our previous work [12], we found that the expected solar PV capacity factor for 34 Indonesian cities (capitals of provinces) was an average of 15.4%. Average annual insolation across Indonesian provinces, as represented by data from 34 cities, varies by less than $\pm 7\%$ [12]. The Indonesian archipelago has the potential to generate 180,000 TWh per year of solar electricity from oceanic areas that never experience waves and wind speeds larger than 4 m and 15 m/s, respectively [12]. The estimated solar energy potential is summarized in Table 1, while the global horizontal irradiation of Indonesia is illustrated in Figure 1.

Solar Energy Potential	Available Area (000 km ²)	Generation Potential (TWh/Year)
Urban rooftop solar PV	-	700–1700
Agricultural solar PV	11–31	2700-8100
Mined areas solar PV	2.3	600
Floating solar PV—freshwater	0.25	64
Floating solar PV—maritime	708	180,000

Table 1. Solar energy potential in Indonesia [12].



Figure 1. Global horizontal irradiation of Indonesia [38].

3.2. Non-Solar Low-Emissions Energy Sources

The Indonesian National General Energy Plan [2] suggests a total of non-solar renewable electricity generation capacity (hydro, wind, bioenergy, geothermal energy) of approximately 235 GW. Annual generation is limited to 1000 TWh per year from these non-solar renewable energy sources assuming an average capacity factor of 50% (about 3 MWh per capita per year). This is much smaller than Indonesia's potential future electricity requirements. In this study, we assume that most future power plants will be solar PV. Supplementation of solar at a modest scale by other low emissions sources may occur.

The assessed potential for large hydropower in Indonesia is 75 GW, while that of small hydropower is 19 GW. The current Indonesian hydropower capacity is about 7 GW [14]. There are insufficient rivers to make hydroelectricity a substantial source of energy.

Wind power potential is assessed as 61 GW. Wind speeds are low due to Indonesia's tropical location. Indonesia currently has negligible wind generation. Indonesia hosts 40% of the global geothermal resources, assessed at a 29 GW power capacity. Currently, Indonesia's geothermal power capacity is about 2 GW [14]. Ocean energy is assessed as 18 GW. There is negligible global ocean energy deployment.

The potential of bioenergy is assessed as 33 GW, compared with 3 GW of installed capacity [14]. The efficiency of the biological capture of solar energy is 20–200 times less than the efficiency of solar [39], and so large amounts of land are required. Bioenergy competes with food production and ecosystems for arable land, water, pesticides and fertilizers.

Indonesia has no nuclear energy capacity. Global nuclear generation and generation capacity have been static since 2010 [15]. Nuclear fails to compete successfully with solar and wind and is neglected in this study.

3.3. Off-River Pumped Hydro Energy Storage

Pumped hydro energy storage (PHES) is by far the dominant option for storing energy for the electricity industry over time scales ranging from hours to a few days because it is the cheapest option [40,41]. Off-river pumped hydro storage, which is vast, low-cost and technically mature, is critical for Indonesia's renewable electricity scenarios [32,41,42]. PHES can provide ancillary grid services, such as mechanical inertia, as a substitute for decommissioned coal and gas power facilities.

Good off-river PHES sites are available throughout Indonesia, including many on the densely inhabited islands such as Java, Bali and Sumatera. Importantly, the vast majority of potential sites require no new dams on major rivers. A total of 26,000 untapped off-river sites for PHES development were identified in Indonesia with a collective energy storage capacity of 800 TWh [41]. The potential sites for 150 GWh greenfield off-river PHES in Indonesia are shown in Figure 2.



Figure 2. Potential 150 GWh greenfield off-river PHES sites in Indonesia (source: [42]; detailed zoomable map is available http://re100.eng.anu.edu.au/ (accessed on 31 October 2023)).

There is a total of 321 TWh of PHES storage volume in the lowest cost classes (A and B) spread all over the archipelago [36] (Table 2). As Indonesian solar resources and electricity demand have low seasonal variations, large-scale (expensive) seasonal storage of energy is not required. The vast solar potential coupled with low-cost, large-scale, mature PHES is an excellent combination to support Indonesia's transition to 100% renewable electricity.

Class A and Class B PHES Potential (TWh)
43
30
30
64
85
69
321

Table 2. Class A and B greenfield PHES storage availability for Indonesia.

3.4. Fossil Power Plants

Indonesia's current electricity generation is 67% sourced from coal-fired power plants [9]. Coal power plants have contracts or power purchase agreements that typically last for 25–30 years. Existing contracts will mostly expire before 2050.

Carbon capture and storage (CCS) technology is largely non-existent within the electricity industry. CCS-equipped fossil fuel power stations would produce substantially more expensive electricity than those without CCS because of (i) additional capital costs and (ii) the energy requirements to run the process. Solar and wind compete successfully [13] with non-mitigated fossil fuel power stations. Thus, it is difficult to see how CCS-equipped fossil fuel power stations could compete with solar PV and wind and thereby become important in the energy industry. An end to new coal-fired power plant construction coupled with a retirement plan is essential to curtail emissions.

The Indonesian government has adopted a policy of stopping new coal plant projects with the exception of those that are under construction or have reached financial closure [43–45]. Currently, there is 35 GW of coal-fired power plant in operation. A further 5 GW (net) is committed to be completed by 2030. The coal construction and retirement plan in Indonesia assumed for this study is available in the Supplementary Materials.

The generation mix includes 16% of electricity from gas-powered plants with a current capacity of about 20 GW [9]. Gas power plants are assumed to be gradually retired at end-of-life following a similar path to the gradual retirement of coal-fired power plants (available in the Supplementary Materials). The early retirement of coal and gas power plants may require payment of compensation to the owners. However, early retirement is unnecessary since the tenfold growth in electricity demand assumed in this study (from 1 to 10 MWh per capita per year, mostly met using solar energy) far exceeds the residual growth of coal capacity.

3.5. Electricity Demand

Rising population, improving living standards and electrification of transport (electric vehicles), heating (electric heat pumps) and industry (electric furnaces) are expected to contribute to a large increase in electricity demand. This study used scenarios of future electricity demand based on per-capita electricity consumption. The current Indonesian electricity consumption is about 1 MWh per capita per year.

In our scenario, we assume the annual per capita electricity consumption to reach 3 MWh in 2030, 6 MWh in 2040 and 10 MWh in 2050 or 2060 (Table 3). The exact dates are not important for the modelling. The consumption in Indonesia's near neighbors Australia and Singapore is around 10 MWh per capita per year. Subsequently, their consumption may rise to 20 MWh per capita per year or more as hydrogen is produced by solar-driven electrolysis of water to decarbonize the chemical industry, metal production and aviation (via synthetic fuel). However, this is not modelled in this study.

	3 MWh/Capita (2030)		6 MWh/Capita (2040)		10 MWh/Capita (2050)	
Indonesia's Region	Population (Million People)	Electricity Demand (TWh)	Population (Million People)	Electricity Demand (TWh)	Population (Million People)	Electricity Demand (TWh)
Sumatera	64	192	68	410	73	726
Java	166	498	177	1060	188	1879
Bali Nusa Tenggara	16	49	17	105	19	186
Kalimantan	18	55	19	116	20	206
Sulawesi	22	65	23	139	25	247
Maluku Papua	9	28	10	60	10	106
Total	296	888	315	1890	335	3350

Table 3. The projected electricity demand (terawatt-hours per year) in Indonesia.

3.6. Network Configuration: HVDC Transmission

Bulk energy transmission is feasible using both high-voltage alternating-current (HVAC) and high-voltage direct-current (HVDC) links. An expensive HVDC converter station at each end favors HVAC for short-distance transmission. HVDC allows for huge amounts of power to be transmitted at a low cost and efficiently over thousands of kilometers. The losses/costs of HVDC are significantly lower than HVAC due to the absence of the line capacitive/reactive charging effect.

Wide-area transmission means local adverse weather can be smoothed using energy exchange with other regions. More than 200 GW of HVDC were installed worldwide as of 2017 and was expected to surpass 400 GW by 2022 based on the announced projects pipeline [46]. This includes power lines carrying 6 GW at \pm 800 kV DC over 2000 km with energy losses of about 3% per thousand kilometers.

In this study, the Indonesian electricity grids were divided into 5 main regions: (1) Sumatera, (2) Java Bali Nusa Tenggara, (3) Kalimantan, (4) Sulawesi and (5) Maluku and Papua, as illustrated in Figure 3. These regions represent 10, 9, 5, 6 and 4 provinces in Indonesia, respectively. In some scenarios, all 5 regional grids were simulated separately. In others, all 5 regional grids were connected by undersea HVDC cables to create an Indonesian supergrid.

3.7. Modelling Assumptions

We modelled Indonesia's future electricity system using an hourly resolution of supply and demand, as demand increases tenfold and as Indonesia moves towards 100% renewable energy. Solar PV supplies most of the energy. Existing hydro, legacy fossil fuel plants and pumped hydro energy storage provided most of the balancing of supply and demand. The modelling tool introduced by Lu et al. [20] provided high-resolution, chronological modelling of the energy supply–demand balance. The model used time series demand and meteorological data to simulate the hourly energy balance in each service area. The model determined the least-cost solution that satisfied the specified resource, reliability and energy constraints for each scenario by optimizing the generation and storage capacity for each region. The model has previously been used to assess 100% renewable electricity/energy scenario for Australia, Southeast Asia, Japan and Bolivia [16–20]. Cheng et al. [47] provides a detailed explanation of the model.

Reliability constraint: the electricity generation must meet the demand at each time interval, which necessitated a zero deficit. Resource constraint: the installed capacity of a technology within a designated service region must not exceed the identified technical resource potential of this technology in this service area. Energy constraint: the aggregate generation output from a certain technology must not exceed the predetermined maximum generation capacity.

anda Aceh

Padar

Makassar





Figure 3. Electricity network configuration: (a) Sumatera, (b) Kalimantan, (c) Maluku and Papua, (d) Sulawesi, (e) Java Bali Nusa Tenggara and (f) Indonesian Supergrid (all regions interconnected).

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.

The model calculated the levelized cost of electricity (LCOE) for each scenario after determining the most effective system configuration. The LCOE of the 100% renewable electricity scenario (10 MWh per capita demand) was calculated using the following equation:

$$LCOE = \frac{Cost_{solarPV} + Cost_{hydro} + Cost_{geothermal} + Cost_{transmission} + Cost_{pumped storage}}{annual electricity demand}$$
(1)

The LCOE of the scenario of gradually phasing out of fossil fuels (demand of 3 and 6 MWh per capita) was calculated using the equation below:

$$LCOE = \frac{Cost_{solarPV} + Cost_{hydro} + Cost_{geothermal} + Cost_{transmission} + Cost_{pumped storage} + Cost_{fossil}}{annual electricity demand}$$
(2)

The annualized cost for technology *i* was calculated by:

$$Cost_{i} = \left(\frac{CAPEX_{i}}{\frac{1 - (1 + r_{i})^{-n_{i}}}{r_{i}}} + FOM_{i}\right) + C_{i} + VOM_{i} + E_{i}$$
(3)

where CAPEX_i is the capital cost of technology i; FOM_i and VOM_i are the fixed and variable operating and maintenance costs of technology i, respectively; r_i is the real discount rate for technology i; n_i is the economic life of technology i and C_i and E_i are the capacity and annual generation of technology i, respectively.

The model also estimated the levelized cost of generation (LCOG) and the levelized cost of balancing (LCOB), as discussed in Section 4. The LCOG is the cost of generating all electricity within the network, regardless of spillage and energy losses. The LCOG is the weighted average cost of generation from each PV farm, geothermal, hydro and existing

river-based hydro. The LCOB is the cost associated with energy storage, transmission infrastructure, spillage and transmission or efficiency losses. The LCOB comprises three components: PHES, HVDC and spillage of excess PV generation during sunny days when storages are fully recharged.

3.8. Cost Assumptions

In this study, a real (inflation-free) discount rate of 5% was used for all technologies. The cost assumptions are summarized in Table 4. USD currency was used.

Technology	Capital Cost	Fixed O&M Cost	Variable O&M Cost	Lifetime (Years)	Purchase Price
PV	530 USD/kW	10 USD/kW p.a.	-	57 USD/MWh	
Hydro	-	-	-	70 USD/MWh	
Geothermal	-	-	-	70 USD/MWh	
Coal	-	-	-	-	
Pumped hydro	500 USD/kWp + 50 USD/kWh	10 USD/kW p.a.	-	-	
HVDC	200 USD/MW-km + 200,000 USD/MW-pair	-	-	50 for transmission lines; 30 for converter stations	
HVAC	1000 USD/MW-km	-	-	40	-

Table 4. Cost assumptions are in USD [16–20,47].

The cost of solar PV electricity has been declining for decades. In this study, for all scenarios, we adopted the 2030 cost projections of the International Technology Roadmap for PV [48]. The capital cost of solar PV is 530 USD/kW, the lifetime is 25 years and the operation and maintenance costs are 10 USD/kW per year.

For hydropower, geothermal and coal power plants, we used the costs reported in "Technology Data for the Indonesian Power Sector" [49]. Energy purchased from hydropower was expected to remain stable at 57 USD/MWh. The costs for geothermal was assumed to be 70 USD/MWh. Electricity supplied from legacy (sunk cost) coal power plants was valued at 70 USD/MWh. The costs for energy storage using pumped hydro were adopted from a study by Lu et al. at 500 USD/kWp (tunnels, pump/turbines, powerhouse, switchyard) and 50 USD/kWh (reservoirs) [20]. Transmission costs were adopted from a study by Lu et al. [20].

In this study, a small amount of electricity from hydrogen (or synthetic methane) was used. The purpose was to avoid the capital costs of storage that are used only very occasionally to ride through prolonged cloudy periods. Since the amount of fuel used in the various scenarios was small, uncertainties in the future cost of green hydrogen had little impact on the overall costs.

At present, the cost of green hydrogen production is substantially higher than conventional hydrogen. Bloomberg estimates that the cost of hydrogen production from natural gas in Indonesia is 1.5 USD/kg, while green hydrogen costs are 2–6 USD/kg [50,51]. There is no industrial-scale green hydrogen production in Indonesia today.

For this study, we assumed the green hydrogen cost to be 2 USD/kg [47]. We assumed that the energy fed to electrolyzers comes from spilled solar PV production. Gas peakers are operated to convert hydrogen into electricity, and this analysis used Lazard's report's cost estimates (average of "low" and "high" cases), substituting the price of hydrogen for the cost of fuel. The price of the gas peaker was costed independently and was not factored into the hydrogen price. The assumed green hydrogen production cost of 2 USD/kg was equivalent to 108 USD/MWh when using a kg H₂ per kWh conversion efficiency of 0.054 [52].

4. Results and Discussion

4.1. Levelized Cost of Electricity

The modelled LCOE figures for 3, 6 and 10 MWh per capita per year are shown in Figure 4. Recall that the current electricity consumption in Indonesia is 1 MWh/person/year. There was a moderate increase in the LCOE as demand increased. This was because the cheap electricity available from the existing (sunk cost) electricity generators was progressively diluted.



Figure 4. Levelized cost of electricity of 3 MWh per capita, 6 MWh per capita and 10 MWh per capita consumption scenarios. The set of bars labelled "pop. weighted average" refer to the five independent regions and is included for comparison with the Indonesian supergrid scenario.

The Maluku Papua region at the eastern edge of Indonesia had the highest LCOE, which was nearly the same for all scenarios (102 USD/MWh). This was primarily due to the high costs associated with the cost of submarine HVDC connections in this region. Java Bali Nusa Tenggara is home to 61% of Indonesia's population. The modelled LCOE was 83–96 USD/MWh. The modelled LCOE values of Sumatera, Kalimantan, and Sulawesi was in the range of 65–80 USD/MWh.

The levelized cost of balancing (LCOB) accounts for the cost of balancing solar electricity to ensure continuous availability, and it amounts to storage plus transmission plus occasional spillage (curtailment) of electricity production on days with lots of sunshine when storage capacities are full. The model tried many different combinations of these components for every hour over 10 years to arrive at the lowest cost that still avoids blackouts. These components can be traded to achieve an optimum. For example, additional investment in storage could reduce spillage. Additional inter-regional transmission could reduce both storage and spillage by smoothing out fluctuations in local weather and demand. Tolerance of a substantial spillage of generated solar electricity could allow reduced investment in storage and transmission.

Figure 5 divides the LCOE into two components, namely, the levelized cost of generation (LCOG) and the LCOB, for the 10 MWh per person per year scenario. At this level of demand, existing (sunk cost) generation was negligible, and the relative costs of a solar-only electricity system became clear. Thus, the LCOG reflects the cost of solar generation systems coupled with available solar insolation. The average modelled solar generation across the 34 cities included in the study was 3.7 kWh/kWp per day with a standard deviation of $\pm 6\%$. Thus, the solar generation costs were similar across the Indonesian archipelago because the insolation was similar in most places. The population-weighted LCOG average across Indonesia was 54 USD/MWh, with a relatively small range of 48–55 USD/MWh across the five modelled regions.



Figure 5. Levelized cost of electricity for 10 MWh per capita scenario (100% renewable).

The population-weighted LCOB average was 37 USD/MWh and ranged from 28–47 USD/MWh across the five modelled regions. There was about twice as much variation between the regions in the cost of balancing compared to the cost of generation. The LCOB in a region will be enlarged if there are substantial weekly, monthly, seasonal and annual variations in insolation.

The population-weighted LCOE average was 91 USD/MWh and ranged from 77–102 USD/MWh across the five modelled regions. This is a variation of \pm 13%, which is a relatively small variation across such a large and populous archipelago.

An Indonesian supergrid that connects all five regions was modelled. The supergrid has the advantage that storage needs can be reduced because local weather and demand can be smoothed out across the whole archipelago. On the other hand, undersea HVDC transmission cost must be borne. The modelled LCOE of an Indonesian supergrid 95 USD/MWh. This is larger than the modelled population-weighted LCOE average of 91 USD/MWh. Thus, a strong interconnection of all five regions was not favored by the model. However, the difference in the LCOE was quite small—only 5%. Given the uncertainty of the input parameters, there was no significant difference.

4.1.1. Key Points

The key points shown by the modelling results are listed below. These points are general and are only weakly dependent on the fine details of the assumptions.

- A fully balanced, solar-dominated electricity system in Indonesia using entirely offthe-shelf components at near-term prices yielded competitive electricity prices around 90 USD/MWh. This LCOE is about 10% lower than the current generation cost of 98 USD/MWh [53].
- 2. The levelized cost of generation (LCOG) was about 60% of the total levelized cost of energy, while the levelized cost of balancing (LCOB) comprised about 40%.
- 3. The LCOG was quite uniform across the archipelago because the insolation is quite uniform ($\pm 6\%$).
- 4. Further reductions in the capital cost of solar generators will lead to corresponding reductions in both the LCOG and LCOB.
- Balancing comprises storage, transmission and spillage. Each component in an optimized configuration is relatively small compared with the LCOE—typically 10–15% of the LCOE for each component.
- 6. Seasonal storage is not required to support a solar-dominated Indonesian electricity system.
- 7. A lower LCOG in the future could reduce the cost of spillage, meaning that the new optimum balancing configuration would tilt in favor of larger solar arrays and against

storage and transmission. Roughly speaking, a 10% reduction in the LCOG will lead to a 6–8% reduction in the LCOE.

- The population-weighted value of the LCOB (37 USD/MWh) was modest. There
 is scope to further reduce this cost through the use of a wider variety of balancing
 techniques than that modelled here, including demand management and batteries
 (including those in electric vehicles).
- 9. Strong interconnection (supergrid) across the archipelago did not reduce the LCOE compared with the population-weighted average of the five separate regions.

4.1.2. Supergrid

An Indonesian supergrid was not advantageous. This was because the weekly, monthly, seasonal and annual variation in insolation is small and is not counter-correlated in different regions (which would reduce the need for storage). Lu et al. recently studied a Southeast Asian electricity system, in which most of the electricity was derived from solar and wind [24]. In one scenario (independent), each of the 11 countries maintained an independent electricity system. Most of the population of these countries (85%) resided at lower than 20 degrees of latitude where there are small seasonal fluctuations in insolation. In another scenario (supergrid 1), the 11 countries were strongly interconnected. A third scenario (supergrid 2) entailed extending their connections to Australia, China and India. The LCOE for supergrid 1 and supergrid 2 was similar (\pm 4%) to the average LCOE for the 11 independent countries (102 USD/MWh). This accords with the results of this study.

In other countries, a strong interregional connection could significantly reduce the LCOE by smoothing out local weather and demand and hence greatly reducing the need for storage. Typically, such countries are not tropical, and there is a winter season with substantially reduced insolation such as in Australia [16] and Japan [47].

Indonesia has a uniform electricity tariff policy [54], which means that customers residing outside Java Bali Nusa Tenggara and Maluku Papua will potentially pay slightly higher prices than the LCOE in their region would suggest.

The estimation of the LCOE in this study (91 USD/MWh for the 10 MWh populationweighted independent regions scenario) was lower than in previous studies. Lu et al. [20] estimated a value of 114 USD/MWh for the equivalent Indonesian scenario. Reyseliani et al. suggested an LCOE of 113 USD/MWh [33]. Apart from the differences in the model assumptions, this lower LCOE in our study as primarily due to the lower solar PV cost assumptions and the larger number of electrical nodes in our model.

The current generation costs in Indonesia are suggested to be 98 USD/MWh [53]. However, the current generation costs depend largely on government subsidies and/or capped coal prices for power generation. The present low-cost coal generation might not be guaranteed in the future. Furthermore, Indonesia has started to implement a carbon tax for fossil power generation. Importantly, the LCOE values reported from this study represent upper bounds for the costs of 100% renewable electricity in Indonesia, because mature, off-the-shelf technologies with known costs were included in the model (with the exception of a small amount of hydrogen or synthetic methane). Future technological advancements or cost reductions could result in lower expenses than those predicted in this study.

Low-cost renewable electricity dominated by solar energy and off-river PHES avoids coal emissions while abating the environmental and social impacts caused by conventional hydroelectricity. This LCOE can be further reduced by incorporating small amounts of hydrogen or synthetic methane burnt in rarely used turbines to avoid the construction of pumped hydro storage that is only required during rare prolonged cloudy periods. This will be explored in the following sections.

4.2. Electricity Generation Mix

As discussed in Section 3, Indonesia's current electricity generation is about 1 MWh per person per year and is currently 83% sourced from coal-fired and gas power plants. We assumed that coal and gas power plants would come online and retire according to the

data shown in Tables S1 and S2 in the Supplementary Materials. In these data, the fossil fuel capacity peaks at 40 GW in 2030 and declines to zero before 2060. The existing hydro and geothermal plants continue to operate with refurbishment as required.

The Indonesian electricity demand is widely expected to grow in line with growth of both the population and affluence and will be greatly augmented by the electrification of transport, heating and industry. We assumed that the per capita demand would grow to 3, 6 and 10 MWh per year in 2030, 2040 and 2060, respectively (exact dates were not important for our study). The existing generation was progressively diluted in the model as the electricity demand increased from 1 to 10 MWh per year.

The annual electricity generation and the energy mix of solar photovoltaics, hydropower geothermal and coal for the scenarios with 3, 6 and 10 MWh per capita generation are shown in Figure 6. The details of each scenario are included in the Supplementary Materials.



Figure 6. (a) Electricity generation and (b) generation mix for scenarios with 3, 6, and 10 MWh per capita generation.

4.3. Electricity Balance Modelling Results

The annual demand reached 3358 TWh under the 10 MWh scenario. However, the annual generation reached 5089 TWh (independent scenario) because there were substantial losses in the storage round trip as well as a substantial excess deployment of solar PV (which was frequently curtailed).

Figure 7 illustrates a picture of the energy balance between supply and demand over a stressful week in an Indonesian supergrid within the 10 MWh per capita demand scenario.

This stressful week occurred using the year 2010 for the solar PV output simulation. In this week, the amount of energy stored in pumped hydro (represented by the blue line) depleted to zero on two consecutive days while covering the overnight demand. Over the last three days of the week, the system experienced energy spillage due to the model's preference for limiting the PHES storage capacity to achieve the most cost-effective solution. As illustrated, the renewable supply and electricity demand were effectively balanced on an hourly basis by pumped hydro energy storage (minimally supplemented by the existing hydropower and geothermal supply). The most stressful week defines the required storage capacity to meet the energy reliability constraint.



Figure 7. Energy supply–demand profile during a stressful week with low availability of renewable energy supply in Indonesia.

4.4. Energy Storage Requirements

As the demand within the electricity system increased, there was an increase in the storage requirements both in terms of power (GW) and energy (GWh). The total required electrical storage values for the five regions operating independently for the 10 MWh per capita scenario were 1130 GW and 15,400 GWh. The integration of all the regions into an Indonesian supergrid substantially reduced the storage to 1030 GW and 10,300 GWh. The reason for this was that strong transmission smooths out local weather and demand at the cost of increased expenditure on transmission.

The storage requirements for the 10 MWh per capita scenario for all the regions operating independently and for an Indonesian supergrid are summarized in Table 5.

Within the 10 MWh per person per year scenario (in which non-solar generation was diluted to negligible levels), we found that the required storage varied in the range of 9–17 TWh compared with the average daily electricity consumption of 9 TWh per day. Thus, the required storage was in the range 24–40 h of average consumption. This confirmed the estimation in previous work [36] that showed that with its low variability in terms of solar resources, Indonesia will require energy storage for daily use rather than for prolonged periods spanning weeks or months. On a per capita basis, the storage power and energy requirements were in the range of three kilowatts and 30–45 kWh, respectively.

10 MWh—Baseline	Annual Demand (TWh)	PHES (GW)	PHES (TWh)	Storage Duration (Hours)
Sumatera (A)	726	218	2.0	9
Java Bali Nusa Tenggara (B)	2065	728	10.7	15
Kalimantan (C)	206	61	1.1	17
Sulawesi (D)	247	78	1.0	12
Maluku Papua (E)	115	44	0.7	16
Total $(A + B + C + D + E)$	3358	1129	15.5	14
Indonesia supergrid	3358	1031	10.3	10

Table 5. Storage requirements for 100% renewable electricity in Indonesia.

From this analysis, we found that the required storage (10–15 TWh) was a small fraction of the available pumped hydro storage in Indonesia. According to the Global Pumped Hydro Atlas [41], there is 321 TWh of Class A or Class B storage potential in Indonesia. Energy planners need choose only the very best sites for PHES development, i.e., those with the lowest cost, environmental impact and social push back.

4.5. Incorporating Hydrogen to Balance Prolonged Periods with Low Availability of Solar

Incorporating a small amount of generation from hydrogen or synthetic methane offers advantages in mitigating solar energy shortfalls during prolonged cloudy periods. The reason for this is that some pumped hydro storage will have to be reserved for prolonged periods of deficient insolation that might occur only once every few years. It is cheaper to maintain a gas peaking plant fueled by hydrogen or synthetic methane. Hydrogen or synthetic methane can be produced using excess solar electricity that would otherwise be spilled.

We found that the worst week during 2010–2020, when the insolation deficit was the highest, was in the year of 2013. This week drove the model to add more solar PV capacity or energy storage that is rarely used. As a result, it generated a higher system cost.

Prolonged periods of low insolation can be natural or human-induced. For example, we analyzed 520 weeks of solar output in Tanjungselor, Kalimantan. There was an anomaly in the solar weekly output during the dry season (April–August) for 2012, 2013 and 2014. We concluded that the anomalously low insolation was related to forest and peat fires, which are often caused by people creating new agricultural areas by burning forests. Frequent or prolonged haze events can reduce the solar irradiation received by PV panels and led to yield losses in PV systems in Singapore by 15–25% [55] and in Malaysia by 18% [56]. We found that forest fires and peat fires happened every year in Indonesia in the period of 2010–2019. The neighboring countries of Indonesia, Singapore and Malaysia, experienced severe air pollution due to forest fires and peat fires in 2013 [56]. They were also reported to be high in 2010 and 2017. The 2015 Indonesian fire season was the most severe [57]. Given these findings, the Indonesian government would have a strong incentive to prevent forest fires when relying on a solar-dominated electricity grid.

Table 6 shows that introducing small quantities of hydrogen or synthetic methane (represented as "Gas" in Figure 8) substantially decreased both the generation and storage requirements. Introducing a 0.5% or 1.4% generation from hydrogen (or synthetic methane) decreased the LCOE by 8% or 14%, respectively. Increasing it beyond 1.4% caused no further improvement in the LCOE. This demonstrates that reserving a small fraction of hydrogen or synthetic methane is a more cost-effective solution to managing periods of prolonged low availability of solar and wind compared to overbuilding an additional solar photovoltaic (PV) or pumped hydroelectric storage (PHES) capacity that would be rarely utilized.

Hydrogen (%)	LCOE (USD/MWh)	Solar PV (GW)	PHES (GW)	PHES (GWh)
-	94.8	3565	1030	10,291
0.2%	89.6	3315	1014	7289
0.5%	86.8	3108	976	6117
1%	82.9	3152	1005	6718
1.4%	82.9	3003	963	5849
2%	81.8	2908	938	5642

Table 6. Incorporation of hydrogen via gas peakers for integrated Indonesia.



Figure 8. An hourly energy supply demand balance during a 'stressful week' with a portion of hydrogen combusted in gas power plants.

4.6. Sensitivity Analysis: $\pm 20\%$ of Cost

The results of the optimization relied on assumptions about the future electricity generation costs in Indonesia, which are uncertain. To examine the impact of the parametric uncertainties, we performed a sensitivity analysis. We varied the costs of solar PV, PHES, hydro, geothermal, transmission and the discount rate by $\pm 20\%$ for the 100% renewable electricity scenario (10 MWh per capita). According to Cheng et al. [47], in a Japanese 100% renewable energy study, examining the worst year was highly effective for the sensitivity analysis in a multiyear simulation. In that study, modeling only the worst year produced similar results to the entire 40-year model in their study. This saved computational time while maintaining accuracy. We adopted this technique in this work. From the ten-year modelling result, the worst year was 2013, which had the highest LCOE (as shown in Figure 9).



Figure 9. LCOE of one-year simulation. The worst year with highest LCOE was 2013, which was referred to for sensitivity analysis.

Changing the solar PV costs had the most significant impact on the LCOE (12%), since solar PV generation constituted the largest portion (~60%) of the overall cost structure. The real discount rate had the next most significant impact, at 8%, highlighting the importance of seeking low investment costs. As shown in Figure 10, decreasing the solar PV costs, energy storage costs and discount rate were the three main factors in reducing the system costs.



Figure 10. Sensitivity analysis of LCOE for the 10 MWh per capita Indonesian supergrid.

5. Conclusions

This paper 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. From our findings in this study, we 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 work 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 an 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 work 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.

Supplementary Materials: The following supporting information can be downloaded at: https: //www.mdpi.com/article/10.3390/en17010003/s1, Figure S1. PV output potential (kWh/kWp) daily average in Indonesia, Figure S2. Ten years of weekly solar output (kWh/week) of 1 kWp solar PV in Tanjungselor, Kalimantan, Table S1. Indonesia's coal-fired power plant retirement plan up to 2060, Table S2. Indonesia's gas power plant retirement plan up to 2060, Table S3. Indonesia's hydropower plant capacity, Table S4. Indonesia's hydro power plant capacity (run off river/base load), Table S5. Indonesia's geothermal power plant capacity, Table S6. Type and length of transmission lines, Table S7. Modelling results. References [58–62] are cited in the Supplementary Materials.

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References

- 1. Indonesia Population—Worldometer, 2023. Available online: https://www.worldometers.info/world-population/indonesia-population/ (accessed on 28 June 2023).
- 2. Ministry of Energy and Mineral Resources Republic of Indonesia. *National Energy General Plan (Rencana Umum Energi Nasional: RUEN);* Ministry of Energy and Mineral Resources Republic of Indonesia: Jakarta, Indonesia, 2017.
- 3. PwC. The World in 2050: PwC. Available online: https://www.pwc.com/gx/en/research-insights/economy/the-world-in-2050.html (accessed on 27 June 2022).
- 4. EMA. Singapore Energy Statistics | Energy Consumption. Available online: https://www.ema.gov.sg/singapore-energystatistics/Ch03/index3 (accessed on 15 July 2021).
- 5. Singapore Population—Worldometer, 2023. Available online: https://www.worldometers.info/world-population/singapore-population/ (accessed on 28 June 2023).
- Blakers, A.; Stocks, M.; Lu, B.; Cheng, C.; Stocks, R. Pathway to 100% Renewable Electricity. *IEEE J. Photovolt.* 2019, *9*, 1828–1833. [CrossRef]
- 7. Ministry of Environmental and Forestry Republic of Indonesia. *Updated Nationally Determined Contribution Republic of Indonesia and Document of Long-Term Strategy on Low Carbon and Climate Resillence* 2050; Ministry of Environmental and Forestry Republic of Indonesia: Jakarta, Indonesia, 2021.
- UNFCC. First Nationally Determined Contribution—Republic of Indonesia. Available online: https://www4.unfccc.int/sites/ NDCStaging/Pages/Party.aspx?party=IDN (accessed on 15 July 2021).
- 9. Ministry of Energy and Mineral Resources Republic of Indonesia. *Capaian Kinerja ESDM 2022 Dan Target 2023;* Ministry of Energy and Mineral Resources Republic of Indonesia: Jakarta, Indonesia, 2023.
- 10. Global Carbon Project. Global Carbon Atlas. Available online: http://www.globalcarbonatlas.org/en/CO2-emissions (accessed on 28 June 2023).
- 11. US EPA. Global Greenhouse Gas Emissions Data. Available online: https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data (accessed on 29 June 2022).
- 12. Silalahi, D.F.; Blakers, A.; Stocks, M.; Lu, B.; Cheng, C.; Hayes, L. Indonesia's Vast Solar Energy Potential. *Energies* **2021**, *14*, 5424. [CrossRef]
- 13. RenewEconomy. Solar Is a Runaway Global Success, and Australia Is Showing the Way Forward. Available online: https://reneweconomy.com.au/solar-is-a-runaway-global-success-and-australia-is-showing-the-way-forward/ (accessed on 28 June 2023).
- Renewable Capacity Statistics 2023. Available online: https://www.irena.org/Publications/2023/Mar/Renewable-capacitystatistics-2023 (accessed on 28 June 2023).
- World Nuclear Power Reactors | Uranium Requirements | Future Nuclear Power—World Nuclear Association. Available online: https://www.world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uraniumrequireme.aspx (accessed on 28 June 2023).
- 16. Blakers, A.; Lu, B.; Stocks, M. 100% Renewable Electricity in Australia. Energy 2017, 133, 471–482. [CrossRef]
- 17. Cheng, C.; Blakers, A.; Stocks, M.; Lu, B. Pumped Hydro Energy Storage and 100% Renewable Electricity for East Asia. *Glob. Energy Interconnect.* **2019**, *2*, 386–392. [CrossRef]
- Lu, B.; Blakers, A.; Stocks, M. 90–100% Renewable Electricity for the South West Interconnected System of Western Australia. Energy 2017, 122, 663–674. [CrossRef]
- 19. Cheng, C.; Gutierrez, N.P.; Blakers, A.; Stocks, M. GIS-Based Solar and Wind Resource Assessment and Least-Cost 100% Renewable Electricity Modelling for Bolivia. *Energy Sustain. Dev.* **2022**, *69*, 134–149. [CrossRef]
- 20. Lu, B.; Blakers, A.; Stocks, M.; Cheng, C.; Nadolny, A. A Zero-Carbon, Reliable and Affordable Energy Future in Australia. *Energy* **2021**, 220, 119678. [CrossRef]
- 21. LUT University; Energy Watch. Global Energy System Based on 100% Renewable Energy; LUT University: Lappeenranta, Finland, 2019.
- Jacobson, M.Z.; Delucchi, M.A.; Bauer, Z.A.F.; Goodman, S.C.; Chapman, W.E.; Cameron, M.A.; Bozonnat, C.; Chobadi, L.; Clonts, H.A.; Enevoldsen, P.; et al. 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. *Joule* 2017, 1, 108–121. [CrossRef]
- 23. Breyer, C.; Khalili, S.; Bogdanov, D.; Ram, M.; Oyewo, A.S.; Aghahosseini, A.; Gulagi, A.; Solomon, A.A.; Keiner, D.; Lopez, G.; et al. On the History and Future of 100% Renewable Energy Systems Research. *IEEE Access* 2022, *10*, 78176–78218. [CrossRef]
- 24. Brown, T.W.; Bischof-Niemz, T.; Blok, K.; Breyer, C.; Lund, H.; Mathiesen, B.V. Response to 'Burden of Proof: A Comprehensive Review of the Feasibility of 100% Renewable-Electricity Systems'. *Renew. Sustain. Energy Rev.* **2018**, *92*, 834–847. [CrossRef]
- 25. Lu, B.; Blakers, A.; Stocks, M.; Do, T.N. Low-Cost, Low-Emission 100% Renewable Electricity in Southeast Asia Supported by Pumped Hydro Storage. *Energy* **2021**, *236*, 121387. [CrossRef]
- 26. Vidinopoulos, A.; Whale, J.; Fuentes Hutfilter, U. Assessing the Technical Potential of ASEAN Countries to Achieve 100% Renewable Energy Supply. *Sustain. Energy Technol. Assess.* **2020**, *42*, 100878. [CrossRef]
- 27. Guenther, M. A 100% Renewable Energy Scenario for the Java-Bali Grid. Int. J. Renew. Energy Dev. 2018, 7, 13. [CrossRef]
- 28. Simaremare, A.A.; Bruce, A.; Macgill, I. Least Cost High Renewable Energy Penetration Scenarios in the Java Bali Grid System. In Proceedings of the 2017 Asia Pacific Solar Research Conference, Melbourne, Australia, 5–7 December 2017.

- Tambunan, H.B.; Hakam, D.F.; Prahastono, I.; Pharmatrisanti, A.; Purnomoadi, A.P.; Aisyah, S.; Wicakson, Y.; Sandy, I.G.R. The Challenges and Opportunities of Renewable Energy Source (RES) Penetration in Indonesia: Case Study of Java-Bali Power System. *Energies* 2020, 13, 5903. [CrossRef]
- Veldhuis, A.J.; Reinders, A.H.M.E. Reviewing the Potential and Cost-Effectiveness of Grid-Connected Solar PV in Indonesia on a Provincial Level. *Renew. Sustain. Energy Rev.* 2013, 27, 315–324. [CrossRef]
- Sani, L.; Khatiwada, D.; Harahap, F.; Silveira, S. Decarbonization Pathways for the Power Sector in Sumatra, Indonesia. *Renew. Sustain. Energy Rev.* 2021, 150, 111507. [CrossRef]
- Stocks, M.; Blakers, A.; Cheng, C.; Lu, B. Towards 100% Renewable Electricity for Indonesia: The Role for Solar and Pumped Hydro Storage. Available online: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9102581 (accessed on 15 September 2020).
- Reyseliani, N.; Purwanto, W.W. Pathway towards 100% Renewable Energy in Indonesia Power System by 2050. *Renew. Energy* 2021, 176, 305–321. [CrossRef]
- Breyer, C.; Gulagi, A.; Solomon Oyewo, A.; Bogdanov, D.; Tumiwa, F.; Simamora, P.; Tampubolon, A.; Gordon, P.; Pujantoro, M. Deep Decarbonization of Indonesia's Energy System A Pathway to Zero Emissions by 2050; IESR: Jakarta, Indonesia, 2021; Available online: https://iesr.or.id/wp-content/uploads/2021/05/IESR-Deep-Decarbonization-Final.pdf (accessed on 28 June 2023).
- Bogdanov, D.; Gulagi, A.; Fasihi, M.; Breyer, C. Full Energy Sector Transition towards 100% Renewable Energy Supply: Integrating Power, Heat, Transport and Industry Sectors Including Desalination. *Appl. Energy* 2021, 283, 116273. [CrossRef]
- Silalahi, D.F.; Blakers, A.; Lu, B.; Cheng, C. Indonesia's Vast Off-River Pumped Hydro Energy Storage Potential. *Energies* 2022, 15, 3457. [CrossRef]
- Energy Data Explorer—Our World in Data. Available online: https://ourworldindata.org/explorers/energy?tab=table& facet=none&country=USA~GBR~CHN~OWID_WRL~IND~BRA~ZAF&Total+or+Breakdown=Total&Energy+or+Electricity= Electricity+only&Metric=Annual+generation (accessed on 28 June 2023).
- Solargis. IRENA Solar Resource Maps and GIS Data for 180+ Countries. Available online: https://solargis.com/maps-and-gisdata/download/indonesia (accessed on 7 July 2020).
- Blankenship, R.E.; Tiede, D.M.; Barber, J.; Brudvig, G.W.; Fleming, G.; Ghirardi, M.; Gunner, M.R.; Junge, W.; Kramer, D.M.; Melis, A.; et al. Comparing Photosynthetic and Photovoltaic Efficiencies and Recognizing the Potential for Improvement. *Science* 2011, 332, 805–809. [CrossRef]
- 40. Blakers, A.; Stocks, M.; Lu, B.; Cheng, C. A Review of Pumped Hydro Energy Storage. Prog. Energy 2021, 3, 022003. [CrossRef]
- Stocks, M.; Stocks, R.; Lu, B.; Cheng, C.; Blakers, A. Global Atlas of Closed-Loop Pumped Hydro Energy Storage. *Joule* 2021, 5, 270–284. [CrossRef]
- 42. Australian National University RE100 Group. Global Pumped Hydro Atlas. Available online: http://re100.eng.anu.edu.au (accessed on 17 December 2023).
- Kementerian ESDM RI—Media Center—News Archives—Speaking at COP26, Energy Minister Gives Indonesia's Commitment to Net Zero Emission. Available online: https://www.esdm.go.id/en/media-center/news-archives/speaking-at-cop26-energyminister-gives-indonesias-commitment-to-net-zero-emission (accessed on 30 June 2022).
- IEEFA. IEEFA: Indonesia's State-Owned Utility PLN's 2060 Net Zero Ambition Not without Flaws and Gaps. Available online: https://ieefa.org/articles/ieefa-indonesias-state-owned-utility-plns-2060-net-zero-ambition-not-without-flaws-and (accessed on 30 June 2022).
- 45. Jokowi Haramkan Proyek PLTU Baru Masuk di RUPTL. Available online: https://www.cnbcindonesia.com/news/202105271855 35-4-248863/jokowi-haramkan-proyek-pltu-baru-masuk-di-ruptl (accessed on 30 June 2022).
- 46. Alassi, A.; Bañales, S.; Ellabban, O.; Adam, G.; MacIver, C. HVDC Transmission: Technology Review, Market Trends and Future Outlook. *Renew. Sustain. Energy Rev.* 2019, 112, 530–554. [CrossRef]
- 47. Cheng, C.; Blakers, A.; Stocks, M.; Lu, B. 100% Renewable Energy in Japan. Energy Convers. Manag. 2022, 255, 115299. [CrossRef]
- Verband Deutscher Maschinen und Anlagenbau (VDMA). International Technology Roadmap for Photovoltaic (ITRPV) Results 2022. Available online: https://www.vdma.org/international-technology-roadmap-photovoltaic (accessed on 30 September 2023).
- 49. Dewan Energi Nasional. *Technology Data for the Indonesian Power Sector Catalogue for Generation and Storage of Electricity;* Dewan Energi Nasional, Kementerian Energi dan Sumber Daya Mineral: Jakarta, Indonesia, 2021.
- 50. Hydrogen Indonesia. Available online: https://www.hydrogen-indonesia.id/green-hydrogen/in-indonesia/potential (accessed on 14 July 2022).
- The Hydrogen Trajectory—KPMG Global. Available online: https://home.kpmg/xx/en/home/insights/2020/11/the-hydrogentrajectory.html (accessed on 14 July 2022).
- 52. Bruce, S.; Temminghoff, M.; Hayward, J.; Schmidt, E.; Munnings, C.; Palfreyman, D.; Hartley, P. *National Hydrogen Roadmap*; National Hydrogen Roadmap: Washington, DC, USA, 2018.
- Keputusan Menteri Energi Dan Sumber Daya Mineral No.169.K/HK.02/MEM/2022. Available online: https://jdih.esdm.go.id/ storage/document/Kepmen%20No.%20169.K.HK.02.MEM.M.2021.pdf (accessed on 20 November 2022).
- Listrik Untuk Kehidupan Yang Lebih Baik—PT Perusahaan Listrik Negara (Persero). Available online: https://web.pln.co.id/pelanggan/tarif-tenaga-listrik (accessed on 22 March 2023).
- 55. Nobre, A.M.; Karthik, S.; Liu, H.; Yang, D.; Martins, F.R.; Pereira, E.B.; Rüther, R.; Reindl, T.; Peters, I.M. On the Impact of Haze on the Yield of Photovoltaic Systems in Singapore. *Renew. Energy* **2016**, *89*, 389–400. [CrossRef]

- 56. Sheldon, T.L.; Sankaran, C. The Impact of Indonesian Forest Fires on Singaporean Pollution and Health. *Am. Econ. Rev.* 2017, 107, 526–529. [CrossRef]
- 57. Field, R.D.; Van Der Werf, G.R.; Fanin, T.; Fetzer, E.J.; Fuller, R.; Jethva, H.; Levy, R.; Livesey, N.J.; Luo, M.; Torres, O.; et al. Indonesian Fire Activity and Smoke Pollution in 2015 Show Persistent Nonlinear Sensitivity to El Niño-Induced Drought. *Proc. Natl. Acad. Sci. USA* 2016, 113, 9204–9209. [CrossRef]
- 58. Home-System Advisor Model (SAM). Available online: https://sam.nrel.gov/ (accessed on 20 November 2023).
- 59. Direktorat Jenderal Ketenagalistrikan. Fossil Power Plants Retirement Plan (unpublished data). Direktorat Jenderal Ketenagalistrikan: Jakarta, Indonesia, 2022.
- 60. Direktorat Jenderal Ketenagalistrikan Statistik Ketenagalistrikan 2020; Direktorat Jenderal Ketenagalistrikan: Jakarta, Indonesia, 2021.
- 61. Direktorat Jenderal Ketenagalistrikan. *Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) PLN 2021–2030;* Direktorat Jenderal Ketenagalistrikan: Jakarta, Indonesia, 2021.
- Indonesia-Google Maps. Available online: https://www.google.com/maps/place/Indonesia/@-2.6007391,117.2664279,5z/data= !4m6!3m5!1s0x2c4c07d7496404b7:0xe37b4de71badf485!8m2!3d-0.789275!4d113.921327!16zL20vMDNyeW4?entry=ttu (accessed on 28 November 2023).

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