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The Challenges and Opportunities of Renewable Energy Source (RES) Penetration in Indonesia: Case Study of Java-Bali Power System

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Abstract: Nowadays, the integration of renewable energy sources, especially grid-connected photovoltaic, into electrical power systems, is increasing dramatically. There are several stimulants especially in the Java-Bali power system, including huge solar potential, a national renewable energy (RE) target, regulation support for prosumers, photovoltaic technology development, and multi-year power system planning. However, significant annual photovoltaic penetration can lead to critical issues, including a drop of netload during the day, ramping capability, and minimal load operation for thermal power plants. This study analyses the duck curve phenomenon in the Java-Bali power system that considers high shares of the baseload power plant and specific scenarios in photovoltaic (PV) penetration and electricity demand growth. This study also analyses future netload, need for fast ramping rate capability, and oversupply issues in the Java-Bali power system. The results showed that the duck curve phenomenon appears with a significant netload drop in the middle of the day because of high power generation from grid-connected PV. Furthermore, the need for fast ramp rate capability is critical for a higher peak load combined with the lowest netload valley. Moreover, the significant load growth with high grid-connected PV penetration level caused unit commitment issues for thermal power plants as baseload operators.

Keywords: duck curve phenomenon; high-penetration level; renewable energy source (RES); photovoltaic (PV); ramp rate; flexibility; netload; baseload; peak load; unit commitment; Java-Bali; Indonesia

1. Introduction

Energy plays a critical role in the global economy. While conventional energy from fossil fuels is increasingly limited, primarily to address climate change and other environmental issues, the use of renewable energy is widely encouraged for the same reasons. In the electrical power field, Renewable Energy Sources (RES), such as geothermal, biomass, hydro, tidal, wind, and solar, generate electricity. One popular type of RES with the highest global potential is solar energy from the sun [1,2]. The major stimulant regarding solar energy is that of reducing global greenhouse gas (GHG) emissions. In general, conversion technologies can be grouped into two categories: Solar photovoltaic (PV) technology and solar thermal technology. Solar PV technology uses semiconductors to directly convert the electromagnetic energy in sunlight into electricity through the PV module [3]. Solar thermal technology uses Concentrated Solar Power (CSP) with high-magnification mirrors to concentrate solar energy into heat energy [4].

Indonesia is an archipelago country spanning the equator. This country has a tropical climate where sunlight shines virtually every day of the year. This favourable condition offers great potential to integrate RES, especially from solar energy to electrical power systems. Some factors that make the country's solar resource so substantial include latitude, longitude, variation, geographic variation, season and climate, as these responsible for the level of solar irradiance distribution that passes through the atmosphere [5]. Indonesia's national energy policy sets the ambitious national target for an optimal power mix of 23% RES sources in 2025 and 31% RES sources by 2050 [6]. Based on the electricity supply business plans from the national electric company (PLN), Indonesia has a great potential to generate more than 207 GW from solar energy [6].

Furthermore, several conditions will play an important role for massive PV growth in Indonesia: PV technology improvement; decreasing materials costs; electricity ratio targets for remote areas; and significant development programs in the next few years to achieve the national RES mandate. There are several reasons for the significant development of electrical generation from solar energy in Indonesia, including great solar potential, national RE target, regulatory support for prosumers, PV technology development, and also power system planning from RES [1,6].

The intersection between electricity price and PV levelised cost of energy (LcoE) will eventually reach grid parity, meaning that PV rooftop systems economically compete with electrical generating by utility companies [7]. Five cities in China and cities in Southern and Central Italy will reach grid parity over the next few years [8,9], and several cities in Indonesia will also achieve grid parity over a similar timescale [2,10]. This condition can also increase PV utilisation into the distribution system.

Today, trends to install grid-connected PV have been significantly increasing all over the world. However, grid-connected PV fundamentally changes the nature of power system operation in terms of steady-state and transient stability performance. Indonesia's power generation sector has been dominated by the use of fossil fuels, particularly coal-fired power plants. This type of thermal power plant is typically used to provide daily baseload, which has a low ramping rate to respond to load fluctuation [11,12]. Studies in several power systems showed the impact of very high penetration levels of solar PV. These studies capture stability and reliability issues, such as voltage stability (rising, fluctuations, and unbalance) [13–15], frequency stability (grid inertia and intermittency) [16,17], and reverse power flow phenomena [18,19]. Another study shows the importance of PV in a hybrid energy system to achieve the most economically feasible option in providing the lowest system net present cost, operating cost and cost of energy [20]. However, it is important to note that the application of distributed generation, i.e., PV, diesel generators, and wind turbines, also brings many drawbacks, such as voltage drops and power losses [15].

The California Independent System Operator (CAISO) is the first power system operator to publish the duck curve phenomenon, i.e., the daily netload chart on a spring day with a significant drop in mid-day caused by high PV generation [21]. This chart shows that the grid operator faces a new challenge to prepare the high ramp rate ability to accommodate the fully utilised solar PV energy during the daytime. This condition results in an overgeneration potential because of the very high penetration level of PV in the system. Like CAISO, several systems in different countries with high PV penetration are also concerned by this issue. Beside supporting ancillary services, some studies also offer mitigation to deal with the duck curve by enhancing power system flexibility, including optimal dispatch based on flexible resources [22], optimal thermal unit commitment [23,24], demand-side management [25], power curtailment [26], and pumped hydro energy storage [27,28]. Some studies offer mitigation using supporting ancillary services from electric vehicles (EV) to the grid [29,30] and advanced battery energy storage systems [31–33] to support the grid system.

The power system operator must mitigate the massive growth of grid-connected PV into the grid system. This condition has changed the behaviour of the electrical power system. The high generation from solar energy during the day potentially leads to the duck curve phenomena. This condition will be a critical issue for power systems with high shares of thermal power plants providing baseload in the energy mix.

Therefore, this study aims to investigate the future challenges of integrating high penetration levels from grid-connected PV into the electrical power system in the Indonesia power grid as a representative of developing countries with a high share of thermal power plants in the future energy mix. The condition of Indonesia's electrical power system, including national power system planning, the Java-Bali power system as the most extensive system in Indonesia, the needs of system flexibility, thermal power plant development planning, RE potency especially from solar energy, and netload curve, due to the impact of PV penetration levels, are explained in Section 2. The methodology and several case studies are discussed in Section 3. Next, Section 4 explains the power system simulation results, including the netload analysis, ramping capability analysis, and baseload analysis. Section 5 summarises the findings from this study. There are previous studies that examined the characteristics and the modelling of the Java-Bali as in References [34–37]. Based on the literature review conducted by the authors, this paper is the first study to analyse the duck curve phenomenon in the Java-Bali power system that considers high shares of a baseload power plant and specific scenarios in PV penetration and electricity demand growth. This study also analyses future netload, need for fast ramping rate capability, and oversupply issues in the Java-Bali power system.

2. Energy Mix Indonesia's Electricity Supply Business Plans

This section explains the national energy policy and Indonesia's electricity supply business plans book (RUPTL) from the PLN about the present power system condition and energy mix in Indonesia, RES potency, planning, and impact, especially from solar PV integration into the grid system.

2.1. Electricity Supply Business Plans

This subsection looks at the power system planning condition in Indonesia with emphasis on the Java-Bali power system, the available system flexibility, and the existing thermal power plant rundown planning to integrate into the grid.

2.1.1. Power System Planning

As the largest archipelago country, Indonesia's system planning is usually island-based, such as Java-Bali, Sumatera, Kalimantan, Sulawesi, Nusa Tenggara, Maluku, Papua, and other smaller systems. Today, power grid systems are commonly inter-area connected with 500 kV, 275 kV, and 150 kV lines. Electrical demand is strongly correlated to economic development, population growth, and consumer lifestyle [34]. PLN, as the electrical state-owned enterprise, has a monopoly on transmission and distribution. Indonesia's electric power development is guided by RUPTL, i.e., the book of electricity supply business plans of Indonesia for the next ten years.

One of the significant parameters for demand forecasting is economic growth with expectations of 6–7% per year, so the load projection is relatively high [38]. The adequacy of future demand and power supply is supported by PLNs long-term guarantee through Power Purchase Agreements (PPAs) for Independent Power Producers (IPPs). Due to the financial crisis, power plant planning from IPPs is dominated by thermal power plant technology with PPAs take-or-pay (TOP) commercial clauses [12]. Unfortunately, economic growth did not meet expectations. In contrast, PLN also receives a mandate to achieve the share of new and RE (23% in 2025 and at least 31% in 2050). This condition will lead to oversupply risk in several systems and overpaying for power generation with low/unutilised operation.

2.1.2. Java-Bali Power System

The Java-Bali interconnected power system is the most extensive power system in Indonesia, comprising approximately 70% of the national capacity (Figure 1). This condition is driven by a larger population and higher economic activities compared to the other islands. The Java-Bali load system consists of five areas: Jakarta; West Java; Central Java; East Java; and Bali. The western to the eastern region is interconnected via 500 kV transmission lines (blue lines). The inter-area from the most western to easternmost parts is interconnected via a 150 kV transmission line (red line). The Java power system is interconnected to the Bali system by 150 kV submarine cables (red line) [37]. The Java-Bali power system is operated by the transmission system operator (TSO) in Gandul, West Java. The peak load is approximately 27 GW.

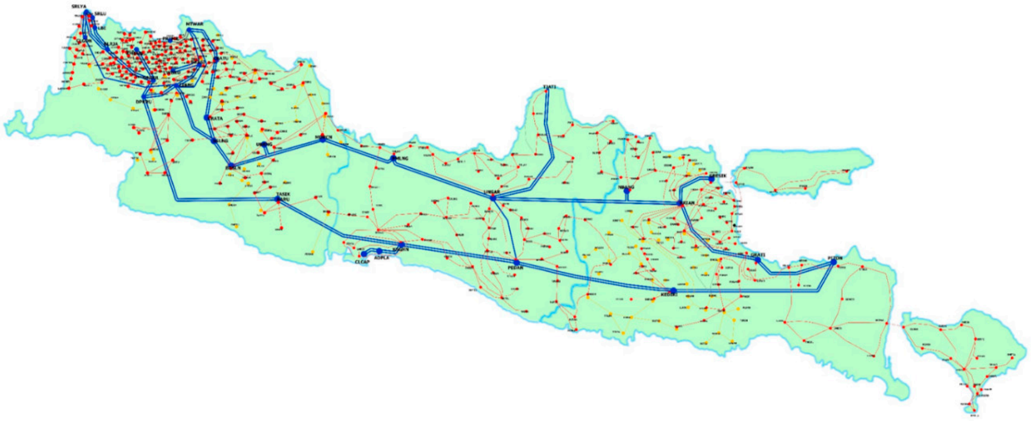


Figure 1. Java-Bali interconnected power system.

The power generation fuel mix year 2019 includes coal (70.92%), gas (21.33%), including liquefied natural gas (LNG), gas fuel (BBG), and compressed natural gas (CNG), and marine fuel oil (MFO) and high speed diesel (HSD), both accounting for approximately 0.14%, as shown in Figure 2. Currently, the power supply is mainly generated from geothermal and thermal power plants as baseload operation. Thermal coal forms the largest share of the fuel mix in 2020 compare to other energy sources (72.61%) and is set to account for 57.56% of the energy share in 2028. From 2019 to 2028, the capacity of a coal power plant will be increasing, but the percentage of the energy mix will be decreasing. Regarding RES, geothermal (4.82%) and hydro (2.89%) contribute the largest shares, with other RES, such as wind, biomass, ocean, and especially solar, still accounting for a lower share of the energy mix than fossil fuel. Over the next few years, PLN aims to achieve the national RE target (23% of the total energy mix) [6]. Several big projects are carried out to build RE power plants, especially PV power plants.

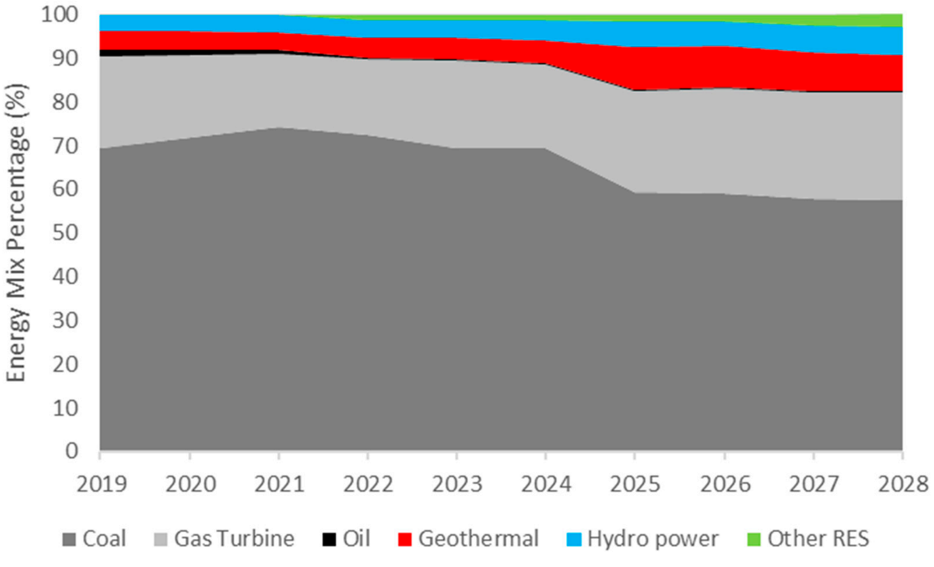


Figure 2. Percentage of the energy mix from 2019 to 2028.

Indonesia's RUPTL have identified four different categories of consumers: Residential (households); commercial (private business); industrial (large business, usually mining or extensive industrial process); and public (for example government sector and street lighting), as shown in Table 1. Most consumers dominate the residential category, but the substantial load comes from the industrial category. In the next few years, consumers, especially from the residential category, will be able to produce their own energy, for example via home PV rooftop installations. This kind of relatively new consumer is called 'prosumers'. In the future, prosumers will significantly increase because of support from government policy and the PLN.

Table 1. The number of customers per category (in thousand).

Years	Residential	Commercial	Public	Industrial
2019	13,584	2628	1410	74
2020	47,657	2763	1500	77
2021	48,038	2915	1597	80
2022	48,442	3069	1703	84
2023	48,835	3224	1816	87
2024	49,205	3382	1936	91
2025	49,582	3541	2065	95
2026	49,919	3711	2207	99
2027	50,245	3901	2361	104
2028	50,561	4091	2526	109

2.1.3. System Flexibility

The operational flexibility of power plants plays an essential role in accommodating the variability in supply and demand. Constraints include higher ramp-rate capability, shorter start-up time and lower start-up costs, shorter minimum uptime and runtime, and lower minimum load [39]. A high ramp rate can make the power plant quickly produce the power in line with system needs. Shorter start-up times resulted in a power plant to reach full load quickly and reduce the minimum time after start-up so that power plants can react rapidly. For thermal systems, especially coal-fire based plant and power plants with a large share of Combined Heat and Power (CHP), operational flexibility depends on some crucial parameters, such as degrees of pressure, flow rate, main devices temperature, and the degree of feedwater bypass [40]. Operating thermal power plants at lower loads increases the range of their operation and also improves flexibility.

The flexibility characteristic of various power plant technologies is summarised in Table 2. Some power plant technologies are designed for baseload operations. This includes geothermal plants, nuclear power plants, coal-fired power plants, steam turbines with oil or gas as boiler fuel, and gas turbine combined cycle plants. These are all called non-flexible power plant. This type needs time for start-up and ramping operations. In contrast, the flexible power plant is designed for load following, i.e., flexible coal-fired power plants, biomass, biogas, and many more. (Power plant technologies that can adjust their generation level in a moderate period to compensate for power supply and load variations.) Moreover, power plants that can adjust their generation level in a short time compensate for the variability are called high flexible power plants, including reservoir hydro, combustion engines, and simple gas turbines. Indonesia's power plants are dominated by non-flexible generation from thermal power plants, especially coal-fired-based power plants [12].

Table 2. Typical flexibility characteristics of various power plant technologies [41].

Power Plant Technology	Minimum Load (% Full Load)	Ramping Rate (% Full Load/Minutes)	Hot Start Up Time (Hours)
Hydro Reservoir	5	15	0.1
Simple Cycle Gas Turbine	15	20	0.16
Geothermal	15	5	1.5
Gas Turbine Combined Cycle	20	8	2
Concentrated Solar Power	25	6	2.5
Steam Plants (gas, oil)	30	7	3
Coal Power	30	6	3
Bionergy	50	8	3
Lignite	50	4	6
Nuclear	50	2	24

2.1.4. Thermal Power Plant

The Java-Bali power system currently has specific power system characteristics, i.e., oversupplying issues from thermal power plants and potential significant penetration levels from grid-connected PV. Indonesia, especially the Java-Bali power system, plans to build coal-fired thermal power plants over the next few years, as shown in Table 3. Based on RUPTL, coal-fired thermal power plant capacity continues to grow annually. The plans indicate that the coal power plant will account for approximately 57.44% of the total energy mix in 2028 [6]. Various power plant technologies are used to generate power in Indonesia's power systems, but thermal power plants produce the most power generation, with the majority coal-fired based. Coal-fired thermal power plant characteristics are constant power output and low ramping rate. Therefore, the coal power plant cannot be adjusted to respond to Variable Renewable Energy (VRE), notably intermittency, peak load preparation, and demand fluctuations. This condition has resulted in a coal-fired thermal power plant being operated as a baseload power plant. The burning of coal fires the boiler to generate very high-temperatures and produce high-pressure steam, which is then used to drive a steam turbine attached to a generator to generate electricity.

Table 3. Thermal power plant planning.

Years	Capacity (MW)
2019	315
2020	4827
2021	2000
2022	924
2023	2000
2024	1660
2025	660
2026	1000
2027	660
2028	0
Total	14,046

2.2. *Renewable Energy Source (RES)*

2.2.1. Renewable Energy Planning

In the process of utilising solar energy, three methods are currently commonly used to generate electricity and other uses, as shown in Figure 3 [42]. In Indonesia, the subject is the process of direct solar irradiation conversion using solar cells or PV modules into electrical energy.

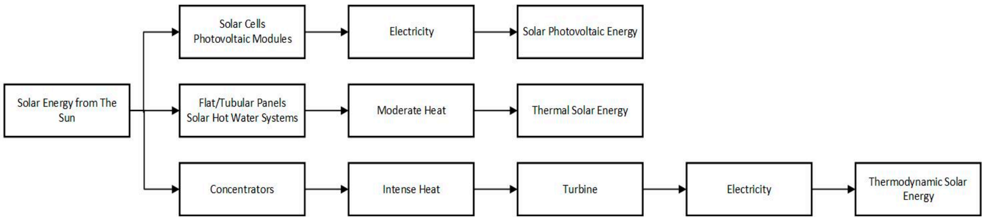


Figure 3. Process of utilising solar energy.

Electricity from RES, especially from solar PV, is growing worldwide. The leading countries for cumulative solar PV capacity are China, the United States, Japan, Germany, and India. China has the most installed solar PV power plant in the world [43]. Their national RE target predominantly causes the growth of electrical generation from RES globally. Government policies support RE targets in most countries. Such government policy objectives are to reduce the carbon emissions of GHGs in the power sector and encourage new generation from RES. Likewise, the Indonesian Government's plans to achieve the RES targets regarding the total primary energy mix of 23 and 31 percent by 2025 and 2050, respectively. As Table 4 shows, RES potency in Indonesia derives from a broad range of renewable technologies and fuels. However, to date, this vast potential has not been accessed properly.

Table 4. Renewable energy potency in Indonesia.

Energy	Potency	Utilisation
Geothermal	29,544 MW	4.9%
Hydropower	75,091 MW	6.4%
Mini-micro hydropower	19,385 MW	1.0%
Bioenergy	32,654 MW	5.1%
Solar power	207,898 MW (4.8 kWh/m^2/day)	0.04%
Wind power	60,647 MW (≥4 m/s)	0.01%
Ocean	17,989 MW	0.002%

2.2.2. PV Power Planning

PLN is employing various efforts to improve the share of RES in the total primary energy mix. One way is via solar power plant development planning from 2019 to 2028, as in Table 5.

Table 5. Solar power plant roadmap planning by the national electric company.

Years	Capacity (MW)
2019	63
2020	78
2021	219
2022	129
2023	160
2024	4
2025	250
2026	-
2027	2
2028	2
Total	908

Java-Bali has significant solar potential in each region. The potential capacity of solar energy in several provinces of Java-Bali island is shown in Table 6. This study assumes the PV power plant generation planning, prosumer growth in distribution level, and solar energy potency according to RUPTL 2019 to 2028 [6].

Table 6. Solar energy potential per province in Jawa-Bali island (Java-Bali and Sumatra power systems are two of the largest power systems in Indonesia. Electricity Subsystem boundaries for the Java-Bali power system, in detail, could be found in Reference [35], while electricity subsystem boundaries for Sumatra power system could be found in Reference [36]).

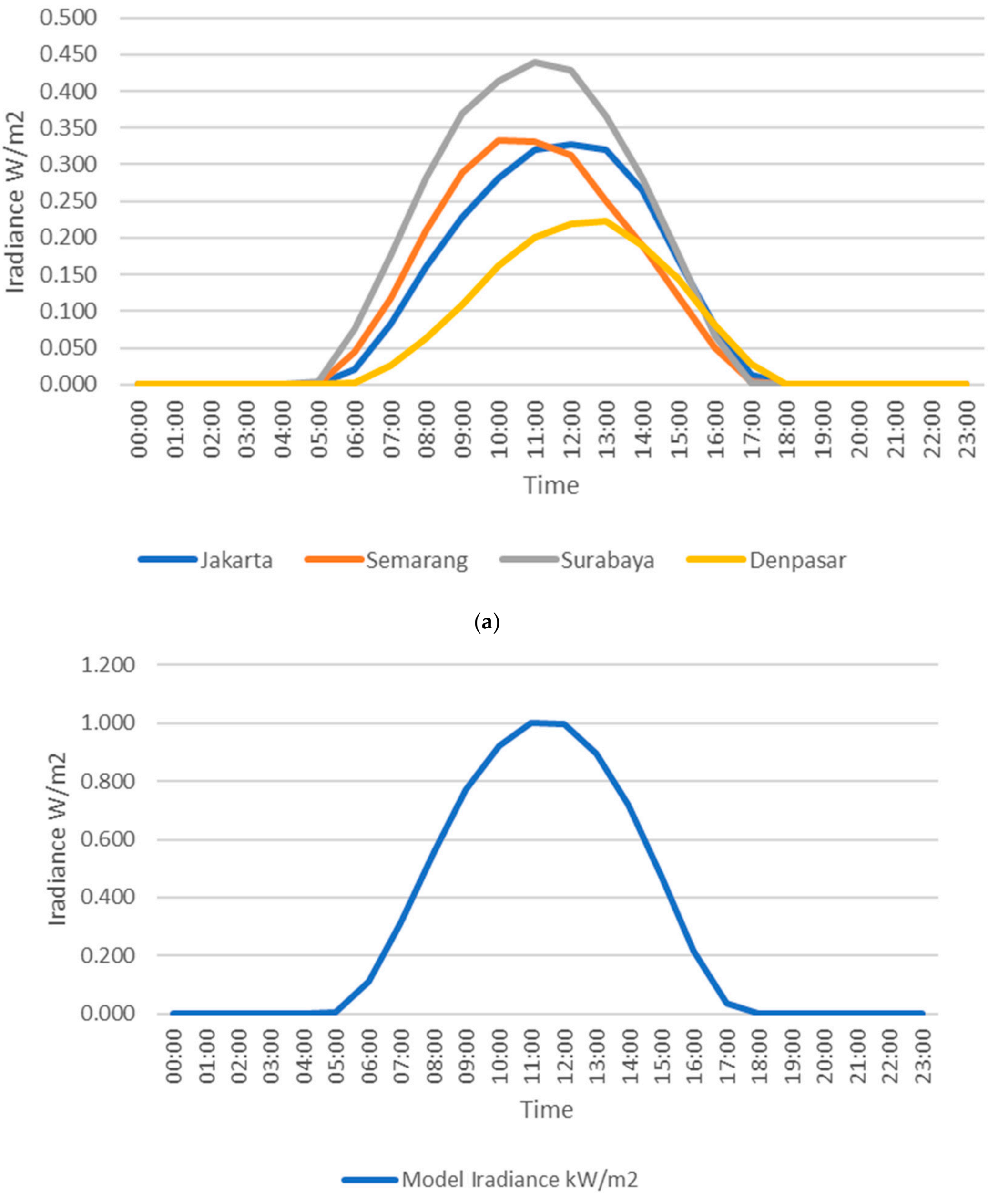
Subsystem	Region	Potential Capacity (MW)
West Java	Saguling	220
	Bekasi	600
	Cirata	145
	Bogor	1
	Cianjur	4
	Jatiluhur	100
	Jatigede	100
	Indramayu	10
	Subang	150
Central Java	Tegal	220
	Gajahmungkur	100
	Kedung Ombo	100
	Pemalang	40
East Java	Tuban	140
	Karangkates	100
	Pasuruan	40
Bali	West Bali	50
	East Bali	50

2.2.3. Netload Power

From the TSO perspective, assume the electrical load consumption data for several days denoted by a set D divided into several time slots denoted by a set T. The netload power on day d at time slots t can be expressed using Equation (1) where $P_{load}(d,t)$ is the actual load power and $P_{PV}(d,t)$ is the total PV power output on day d at time slot t [44].

$$P_{net}(d,t) = P_{load}(d,t) - P_{PV}(d,t),\ d \in D, t \in T \tag{1}$$

The availability of solar energy resources on the ground surface is an essential factor in utilising PV systems. This depends on solar irradiation as the amount of solar energy over an area in a specific time expressed in kWh/m^2. The Java-Bali region consists of Jakarta in West Java, Semarang in Central Java, Surabaya in East Java, and Denpasar in Bali. At one time frame, the easternmost area in Java island is the first area to experience both sunrise and sunset compared to the most western area. Based on solar irradiation databases, the energy potency in some regions in Java-Bali is shown in Figure 4a. Due to the geographical aspect, Java-Bali extends from west to east, so there will be differences in solar irradiance in each region. The solar output model in this study involves the solar comparison of different locations based on the geographic location of the Java-Bali power system. The Java and Bali islands are interconnected by the transmission line system. Therefore, we could model the solar irradiance of the Java-Bali power system as in Figure 4b. The interannual data of Java-Bali island, located at −6.1748 latitude and 106.7863 longitude, are based on the National Aeronautics and Space Administration (NASA) predictions of global energy resource (POWER) database. The monthly maximum solar irradiance is in December 2014, where the maximum solar daily irradiance is on 17 December.



(**a**)

(**b**)

Figure 4. (**a**) Solar irradiance in Jakarta (nearby West Java), Semarang (Central Java), Surabaya (East Java), and Denpasar (Bali); (**b**) representation model of solar irradiance in Java-Bali.

3. Methodology

To analyse the high penetration level impact of grid-connected solar PV into power systems regarding the proportion of thermal power plants in the energy mix, the proposed method conducted in this study is portrayed in Figure 5. Basically, this methodology has three stages: (1) System parameters of power grid and PV power plants; (2) thermal power plants and PV output; and (3) analysis.

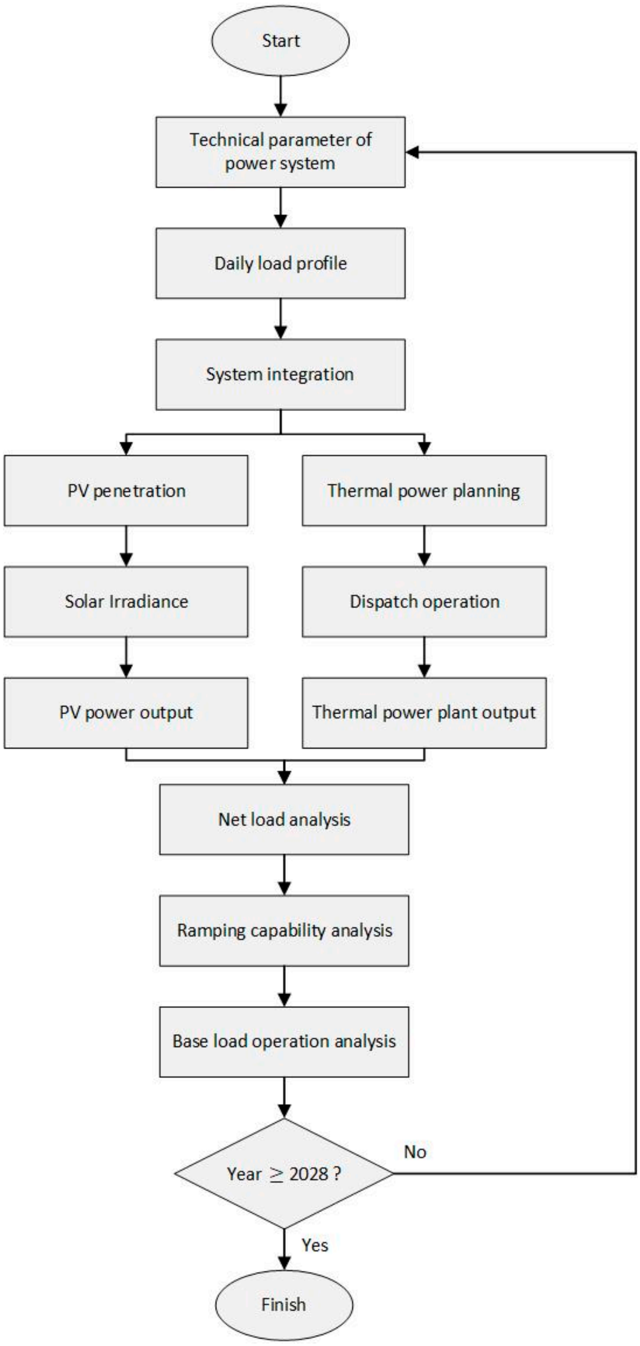


Figure 5. The flowchart of grid-connected photovoltaic (PV) penetration level.

The analysis integrating grid-connected PV into the Java-Bali power system consists of four case studies, as shown in Table 7. The simulations are combined with power system load growth and PV penetration level to analyse the sensitivity analysis of each case. The simulations also consider the integration of a new thermal power plant onto the system.

Table 7. The scenario of load growth and PV penetration level.

Case Study	Scenario
I	Significant load growth with a high PV penetration level
II	Slow load growth with a low PV penetration level
III	Significant load growth with a low PV penetration level
IV	Slow load growth with a high PV penetration level

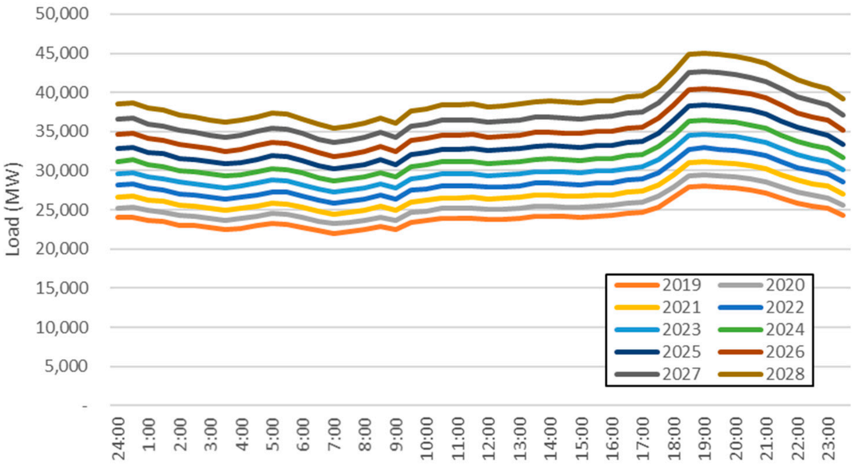
Scenario I is a scenario where peak load growth and PV capacity growth are considered to be optimistic. The peak load is considered to meet the power system planning target so that the daily load profile will be scaled according to the system plan. PV capacity growth is set to be optimistic according to the time plan, solar energy potential is optimally utilised, and solar home PV rooftop massively integrates to the system in accordance with the growth of household customers.

Scenario II is a scenario where peak load growth is considered to be pessimistic or not in accordance with the power system planning. The peak load is considered not to meet the planning target so that the typical load profile of the system will be scaled based on the average sales realisation of the last five years (4.62%). However, PV capacity growth is said to be non-optimal because of late construction, solar energy potential is not optimally utilised, and solar home PV rooftop grows slowly.

Scenario III is a scenario where peak load growth and PV capacity growth are considered to be optimistic. The peak load is considered to meet the power system planning target so that the daily load profile will be scaled according to the system plan. However, PV capacity growth is said to be non-optimal because of late construction, solar energy potential is not optimally utilised, and solar home PV rooftop grows slowly.

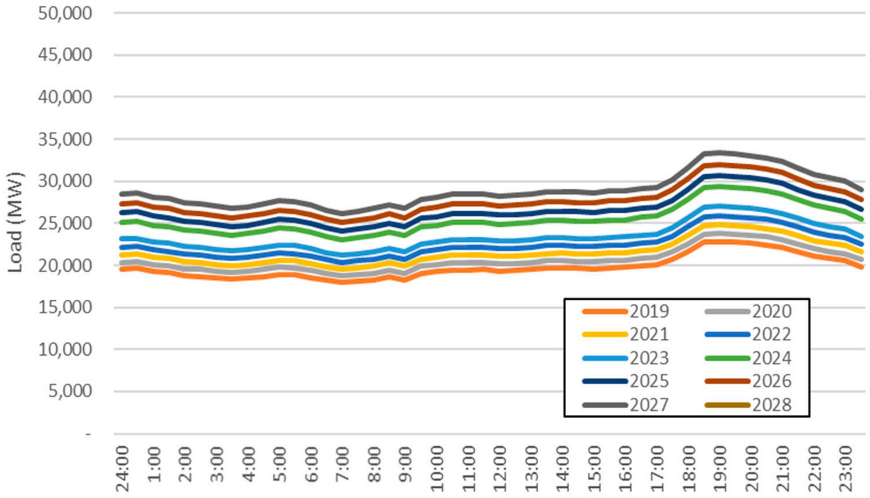
Scenario IV is a scenario where peak load growth is considered to be pessimistic or not in accordance with the power system planning. The peak load is considered not to meet the planning target so that the typical load profile of the system will be scaled based on the average sales realisation. On the other hand, PV capacity growth is set to be optimistic according to the time plan, solar energy potential is optimally utilised, and solar home PV rooftop massively integrates to the system in accordance with the growth of household customers.

The typical daily load profile chosen is used as the model of system load. The typical hourly electricity load profile for the Java-Bali power system is shown in Figure 6a,b. Figure 6a is the load curve of the Java-Bali system with significant load growth for the years 2019–2028, while Figure 6b is the load curve of the Java-Bali power system with relatively low load growth. Load data were recorded on the 6 January 2019. Electricity consumption fluctuates throughout the day. The electricity consumption at night is higher than electricity consumption during the day time. The peak load typically occurred at 18:00 to 19:00, as a result of residential activities.



(**a**)

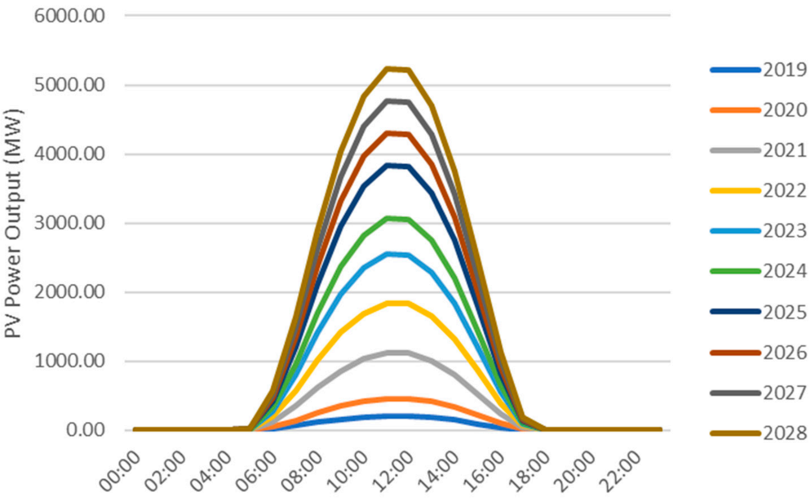
Figure 6. *Cont.*



(**b**)

Figure 6. (**a**) Java-Bali system with significant load growth; (**b**) Java-Bali system with slow load growth.

Based on the representation model of solar irradiance in the Java-Bali power system, the annual PV power generation during the day is illustrated in Figure 7. Figure 7a is the high PV penetration level in the Java-Bali power system, while Figure 7b shows the low PV penetration level in the Java-Bali power system. The PV power output is a summary of the prosumer, solar power plant roadmap planning, and also the capacity of solar potential reported from each province in Java-Bali. The growth of home solar PV rooftop is assumed to increase 0.01 percent every year from 5500 VA customers of the residential category.



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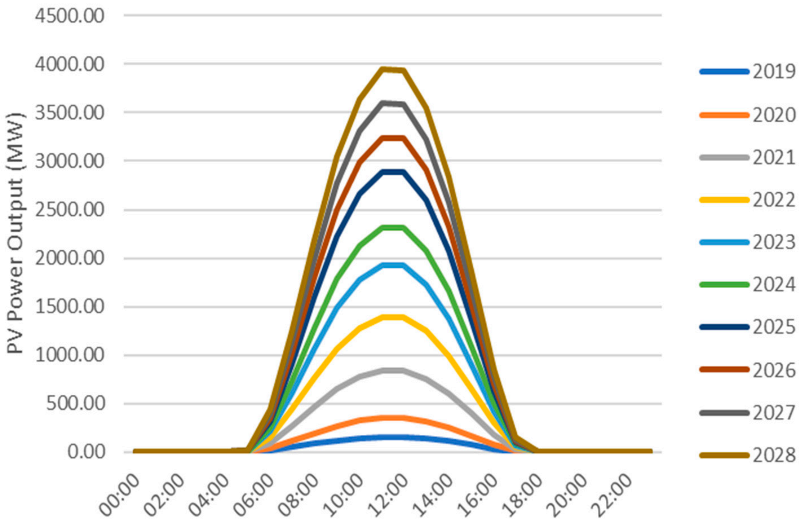


(**b**)

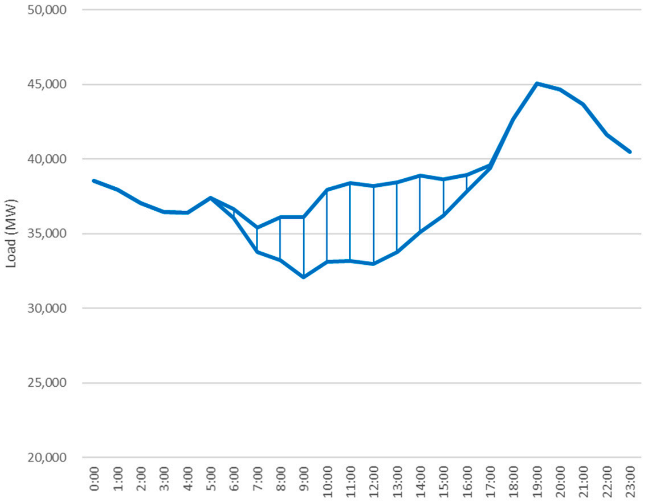
Figure 7. (**a**) High PV penetration level in the Java-Bali power system; (**b**) low PV penetration level in the Java-Bali power system.

4. Simulation Results

This section discusses the system conditions from 2019 until 2028 as planned years, including netload analysis, ramp rate analysis, and baseload operation analysis in the Java-Bali power system.

4.1. Netload Analysis

Simulation results show a belly in the daily load profile that represents that the PV power output is at maximum, where the netload is at the lowest, as shown in Figure 8a–d. This phenomenon, called the Java-Bali duck curve–which the belly grows–depends on the grid-connected PV penetration level. PV power plants produce the highest output in midday depending on sunlight availability. Therefore, the duck curve significantly drops in middle day netload conditions. Both loads with significant growth, as shown in Figure 8b,d, experience the same phenomenon. Netload shows a significant drop during mid-day, as shown in Figure 8a,d, while for Figure 8b,c, it drops lower. The belly typically slowly occurs to the lowest from 05:30 to 11:00. and slowly increases from 11:00 to 17:30 in west Indonesia times.



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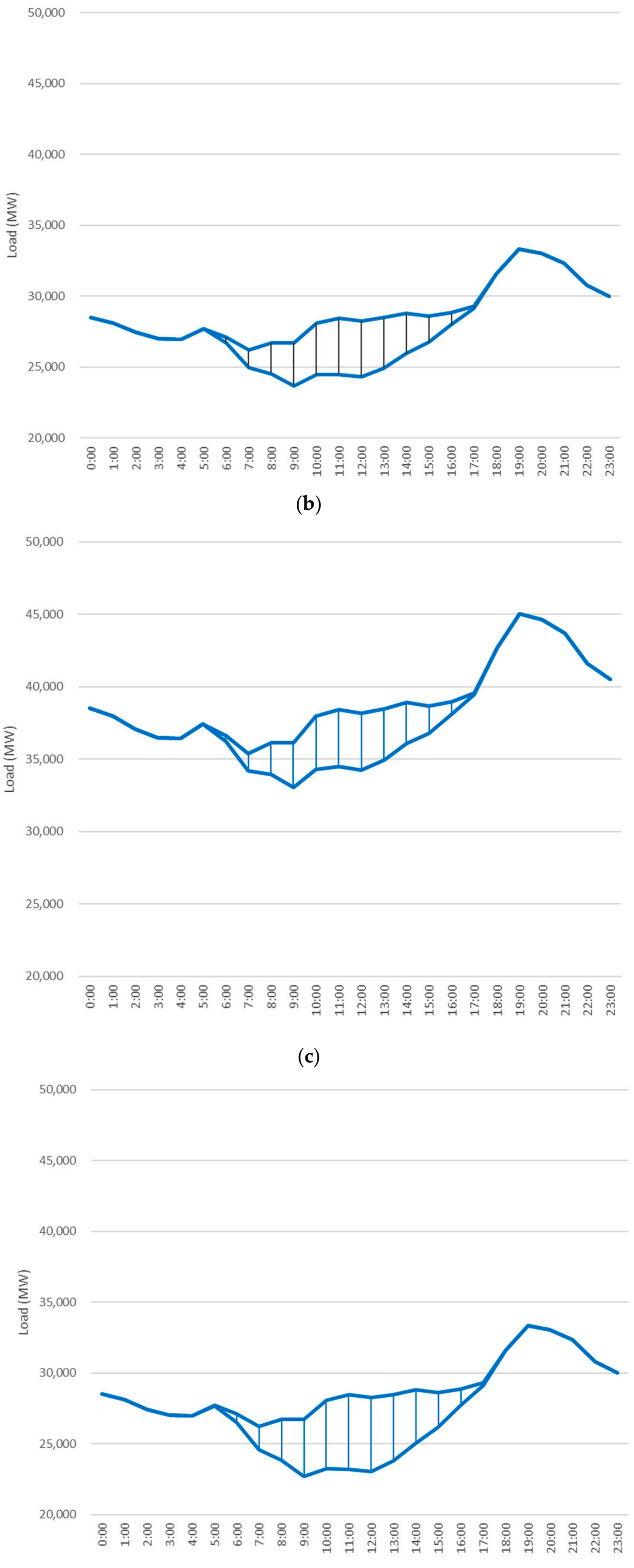


(**b**)

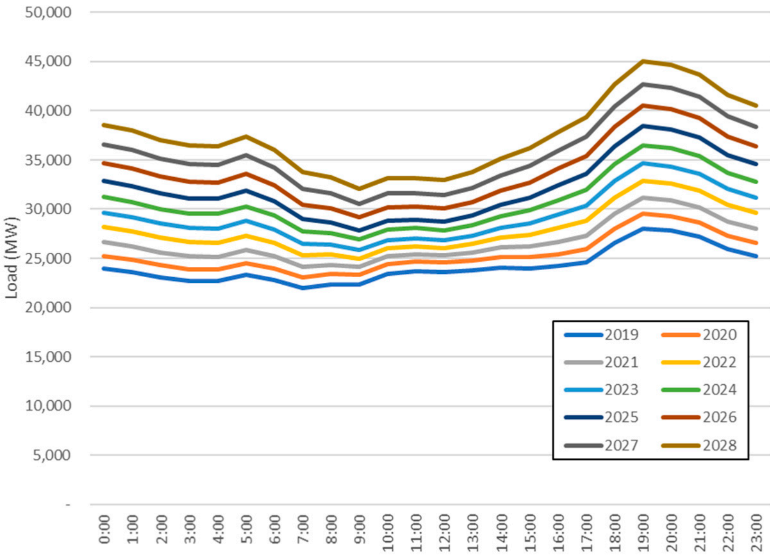
(**c**)

(**d**)

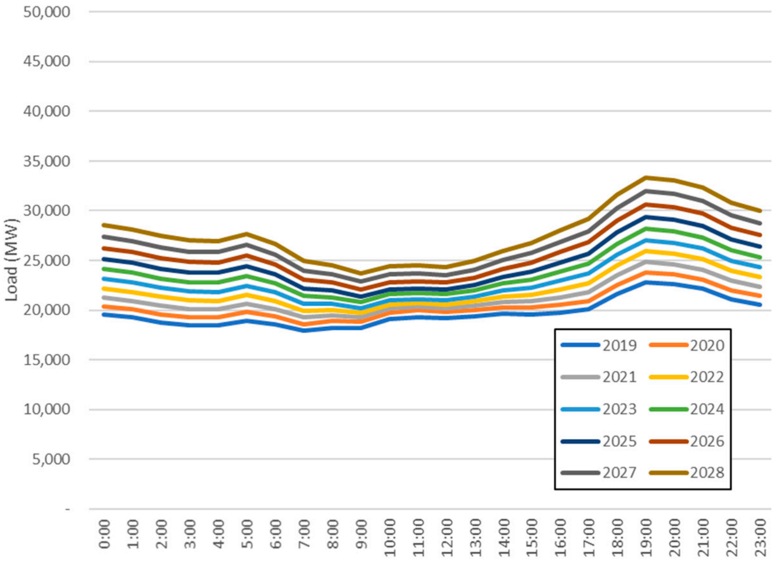
Figure 8. (**a**) Case study I: Netload analysis on significant load growth with high PV penetration level; (**b**) case study II: Netload analysis on slow load growth with low PV penetration level; (**c**) case study III: Netload analysis on significant load growth with low PV penetration level; (**d**) case study IV: Netload analysis on slow load growth with high PV penetration level.

4.2. Ramping Capability Analysis

According to the simulation results in Figure 8, the load dispatch centre must balance the supply and demand in the power system to meet the upcoming ramps down in the morning when the sun begins to shine and ramps up in the late afternoon when the sun begins to set, as shown in Figure 9a–d. The first challenge is in the morning hours when the system operator faces low demand combined with increasing generation from PV. The morning ramp requires decreasing output from power plants. Ramp down capability is vital for power plants to respond to this situation. The second challenge is in the late afternoon hours when the system operator prepares for peak load combined with decreasing generation from PV. The late afternoon ramp requires the fast ramp-up from power plants as load followers.

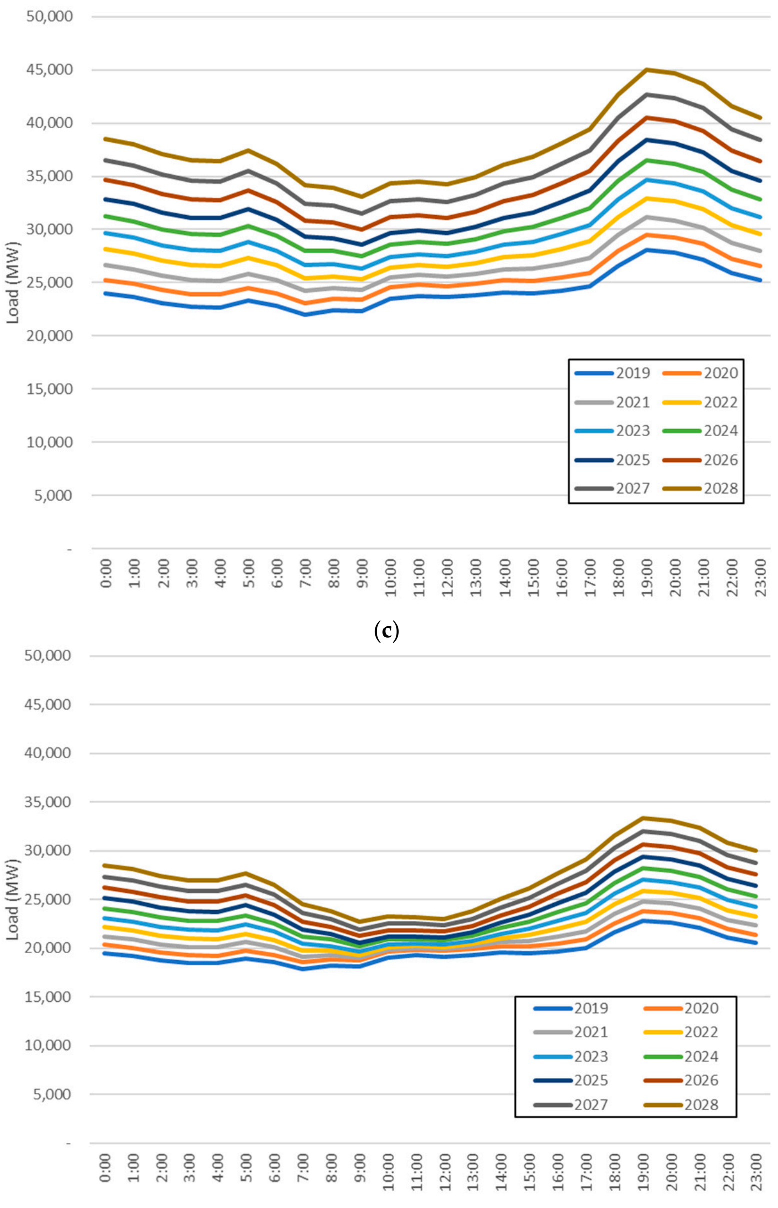


(**a**)



(**b**)

Figure 9. *Cont.*



(**c**)

(**d**)

Figure 9. (**a**) Case study I: Ramp rate analysis on significant load growth with high PV penetration level; (**b**) case study II: Ramp rate analysis on slow load growth with low PV penetration level; (**c**) case study III: Ramp rate analysis on significant load growth with low PV penetration level; (**d**) case study IV: Ramp rate analysis on slow load growth with high PV penetration level.

Figure 9a,d show the need for fast ramp capability to respond to the high penetration level of grid-connected PV. The higher peak load combined with, the lower belly results in need for fast ramp rate performance, which is important and essential for the power system, as shown in Figure 9a rather than Figure 9b–d.

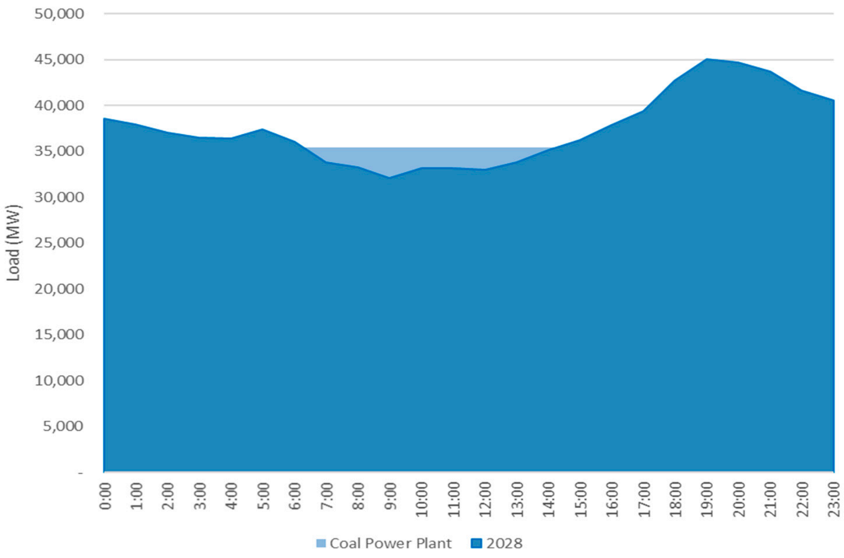
The need for a fast ramp rate, especially a range of fast ramp-ups for all possible scenarios is summarised in Table 8. In 2028, the system operator must prepare 1555 MW to 2097 MW to meet the system peak load. The system operator must operate fast response power plant resources, such as hydro, gas turbines, and also diesel to follow the peak load.

Table 8. Ramp rate needs issues.

Years	Ramp Rate (MW/hours)
2019	781.27–969.76
2020	832.81–1044.70
2021	897.98–1140.69
2022	959.27–1234.50
2023	1051.48–1368.39
2024	1159.94–1522.70
2025	1254.98–1657.05
2026	1352.53–1794.56
2027	1452.71–1941.94
2028	1555.61–2097.53

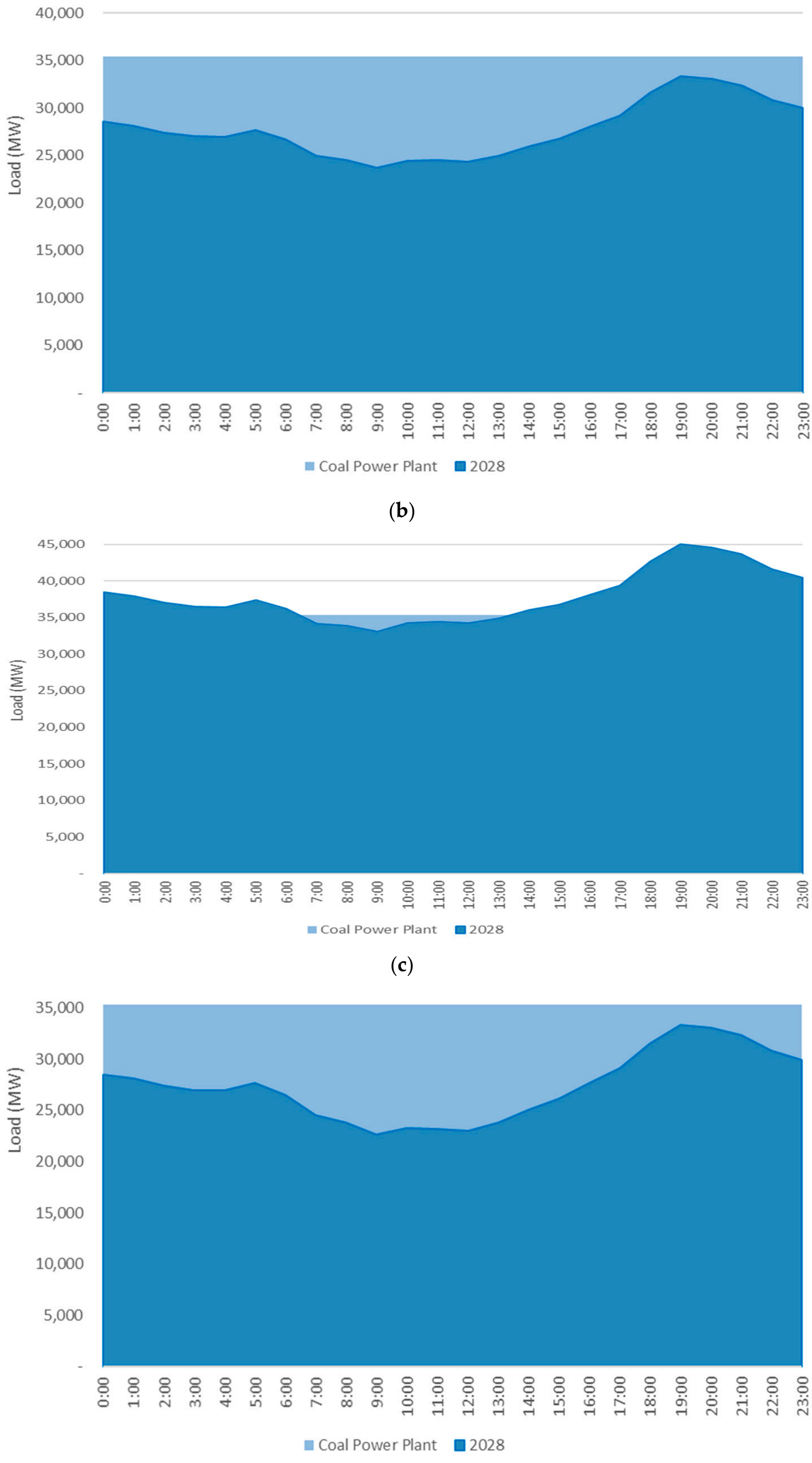
4.3. Baseload Operation Analysis

According to the simulation results in Figure 10a–d, there is overgeneration in all scenarios, especially from thermal power plants as the baseload power plant. The majority of thermal power plants in the Java-Bali power system operate with the TOP commercial clause, also known as must-run power plants. Therefore, the power system operator faced challenges to reduce the generation from conventional power plants with the TOP scheme. The issues are technical and economic limits from thermal power plants to reduce the power output. The critical condition, as shown in Figure 10b,d, is that of significant supply combined with the slow growth of demand. The power generation from thermal power plants will be absorbed by consumers if the electricity demand reaches the load growth target Figure 10a,c shows the case study with significant load growth and high PV penetration which also cause Unit Commitment (UC) issues.



(**a**)

Figure 10. *Cont.*



(**b**)

(**c**)

(**d**)

Figure 10. (**a**) Case study I: Baseload analysis on significant load growth with high PV penetration level; (**b**) case study II: Baseload analysis on slow load growth with low PV penetration level; (**c**) case study III: Baseload analysis on significant load growth with low PV penetration level; (**d**) case study IV: Baseload analysis on slow load growth with high PV penetration level.

5. Discussion

As we can see from the simulations above, the belly stiffness in the Java-Bali power system is due to grid-connected PV integration from 2019 to 2028. There is a large gap between the peak load and the off-peak load. Simulation results for netload analysis reveal the curve in the shape of a duck in the daily load profile. This phenomenon is called the Java-Bali duck curve. This condition causes the risk of overgeneration occurrence where the supply of power could over exceed the demand by a large proportion, and therefore, causes inefficiency. During these conditions, the system operators must reduce the power output from conventional power plants by either turning off the plant or reducing power plant generation levels. The duck curve condition causes several technical challenges and economic impacts in power system dispatch during high grid-connected PV penetration level conditions. The generators will experience more cycling, starting up and shutting down. In addition, the power system dispatcher needs to reduce and add the generation in short periods to balance demand and supply [45,46]. Simulation results for netload power also identified the need for a flexible generation with sufficient ramping capability to balance the system at morning ramp with low demands and peak load during large amounts of PV penetration. The power plant and system operator must respond to the ramp-up or down periods during these critical times. For the future operational system, this study provides some insights for the Indonesian national electrical company to consider the flexibility power options and also calculate the penetration level, especially from grid-connected PV [47–49].

6. Conclusions

This study presents a multi-year netload analysis of high grid-connected PV penetration levels into one of the largest power systems in Indonesia. The analysis and evaluation of power system planning were proposed. A combination of load growth and grid-connected PV penetration level was also proposed, including netload analysis, ramping capability analysis, and baseload operation analysis. The results showed that the duck curve phenomenon appears with a significant netload drop in the middle of the day because of high power generation from grid-connected PV. Increased grid-connected PV annually will change the netload shape in the middle of the day. Furthermore, the higher peak load combined with the lowest netload valley results in the need to increase ramp rate capability, and this is very important to face morning and late afternoon ramps. Moreover, the significant load growth with high grid-connected PV penetration level caused the UC issues for thermal power plants as baseload operators. However, the national electrical company, especially the system operators in the load dispatch centre, should carry out proper planning to deal with this condition.

Future works could calculate the grid parity in Indonesia to improve the penetration level of grid-connected PV penetration into the power system, explore with different daily loads, investigate the technical and economic impact for a minimum load operation, and explore the flexibility option.

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Abbreviations

BBG	Bahan bakar gas–gas fuel
CNG	Compressed natural gas
CSP	Concentrated solar power
EV	Electric vehicle
GHG	Greenhouse gas emission
GW	Electrical power unit used for active power–giga watt

HSD	High speed diesel
IPP	Independent power provider
kV	Electrical power unit used for voltage–kilovolt
LCoE	Levelised cost of energy
LNG	Liquefied natural gas
MFO	Marine fuel oil
MW	Electrical power unit used for active power–mega watt
NASA	The National Aeronautics and Space Administration
PLN	Perusahaan listrik negara–national electric company
POWER	Prediction of worldwide energy resources provided by NASA
PPA	Power purchase agreement
PV	Photovoltaic
RE	Renewable energy
RES	Renewable energy resources
TOP	Take or pay agreement
TSO	Transmission system operator
UC	Unit commitment
VRE	Variable renewable energy

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