CONSULTATION SERVICES ON RENEWABLE ENERGY PENETRATION STUDY FOR PENINSULAR MALAYSIA AND SABAH

Final Report for Peninsular Malaysia System

FOR THE SINGLE BUYER

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Tasks and objectives:

Perform studies to determine acceptable level of renewable energy (VRE), particularly solar and wind, energy penetration into Peninsular Malaysia and Sabah systems; to recommend measures to mitigate the adverse impacts in case the penetration limit is exceeded. The measures may include increase of system spinning reserve, operating reserve, and incorporation of battery energy storage; and to recommend capacity credit of solar and wind power plants in Peninsular Malaysia and Sabah for planning and operation purposes.

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ABBREVIATIONS AND ACRONYMS

AEDP	Alternative Energy Development Plan (Thailand)
AEMO	Australian Energy Market Operator
AGC	Automatic Generation Control
BNEF	Bloomberg New Energy Finance
CAISO	California Independent System Operator
CECRE	Control Centre of Renewable Energies (Spain)
CPUC	California Public Utilities Commission
CSP	Concentrating Solar Power
ELCC	Effective Load Carrying Capacity
GCC[1]	Grid Control Cooperation (Germany)
GCC[2]	Generation Control Centre (Spain)
GHG	Greenhouse Gas
GLDPM	Generation and Load Data Provision Methodology
HCEI	Hawaii Clean Energy Initiative
HHI	Herfindahl-Hirschman Index
FIT	Feed-In-Tariff
FOR	Forced Outage Rate
FRT	Fault Ride Through
LDC	Load Duration Curve
LOLE	Loss of Load Expectation
LSS	Large Scale Solar
LVRT	Low Voltage Ride Through
MGC	Malaysian Grid Code
MOU	Memorandum of Understanding (Hawaii, USA)
NEG	National Energy Guarantee (Australia)
NEM	Net Energy Metering
NREAP	National Renewable Energy Action Plan (Spain)
NREP	National Renewable Energy Program (Philippines)
NWP	Numerical Weather Prediction
PSD	Power Spectral Density
PV	PhotoVoltaic
RE	Renewable Energy
REE	Red Electrica de Espana (Spain)
RES	Renewable Energy Source
RET	Renewable Energy Target (Australia)
RETI	Renewable Energy Transmission Initiative (California, USA)
RPS	Renewable Portfolio Standards (Hawaii, USA)
SR	Spinning Reserve
TSRS	Malaysian Transmission System Reliability Standards
VRE	Variable Renewable Energy

EXECUTIVE SUMMARY

The incorporation of renewable energy resources in Peninsular Malaysia is on the increasing trend. Higher penetration of solar in the system is favourable to achieve the national targets of 35% carbon reduction by 2030, and Herfindahl-Hirschman Index (HHI) of lower than 0.4 by 2025.

The Single Buyer (the "*Customer*") entrusted DNV GL for the Consultation Services on Renewable Energy Penetration Study for Peninsular Malaysia and Sabah (the "*Project*"). This study will focus on Variable Renewable Energy (VRE), which specially refers to solar power generations in the Malaysian context.

Project Objectives

The key objectives of this project are to:

- Provide a literature review on the variable renewable energy development status and drivers of countries in Europe, US and Asia Pacific; further investigate into the control measures adopted by selected utilities with high penetration to manage the variable renewable energy;
- To determine acceptable level of VRE, particularly solar energy penetration into Peninsular Malaysia;
- To recommend measures to mitigate the adverse impacts in case the penetration limit is exceeded;
- To suggest capacity credit of solar generation in Peninsular Malaysia for planning and operation purposes.

Key Study Methodology

DNV GL performed comprehensive studies to investigate the impact of solar penetration with tested scenarios from 5% to 70% of peak demand based on the Peninsular economic dispatch model and grid system model. The studies investigated the aspects of long-term capacity planning, mid-term and short-term operations with the generation system model in PLEXOS; and the transmission system adequacy and grid stability with the grid model in PSS®E. The solar capacity credits are computed with load and solar profiles from 2025 to 2035 based on effective load carrying capacity method. The overall study workflow and study tool are illustrated in Figure 1.

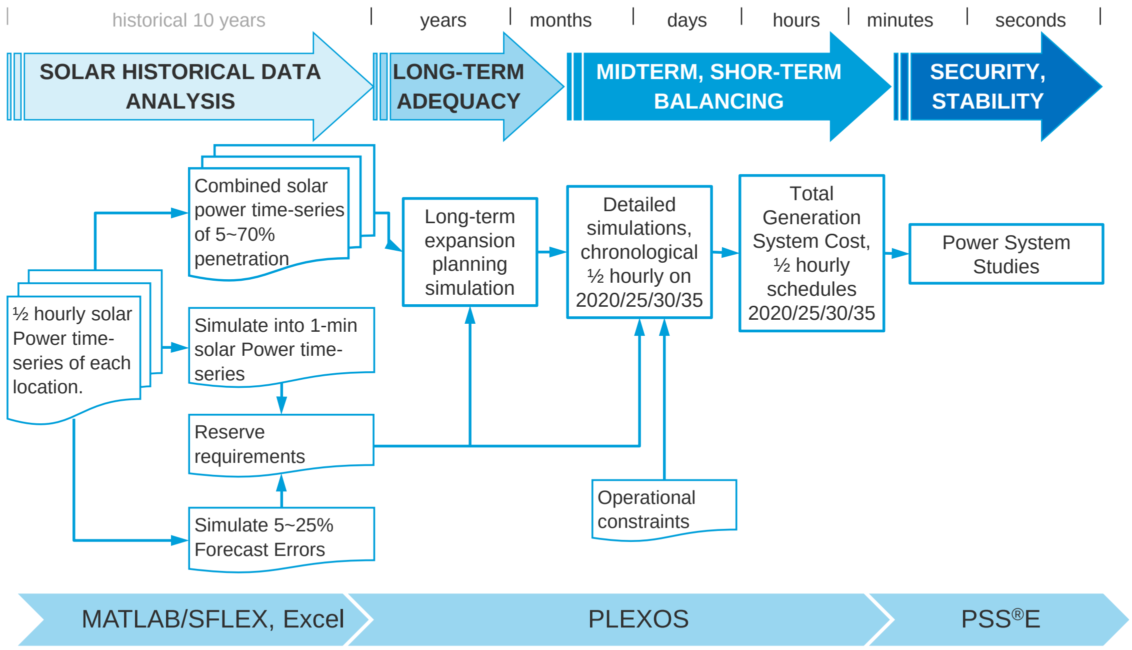

Figure 1 - Overall study workflow and study tools

Key Results

The key findings are summarised and illustrated in below Figure 2.

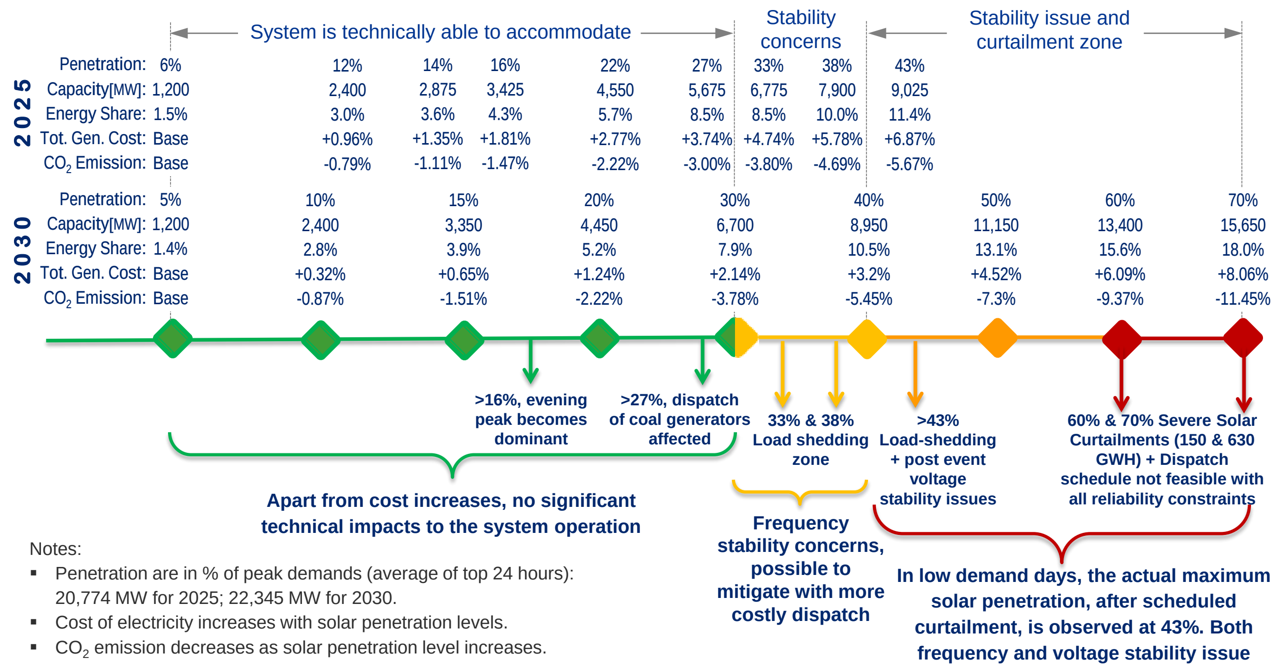

Figure 2 - Penetration limit assessment for Peninsular Malaysia

Recommendations

1. Penetration level based on current system and operation practices

The study results are evaluated on three aspects:

- Reliability: system frequency stability with credible contingent events.
- Affordability: incremental cost of electricity.
- Environment Sustainability: contribution towards CO_2 emission reduction

Numerical results for the above three criteria are normalized to scores on a scale of 0 to 10, and plotted in the energy trilemma in Figure 3 for various solar penetration levels. The total scores corresponding to each penetration level are illustrated in Figure 4, considering the three scores are of equal importance.

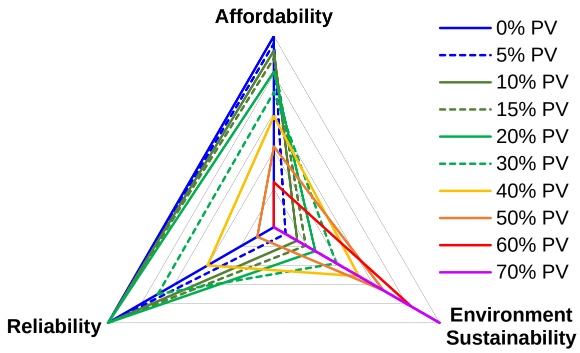

Figure 3 - Energy trilemma for various solar penetration levels

Consider all the three dimensions, the penetration level of 20% brings the most benefits. Based on the system stability test results, the system is technically capable to accommodate penetration up to 30%, which promotes further environment sustainability and reduces the affordability.

Penetrations 30-40% further stretch the system towards environment sustainability while compromise the affordability. Stability of the system under contingent events is compromised, but could be mitigated with more costly dispatch, thus further reduced the affordability.

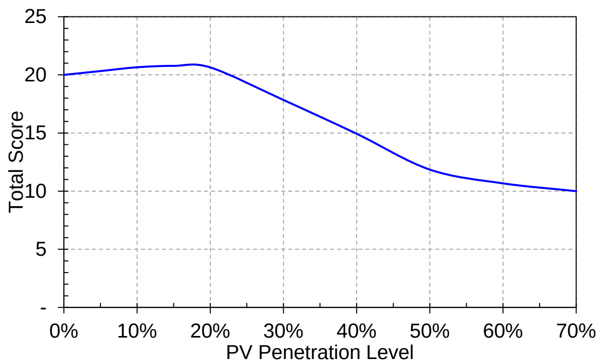

Figure 4 - Total scores corresponding to various solar penetration levels

Penetration above 40% resulted in scheduled solar curtailments. System under contingent condition shows both frequency and voltage stability issues due to low inertia and governor response from online conventional generators.

2. Measures to enable higher renewable penetration

Interconnection Standards (Grid Codes)	Extend the core technical requirements to small scale solar installations, including: •low-voltage ride through •reactive power range and voltage regulation support •overfrequency response
Wider balance area with interconnection	Interconnection with neighbouring system to enable: •electricity trading to allow sufficient online units locally •neighbouring generators to contribute to overall inertia and provide governor response during a contingent event
Operation improvement	Improvements in operaions including: •shorter dispatch interval to reduce the reserve requirement to mitigate "clear-sky ramps" and prediction errors •higher renewable forecast system accuracy
Diversified renewable portfolio	Increase the diversity of renewable portfolio: •to compensate for the low capacity facotr of solar generation, which only contributes to renewable energy share during daytime •to incorporate more dispatchable renewable generation, such as biomass, hydro, and biogas generators.

1 INTRODUCTION

The incorporation of renewable energy resources in Peninsular Malaysia is on the increasing trend, with many government incentives introduced, such as Feed-In-Tariff (FIT), Net Energy Metering (NEM), and Large Scale Solar (LSS). It is expected that there will be 1200 MW of LSS power plant by 2020, and the installed capacity will only increase in the following years. Higher penetration of solar in the system is favourable to achieve the national targets of 35% carbon reduction by 2030, and Herfindahl-Hirschman Index (HHI) of lower than 0.4 by 2025.

The renewable energy generally includes solar photovoltaic, wind, hydroelectric, biomass, biogas, tidal and geothermal power generations. Of the various forms of renewable energies, the hydroelectric, biomass, biogas, tidal and geothermal power generations store the primary energy, and their generation are controllable (dispatchable) and similar to conventional fossil fuel generators. This study will focus on Variable Renewable Energy (VRE), which specifically refers to solar power generations in the Malaysian context.

The availability of solar and wind energy and their generation outputs are dictated by weather conditions. As the penetration level increases and becomes a significant portion in the generation mix, the solar and wind output fluctuations could pose reliability risks to the grid system. A sudden drop of outputs due to weather conditions could result in significant power imbalance, poses risk on reliability of supply, and deteriorate the frequency quality. The high penetration of solar and wind generations could also result in increased load-following duties of conventional generation plants.

Unlike the fully dispatchable conventional power plants, uncertainty in the solar and wind generation outputs poses a challenge in incorporating them in the long-term generation capacity planning analysis. Their full rated capacity cannot be effectively used, and the reliability calculations such as reserve margin and Loss of Load Expectation (LOLE) may not be determined accurately.

The Single Buyer (the "*Customer*") entrusted DNV GL for the Consultation Services on Renewable Energy Penetration Study for Peninsular Malaysia and Sabah (the "*Project*"). The objectives of the study are:

- To determine acceptable level of renewable energy (RE), particularly solar energy penetration into Peninsular Malaysia system.
- To recommend measures to mitigate the adverse impacts in case the penetration limit is exceeded. The measures may include increase of system spinning reserve, operating reserve, and incorporation of battery energy storage.
- To recommend capacity credit of solar and wind power plants in Peninsular Malaysia for planning and operation purposes.

DNV GL has conducted the studies in six (6) tasks as follows:

1) Literature review on renewable energy development status and progress in developing and developed countries including Malaysia.
2) Literature review on control measures adopted by grid system operators to manage the impact of high penetration of intermittent renewable energy.
3) Develop detailed study approach, methodology and the boundary conditions for technical assessments of solar penetration limit.
4) Based on the proposed methodology, perform the technical studies and assessments to determine: the acceptable penetration limit of solar with the defined boundary conditions; the system impacts if the limit is breached; potential mitigation measures to overcome the violations. Perform statistical analysis with historical solar irradiance data, to recommend the capacity credit of solar energy in Peninsular Malaysia and Sabah for long-term generation planning.
5) Based on the study results, recommend the acceptable solar penetration levels with and without additional mitigation measures; recommend the solar capacity credit for system planning and operation purpose in Peninsular Malaysia.
6) Identify two utility companies with high penetration level of solar and/or intermittent renewable energy, arrange site visits and knowledge sharing sessions.

2 LITERATURE REVIEW ON RENEWABLE ENERGY DEVELOPMENTS

2.1 Renewable Energy Development and Drivers of Selected Counties

DNV GL conducted a literature survey on the renewable energy development drivers, status, and future targets of the 10 countries or states, including Global, Australia, California, China, Germany, Hawaii, India, Philippines, Spain, Thailand, and Malaysia.

For relevance to this *Project*, the surveyed data of installed capacity share and electricity production share categorised into:

- Non-Renewable Energy (Non-RE), includes nuclear and fossil-fuel based generators such as coal, gas oil, etc.
- Dispatchable Renewable Energy, including hydroelectric, biomass, biogas, biodiesel, geothermal, concentrate solar and ocean power generations.
- Variable Renewable Energy, mainly on wind and solar photovoltaic generators.

By the time of this report, only a few surveyed countries published the statistical data of 2017. For alignment, we used the 2016 data of the surveyed countries for comparison and processing in this report.

An overview of the VRE development in the surveyed countries and states is presented in the following text. The *Surveyed Period* refers to from year 2007 to 2016, and detailed data are available in section 7.

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2.1.1 Australia

The capacity and energy share of Australian power system is summarised in Figure 5. The installed VRE nameplate capacity includes 4.3 GW Wind and 5.2 GW Solar photovoltaic generators, accounts a 18.7% of the total installed capacity of 51 GW. The VRE contributes 7.9% of the total electricity generation.

The Wind installed capacity grew steadily for the *Surveyed Period* at a compound annual growth rate of 14.8%. A significant slowdown was observed in 2016 with only 2.2% growth (total 93 MW added).

The Solar installed capacity grew rapidly from 2010 to 2012, with annual growth rates of 280%, 249% and 74% respectively. Due the massive growth in this period, the compound annual growth rate is 61.4% for the *Surveyed Period*. Comparing to the slowdown in wind, a total of 845 MW solar was added in 2016, represented a growth rate of 19.4% from previous year.

Growth has been driven by the Renewable Energy Target (RET) with government subsidies, which mandated more than 23.5% of energy share from renewables[1] by the year 2020.

AEMO advises there is an increasing concern that there is currently insufficient incentive to both drive investment in new flexible, dispatchable resources and maintain existing such resources. There are increasing risks of not meeting the reliability target of 0.002 per cent of the annual consumption not being supplied. The situation will be exacerbated in future years as current dispatchable generation (such as coal and gas) exits the market.

The Energy Security Board has recently announced the National Energy Guarantee (NEG)[2] combining the Reliability guarantee and Emission guarantee. NEG aims to support the provision of reliable, secure and affordable electricity with focus on ensuring: 1) the reliability of the system is maintained; 2) electricity sector emissions reductions meet the Australia's international commitments; 3) the above objectives are met at the lowest overall costs.

The Guarantee will require retailers to contract with, or directly invest in, generation, storage or demand response so that:

- there is a minimum amount of dispatchable energy available to meet consumer and system needs (reliability requirement); and
- the average emissions level of the electricity they sell to consumers supports Australia's international emission reduction commitments (26~28% by 2030) [3].

The Guarantees aim to encourage new investment in clean and low emissions technologies while allowing the electricity system to continue to operate reliably. The integration of energy and climate policy is expected to reduce the risk premium on new investments improving the affordability of electricity. Increased contracting in a more liquid contract market is also expected to reduce the level of wholesale electricity spot prices and their volatility.

Summary Notes

VRE Power and Energy shares are above world average levels.

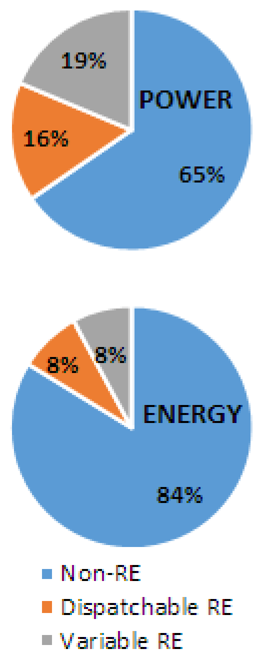

Figure 5 - Capacity and energy share of Australian power system

Lack of investment in developing new and maintaining the flexible, dispatchable generations.

Target energy share 23.5% in 2020 from current 16.2%.

With the NEG, the supply reliability is back on the table. Together with the emission guarantee form the core requirements. A more liquid contract market is proposed to solve the affordability of electricity.

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[1] http://environment.gov.au/minister/hunt/2015/pubs/mr20150623.pdf

[2] http://www.coagenergycouncil.gov.au/publications/energy-security-board-national-energy-guarantee-consultation-paper

[3] http://www.environment.gov.au/climate-change/publications/factsheet-australias-2030-emissions-reduciton-target

2.1.2 California

The capacity and energy share of California power system is summarised in Figure 6. The installed VRE nameplate capacity includes 5.64 GW Wind and 8.62 GW utility scale Solar and estimated 5 GW rooftop solar generators, accounts a 22.9% of the total installed capacity of 84 GW. The VRE contributes 17.2% of the total electricity generation. California imports electricity from interconnected balancing areas.

VRE Power share ranks No. 4; Energy share ranks No. 3. Well above the world average levels.

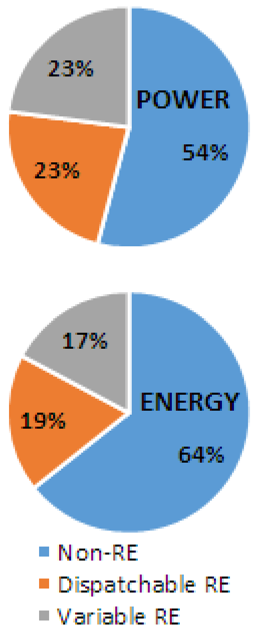


Figure 6 - Capacity and energy share of California power system

The Wind installed capacity grew rapidly in year 2011 and 2012, with annual growth rates of 42.8% and 61.8% respectively. A compound annual growth rate of 14.1% was observed for the *Surveyed Period*. Two halts were observed in 2013 and 2016 with 0% growth.

The Solar installed capacity grew rapidly in year 2011 and 2012, with annual growth rates of 280% and 249% respectively. Due the massive growth in the two years, the compound annual growth rate is 44.2% for the *Surveyed Period*. Compare to the slowdown in wind, total 2 800 MW solar was added in 2016, represented a growth rate of 39.6% from previous year. The Solar growth has been driven by the California Solar Initiative and the New Solar Homes Partnership (GoSolar California).

Driven by the RPS[7], which mandates renewable energy mixes: 33% by 2020 and 50% by 2030.

In California, energy and environmental policy initiatives are driving electric grid changes. Key initiatives include the following[4]: 1) 50 percent of retail electricity from renewable power by 2030; 2) greenhouse gas emissions reduction goal to 1990 levels; 3) regulations in the next 4-9 years requiring power plants that use coastal water for cooling to either repower, retrofit or retire; 4) policies to increase distributed generation; and 5) an executive order for 1.5 million zero emission vehicles by 2025.

By end of 2016, electricity from RPS generators reached 30% share, 5% more than the target.

To help achieve the target, the California Public Utilities Commission (CPUC) started California Solar Initiative moved the consumer renewable energy rebate program for existing homes from the Energy Commission to the utility companies under the direction of the CPUC. The Energy Commission also announced New Solar Homes Partnership, a $400 million program, offers incentives to encourage solar installations, with high levels of energy efficiency, in the residential new construction market for investor-owned electric utility service areas[5].

Record high net-load ramp (13GW in 3 hours) was observed. The ISO is seeking flexible resources.

The added solar and wind installed is estimated to be 4 GW by year 2020[6], and an additional 10 GW to 15 GW renewables (including VRE and dispatchable RE) will be added to the grid from year 2020 to year 2030. A slowdown in the renewable investment is expected in coming years.

Growth is expected to slowdown in the coming years.

With the massive development of solar photovoltaic generations, California experienced an actual 3-hour net-load ramp of 12.96 GW on 18 December 2016 during sunset in late afternoon. CAISO is exploring flexible resources to enable further integration of VRE.

[4] https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

[5] http://www.energy.ca.gov/renewables/

[6] https://www.caiso.com/Documents/RenewableIntegrationUnlockingDividends.pdf

[7] The Renewable Portfolio Standard (RPS) qualifies Wind, Solar, Biomass, Geothermal and Small Hydro generators; but excludes large hydroelectric generators rated 30MW and above.

2.1.3 China

The capacity and energy share of China power system is summarised in Figure 7. The installed VRE nameplate capacity includes 148.6 GW Wind and 77.4 GW Solar generators, accounts a 13.7% of the total installed capacity of 1 654 GW. The VRE contributes 5.1% of the total electricity generation.

The Wind installed capacity grew rapidly from 2010 to 2013, with average of 15 GW added annually. The wind development was further accelerated from 2014 to 2016 with annual added capacity of 20 GW, 33 GW and 19 GW respectively. A compound annual growth rate of 42.8% was observed for the *Surveyed Period*.

The Solar installed capacity grew rapidly in recent years with annual added capacity of 11 GW in 2013 and 2014, 15 GW in 2015, and 34 GW in 2016. Due the massive growth in these years, the compound annual growth rate is 94.2% for the *Surveyed Period*.

Driven by the combat to severe air-pollution, climate change, and government support to the Chinese renewable energy industry development. China committed to reaching peak CO_2 emissions by 2030 and further reduce it to 50% of year 2016 by 2050[8].

China is the world leader in domestic investment in renewable energy and associated low emissions energy sectors. China invested US$103bn in this sector in 2015, up 17% year to year per Bloomberg New Energy Finance (BNEF) – two and half times the amount undertaken by the U.S.[9]. China continued to be a global leader of investment in clean energy projects in 2017 as it further positioned itself as the world leader in new energy technologies such as batteries and electric vehicles.

To optimise the current energy mix and support the Chinese renewable energy industry development, the government has set installed capacity targets: Wind 350 GW and Solar PV 200 GW by 2020. It translates into annual additional capacity of 50 GW Wind and 30 GW solar.

Severe wind curtailments have been observed in the northeast and northwest parts of China. The Chinese National Energy Administration published 2017 wind curtailment statistics: country average 12%, Xinjiang 29% and Gansu 33%.

VRE Power share is above world average level, while energy share below.

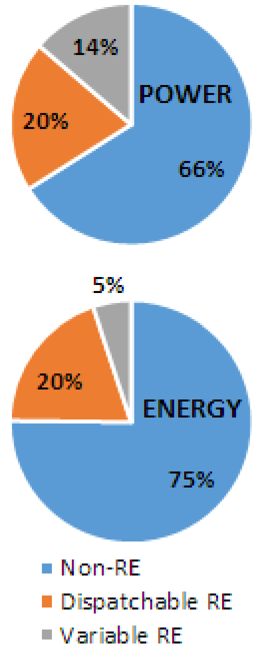


Figure 7 - Capacity and energy share of China power system

Driven by the combat to severe air-pollution, climate change, and government support to the Chinese renewable energy industry development.

Accelerated deployment of wind and solar is expected in the coming years, with annual additional capacity of 50 GW Wind and 30 GW solar.

Resolving the curtailments is key to build a healthy renewable generation industry.

[8] National Development and Reform Commission of China: China Renewable Energy Outlook 2017
[9] http://ieefa.org/wp-content/uploads/2017/01/Chinas-Global-Renewable-Energy-Expansion_January-2017.pdf

2.1.4 Germany

The capacity and energy share of German power system is summarised in Figure 8. The installed VRE nameplate capacity includes 49.6 GW Wind and 40.7 GW Solar generators, accounts a 45.8% of the total installed capacity of 197 GW. The VRE contributes 21.2% of the total electricity generation. Among the surveyed countries, Germany has the highest VRE penetration.

VRE Power share ranks No. 1; Energy share ranks No. 2. Well above the world average levels.

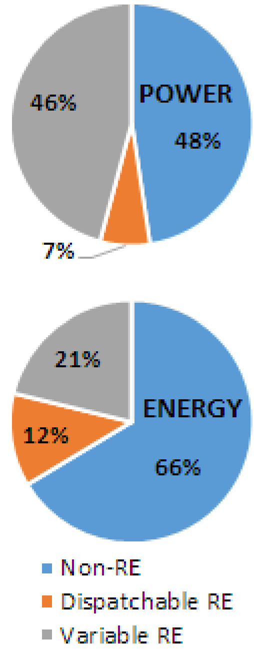


Figure 8 - Capacity and energy share of German power system

On the base of 22 GW cumulated Wind installed capacity in 2007, the Wind installed capacity grew steadily for the *Surveyed Period*, with a compound annual growth rate of 9.4%. The growth of wind continues in terms of added capacity, average 5 GW is added each year from 2014 to 2016.

On the base of 4.2 GW cumulated Solar installed capacity in 2007, the Solar installed capacity grew rapidly from 2009 to 2013, with an average annual added capacity of 6 GW. The growth slowed down from 2014 to 2016, with 1-2 GW annual added capacity. The compound annual growth rate is 28.9% for the *Surveyed Period*.

The German high voltage transmission grid is operated by the 4 TSOs – Amprion, TenneT, 50Hertz and TransnetBW. Since 2010, the TSOs have implemented a common reserves procurement and activation scheme called Grid Control Cooperation (GCC). The German electricity market is organized as a bilateral market with a voluntary power exchange, EPEX Spot, which operates day-ahead and intra-day markets which allow trading with neighbouring countries. Trades for the intra-day market close up to 15 minutes before delivery and provide a way for participants to balance any forecasted deviations in their production and consumption (e.g. from changes in VRE outputs).

The main drive is similar as China: protect the environment and support the renewable industry development. German government has released the latest Renewable Energy Sources Act (2017) [10] to "enable the energy supply to develop in a sustainable manner in particular in the interest of mitigating climate change and protecting the environment, to reduce the costs to the economy not least by including long-term external effects, to conserve fossil energy resources and to promote the further development of technologies to generate electricity from renewable energy sources."

Renewable energy share increases 15% per decade from 2020 to reach 65% in 2050.

Managed the high shares of VRE with very modest changes of power system, and with negligible curtailment.

Renewable energy in Germany is mainly based on wind, solar and biomass. The targeted share of renewable energy as stated in the Renewable Energy Sources Act (2017) are: 35% by 2020, 50% by 2030, 65% by 2040 and 80% by 2050. As the share of electricity from renewables in 2016 is close to the target of 2020, the renewable investment slowdown in recent years.

Invested great efforts on improvements of balancing, generation control and dispatch, and analytical tools.

Germany has so far managed to integrate and balance high shares of variable renewable energy with very modest changes to its power system, and with modest curtailment[11]. The ISOs have invested great efforts on improvement of balancing and intra-day market, generation control and dispatch software and analytical tools.

[10] https://www.bmwi.de/Redaktion/EN/Artikel/Energy/eeg-2017.html
[11] https://www.bundesnetzagentur.de/EN/General/Press/MediaSection/Publications/Publications-node.html

2.1.5 Hawaii

VRE Power share ranks No. 3; Energy share ranks No. 4. Well above the world average levels.

The capacity and energy share of Hawaii power system is summarised in Figure 9. The installed VRE nameplate capacity includes 0.2 GW Wind and 0.55 GW Solar generators, accounts a 25% of the total installed capacity of 3 GW. The VRE contributes 17% of the total electricity generation. Among the surveyed countries, Hawaii ranks the 3rd highest VRE penetration.

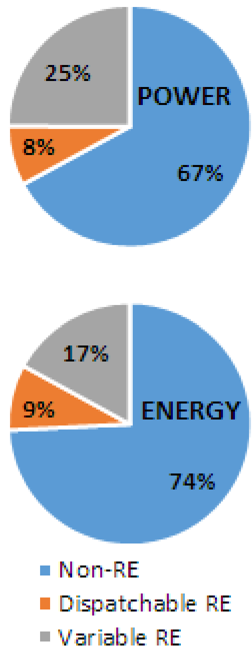


Figure 9 - Capacity and energy share of Hawaii power system

For Wind power, a 30 MW in 2011 and 114 MW in 2012 were added for the *Surveyed Period*.

The Solar installed capacity grew steadily from year 2012 to 2016, with average annual added capacity 118 MW. The compound annual growth rate is 74.5% for the *Surveyed Period*, due to very low capacity in 2007. The solar installation in Hawaii is mainly customer side distributed rooftop solar photovoltaic system.

Hawaii grid heavily relies on imported oil for electricity production, and is keen reduce consumption of oil, which must be imported, often from unstable, turbulent places over thousands of miles of open ocean. As VRE penetration increases, Hawaii grid experienced wind and solar curtailments. In Maui Electric, where VRE represents 24.3% in fuel mix, curtailed about 20% wind energy in 2013, the curtailment has been eased to 5.2% in 2017 with implementation of REWatch.

Driven by the RPS, target 100% renewable energy by 2045.

Great interests to reduce imported oil from unstable and turbulent places over thousands of miles of open ocean.

Experienced curtailments in the past few years.

To reduce the islands' dependency on fossil fuels and protect Hawaii's environment, The State of Hawaii has a bold energy agenda – to achieve 100 percent clean energy by the year 2045[12]. To achieve this aggressive goal, the Hawaii Clean Energy Initiative (HCEI) is structured for collaborative engagement and partnerships with all stakeholders. The initiative was launched in 2008 when the State of Hawaii and U.S. Department of Energy signed a ground-breaking Memorandum of Understanding (MOU) to collaborate on the reduction of Hawaii's heavy dependence on imported fossil fuels. To turn that vision into reality, HCEI is transforming the financial, regulatory, legal and institutional systems that govern energy planning and delivery within the state[13].

In 2016, customers of Hawaiian Electric, Maui Electric and Hawaii Electric Light Company were served by 2,283 GWh of renewable energy, 25.8% share of total energy consumption. Compared with the 9.4% share in 2008, the renewable portfolio standards (RPS) share increased 16.4% share within eight (8) years. The Hawaii government need to speed up the investment on the RE projects in future, otherwise, RPS share will only be 85.25% by 2045 based on the past eight (8) years RE development pace.

Actively looking into biomass and biodiesel controllable renewable resources.

Many of the new development are based on biomass and biodiesel and the like controllable RE technologies.

[12] http://energy.hawaii.gov/
[13] http://www.hawaiicleanenergyinitiative.org/wp-content/uploads/2015/02/HCEI_FactSheet_Feb2017.pdf

2.1.6 India

VRE Power and Energy shares are below world average levels.

The capacity and energy share of India power system is summarised in Figure 10. The installed VRE nameplate capacity includes 28.9 GW Wind and 9.9 GW Solar generators, accounts a 12% of the total installed capacity of 312 GW. The VRE contributes 5% of the total electricity generation.

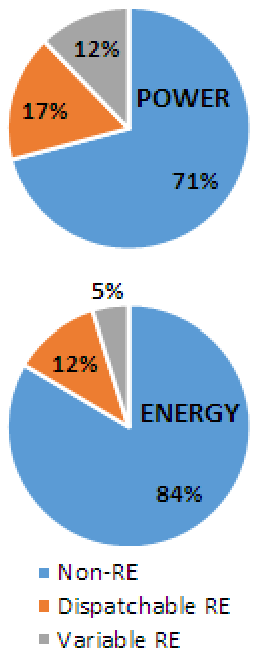


Figure 10 - Capacity and energy share of India power system

The Wind installed capacity grew moderately from 2010 to 2015, with average of 2.3 GW added annually. The wind development was accelerated in 2016 with annual added capacity of 3.8 GW. A compound annual growth rate of 15.6% was observed for the *Surveyed Period*.

The Solar installed capacity grew moderately from 2012 to 2014, with average of 0.9 GW added annually. The deployment has been accelerated in the past 2 years with annual added capacity of 2.1 GW in 2015 and 4.4 GW in 2016. Due the very low installed capacity (4 MW) in 2007 the compound annual growth rate is computed as 138% for the *Surveyed Period*.

The government of India, in pursuit of energy security and for minimizing impact on environment, has been prioritizing the development of RE sector through its policies and programmes[14].

India has significant potential of generation from RE sources. The RE potential in India is estimated as 897 GW comprising of 749 GW of Solar Power, 103 GW of Wind Power, 20 GW of Small Hydro Power and 25 GW of Bio-Energy. The Installed capacity by Mar 2016 from renewable energy sources is 43 GW, only 4.8% of the total RE potential.

Driven by energy security and minimising impact to the environment.

Renewable Energy sector is now poised for a quantum jump as India has reset its Renewable Energy capacity addition target to have installed capacity of 175 GW by 2022, in view of the significant renewable energy potential in the country and commitment made by the investors/stakeholders. It includes 100 GW solar, 60 GW wind, 10 GW biomass and 5 GW small hydro. Based on the projections of capacity addition targets from Renewable Energy Sources by the year 2022 as furnished by MNRE and considering a RES capacity addition of 100 GW during the period 2027, expected electricity share from various Renewable Energy sources has been estimated around 20% in the year 2022 and 24% by 2027[15].

Target 160 GW VRE by 2022, annual added capacity of 20 GW. Another 100 GW from 2022 to 2027, annual added 20 GW.

Compared with the total 39 GW solar and wind power capacity by 2016, India need to install another 121 GW solar and wind power capacity in coming 6 years – annual added capacity of 20 GW. Huge investments are expected in India for coming years.

The targets are very ambitious. The VRE capacity would account for 80% of peak demand by 2022, and exceeds the peak demand by 2027.

Based in the historical demand growth[16], the peak demand would be about 200 GW and 245 GW in 2022 and 2027 respectively. The installed 160 GW VRE by 2022 would account for 80% of peak demand; and further additional 100 GW VRE into the system by 2027 would result VRE capacity greater than the peak demand.

[14] http://www.cea.nic.in/reports/committee/nep/nep_dec.pdf
[15] http://www.cea.nic.in/reports/committee/nep/nep_dec.pdf
[16] http://powermin.nic.in/en/content/power-sector-glance-all-india

2.1.7 Philippines

The capacity and energy share of Philippines power system is summarised in Figure 11. The installed VRE nameplate capacity includes 0.43 GW Wind and 0.54 GW Solar generators, accounts a 4.5% of the total installed capacity of 21.4 GW. The VRE contributes 2.3% of the total electricity generation.

The Wind installed capacity was 33 MW in 2007, no new development until 2013. A 300 MW was added in 2014, and 90 MW in 2015. No additional wind was added in 2016. A compound annual growth rate of 32.9% was observed for the *Surveyed Period* due to very low base at the beginning.

The Solar development started in 2014 with 21 MW, another 100 MW was added in 2015, and 400 MW in 2016. Due the very low installed capacity (< 1 MW) in 2007 the compound annual growth rate is computed as 110% for the *Surveyed Period*.

Philippines aim to address the challenges of climate change, energy security, access to energy as well as cost-effective electrification to the remote areas or islands by deployment of renewable energy. The National Renewable Energy Program (NREP) outlines the policy framework enshrined in Republic Act 9513 which will help the country achieve the goals set forth in the Renewable Energy Act of 2008. The renewable target in NREP 2011-2030 is outlined as: Solar 275 MW by 2020, then 1 MW per year till 2030; wind 1.94 GW by 2020, 2.38 GW by 2025 and stay the same till 2030. The NREP mainly focus on Hydroelectric power.

Solar power has attracted a lot of attention in past few years, the total solar installed capacity exceeded the 2030 target of previous Act. The wind development is quite behind the 2020 target, and '0' added capacity in 2016.

The coming NREP 2017-2040 is expected to review the current renewable development trends and update the targets.

VRE Power and Energy shares are below world average levels.

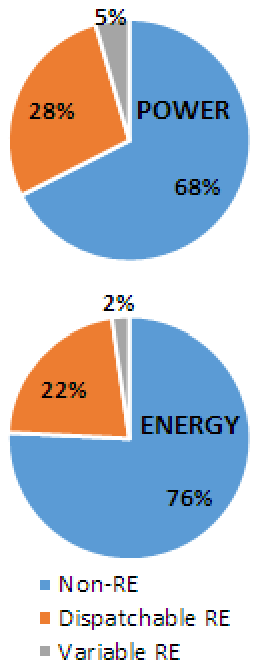


Figure 11 - Capacity and energy share of Philippines power system

The actual solar capacity at 2016e exceeded the 2030 target of NREP 2011-2030.

The coming NREP 2017-2040 is expected to review the targets

2.1.8 Spain

The capacity and energy share of Spain power system is summarised in Figure 12. The installed VRE nameplate capacity includes 23.1 GW Wind and 7.0 GW Solar generators, accounts a 28.5% of the total installed capacity of 105 GW. The VRE contributes 23.2% of the total electricity generation. Among the surveyed countries, Spain has the highest VRE energy share.

On the base of 14.8 GW cumulated Wind installed capacity in 2007, the Wind installed capacity was added at an average of 1.6 GW annually from 2008 to 2012. However, new installation halted from 2013 till now. A compound annual growth rate of 5% is observed for the *Surveyed Period*, due to lack of new installation since 2013.

The cumulated Solar installed capacity was 0.74 GW in 2007, a big surge in 2008 with 2.7 GW additional solar installed in a year. After the surge, Solar growth has been very small, with average annual new capacity of 0.1 GW, where no new capacity added in 2014 and 2016. The compound annual growth rate is 23.3% for the *Surveyed Period* due to the surge in 2018.

Renewable energy has a number of positive effects on Spanish society, including the sustainability of energy sources, reduction in polluting emissions, technological change, the opportunity to advance towards more distributed forms of energy, reduction of energy dependence and the trade balance deficit and increase in rural employment and development[17].

The development of renewable energies is a priority for Spanish energy policy and the 40% renewable energy share target for year 2020 in their NERAP 2011-2020. The targeted renewable generation sources include: 1.6 GW Biofuel, 22.5 GW hydroelectric, 5.1 GW Concentrated Solar Power, and VRE of 38 GW wind and 8.4 GW solar photovoltaic.

The cumulated VRE capacity is behind the 2020 target, solar by 1.9 GW and wind by 15 GW. In the past 3 year, there is almost '0' VRE capacity added to the grid.

Although the installed VRE capacities are behind the targets, the Spanish electricity generation achieved the 40% energy share from renewables target by 2016e.

VRE Power share ranks No. 2; Energy share ranks No. 1. Well above the world average levels.

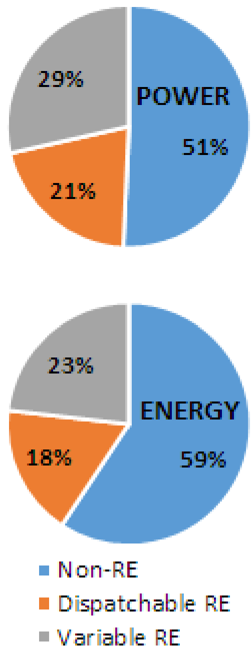


Figure 12 - Capacity and energy share of Spain power system

The NERAP 2011-2020 set VRE targets: 38 GW wind and 8.4 GW solar. The cumulated wind and solar capacity is behind the 2020 target, by 1.9 GW and 15 GW respectively.

Almost '0' VRE capacity were added for the past 3 years.

Spain achieved 40% energy share from renewables target by 2016e

[17] National renewable energy action plan of Spain

2.1.9 Thailand

VRE Power and Energy shares are below world average levels.

The capacity and energy share of Thailand power system is summarised in Figure 13. The installed VRE nameplate capacity includes 0.51 GW Wind and 2.15 GW Solar generators, accounts a 6.4% of the total installed capacity of 41.6 GW. The VRE contributes 1.2% of the total electricity generation.

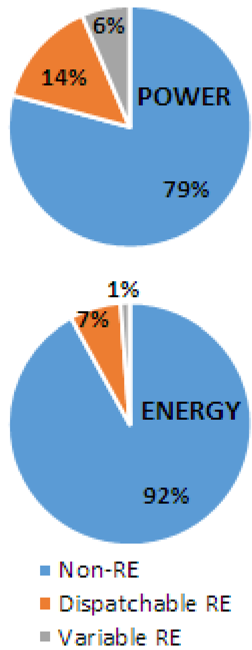


Figure 13 - Capacity and energy share of Thailand power system

For the *Surveyed Period*, there were 105 MW Wind added in 2012, 110 MW in 2013, and 270 MW in 2016. Wind power develop of other years are negligible. A compound annual growth rate of 99.8% was observed for the *Surveyed Period* due to very low base in 2007 (1 MW only).

The Solar power development grew rapidly starting 2012 with 300 MW added capacity; 450 MW in 2013, 475 MW in 2014. A relatively low growth (120 MW) was observed in 2015, followed by a big rebound in 2016 (730 MW). Due the very low installed capacity (32 MW) in 2007 the compound annual growth rate is computed as 59.6% for the *Surveyed Period*.

Thailand government pledges a 20 to 25 percent reduction in its emission of greenhouse gases by 2030. Thailand is a “net” energy importer, and aims to enhance energy security, improve environmental quality (particularly to reduce air pollution) and the creation of new job opportunities, as well as provision of cost-effective electrification options to the remote areas or islands through renewable energy development.

AEDP sets 20% electricity from renewables in 2036.

Total 9 GW VRE and 6.85 GW bioenergy, account 18% and 14% of 2036 peak demand.

The Alternative Energy Development Plan (AEDP2015)[18] promote electricity generation from waste, biomass, biogas power generation, hydro, and wind and solar if the cost will be able to compete with power generation using LNG. The AEDP2015 sets a target of 20% energy from renewables by 2036, which mainly comprises capacities of: Waste 0.5 GW; Biomass 5.6 GW; Biogas 1.28 GW; Wind 3.0 GW, and Solar 6.0 GW.

Comparing with the present status, the additional capacities in the next 20 years are: Waste 0.5 GW; Biogas 0.97 GW; Wind 2.5 GW; Biomass 3.1 GW; and Solar 3.85 GW. The combined bio-energy capacity is the largest.

The forecasted peak demand is 49.7 GW in 2036, where the combined VRE capacity accounts about 18%, and the bio-energy accounts 14%.

[18] http://www.eppo.go.th/index.php/en/policy-and-plan/en-tieb/tieb-aedp

2.1.10 Malaysia

VRE Power and Energy shares are below world average levels.

The capacity and energy share of Malaysia power system is summarised in Figure 14. The installed VRE nameplate capacity includes 0.33 GW Solar generators, accounts a 1.1% of the total installed capacity of 28.9 GW[19]. The VRE contributes 0.2% of the total electricity generation.

The VRE, mainly solar photovoltaic technology, started to grow from 2013, with approx. 106 MW added. An average 65 MW was added annually from 2014 to 2016. A compound annual growth rate of 53.6% was observed for the *Surveyed Period* due to very low base in 2007 (7 MW).

In the past, renewable energy development in Malaysia has been mainly on the hydroelectric generation.

In recent years, Solar development has been a hot topic in both Peninsular Malaysia and Sabah, with overwhelming applications. A cumulative capacity of 1.2 GW is expected by 2020, and an accelerate growth in the years follows.

Malaysian Government intends to reduce the greenhouse gas (GHG) emissions intensity of GDP by 45% by 2030 relative to the emissions intensity of GDP in 2005. This consist of 35% on an unconditional basis and a further 10% is condition upon receipt of climate finance, technology transfer and capacity building from developed countries. The electricity generation industry is expected to be a key contributor to the reduction of greenhouse gas emissions.

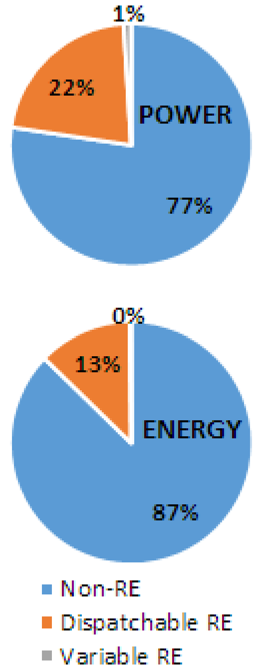


Figure 14 - Capacity and energy share of Malaysia power system

2.2 Summary of renewable development and drivers

The consolidated installed capacity and electricity production shares of surveyed countries by end of 2016 are shown in Figure 15 and Figure 16 respectively. The surveyed data are in Table 27 and Table 28.

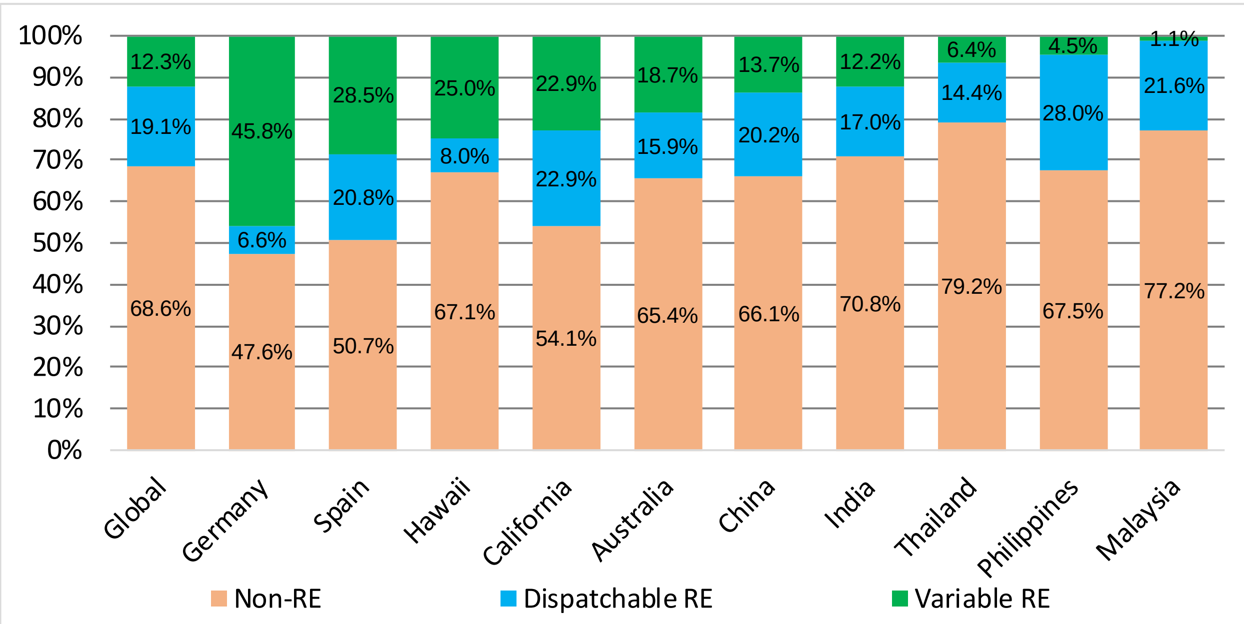


Figure 15 – Installed Capacity Share by 2016

[19] The figure includes generation resources of Peninsular Malaysia, Sabah and Sarawak.

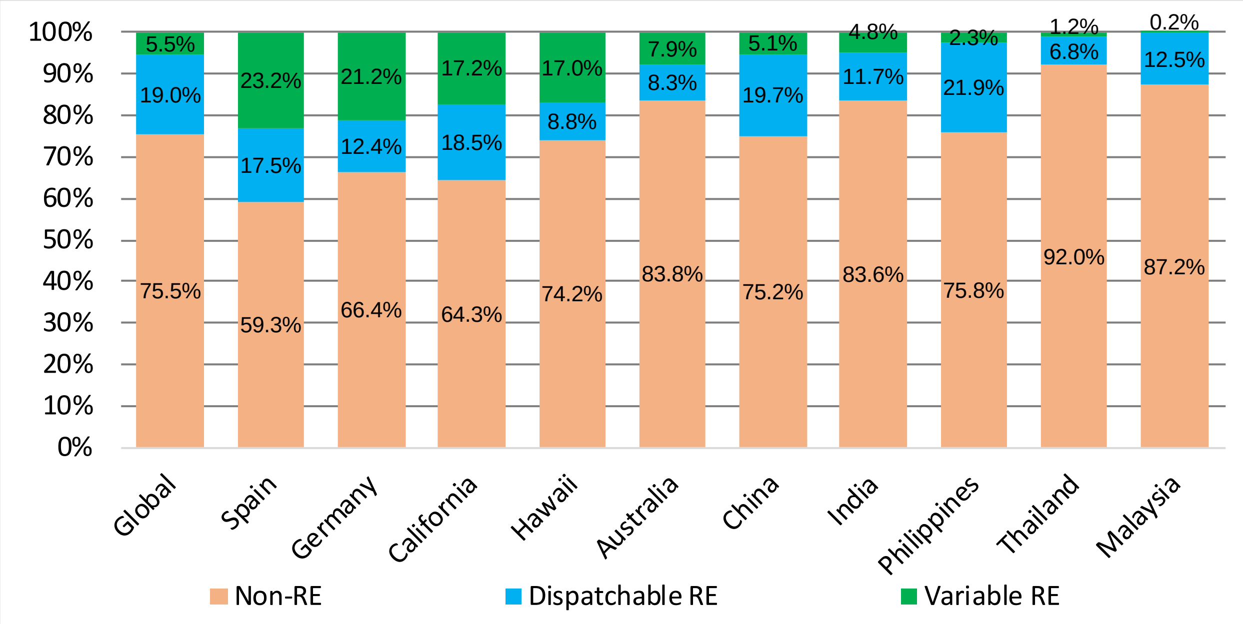


Figure 16 – Electricity Generation Share by 2016

2.2.1 Development status

On the renewable energy development, Europe and the USA have been leading. Countries and states such as Germany, Spain, California and Hawaii have achieved very high share of electricity from renewables; and have achieved their 2020 targets. As the variable renewables energy penetration level getting higher, the utilities are facing balancing issues in recent years. Utilities in Europe and the USA have invested and continue to invest significant efforts in managing the intermittent renewable resources, enable them to progress to even higher targets mandated by legislations.

In Asia, China is further accelerating their renewable energy development with massive deployment targets of annual new installation 50 GW wind and 30 GW solar in the next 4 years. However, the geographical mismatch of renewable resource and load centres has resulted in high renewable curtailments. The growth of wind and solar power development have been accelerated in India, the Indian Government pledges very ambitious target of annual addition 20 GW wind and solar until 2022, and grow further at the same rate till 2027.

In Southeast Asia, renewable energy development is at the starting phase. However, Southeast Asia is very rich of renewable energy, especially on hydroelectric, bioenergy and solar. It’s expected to grow rapidly as the cost of technologies becoming more and more competitive.

2.2.2 Drivers

The most significant driver for the renewable energy developments has been governments’ commitments to combat global warming and climate changes due to greenhouse gas emissions.

Energy security is another important driver for energy importing counties countries and states. Combating the severe air-pollution and support to the renewable energy industries have also been important drivers.

2.2.3 Economic competitiveness

The economic competitiveness of renewable technologies has fuelled the rapid developments in recent years.

With the continued rapid growth in solar photovoltaic deployment to a level between 1,750 and 2,500 GW by 2030 form the installed capacity of 296 GW at 2016e. Massive new solar photovoltaic installation is expected in the next 14 years, with average 100 GW added capacity per annum. The global average total installed cost of utility-scale photovoltaic systems could further fall from around USD 1.8/W in 2015 to USD 0.8/W in 2025[20].

Historically, the solar PV market's cost reductions have been driven by both module and inverter cost declines. The next wave of cost reduction is expected mainly (about 70%) from lower balance of system costs, as illustrated in Figure 17.

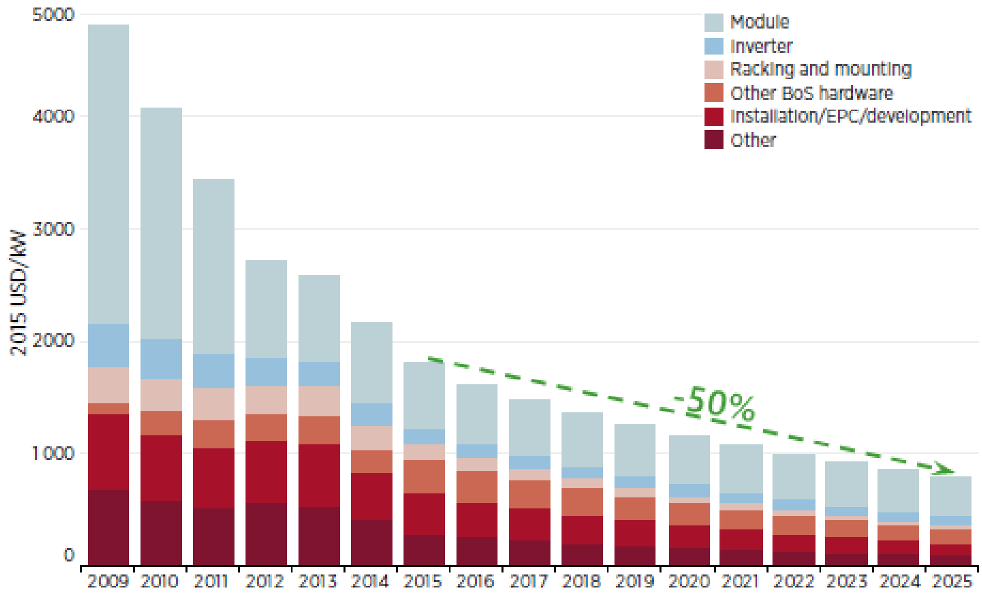


Figure 17 - Global weighted average utility-scale solar PV total installation costs 2009-2025

Driven by the maturity of technology and project development, the deployment at scale, and the competitive procurement of renewable energy, the cost for electricity from solar PV and wind is falling rapidly worldwide (Figure 18). The fall in electricity costs from utility-scale solar photovoltaic (PV) projects since 2010 has been remarkable: the global weighted average levelised cost of electricity (LCOE) of utility scale solar PV has fallen 73% since 2010, to USD 0.10/kWh for new projects commissioned in 2017[21]. The LCOE from utility-scale solar photovoltaic (PV) projects are expected to fall steadily to below USD 0.07/kWh by 2020 (Figure 19).

In Peninsular Malaysia, the 2017 LSS cycle 2 bidding excise attracted 85 bids, totalling 1442 MW – about 3 times the quota. The averaged offered price of top 10 offers for the large scale solar photovoltaic (10-30MWac category) fall 13.5% comparing to the 2016 offers[22], which confirmed the trend of price reduction.

In India, the first auction of 500 MW in 2017 was oversubscribed 6 times over, interested developers submitting bids for 3.1 gigawatts. The tariff bids were between Rs 2.47/kWh (3.8 US¢/kWh) and Rs 3.29/kWh (5.07 US¢/kWh). Although being questionable if the price was financially sustainable, it does demonstrate the continuous trend of price reduction from solar photovoltaic energy.

[20] IRENA, Renewable Power Generation Costs in 2017.

[21] IRENA, Renewable Power Generation Costs in 2017.

[22] Suruhanjaya Tengaga (Energy Commission of Malaysia), 2017 and 2016 LSS Bid Opening Prices.

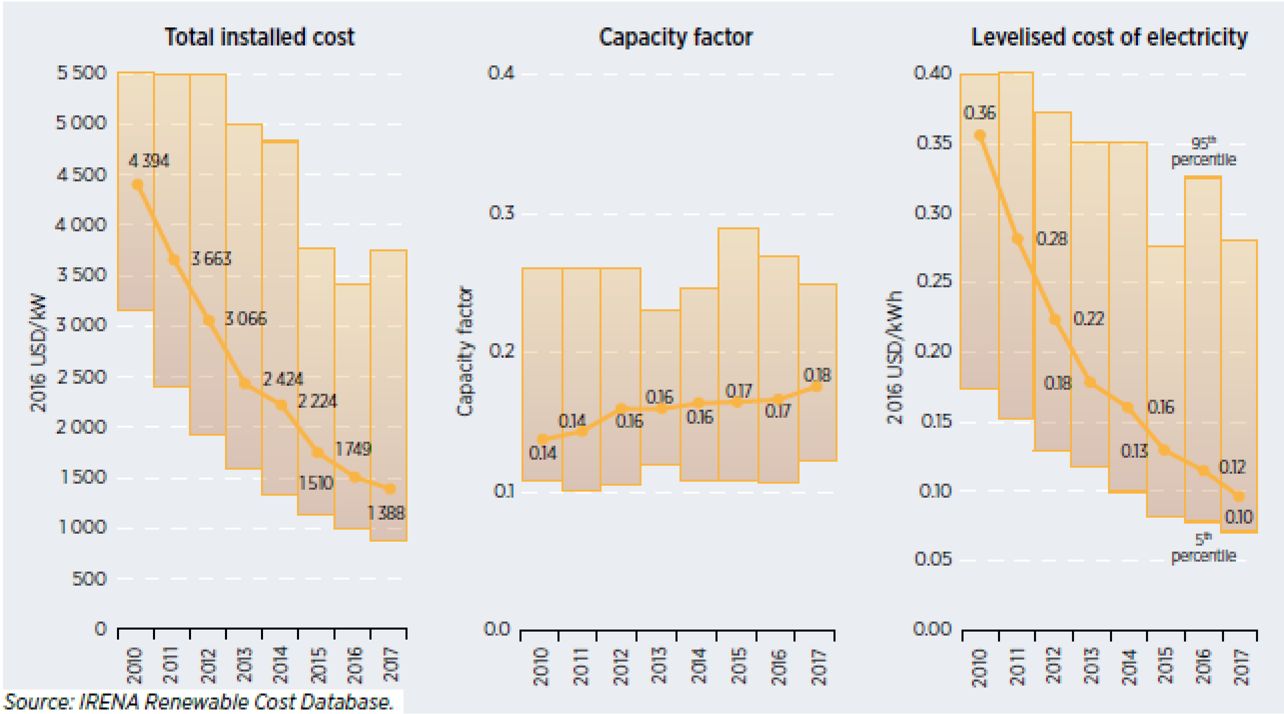


Figure 18 – Solar photovoltaic technology and development maturity

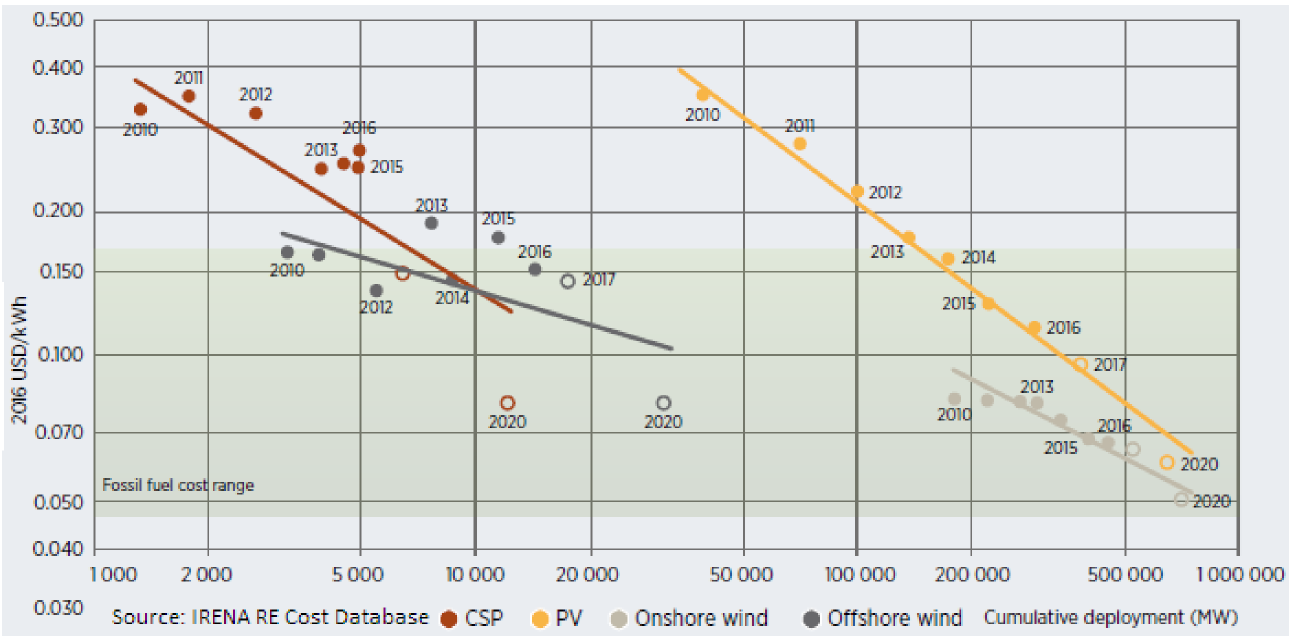


Figure 19 – LCOE of wind and solar energy 2010-2017

2.3 Energy Transition Outlook

DNV GL devotes 5% of the group's revenue into research and innovation projects every year, and the *Energy Transition Outlook*[23] is one the research and innovation projects built on DNV GL's expert energy model.

The model of the world energy system up to 2050 in Figure 20 and Figure 21 shows that a cleaner, more electrified world is within our reach. By mid-century, the world will run much more on electricity as its share in total energy supply rises to 40% compared with 18% today. 72% of electricity will be from wind turbines and solar panels, as producing power from wind and sunlight becomes cheaper than burning fossil fuels.

However, our findings also flash a red warning light over global warming. In our outlook, we forecast that the average global temperature will rise by 2.5 degrees Celsius compared with pre-industrial levels before the

[23] https://eto.dnvgl.com/2017/main-report

end of the century, significantly beyond the Paris Agreement's least ambitious target to limit warming to "well below 2°C".

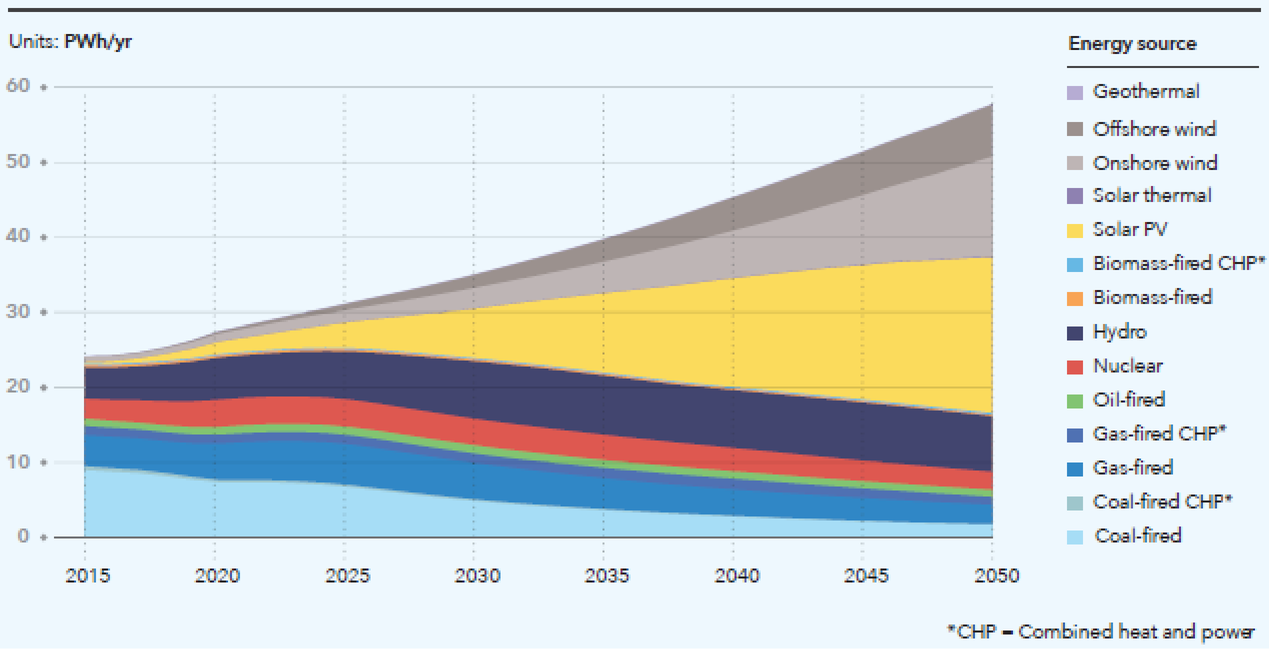


Figure 20 – Global electricity production by generation type

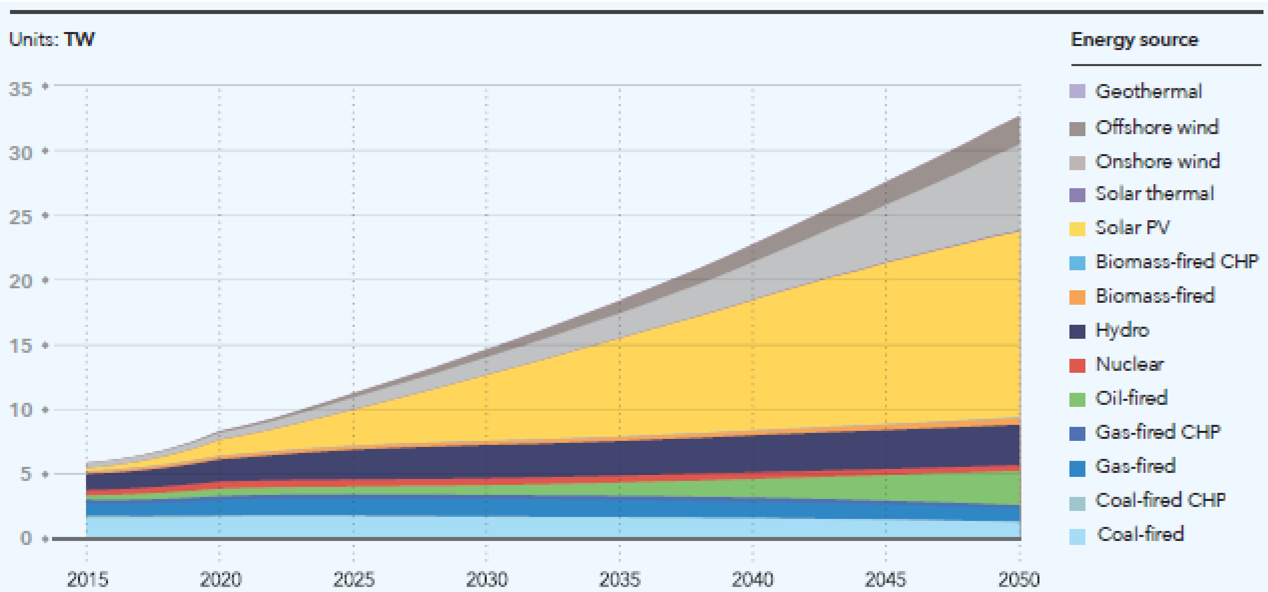


Figure 21 – Global electricity capacity by generation type

3 LITERATURE REVIEW ON CONTROL MEASURES ADOPTED BY UTILITIES WITH HIGH VRE

DNV GL surveyed the 4 most relevant candidates (Germany, Spain, California and Hawaii) with high solar photovoltaic energy penetration levels on: what are the challenges they had faced and are facing for integration of VRE; and what control measures these candidates adopted to manage the intermittent renewable energy generations.

3.1 Germany

The German high voltage transmission grid is operated by 4 TSOs – Amprion, TenneT, 50Hertz and TransnetBW, as illustrated in Figure 22.

Renewable energy in Germany is mainly based on wind, solar and biomass. Despite the nuclear phase-out, Germany is a net electricity exporter, 47.5 TWh in 2016.

Germany is an early mover on renewable energy development, and had world's largest solar photovoltaic installed capacity until 2014. As of 2016, Germany installed 40.7 GW solar photovoltaic installed capacity – the 3rd largest after the USA and China.

By year 2016e, Germany has total VRE capacity is 90.3 GW, 45.8% of the total power generation capacity of 197 GW. The electricity generated from VRE reached 116.69 TWh, accounting 21.23% of the total electricity generation. Among the 4 TSOs, TenneT (59%) and 50Hertz (53%) have high VRE share of installed capacity.

Germany has the highest VRE penetration level among the surveyed countries and states.

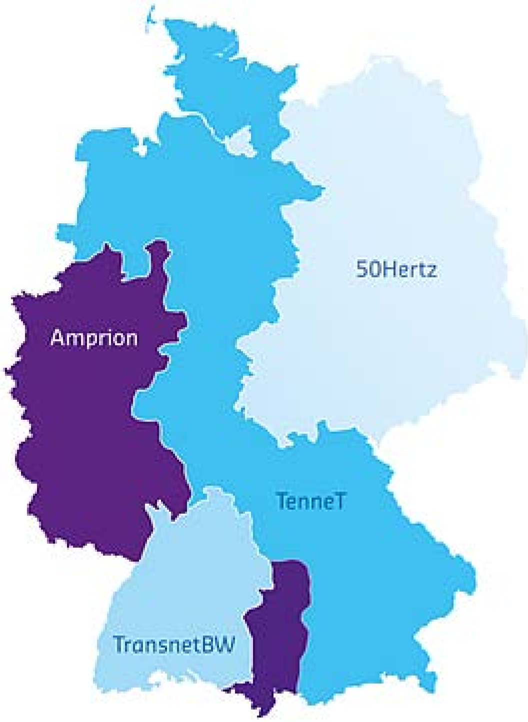


Figure 22 - Transmission system operators in Germany

The German electricity market is organized as a bilateral market with a voluntary power exchange, EPEX Spot. EPEX Spot operates day-ahead and intra-day markets which allow trading between neighbouring countries. Trades for the intra-day market are closed 15 minutes before delivery, which provide a way for participants to balance any forecasted deviations in their production and consumption (e.g. from changes in VRE outputs).

The German government is very supportive of renewable energy development. In order to achieve an 80 – 90% reduction in Greenhouse Gas (GHG) emissions by 2050, the government published a policy paper in 2050 promoting a target of 100% RE for electricity by 2050, so as to achieve cost-effective, environmentally friendly electricity system[24]. German government has released the latest Renewable Energy Sources Act (2014) to "enable the energy supply to develop in a sustainable manner in particular in the interest of mitigating climate change and protecting the environment, to reduce the costs to the economy not least by including long-term external effects, to conserve fossil energy resources and to promote the further development of technologies to generate electricity from renewable energy sources." Targets are set:

	2020	2030	2040	2050
Share of RE electricity consumption	At least 35%	At least 50% *Renewable Energy Sources Act 2025: 40 to 45%*	At least 65% *Renewable Energy Sources Act 2035: 55 to 60%*	At least 80%

[24] https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/energieziel_2050.pdf

3.1.1 Challenges of high VRE penetration

In Germany, the increasing VRE generation penetration level and the associated decrease in conventional generation had given rise to the following challenges.

3.1.1.1 High volatility in short time periods arising from fluctuations in VRE generation.

In the 50 Hertz control area with 19.44 GW of VRE (12.76 GW Wind + 6.68 GW PV), gradients of > 800 MW in 15 minutes or 2,400 MW in one hour can be expected[25]. The one-hour ramp represented a 16% of 50 Hertz's maximum demand (~15 GW).

The extreme case experienced in Germany was the solar eclipse in 20th March 2015 which led to a 6 GW fall in solar generation in 45 minutes followed by a 13.7 GW increase in 1 hour 15 minutes[26], as indicated in Figure 23. The system overcame the extreme event and remain stable.

The power system needs to be able to accommodate these short-time and high-magnitude fluctuations, while maintaining system stability and supply security.

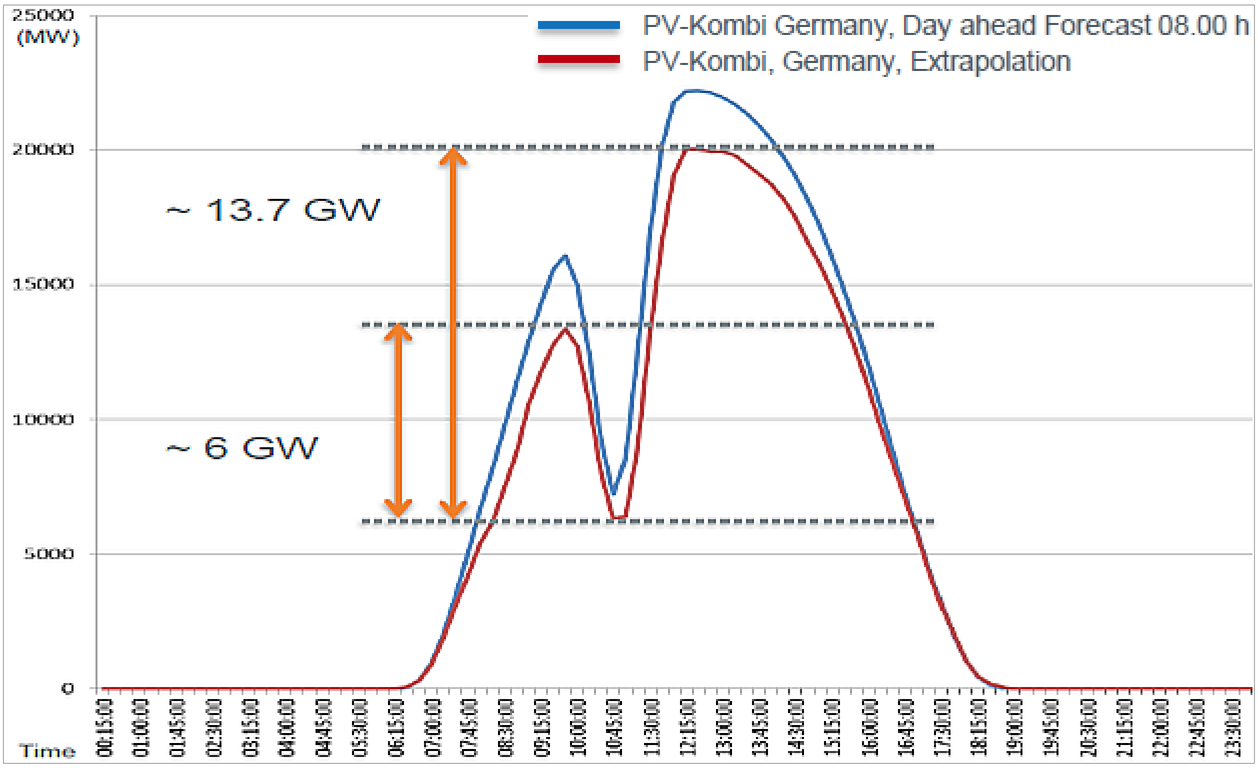
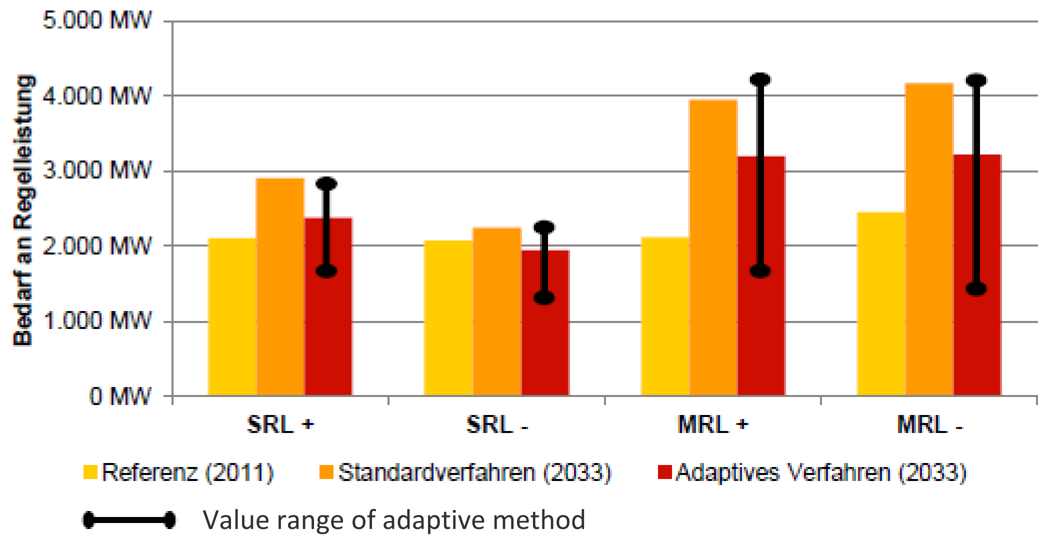


Figure 23 – Short time high magnitude fluctuation due to solar eclipse

3.1.1.2 Increase in reserve requirements

The high volatility in short time-periods of VRE outputs increases the reserve requirements, particularly the secondary and tertiary reserves. A study by the German Energy Agency (dena) in 2014 found that by 2030, due to the increase in VRE generation, the forecasting errors would increase requirements of secondary reserve by 10 - 40 percent; and the tertiary negative reserve by 70 percent, and positive reserve by 90 percent based on existing quarterly based reserve dimensioning methodologies[27]. If adaptive method is used, i.e. the reserves are computed day-ahead based on the forecasted load and VRE feed-in, the average increase of reserves could be lower. However, even with adaptive method, the tertiary reserve requirements in 2030 would be significantly increased as compared with today. The results are plotted in Figure 24.

[25] http://japan.ahk.de/fileadmin/ahk_japan/Dokumente/03_Schucht_50Hertz_.pdf
[26] http://en.unecon.ru/sites/default/files/en/michael_kranhold.pdf
[27] https://www.dena.de/fileadmin/dena/Dokumente/Themen_und_Projekte/Energiesysteme/dena-Studie_Systemdienstleistungen_2030/Ergebniszusammenfassung_dena-Studie_Systemdienstleistungen_2030.pdf



SRL: Secondary Reserves; *MRL*: Tertiary Reserves; *Referenz(2011)*: reference level of 2011
Standardverfahren (2033): reserves dimensioned on quarterly basis (existing method).
Adaptives Verfahren (2033): reserves dimensioned on daily basis (adaptive method).

Figure 24 – Increasing reserves requirement as VRE penetration increases

3.1.1.3 Shortage of ancillary services providers

Shortage of conventional generators to provide ancillary services including frequency regulation, voltage control and black-start – these ancillary services contribute to the stable operation of the power system and are largely provided by conventional thermal power plants.

As the proportion of RE generation increases and displaces thermal generation, there might be times when insufficient thermal generation is online to provide the required ancillary services. In this case, there might be a need to curtail VRE generation to keep sufficient thermal generators online to meet reliability requirements. On 30 April 2017, Germany experienced 85 percent of system loads were supplied by VRE[28], as shown in Figure 25.

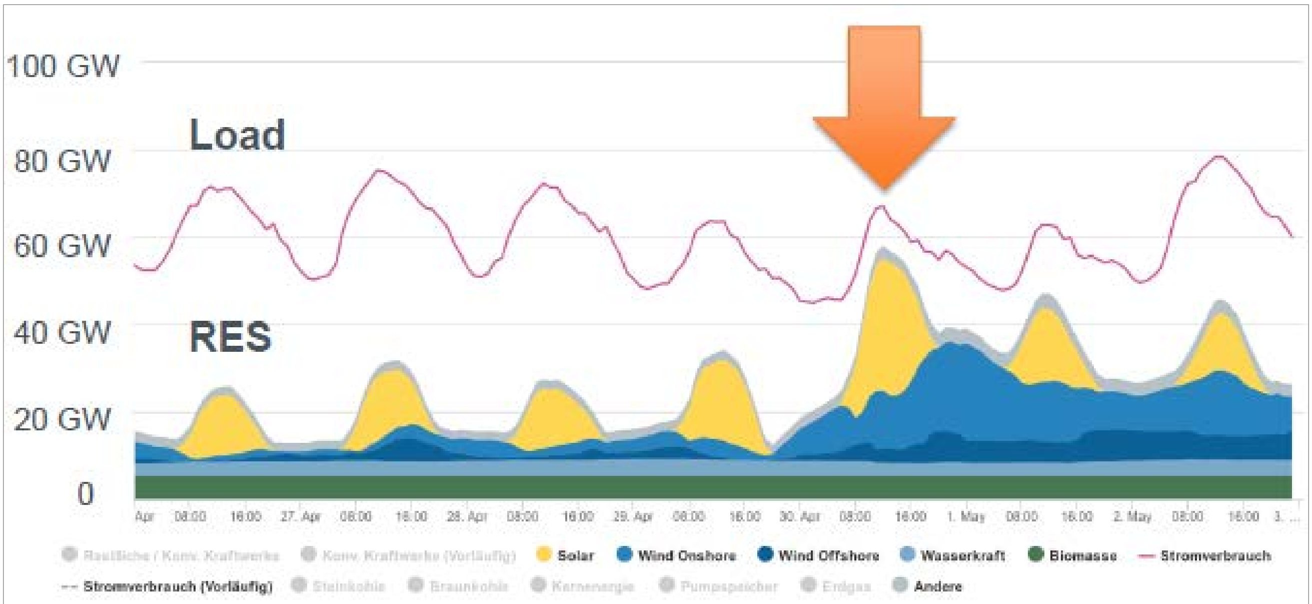


Figure 25 – Majority of loads were supplied by VRE

To avoid curtailment of VRE generation, alternative sources of ancillary services need to be identified to ensure stable operation of the power system.

[28] Dispatching and evacuation of RE generation, by Dr. Niels Ehlers, Head of Concepts and System Strategy, 50Hertz

3.1.2 Control measures for high VRE integration

With the interconnections among the 4 control regions in Germany, the TSOs cooperate very closely to manage the power system while each TSO retains control over its own control region. As a result, renewable integration initiatives and control measures are typically implemented collectively. The control measures that have been implemented in Germany to mitigate the challenges introduced by high VRE penetration are discussed in following texts.

3.1.2.1 Interconnection standards

Interconnection standards for renewables connected at MV and LV levels in Germany have been developed by BDEW and FNN to include requirements to support the integration of renewables. Important grid connection requirements include energy management, fault ride through capability, active power droop control, reactive power behaviour, dynamic grid stabilization and power quality.

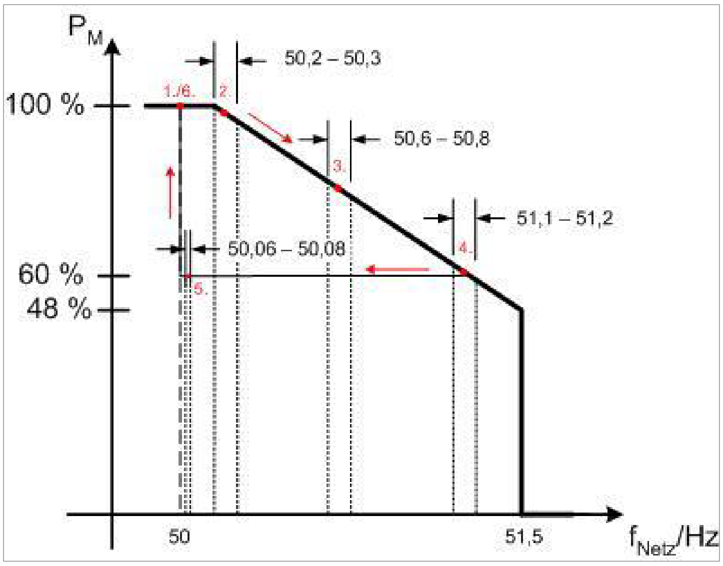


Figure 26 - Frequency droop requirements

Prior to the implementation of active power droop control at higher frequencies, Germany had adopted a fixed frequency cut-off at 50.2 Hz for photovoltaic inverters connected to the grid. This introduced a 'yo-yo effect' where significant amounts of photovoltaic generation would drop off when this threshold was breached, exhausting the system's primary frequency control and rendering the system unstable. Similarly, when the photovoltaic inverters were reconnected to the grid at the same time, the sudden spike in frequency would trigger the shutdown again.

The grid codes introduced the active power reduction during over-frequency characteristic that requires a Gradient = (P_{MAX}-P)/(f-50.2Hz) = 20, or a 5% droop, had successfully mitigated the issue. The droop characteristic is shown in Figure 26. The droop control requirement is further verified with system testing, e.g. hardware-in-the-loop testing and software model validation[29] by accredited third-party institutions.

As a result, major of VRE installations had to be retrofitted in order to avoid sudden curtailment at a fixed over- or under- frequency (50.2 Hz or 49.5 Hz).

The grid connection codes are necessary for not only VRE, but for all generators and loads. There are needs to verify the behaviours of the generators are reflecting the physical realities.

3.1.2.2 Widen the balancing area with coordinated grid controls

Prior to the 2009, each TSO balanced their grid independently which lead to several sources of inefficiencies including counteracting activation of reserves and higher costs due to procurement from a smaller pool of qualified reserve providers. The GCC was introduced in 2009-2010 as an initiative to coordinate the balancing

[29] https://www.dnvgl.com/cases/the-german-50-2-hz-problem-80862

activities of the 4 TSOs to achieve cost savings in power system operations. The GCC was structured into 4 modules as follows:

- Module 1: Preventing conflicting activation of reserves through controlled and measured energy exchanges between control areas.
- Module 2: Joint dimensioning of reserve requirements which is centrally procured and activated.
- Module 3: Common procurement of secondary reserves.
- Module 4: Use of nation-wide merit order to determine dispatch of secondary and tertiary reserves.

The implementation of GCC has been effective in mitigating the costs of balancing the intermittency associated with the increase in RE generation in Germany. Figure 27 shows the trend of reserves requirement and VRE generation. From 2008 to 2015, VRE generation increased by approximately 200% while reserve requirements decreased by approximately 20%. And the balancing cost reduced by 70% for the same period form a level of €680m per annum in 2008 [30].

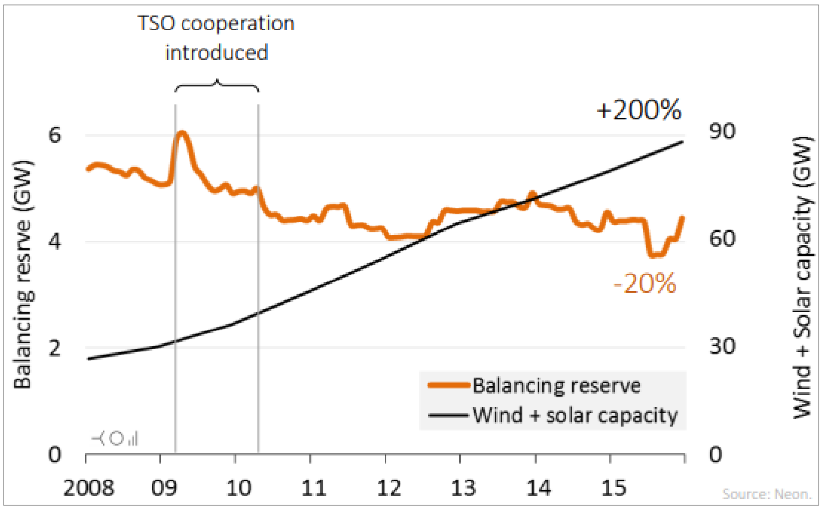


Figure 27 – Managed balancing reserve volume with increasing VRE penetration

3.1.2.3 Implement and improve VRE forecasts

To main stable operation of the power grid, the power supply must always match the power demand. However, the sun does not shine and the wind does not blow with constant intensity, introducing challenges for the system operators on balancing the supply and demand in real-time.

Like load forecasting, implement and continuous improvement of VRE production forecasting are of paramount importance to the stable and economic operation of power system. German TSOs have all implemented renewable production forecasting systems, the forecast and actual results are published [31,32]. From our analysis of the forecasted solar power and actual turnouts time series data from 50 Hertz between 2015 and 2017, 99.82% of the forecast errors are within ±5% of the nameplate capacity.

Germany continues pursue better forecasting for solar and wind power generation. One of the research and developments is the EWeLiNE project[33], Fraunhofer and the German Weather Service have been working to develop better models for forecasting the generation of renewable electricity.

The EWeLiNE model includes 1.9 million photovoltaic facilities and wind farms operating in Germany, aiming to calculate precisely how these facilities will convert the weather into electricity. Now they have launched a platform for transmission system operators to test the new models live.

[30] www.neon-energie.de/balancing, Lion Hirth
[31] http://www.50hertz.com/en/Grid-Data/Photovoltaics/Forecast-Photovoltaics-feed-in
[32] https://www.tennettso.de/site/en/Transparency/publications/network-figures/actual-and-forecast-photovoltaic-energy-feed-in_land?zeige_datum=2018-02-28&zeit_von=06:00:00&zeit_bis=12:00:00&sub=total
[33] https://www.fraunhofer.de/en/press/research-news/2016/June/better-forecasting-for-solar-and-wind-power-generation.html

3.1.2.4 Improve flexibility of power system

The outputs form wind turbines and photovoltaic power plants are variable by nature, which necessitates fundamental change in the power system and power markets – must cope with highly fluctuating feed-in. As the VRE represent a high share of power consumption, the online conventional power plants (i.e. nuclear and coal) must respond flexibly to the rapid changes in power supply and demand.

The German power system offers abundant technical potential for flexibility (much higher than the actual demand for flexibility)[34]. As shown in Figure 28, conventional hard-coal and lignite power plants have been retrofitted for flexible operations to manage the variable VRE feed-in. During the depicted example week in March 2016, the baseload operation of nuclear and coal power plants was significantly reduced while VRE generation was high.

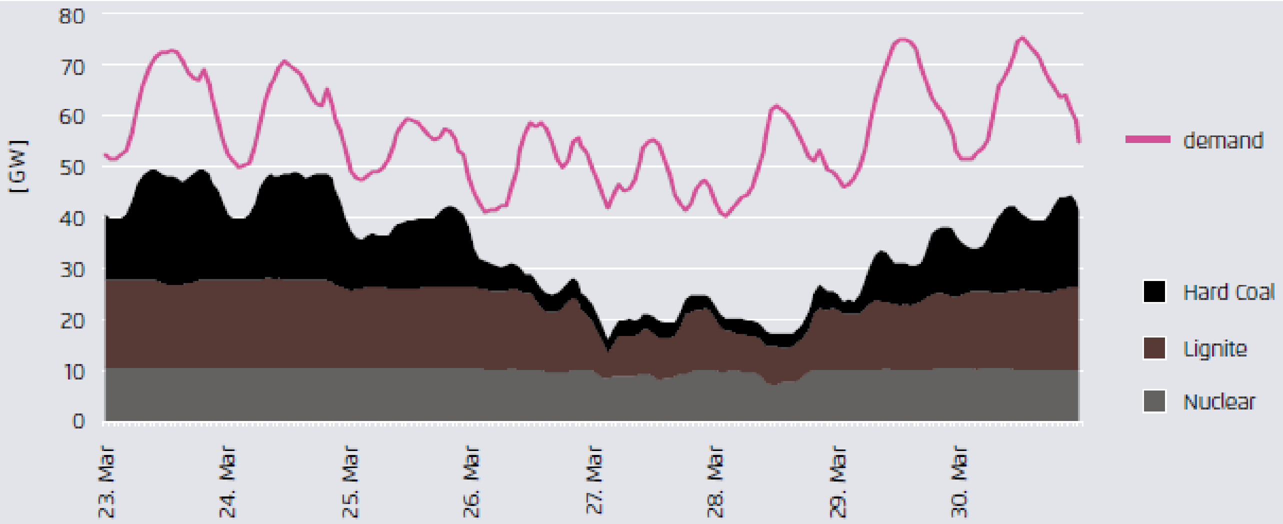


Figure 28 – Flexible operation of conventional generators

Several other flexibility options exist to incorporate variable energy sources into the power system. These include, for example, demand-side management, the expansion of grid infrastructure (including smart grid solutions) and, in the long-term, expanded storage.

3.1.2.5 Market design to accommodate VRE

The German electricity market, EPEX Spot, operates day-ahead and intra-day markets which allow trading between neighbouring countries. Trades for the intra-day market are closed 15 minutes before delivery, which provide a way for participants to balance any forecasted deviations in their production and consumption.

With the incentives set right, market participants have proven capable of self-balancing their volatile RES portfolio.

3.1.2.6 Other ongoing efforts

Development of alternative sources of ancillary services. In a 2014 study, the German Energy Agency (dena) found that by 2030, majority of primary reserve will be provided by non-conventional power plants. They anticipate alternative sources of ancillary services coming from the large and growing fleet of wind turbines, utility-scale solar, demand response and battery storage[35].

Alternative sources of voltage control include additional compensation systems, converter stations of HVDC lines, and phase shifters. Wind power plants are technically capable to provide balancing power and voltage

[34] Agora Energiewende 2017, Flexibility in thermal power plants, With a focus on existing coal-fired power plants

[35] https://www.dena.de/fileadmin/dena/Dokumente/Themen_und_Projekte/Energiesysteme/dena-Studie_Systemdienstleistungen_2030/Ergebniszusammenfassung_dena-Studie_Systemdienstleistungen_2030.pdf

control services. 50Hertz is currently involved in pilot projects in Germany to test this within the German market framework[36]. There are also intentions to pilot the use of RE generation for black-start

Improve the reserve dimensioning methodology. The German TSOs currently use a reserve dimensioning methodology that was jointly developed by the 4 TSOs and the University of Aachen with support of the government. The current Graf-Haurich method is based on a 3-month ahead forecast with hourly resolution. There is ongoing research to advance the reserve dimensioning methodology be applied daily with 15-minute resolution. It is anticipated that the improved reserve dimensioning methodology will mitigate the need for higher amounts of reserves.

3.2 California

As shown in the utilities map in Figure 29, California ISO (CAISO) manages the flow of electricity for about 80 percent of California and a small part of Nevada, which encompasses all the investor-owned utility territories and some municipal utility service areas.

The California ISO is one of nine independent system operators in North America. Collectively, they deliver over 2.2 million gigawatt-hours of electricity each year and oversee more than 270,000 miles of high-voltage power lines. Two-thirds of the United States is served by these independent grid operators.

The installed VRE nameplate capacity 19.3 GW by 2016e, accounts a 22.9% of the total installed capacity. The VRE contributes 17.2% of the total electricity generation.

California imports electricity from interconnected balancing areas ranging from 6 to 11 GW[37].

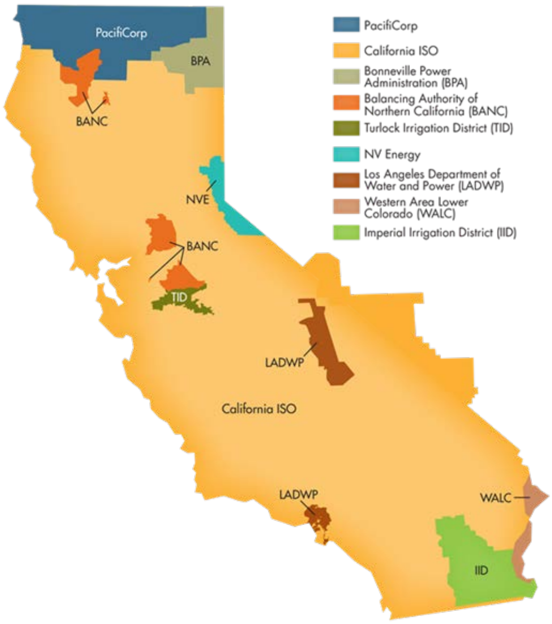


Figure 29 - Utilities in California

In California, energy and environmental policies are driving electric grid changes. Key initiatives[38] include:

- 50 percent of retail electricity from renewable power by 2030;
- Greenhouse gas emissions reduction goal to 1990 levels;
- Regulations in the next 4-9 years requiring power plants that use coastal water for cooling to either repower, retrofit or retire;
- Policies to increase distributed generation; and
- An executive order for 1.5 million zero emission vehicles by 2025.

To fulfil the Renewable Portfolio Standard, approximately 4 GW renewables will be added to the system by 2020, and an additional 10 to 15 GW unspecified renewables by 2030[39]. The renewable capacity and targets of California power system is summarised in Figure 30.

[36] https://d2oc0ihd6a5bt.cloudfront.net/wp-content/uploads/sites/837/2017/06/The-German-energy-transition-_-integration-of-renewable-energy-.pdf
[37] http://www.caiso.com/TodaysOutlook/Pages/supply.aspx
[38] https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf
[39] https://www.caiso.com/Documents/RenewableIntegrationUnlockingDividends.pdf

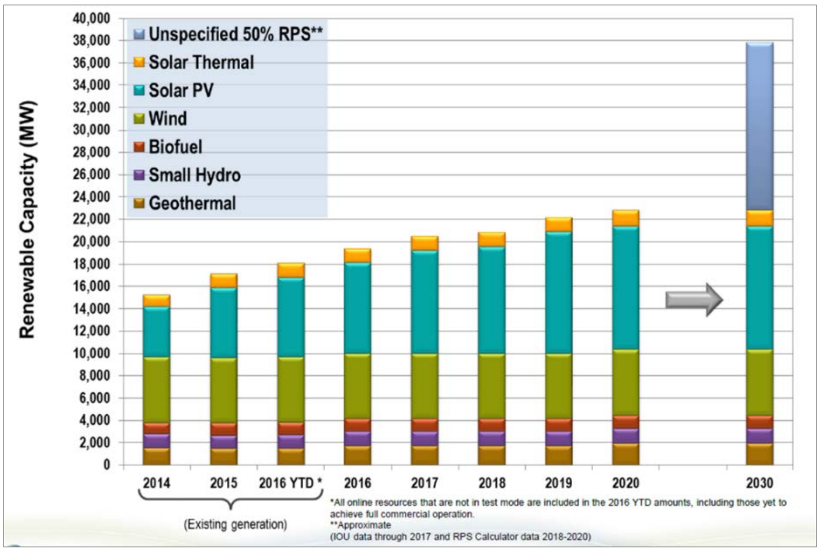


Figure 30 - Renewable capacity and targets of California power system

3.2.1 Challenges of high VRE penetration

In California, the ISO performed detailed analysis for every day of the year from 2012 to 2020 to understand changing grid conditions. The analysis shows how real-time electricity net demand changes as policy initiatives are realised. Several conditions emerge that will require specific resource operational capabilities[40].

3.2.1.1 High volatility in a short time periods

The California system features a load profile of evening peak. Due to the large deployment of solar photovoltaic generation, the ISO experiences frequently short-time and steep ramps due to the sunset and evening load pickup. When the ISO must bring on or shut down generation resources to meet an increasing or decreasing electricity demand quickly, and over a short period.

As depicted in Figure 31, the 3-hour netload ramp, due to combination of subset and evening load pickup, reached 12.96 GW or 4.3 GW per hour. Part of the netload increases is diverted to the power import through interconnectors, and non-spinning reserve generators are frequently dispatched during this period.

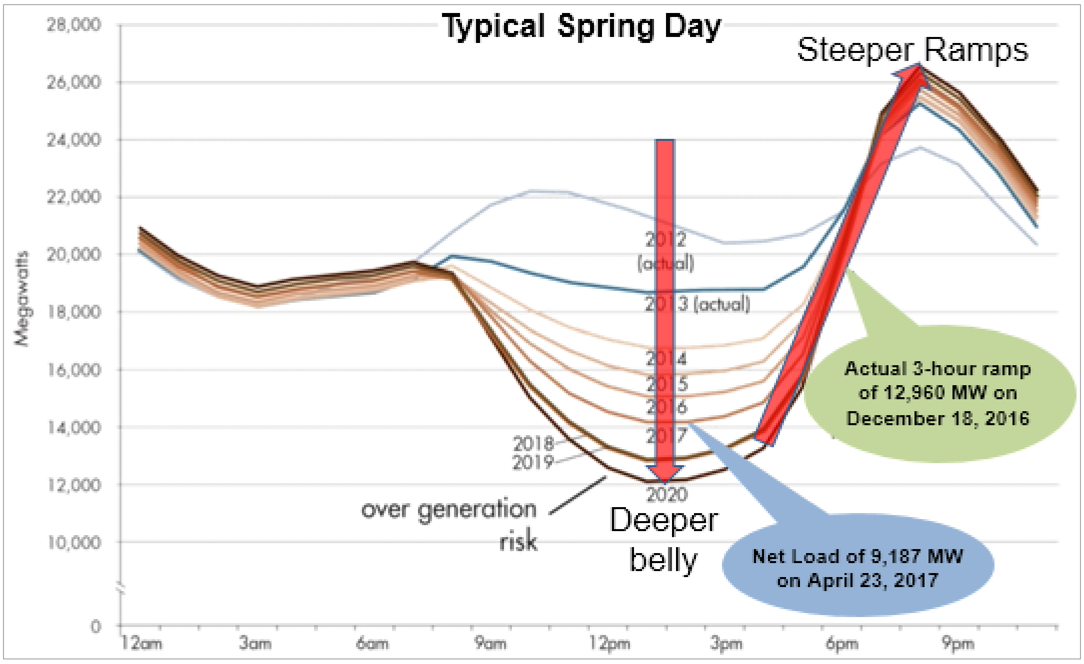


Figure 31 – California grid net-load profile of typical spring day

40 https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

3.2.1.2 Oversupply risk

As the VRE penetration becomes higher and higher, deeper bellies are formed during peak irradiance periods of the daily netload profile (Figure 31). This results on oversupply or curtailment risk – when more electricity is supplied than is needed to satisfy real-time electricity requirements.

On the other hand, the deep bellies will further exacerbate the evening ramp, making the netload ramps even steeper.

3.2.1.3 Decreased frequency response

The high VRE penetration resulted in decreased frequency response – when less dispatchable resources are operating and available to automatically adjust electricity production to maintain grid reliability.

New types of technologies and technical specifications are necessary to reliably and efficiently operate the system with high levels of renewables.

3.2.2 Control measures for high VRE integration

California ISO has undertaken several initiatives to improve the current market structure and enhance renewable integration.

3.2.2.1 Interconnection Standards (Grid Codes)

Technical specifications (or grid codes) that improve reliability and controllability of variable generation renewable resources are one example.

These standard requirements include[41]: 1) Voltage regulation and reactive power capability; 2) Low and high voltage ride-through; 3) Inertial-response; 4) Ramp rate and curtailment control; 5) Frequency control (governor action).

3.2.2.2 Renewable Energy Transmission Initiative

California's Renewable Energy Transmission Initiative (RETI)[42] evaluated ideal locations for renewable development in California in order to identify major upgrades to the electric transmission system[43].

Deployment of synchro-phasor measurement tools provides for sub-second monitoring of grid conditions and thus enhances the ability of system operators to deliver interconnection-wide networking, event analysis, model validation and real-time controls on a wide-area basis. By improving detection and mitigation of power system vulnerabilities, synchro-phasor technology can significantly increase the reliability of the interconnection, and allow for the release of latent transmission capacity at very low cost to foster a more robust west-wide market for renewable energy[44].

3.2.2.3 Improve VRE forecasts

Improved Forecasts to facilitate Renewable Integration, CAISO installed a new fifth-generation load-forecasting tool that will be able to handle multiple sources of input, including multiple weather services that provide forecast data for meteorological conditions such as wind speed, temperature, barometric pressure, and solar irradiance. CAISO system operators generally requires energy forecasts from individual solar farms in three specific time periods:

1) Day-ahead: 18–42 hours before the operating hour;
2) Hourly: 105 minutes before the operating hour;
3) Intra-hour: every 15 minutes for the next two hours[45].

[41] https://www.caiso.com/Documents/RenewableResourcesandCaliforniaElectricPowerIndustry-SystemOperations_WholesaleMarketsandGridPlanning.pdf
[42] http://www.energy.ca.gov/reti/
[43] http://www.caiso.com/Documents/WSPInitiativeTopicSuggestions-InterconnectionProcessEnhancements2018.pdf
[44] https://www.caiso.com/Documents/IP-1-ISOUsesSynchrophasorData_GridOperations_Control_AnalysisandModeling.pdf
[45] http://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC-CAISO_VG_Assessment_Final.pdf

3.2.2.4 Improve power system operation

California ISO operates a real-time (spot) market, where the utilities can buy power to meet the last few increments of demand not covered in their day ahead schedules. The real-time market secures reserves, held ready and available for ISO use if needed, and the energy needed to regulate transmission line stability.

The real-time market system dispatches power plants every 15 and 5 minutes, although under certain grid conditions the ISO can dispatch for a single 1-minute interval. The ISO improved the AGC controller to enable fast dispatch (high-pass signals at 1-second interval) to advance technologies such as battery storage system.

3.2.2.5 Market design to accommodate VRE

California has well-developed market mechanisms and frameworks that are designed to integrate the variable renewables, while ensuring the reliability of the power system – to "keep the lights on".

California has an inherent flexibility from its many natural gas power plants, which altogether provide about 60% of California's power. The market is designed to allow these plants to profit from selling into both the normal day-ahead wholesale market, as well as into the ancillary markets. The ancillary market is designed to provide balancing power for short-term fluctuations in demand and generation. The ISO has developed two innovative mechanisms for ensuring flexibility and reliability to balance variable renewables.

The first of these is more of a mandate, which requires power generators to bid a portion of their most flexible capacity into the market at all times, so that he grid operator can call upon that capacity when needed to balance renewables.

A second mechanism by the ISO is called the "Flexible Ramping Product", enables the ISO to shift generation in time, from low-ramp to high-ramp periods. With the Flexible Ramping Product, the ISO pays fast-ramp generators to remain "off" during low-ramp periods, so that the generator is then available to turn "on" during high-ramp periods, at the dispatch order form the ISO. The capacity payments made to the generators to remain off during low-ramp periods, coupled with the payments when the generator is used during high-ramp periods, should be sufficient to compensate the generator for lost revenue while "off". The Flexible Ramping Product is designed to allow both loads and all types of generators to participate, including wind and solar, and energy storage.

One key aspect of the Flexible Ramping Product is that it introduces a new scheme for allocating the extra costs of flexibility. The basic principle of this new scheme is this: the market costs of ramping capacity under the Flexible Ramping Product should be paid by those market participants who are creating the need for greater flexibility.

3.2.2.6 Other ongoing efforts

The battery energy storage system can adjust its output rapidly in response to the variability of renewable output, providing very-fast regulation services. The storage also takes advantage of the potential surplus of wind energy in the overnight (off-peak) hours to store energy for release in the peak hours.

Energy storage resources have a number of characteristics that are particularly suited for facilitating renewable integration. They can provide a very fast response to control signals, frequency response and automated dispatch commands. They have '0' minimum stable load, very high ramp rates, and are capable of instantly start and stop. They are thus well-suited providing the regulation services that the ISO has identified as potentially important to renewable integration. CAISO has started initiative for Energy Storage and Distributed Energy Resources[46].

Additionally, load shifting and demand response[47] capabilities are needed, in response to market prices, along with greatly improved coordination and control of these demand side and storage capabilities and more efficient use of transmission infrastructure through advanced operational technologies.

46 http://www.caiso.com/Documents/NewInitiativeEnergyStorage-DistributedEnergyResourcesPhase3IssuePaperPostedCall101217.html
47 https://www.caiso.com/informed/Pages/CleanGrid/Demand_Response.aspx

Increased price-responsiveness by power consumers will also facilitate renewable integration. There is much interest in dynamic demand response, which as a resource can potentially follow the variability of renewable output, through direct dispatch signals sent by the ISO[48].

3.3 Hawaii

Hawaiian Electric Company has been providing energy to the islands' development from a Hawaiian kingdom to a modern state. Hawaiian Electric Company, and its subsidiaries, Maui Electric Company, and Hawaii Electric Light Company, serves 95% of the state's 1.4 million residents on the islands of Oahu, Maui, Hawaii Island, Lanai and Molokai. Map of Hawaii is shown in Figure 32.

On the Mainland, power utilities can get power from another utility, often in a different state, through a grid of interconnected transmission lines. In Hawaii, each island generating system must stand alone without backup from other utilities. Hence, Hawaiian Electric, Hawaii Electric Light, and Maui Electric need to: be more reliable and self-reliant than other utilities; have enough generators to produce power during "Peak" time - or when people use the most electricity (usually after work during weekdays); install more reserve generation to account for generating units taken down for regular maintenance and to cover the potential unplanned loss of the largest generating unit.

In 2016, customers of Hawaiian Electric, Maui Electric and Hawaii Electric Light Company were served by almost 991 megawatts of renewable energy resource capacity (including 543 megawatts of customer-sited rooftop solar). Total generation capacity available to meet our customers' electricity needs is approximately 3,015 megawatts.

Figure 32 – Map of Hawaii

These renewable energy sources resulted in 2,283 gigawatt-hours, or 25.8 percent, of electric sales in 2016, as reported to the Hawaii Public Utilities Commission in our annual Renewable Energy Portfolio status report. This does not include energy savings from solar water heating or quantifiable energy efficiency.

Hawaii electricity generation was an oil-based system. Switching to a renewable based system for Hawaiian electric companies will take investment and may be more expensive, especially at first[49], the State of Hawaii has a bold energy agenda – to achieve 100 percent clean energy by the year 2045. Along with reducing the islands' dependency on fossil fuels and increasing efficiency measures, the clean energy plan is also contributing to the state's economic growth[50].

Hawaii aims to reduce its consumption of oil[51]. Fuel oil must be imported to Hawaii, often from unstable, turbulent places over thousands of miles of open ocean. Oil prices are lower today but Hawaii is vulnerable economically to increases in the price of oil and disruptions in supply. To increase energy security and keep more of the energy dollars at home, Hawaii is incentivised to local renewable resources at more stable prices.

[48] https://www.caiso.com/Documents/RenewableResourcesandCaliforniaElectricPowerIndustry-SystemOperations_WholesaleMarketsandGridPlanning.pdf
[49] https://www.hawaiianelectric.com/clean-energy-hawaii/clean-energy-facts/reliability
[50] http://energy.hawaii.gov/
[51] https://www.hawaiianelectric.com/clean-energy-hawaii/clean-energy-facts/renewable-energy-sources

As islands in the middle of the Pacific, Hawaii is vulnerable to rising sea levels, longer and more violent storms, and longer, drier droughts. Although its carbon footprint and contribution to global climate change are small, Hawaii is determined to do its part on reduction of greenhouse gas emissions.

3.3.1 Challenges of VRE integration

Challenges to the Hawaii Electric grid with increasing penetrations of wind and solar energy are mainly related to rapid output power fluctuations from wind and solar, which caused:

1) curtailment of wind and solar energy[52] (from 5% to 20%)[53];
2) Higher frequency response duty of thermal generation unit operation during loss-of-load events, generator trip events and wind and solar power variation[54].

3.3.2 Control measures for VRE integration

Hawaii has put in place a set mitigation measures[55] to maintain stable operation of the grid, including:

1) Implement renewable forecast program, the REWatch.
2) allocating down reserves to wind and solar plants;
3) Relaxing fixed operating schedules for a few thermal units;
4) providing reserves from alternate resources such as a BESS or demand response.

Currently Hawaii Electric are looking at improved VRE generator technologies – the "electronic shock absorber"[56] patented by engineers at Hawaiian Electric Company. It's basically integrated battery storage within the renewable generators. The very interesting aspect is: the controls takes into account very short-term renewable output forecasts, and use the forecasts to regulate the output power and the battery state-of-charge. One step advance than the common collocated BESS for VRE output smoothing applications. Hawaii aim to smooth the rapid fluctuations of wind in the short term[57].

Hawaii is also developing large-scale electric storage system, including very large chemical, mechanical and electronic "batteries". But some of technologies are in very early stages of development. At present, large batteries or other storage can be very expensive, adding to the cost of every kilowatt hour of electricity produced.

The recent renewable developments are with more focus on biomass and biodiesel and the like controllable renewable technologies, which are crucial to achieve the 100% renewable ambition by 2045.

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[52] https://www.hawaiianelectric.com/clean-energy-hawaii/clean-energy-facts/reliability/24-hour-availability
[53] https://www.mauielectric.com/clean-energy-hawaii/clean-energy-facts/wind-energy-integration
[54] https://www.nrel.gov/docs/fy13osti/57215.pdf
[55] https://www.nrel.gov/docs/fy13osti/57215.pdf
[56] https://www.google.com/patents/US7432611
[57] https://www.hawaiianelectric.com/clean-energy-hawaii/clean-energy-facts/reliability

3.4 Spain

The Spanish high voltage transmission grid is operated by Red Eléctrica de España (REE), the Spanish TSO.

Overall renewable capacity is summarised in Figure 33. The installed VRE nameplate capacity includes 23.1 GW Wind and 7.0 GW Solar generators, accounts a 28.5% of the total installed capacity of 105 GW. The VRE contributes 23.2% of the total electricity generation. Among the surveyed countries, Spain has the highest VRE energy share.

Spain has a large hydroelectric power generation capacity of 20.35 GW, accounting to 19.3% of the total capacity, or 68% of the VRE installed capacity.

The hydroelectric generators help largely to mitigate the fluctuations of renewable outputs.

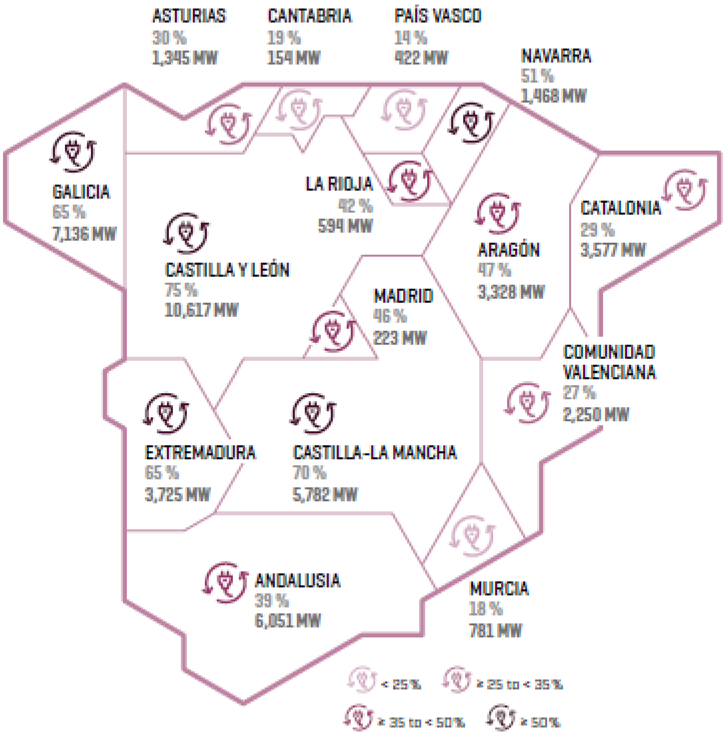

Figure 33 - Renewable capacity share in Spanish power system

The evolution of generation capacity of Spanish Peninsular system is illustrated in following Figure 34.

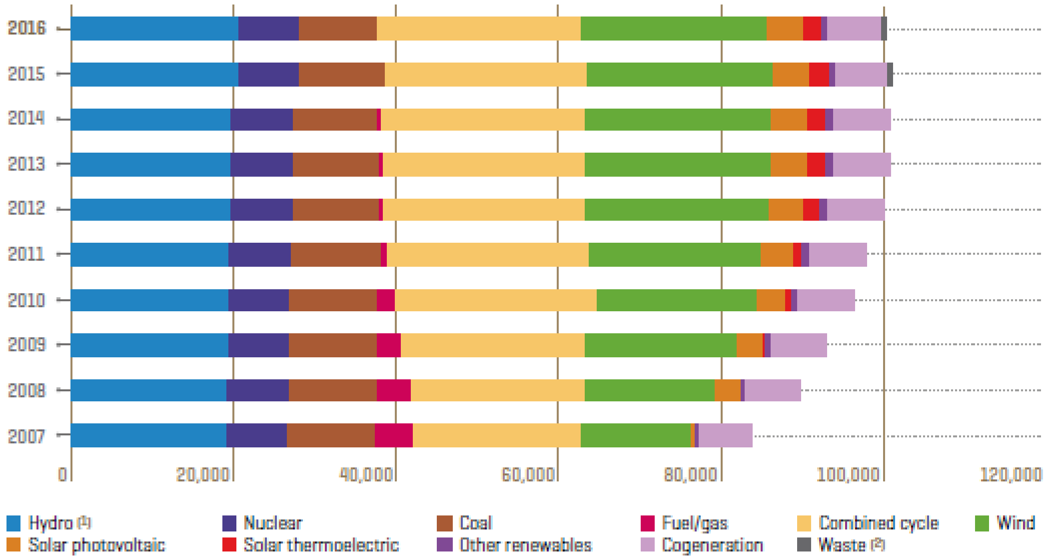

Figure 34 – Install capacity share of Spanish peninsular

Spain's current renewable energy target follows the binding EU target of 20% of final energy consumption by 2020 (part of EU Directive 2009/28/EC[58]). In response to this, the Ministry of Energy, Tourism and Digital Agenda prepared and published the National Action Plan for Renewable Energies (NREAP) 2011-2020[59].

Since 2013, there have been little capacity additions. This has been attributed to abrupt changes to the government's renewable policy and uncertainty over future policy. These changes were initially driven by the growing budget deficit and economic crisis in 2008. There was further scaling back of government support

[58]http://www.minetad.gob.es/energia/desarrollo/EnergiaRenovable/Documents/20100630_PANER_Espanaversion_final.pdf
[59] http://www.minetad.gob.es/ENERGIA/DESARROLLO/ENERGIARENOVABLE/Paginas/Paner.aspx

for VRE generation with the change in government. For example, the generous FiTs that were intended to stimulate the installation of solar generation were reduced significantly, leading to a 15-50 percent decrease in revenue for solar farms. In 2014, the government implemented a renewable remuneration scheme ("Régimen Retributivo Específico") to replace the FiT. The scheme allows the government to review input parameters every 3-6 years which determine the amount of remuneration, which introduce uncertainties over the long-term payments through the scheme.

3.4.1 Challenges of VRE integration

The safe integration of VRE remains one of the great challenges to the operation of the electricity system. Among other unique characteristics, the VRE integration poses great challenges[60] to the Spanish electricity system mainly due to: 1) the challenging daily load profile of the Spanish peninsula; 2) the very high variability of VRE generation and often mismatches with load profile; and 3) the limited capacity of interconnection with the rest of continental Europe.

3.4.1.1 Challenging load profile

The load profile of Spanish power system is characterized by very large differences between peak and valley load, with a maximum / minimum load ratio in the range of 1.5 to 1.7 [61]. The system operator needs to ensure sufficient flexible generation to meet the load profile requirements throughout the day. This challenge is exacerbated by the priority dispatch of renewables. Figure 35 below briefly illustrate the issues associated with very low demand from midnight to early morning.

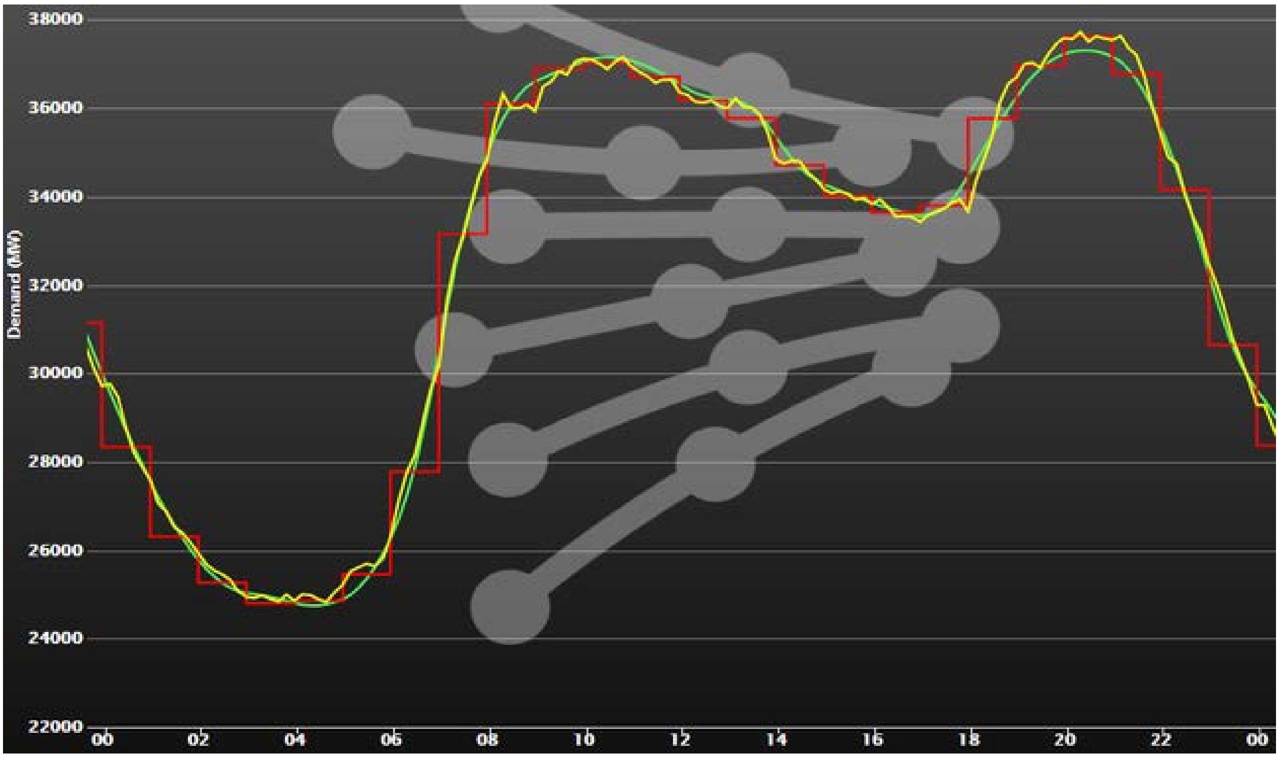

Figure 35 – Load profile of a weekday [62]

As a consequence, the dispatchable power generating units must operate in a more demanding regime and with greater flexibility due to the fact that they are the principle units responsible for keeping up with the demand load curve throughout the day. This requirement has increased even more in recent years due to the increased quota of renewable energy capacity installed in the system and the priority regarding its operation over other technologies.

[60] http://www.ree.es/en/red21/integration-of-renewables

[61] https://cdn.osisoft.com/corp/en/media/presentations/2014/EMEA2014/PDF/EMEA14_REE_Gil_BigDataAnalyticsandRealTimeDataAwarenessatCECREControlCenterforRenewableEnergies.pdf

[62] http://www.ree.es/en/activities/realtime-demand-and-generation, on 17/01/2018

3.4.1.2 Very high variability of VRE

The variability associated with renewable generation is very high, particularly with weather disturbances. The weather patterns significantly affect the generation output of solar and wind generation, which requires the system operator to schedule dispatchable generator to balance the variabilities to ensure the safe operation of the grid. From an analysis on the 2012 whole year wind power output time-series, the percentage of demand that can be met by wind generation can vary from 1% to above 65%, ref to Figure 36.

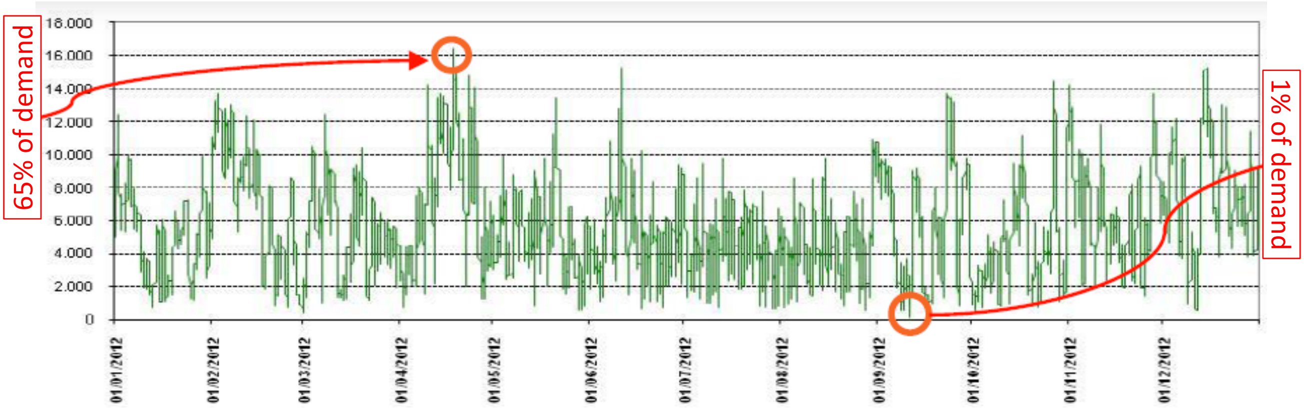

Figure 36 – Wind power output time-series of a year

Another challenge is the mismatch of the wind generation profile and the load profile. The dispatch become very difficult when there is a strong wind from midnight to early morning, ref Figure 37.

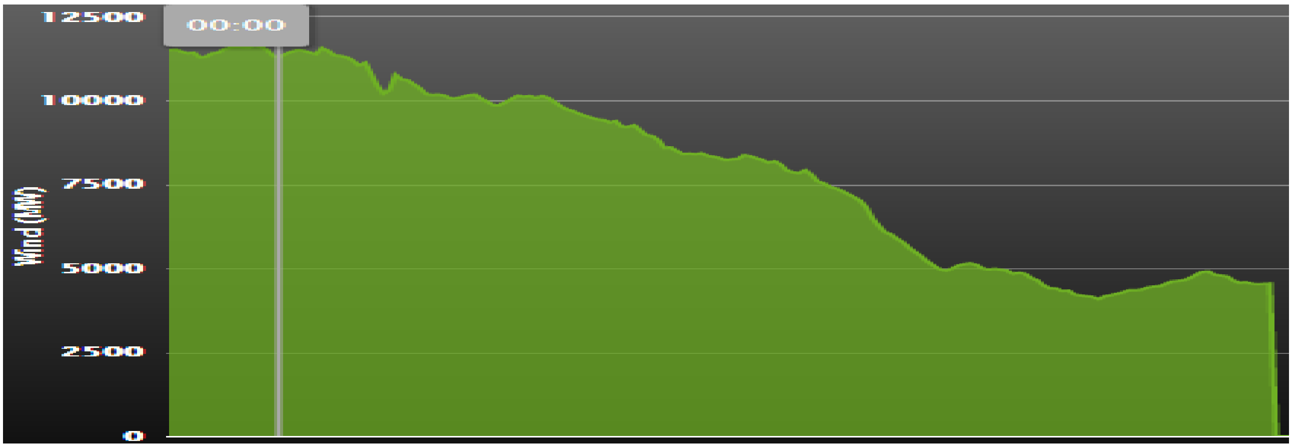

Figure 37 – Possible mismatch between load and VRE generation profile [63]

3.4.1.3 Lack of interconnections to neighbouring grids

The interconnections to neighbouring grids can be used to import or export energy to balance short- and medium-term demand and supply fluctuations in the grid. The lack of these interconnections means that the Spanish power system must be able to handle all fluctuations using domestic resources. In 2018, Spain had a total of 2.3 GW of import and 1 GW of export capacity, equivalent to just 3.2% of total installed capacity.

The commissioning of the new interconnection with France has increased the existing interconnection capacity between the two countries. Strengthening interconnections can allow the mitigation of the required limitations associated to scenarios where there is a high level of energy production from renewable sources by facilitating the export of electricity to other electricity systems. However, even with the new interconnection, our interconnection capacity with France remains well below the guidelines given by the European Union (interconnection level of at least 10% of installed capacity by 2020).

[63] http://www.ree.es/en/activities/realtime-demand-and-generation, on 17/01/2018

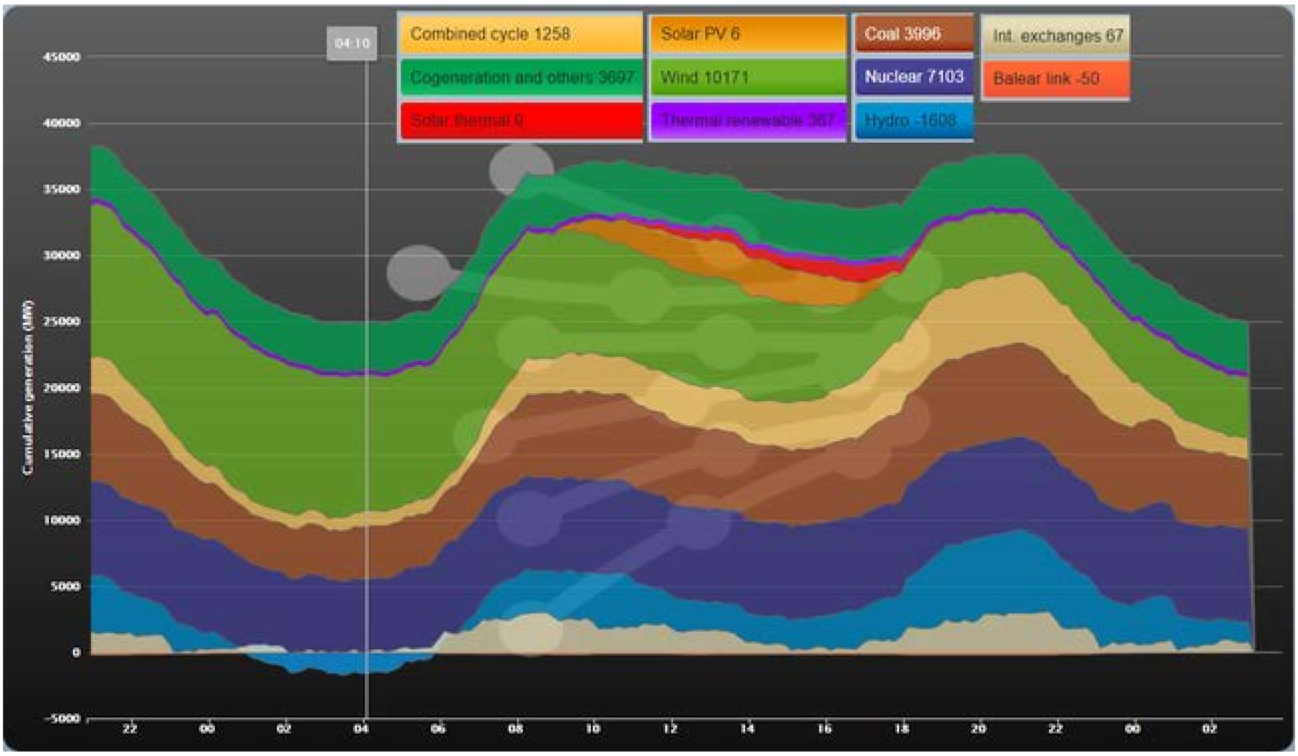

Figure 38 – Resulted generation mix due to mismatch of load and wind generation profiles [64]

Refer to the load profile (Figure 35) and the wind output profile (Figure 37) of the same day, the resulted generation mix is illustrated in Figure 38.

The Spanish power system must handle all fluctuations using domestic resources. When the wind generation is high during the early morning period, sufficient reserves must be scheduled for safe operation of the grid, e.g. the hydroelectric and combined cycle generation. However, due to lack of interconnection capacity, the high wind actually forced most of hydroelectric generators offline – reducing the reserve and ramping capacity of the power system.

3.4.2 Control measures for VRE integration

REE has adopted the following control measures to mitigate the increased VRE penetration.

3.4.2.1 Interconnection Standards (Grid Codes)

Royal Decree 413/2014 establishes the connection requirements to obtain authorization from REE while Operating Procedure 3.7 describes additional criteria for RE generation. The connection requirements include connection to a GCC, fault ride through capabilities and reactive power management.

Prior to the introduction of fault ride through requirements, the number of trips due to voltage dips were increasing as the amount of wind generation increased. In response to this, REE worked with the industry to develop testing and verification procedures to determine that the new and existing RE generation is compliant with the Fault Ride Through requirements[65]. The improved grid code has been effective in reducing the number of trips due to voltage dips[66].

3.4.2.2 Implement and improve VRE forecast

In order to integrate the maximum amount of generation from renewable energy sources into the electricity system, whilst ensuring quality levels and security of supply, Red Eléctrica de España designed, put in place and started the operation of the Control Centre of Renewable Energies (CECRE) in mid-2006. The CECRE, a

[64] http://www.ree.es/en/activities/realtime-demand-and-generation, on 17/01/2018
[65]http://www.nerc.com/comm/PC/Integration%20of%20Variable%20Generation%20Task%20Force%20IVGT/Sub%20Teams/Operation/Paper_126_Cena%20(2-4_Task%20Force).pdf
[66] http://ieeexplore.ieee.org/document/6345431/

separate unit within the grid control centre, has been a pioneering centre, of world reference regarding the monitoring and control of renewable energies.

The CECRE monitors real-time VRE generation through a network of Generation Control Centres (GCCs) which must provide updates every 12 seconds on over 200,000 analogy and digital telemetries including the connection status, production of active and reactive power, and voltage at the connection point. All VRE generating plants or clusters larger than 1 MW must be registered with a GCC. Through the GCCs, the CECRE receives real-time tele-measures on approximately 96% of wind generation, 100% of CSP generation and 70% of PV generation.

The CECRE sends out set-points for wind and solar plants to their respective GCCs which must be followed within 15 minutes. This relatively fast response allows the REE to monitor and control the VRE generation as a last resort close to real-time when downward tertiary and secondary control reserves are exhausted. This gives the following benefit: a) fewer downward reserves need to be scheduled; and b) VRE generation is maximized since it is not pre-emptively curtailed for supply security reasons.

The advanced forecasting methodology used by CECRE for forecasting wind generation is called SIPREOLICO and was co-developed with the University Carlos III of Madrid. SIPREOLICO is a neural network prediction method with over 800 network nodes and can be used to forecast outputs for individual wind farms. Inputs used include meteorology forecast based on a numerical weather prediction (NWP) model, real-time tele-measures from wind and solar plants, and the forecasted generation of individual RE generation. The forecast errors for wind generation have improved significantly over time – the mean absolute error for hour-ahead forecasts have decreased from 12% in 2008 to 4% in 2015[67]. Ongoing efforts to improve SIPREOLICO are focused on improving the meteorology forecast including increasing spatial resolution and increasing frequency.

3.4.2.3 Increase interconnection capacity

The European Council has set a guideline for all EU countries to have international interconnectors equivalent to 10% of their installed capacity by 2020 and 15% by 2030[68]. One of the objectives for these interconnections is to support the integration of renewable energies by giving countries the ability to exchange power with neighbouring grids to balance their grid[69]. This takes advantage of geographical diversity to smoothen variations in RE generation, technology diversity in generation mix and complementary load profiles.

The commissioning of the new interconnection with France in 2015 has increased the existing interconnection capacity between the two countries. In 2018, Spain had a total of 2.3 GW of import and 1 GW of export capacity, equivalent to just 3.2% of total installed capacity.

3.4.2.4 Power electronics and Flexibility solutions

REE's R&D is focused on power electronics and flexibility solutions[70]. The power electronics program is focused on enabling more reliable power management including converter designs and topologies, material performances, control strategies and methodologies.

The flexibility program is focused on developing alternative flexibility resources including storage technologies, enabling VRE generators to provide flexibility services, demand side management, and tools to monitor real-time system flexibility.

3.5 Summary of Challenges and Control Measures

Some of challenges could be specific to a grid system, however, there are many common characteristics. And the control measures adopted by utilities with high VRE penetration levels have also many similarities. The challenges and control measures are summarised in following text.

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[67] http://www.ieawindforecasting.dk/-/media/Sites/IEA_task_36/BCN-2016/IEAWindTask36-ExpGapsForecastingWorkshop_Barcelona_Rodriguez_2016.ashx?la=da
[68] https://ec.europa.eu/clima/sites/clima/files/strategies/2030/docs/2030_euco_conclusions_en.pdf
[69] http://www.ree.es/en/red21/strengthening-interconnections
[70] http://www.ree.es/en/red21/rdi/grid2030-program

Challenges	Control Measures
VRE generator technical requirements Very limited connection requirements in the early years when VRE penetration level was low, e.g. dynamic behaviours (LVRT, frequency response, dynamic voltage support, etc.) of VRE generators were not specified. The lack of connection standard had resulted in undesired frequent VRE generator disconnections and cascading effects.	**Interconnection standards (Grid Codes)** Strengthen the interconnection standards (Grid Codes) to ensure the VRE generators' steady-state and dynamic behaviours fulfil power system operation requirements. Germany and Spain had also required the early installations to be retrofitted for compliance to new grid codes requirements. Third-party verification, including dynamic behaviours, is required.
High variability and stochastic nature of VRE The high variability and stochastic nature of VRE generation output pose challenges on stable power system operation.	**Implement and improve VRE forecasts** All the 4 system operators implemented VRE forecasting system, and have been continuously improving the forecast accuracy. The VRE forecasting is the key enabler for stable power system operation. For example, the German 50Hertz achieved 99.82% of the Solar forecast errors are within ±5% of the nameplate capacity. The Spanish REE achieved ±4% forecast error in 2018. Refer to solar eclipse event (Figure 19), among other factors, the forecasts had been crucial for the system to overcome the huge power fluctuation.
Increase in reserve requirements The variability and stochastic nature of VRE increase the reserve requirements on both the volumes and ramp rates. The challenge could be exacerbated as penetration level become high, coupled with specific characteristics of the grid. For example, the "duck" curve of California resulted from large solar photovoltaic installation and its evening peak load profile; the high-wind during early morning coupled very deep valley of Spanish load profile; and the like for Germany.	**Widen the balancing area, interconnections** Interconnections have been widely employed by utilities for mutual assistances, to improve reliability of supply. Widen the balancing area with interconnection has two effects: achieve geographically diversified VRE variability; and sharing of reserves. Both result in less reserve requirements. The interconnection also allow short-term trading of excess energy from VRE, enables optimum utilisation of generation resources in the interconnected systems. A good example is the GCC in Germany and later on the IGCC among Germany and the neighbouring systems. **Improve reserve dimensioning methodology** Germany studied adaptive reserve dimensioning, taking into account daily VRE forecasts.

Challenges	Control Measures
High penetration, shortage of ancillary services providers As the penetration level become high, the existing flexible generators such as hydroelectric and open cycle gas turbine generators would be pushed offline, reduce the reserve providing generators in the system during the VRE high generation periods. At the same time, higher reserves are required for stable operation of the system.	Improve flexibility of power system Improve flexibility of existing baseload generators, enable these generators to provide ancillary services to the system. Strengthen the transmission grid to allow the flexible operation of existing generators. Market design to accommodate VRE In general, high penetration of VRE into the system tend to reduce the load factor of existing conventional generators, in turn their revenue. However, these generators are still required to “keep the lights on” by providing backup energy. Both Germany and California designed an ancillary services market with high incentives. The market creates another revenue stream for conventional generator and make them financially viable with reduced load factor. Alternative reserve providers The battery storage technologies are promising with ‘0’ stability limit and very fast ramping capability. The VRE generators such as wind turbines are technically capable of providing balancing power and voltage support services.

4 VRE PENETRATION STUDY ON THE PENINSULAR MALAYSIA SYSTEM

4.1 Develop the detailed study methodology

DNV GL recognises the fundamental tenets of power system operations: the ability to reliably forecast load; the ability to plan sufficient generation to meet future demand economically and reliably; the ability to balance instantaneously the load with generation; and resilience of the system to withstand credible contingent events without cascading loss of loads or generations. The aspects are illustrated in Figure 39.

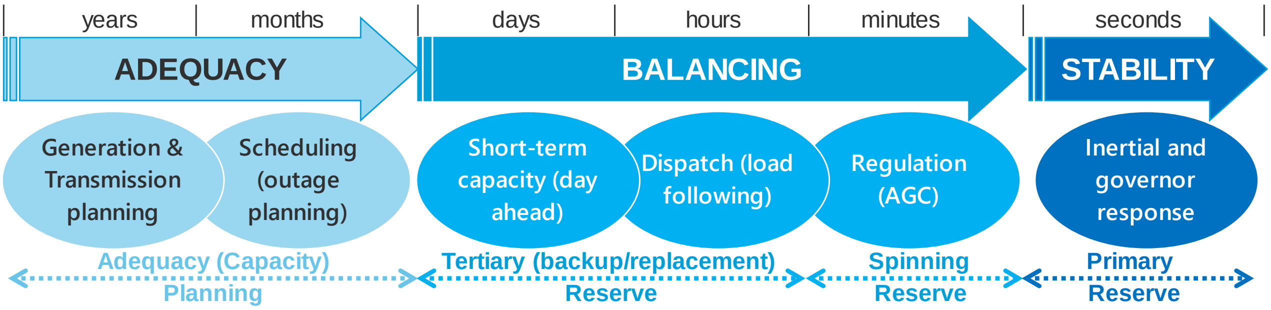
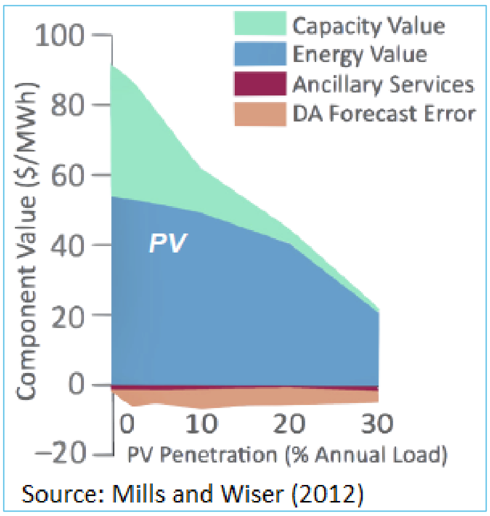


Figure 39 – Aspects of a grid system planning and operations

These fundamental tenets are challenged in the new resource paradigm with high penetration of solar and wind generations:

1) The net load forecast is challenged due to the variable and intermittent nature of solar and wind generations. The grid operator must keep sufficient secondary and tertiary reserves for balancing.
2) On the long-term generation planning realm, the capacity credit estimation is challenged due to intermittent nature of solar generations.
3) For tropical climate, cloud coverages are much more diversified comparing to continental climate – often varying from one place to another with small spatial separation. This commonly results in more power output fluctuations for a single solar farm due to more frequent weather changes, but less for multiple solar farms with spatial diversity.

Two studies in the US showed consistently the second effect, as illustrated in Figure 40: the economic value of solar photovoltaic generation declines rapidly with increased penetration levels, as illustrated in figure of CAISO case study by Mills and Wiser in 2012 and EPRI study in 2017 with US-REGEN model. The main drivers are rapid decline of capacity value (credit) and decline of energy value due to modification of the economic dispatch of existing conventional generators and the expected curtailments of solar photovoltaic generations.



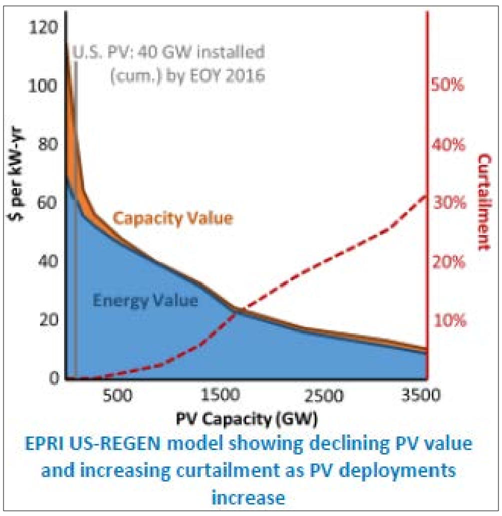
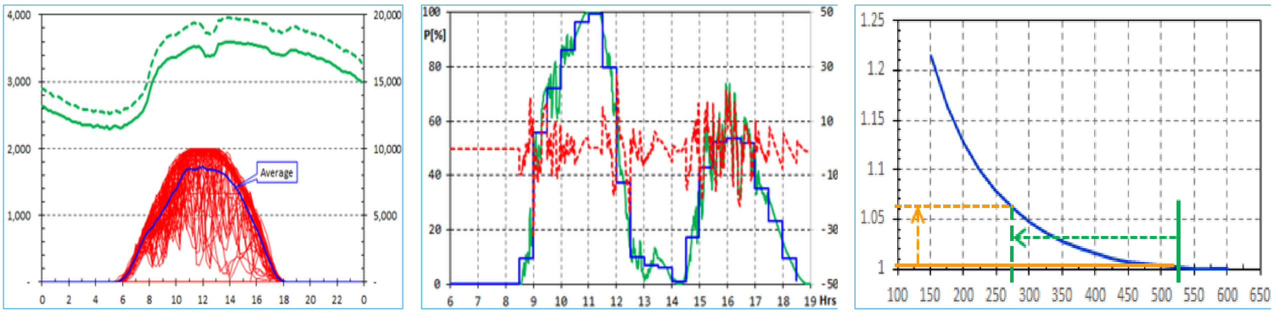


Figure 40 – Economic Values of Solar Photovoltaic as Penetration Increases

There are three important aspects for analysing the impact of integrating solar photovoltaic and wind generations in the grid system at large scale:

1) How well the solar and wind outputs profiles match the system load profile, especially the peak-load periods, which greatly impact the capacity credit ($MW_{ELCC}/MW_{NAMEPLATE}$). This in turn affects the amount of additional conventional generation capacity to meet future demand growth with same LOLE in capacity expansion planning. Refer to Figure 41 (a).
2) How variable would the solar and wind output be at a given dispatch period, which affects the reserve requirements in operational planning, both the amount and ramp rate. Refer to Figure 41 (b).
3) For capacity expansion planning, the demand growth must be met mainly by adding conventional generators as the VRE capacity credit declines, which result repeated CAPEX and lower utilisation of conventional generators. Additionally, during operational planning, the power output fluctuation of VRE will require more reserves from conventional generators, implying less efficient operating point and low annual utilisation rate for conventional power plants. Refer to Figure 41 (c).



(a) (b) (c)

Figure 41 – The key aspects of VRE integration

The above three factors will modify the economic dispatch of existing or new conventional generators in terms of their production costs. From experiences and review of various study reports, the overall production cost will generally increase as VRE penetration level increases.

Although the impacts are generally known, the degrees of impacts are specific to each system. It depends on the irradiance profile versus the load profile, climate variations, existing generation mix, etc. Hence, quantitative investigations are required specifically for Peninsular system – the purpose of this study.

DNV GL conducted the study with a systematic analysis methodology illustrated in Figure 42. The required software platforms are also indicated in Figure 42. The proposed analysis methodology examines the VRE penetration limit and capacity credit analysis – specifically based on the Single Buyer's current practices of load and renewable forecast, generation and reserve scheduling – and focuses on the reserves and ramp rate requirements and the resulted production cost.

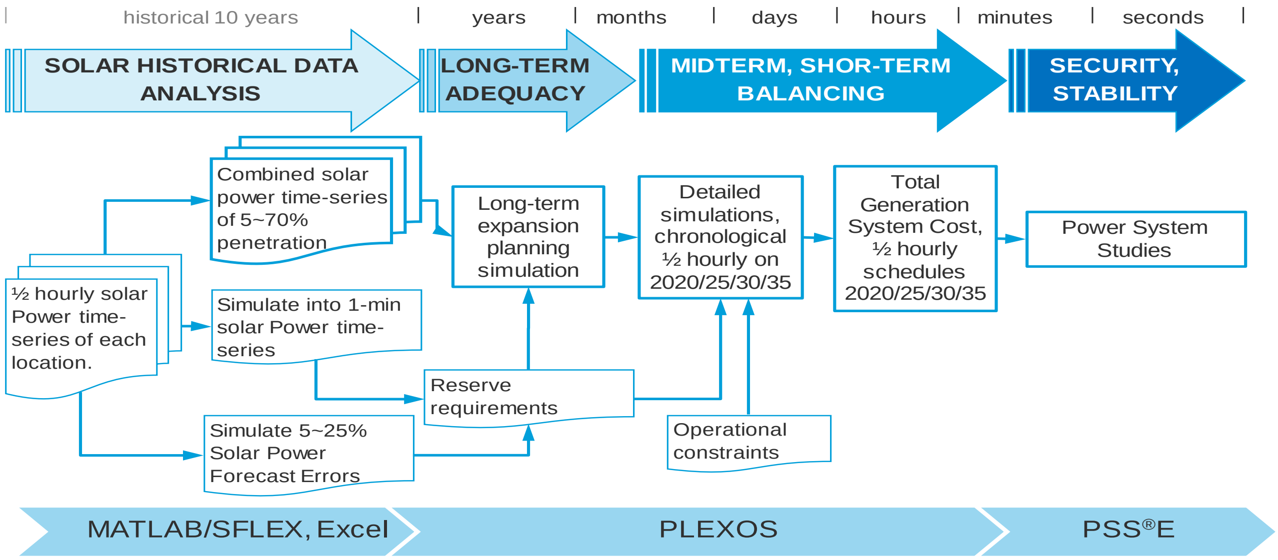


Figure 42 – Overall study workflow and applications

The proposed analysis mainly consists of 4 phases:

1) Solar data processing, variability analysis
   To perform quantitative investigations, irradiance data from areas with most solar installations in Peninsular are required. We have performed the system reserve analysis with historical irradiance data sets from multiple points of the potential areas, where solar generations are expected to grow. The solar irradiance data processing workflow is illustrated in Figure 43. The data analysis is mainly conducted in MATLAB and Excel VBA programming. Analysis results are presented in 4.2.
2) Long-term capacity planning and Mid/short-term operation studies
   Long term capacity planning and mid/short-term operation simulation studies are carried out with Peninsular system model in PLEXOS. System adequacy and half-hourly balancing schedules are generated with different PV penetration levels computed in Phase 1. Simulation study workflow is explained in Figure 44. System energy mix and cost analysis are conducted with the PLEXOS results. Simulation results are detailed in 4.3 and 4.4.
3) Transmission system adequacy and Stability studies
   Quasi-dynamic simulations are performed with the PSS®E power flow model with the ½ hour schedules computed for the study years. Transient stability is analysed in PSS®E on the challenging snapshot of low demand Sunday noon and high solar output. Category B events are tested to evaluate the system frequency responses and voltage recovery, aiming to explore the technical limit for various PV penetration levels. Simulation results are shown in 4.5.
4) Solar capacity credit analysis
   The solar capacity credit is evaluated with effective load carrying capacity (ELCC) method over a 10-year period, so that the results provide high level of confidence. Results are presented in 4.6.

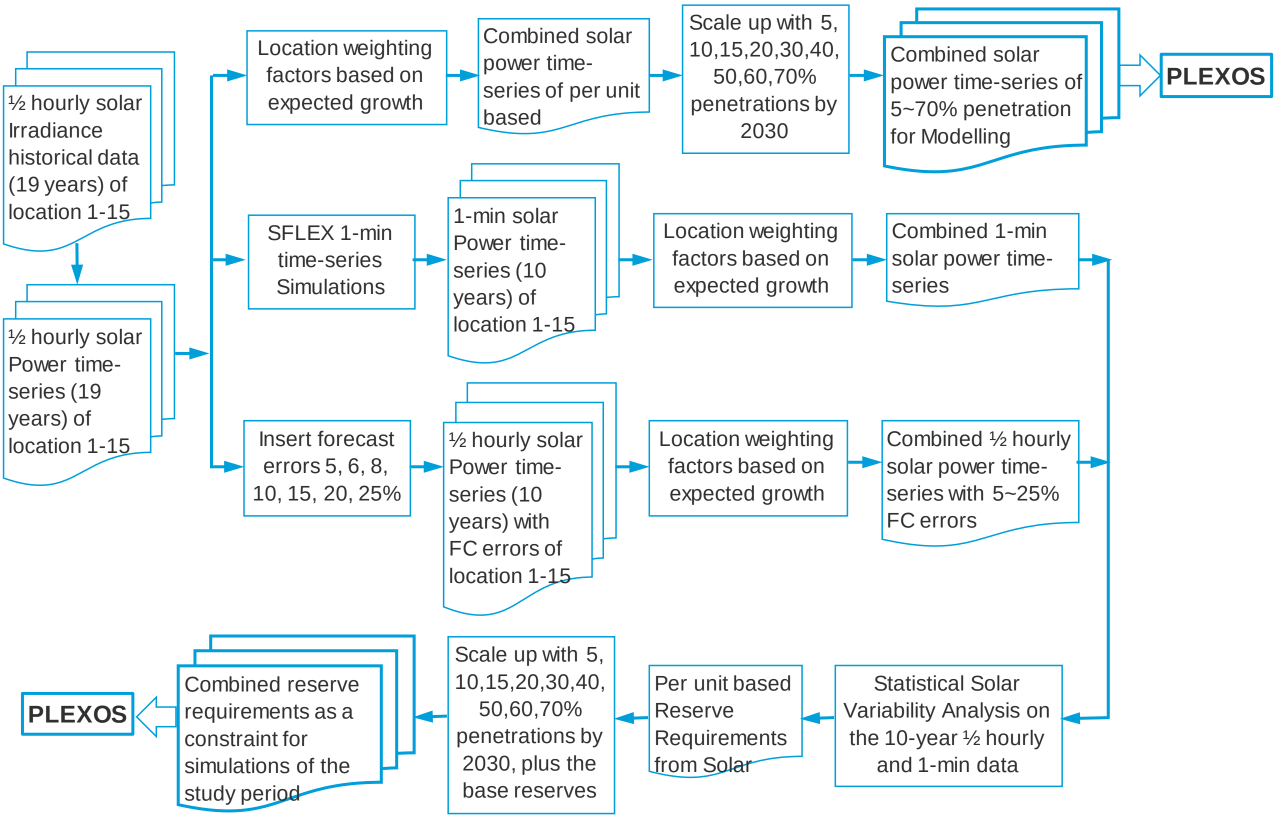


Figure 43 – Data processing and solar variability analysis workflow

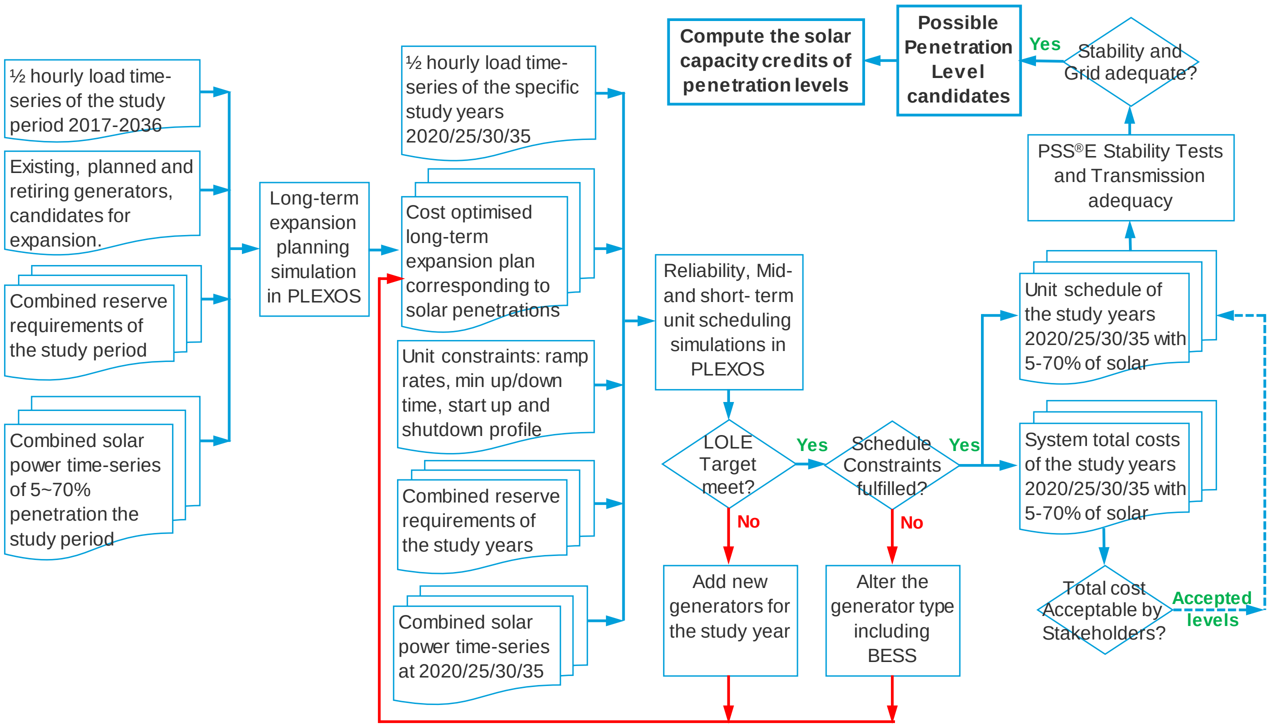


Figure 44 – Long-term capacity planning, mid/short-term operation and grid study workflow

4.2 Solar data processing and variability analysis

4.2.1 Identify the solar growth areas

From the solar resource map, the indicated high yield areas are more likely to have protentional solar development in a competitive bidding environment. The proposed sites in past LSS biding exercises also indicates the likely solar growth areas. By analysis of the two sources, we have identified 5 areas in Peninsular Malaysia where solar photovoltaic installations are expected to grow, including Kedah, Perak, KL-NS-Melaka, Pahang, Johor, and Kelantan Figure 45.

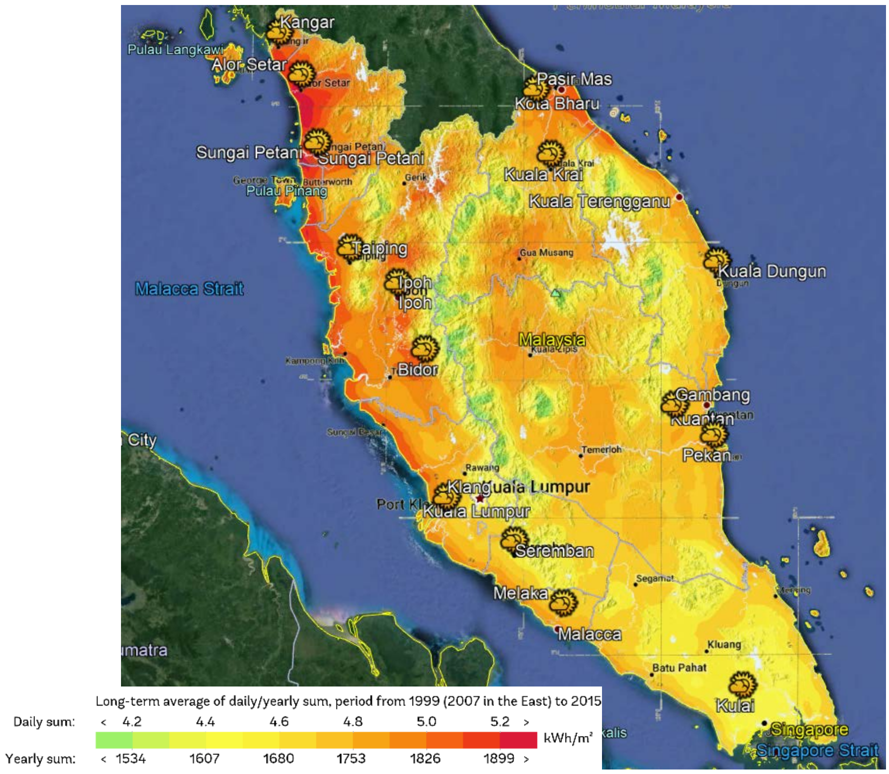


Figure 45 - Solar irradiation map of Malaysian Peninsular

Among the chosen locations, many are in the high irradiance yield areas, such as Kedah and Perak. In the meantime, KL-NS-Melaka is also chosen as one potential development area even though it's solar irradiance is not as high. The solar capacity in this area is expected to grow in the future, especially the distributed small scale and rooftop solar panels.

The current PV development status of the chosen locations and the respective weightage based on current development are summarised in Table 1.

Table 1 Current development status in selected locations

States	KEDAH	PERAK	KL-NS-MLK	PAHANG	KELANTAN	JOHOR	TOTAL
Developed [MW]	310	200	320	190	45	40	1,105
Weightage based on developed PV	28%	18%	29%	17%	4%	4%	100%

To project the future distributions of solar capacity, 3 other weighting factors are considered: total area in km², solar irradiance yield per area in kWh/m², as well as nodal factor. Total area in one location dictates the potential special capacity to place PV panels. The larger area, the more PV capacity could be installed. Locations with high yield per area are given more weighting because yield per area is beneficial to the success of the project, offering lower PV energy price in RM/kWh. Nodal factor is included to penalise the selected areas connected to nodes with high nodal factor. The 4 factors are combined into one weightage. Detailed data and calculated results are recorded in Table 2.

Table 2 Weighting factors for selected areas

States	Area [km²]	Developed [MW]	High Yield Area [kWh/m²]	Nodal Factor	Weightage combining
	10%	30%	30%	30%	all 4 factors
KEDAH	9,427	310	1,972	1.00880	23.6%
PERAK	21,035	200	1,863	1.00840	18.9%
KL-NS-MLK	16,454	320	1,753	1.00436	26.8%
PAHANG	35,840	190	1,717	1.00738	17.3%
KELANTAN	15,099	45	1,826	1.01050	8.5%
JOHOR	19,102	40	1,644	1.00948	4.9%
Total:	116,957	1,105			100.0%

4.2.2 Acquire ½ hourly historical irradiance data

In total, 15 sets of time-series irradiance data are used to represent the solar output variability in Peninsular Malaysia system. For Kedah, Perak, KL-NS-Melaka, and Pahang-Terengganu, we have chosen 3 locations to give a fair indication of the solar variability of the area. For Kelantan, we have chosen 2 sets, and 1 set for Johor. For each identified area, we purchased the ½ hourly historical (1999 to 2017) solar irradiance data. Multiple locations in one area is illustrated in Figure 46.

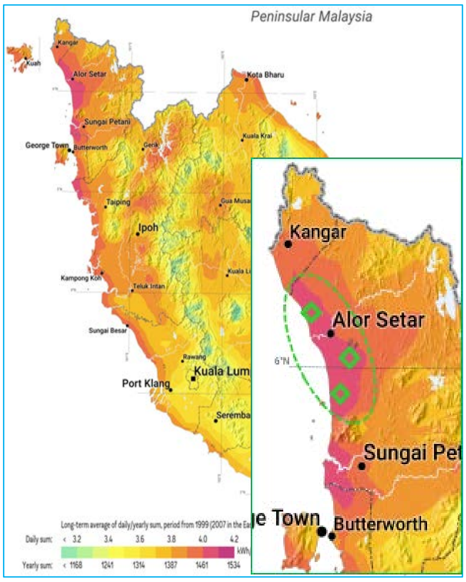


Figure 46 - Choose 3 locations in each selected area

The quality of the historical irradiance data is of paramount importance to the credibility of the study results. DNV GL has compared solar irradiance data from SolarGIS to sources of available data at locations across the world. DNV GL considers the SolarGIS dataset to provide a reasonably accurate estimation of long-term irradiance conditions and to be the preferred source of long-term irradiance reference data where nearby high-quality ground-based irradiance measurements are not available.

Therefore, 15 sets of solar irradiance data are purchased from SolarGIS. For each location, we performed high-level energy assessment to process the historical dataset to obtain the ½ hourly solar power output (MW) time-series data, preserving the power output variabilities of each location. Additionally, each dataset is weighted based on the current and expected future developments as mentioned in Chapter 4.2.1.

4.2.3 Process the solar power output data into 1-minute data

The ½ hourly power time-series is good to analyse how well the solar outputs match the peak-load periods and to setup future dispatch scenarios. However, it not sufficient for analysis on how variable would be the solar output at a given dispatch period, i.e. reserve requirements computation.

DNV GL has developed the SFLEX– a stochastic model that creates high-frequency variability around given average profiles. The model produces simulated data with accurate power spectral density analysis, which measures the magnitude of fluctuations at different frequencies. To account for non-stationarity (the change in variability over time and at various levels of power output), SFLEX uses a modified ARCH (autoregressive conditional heteroskedasticity) model. The SFLEX takes the ½ hourly averaged solar power output data of a calendar year, analyses the PSD, and effectively creates 1-minute interval solar generation data suitable for balancing analysis.

The 10-year ½ hourly solar power output of each of the 15 locations are processed into 1 min power time series using SFLEX. Each location is processed individually to preserve the locational variabilities. Firstly, as illustrated in Figure 47, one-year length of the ½ hourly averaged solar power output are used for SFLEX model training. Then, the trained model is used to generate 1 min data series for 10-year data. Lastly, the multiply locational time-series data within one control area is averaged into one time-series based on the distribution factor, which will reasonably represent the consolidated spatial effect of solar farms located within the control area.

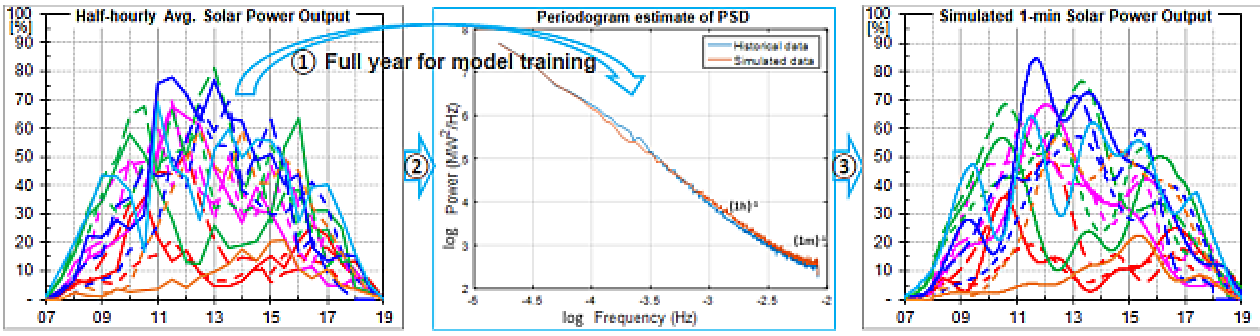


Figure 47 – Half-hourly to 1-min data simulation

The variability of half-hourly and 1-min solar power data from different locations is illustrated in Figure 48 and Figure 49. The spatial difference between various locations has a significant impact on the respective solar power output, showing distinctive output curves in the same duration. At the same time, in each specific location, the power output fluctuates constantly in high magnitude throughout the time.

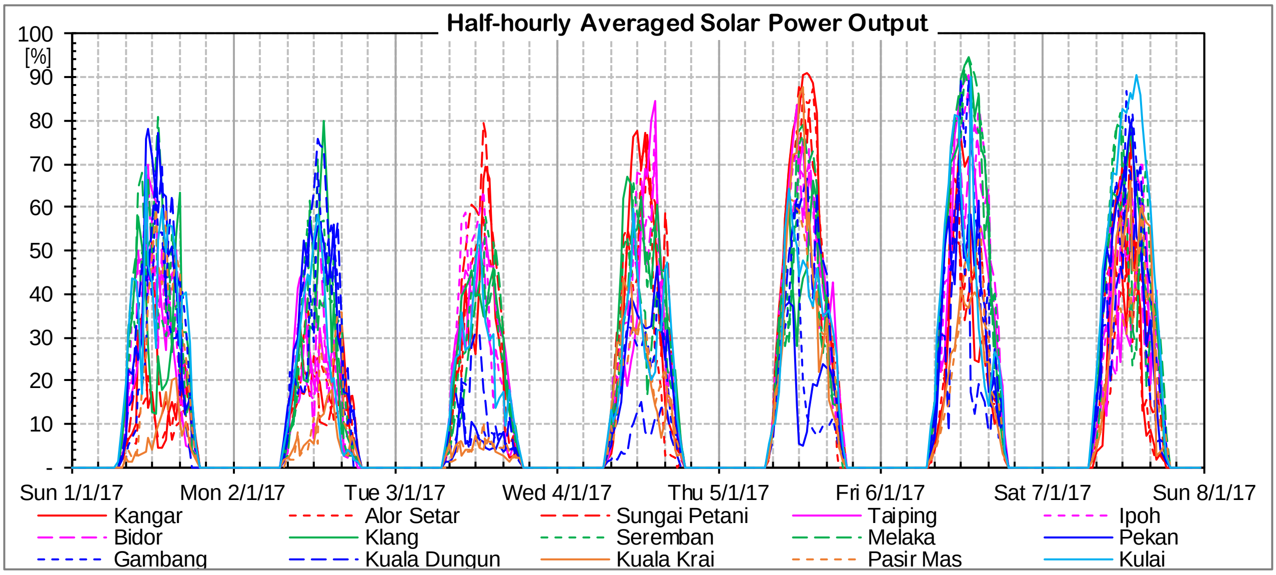


Figure 48 - Half-hourly averaged solar power output for a sampled week

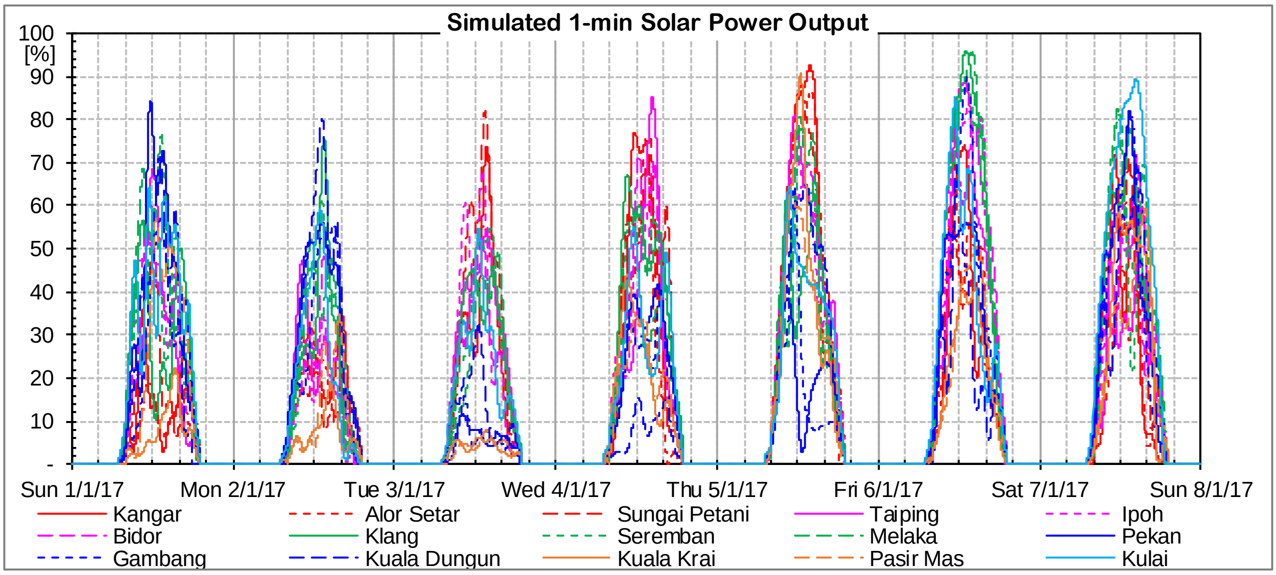
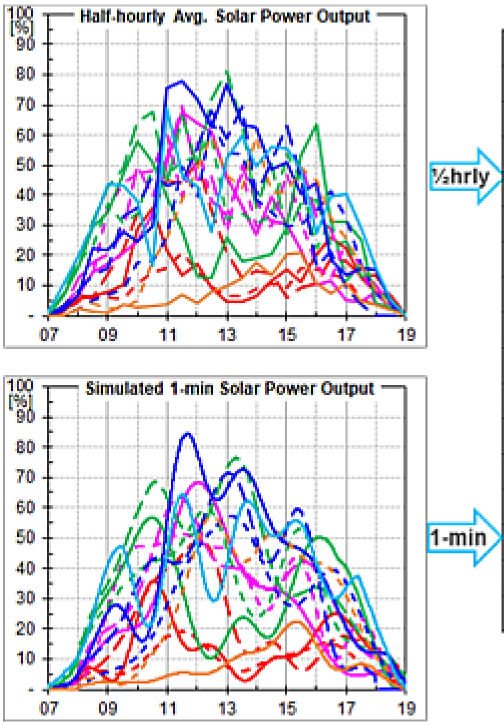


Figure 49 - Simulated 1-min solar power output for the sampled week

4.2.4 System wide solar generation combination

As the active power balancing is a system wide matter, the solar PV generation outputs of all locations are combined into system wide solar power output time-series datasets. The combined datasets represent reasonably the geographical variances of solar power outputs in Peninsular Malaysia.

Figure 50 illustrate combination process with location weightage. When the power output profile of individual location on the left are compared to the combined ones on the right, the fluctuations are smoothed out naturally by geographical weather diversities.



List of Points	Weight
Kangar	7.881%
Alor Setar	7.881%
Sungai Petani	7.881%
Taiping	6.300%
Ipoh	6.300%
Bidor	6.300%
Klang	8.924%
Seremban	8.924%
Malacca	8.924%
Pekan	5.760%
Gambang	5.760%
Kuala Dungun	5.760%
Kuala Krai	4.256%
Pasir Mas	4.256%
Kulai	4.892%
Total	100.00%

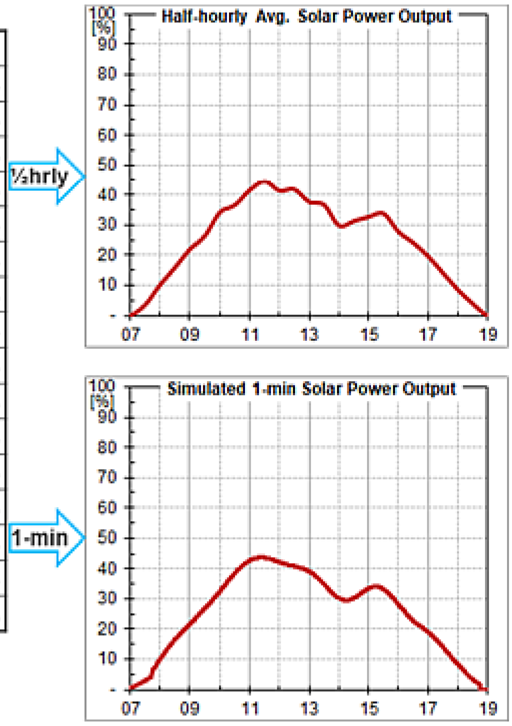


Figure 50 - Combining the power time-series with location weightage

Three datasets are combined, including the ½ hourly dataset, the ½ hourly dataset with expected forecast errors inserted to each location, and the 1-minute dataset.

The combined ½ hourly power time-series are used for: Long-term capacity expansion planning in PLEXOS; and Mid/short-term unit commitment schedule computation in PLEXOS to compute the future dispatch scenarios and total generation cost of the study years. The combined 1-min and the ½ hourly with forecast errors dataset are used to reserve analysis.

The combined solar output of the same week is shown in Figure 51, the high magnitude fluctuations of individual location are largely smoothed out.

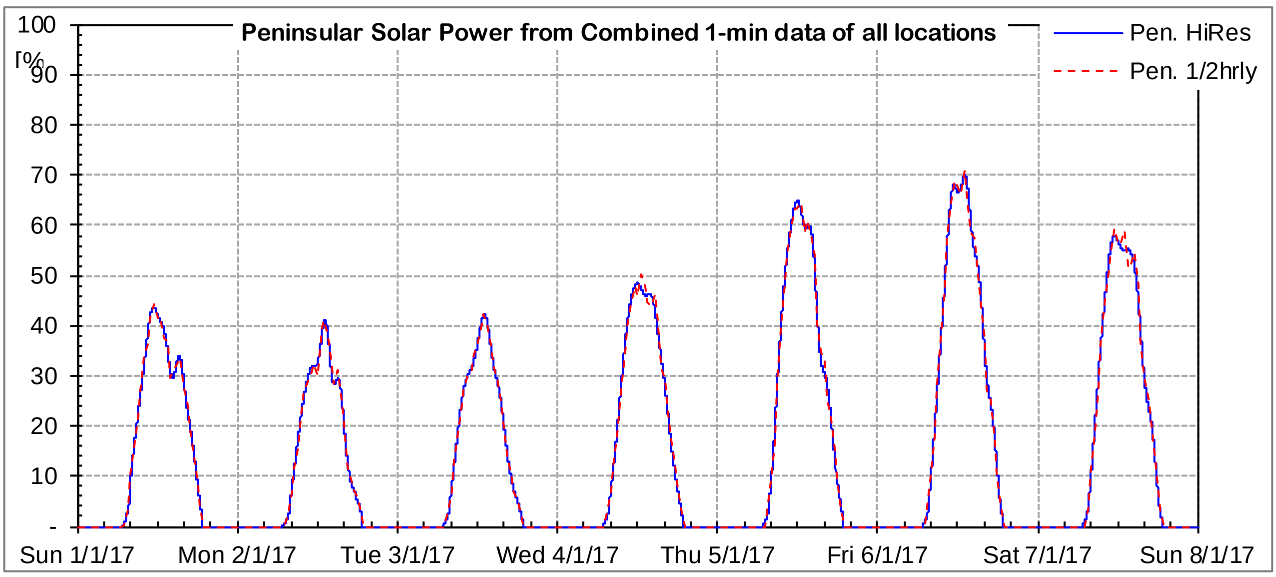


Figure 51 - Combined half-hour and 1-min solar power output for the sampled week

4.2.5 Solar variability and reserve requirement analysis

The 1-min solar power output time-series generated in 4.2.4 are used in this section for solar variability and reserve capacity analysis. The reserve capacity is determined to be sufficient to balance the solar power output deviation within the ½ hourly dispatch interval, which includes natural PV fluctuations/ramping as well as imbalance cause by inaccurate power output forecast. The resulting reserve requirement is further utilised as a constraint in mid- and short-term unit scheduling simulations in PLEXOS.

To emulate solar power output forecast, forecast errors of 5-25% were inserted to each of the data point in the 10-year ½ hourly solar power time-series of each of the 15 locations. In the simulation, only non-zero data points, i.e. periods with solar generation, are simulated with forecast error. For each location, forecast error are insert to approximately 85,000 non-zeros points, which gives reasonably confident outcomes.

The weighted combination of ½ hourly time-series are compared with the 1-min data series to analyse the reserve requirements. The data processing workflow is summarised in Figure 52.

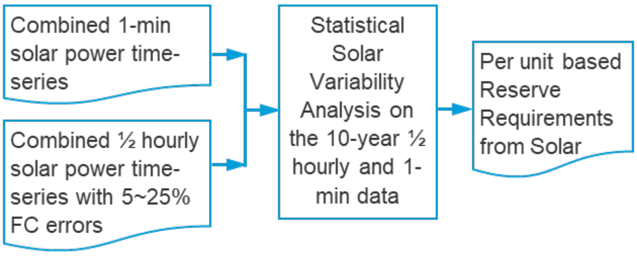


Figure 52 - Workflow for reserve requirement calculation

The Figure 53 illustrated the reserve requirement for 0% and 20% forecast error. The ½ hourly power forecast and 1-min power output are plotted on the primary vertical axis, and the up and down reserve in percent of the total PV capacity is plotted on the secondary vertical axis. Regulation reserves are required to compensate the differences between schedule and outturn.

By comparisons of the two figures, forecast errors directly impact the magnitude of delta power between the schedule and outturn. It's worth to note that, with ½ hourly dispatch interval, delta power exists even without forecast error. This is due to continuous ramping nature of solar output within a dispatch interval, also called *clear-sky ramps*, as illustrated in left hand side of Figure 53. The differences are more significant during morning sunrise and afternoon sunset periods.

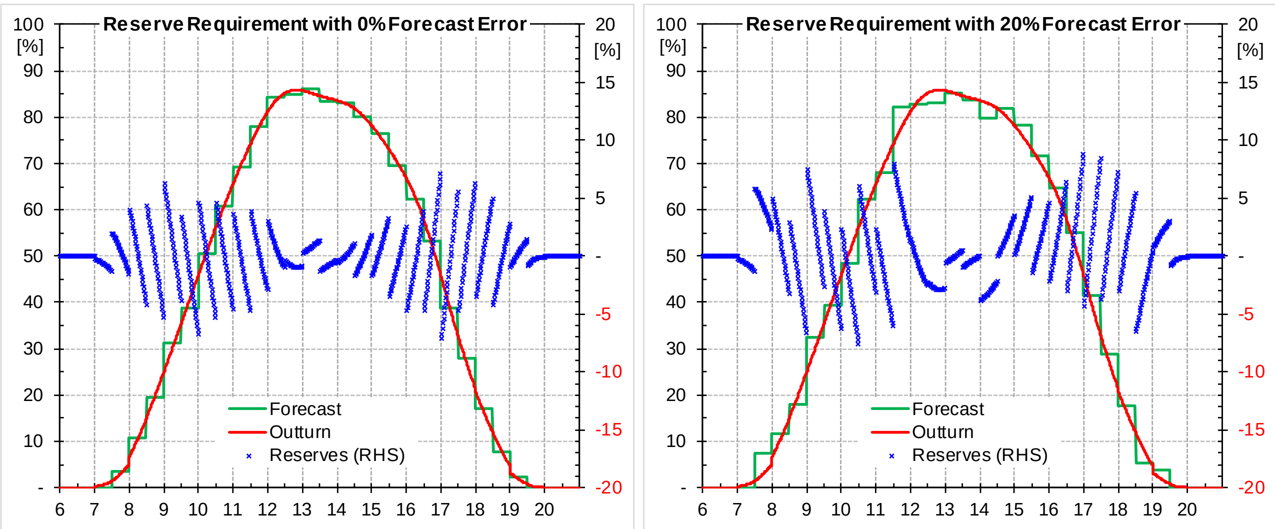


Figure 53 – Delta power within a dispatch interval with 0% and 20% forecast error

For each forecast error level, approx. 2.68 million non-zero data points are processed, which gives confident outcomes. The simulation results are processed statistically, and the probability distributions are plotted in Figure 54, which illustrates forecast errors has a direct impact on the reserve quantum.

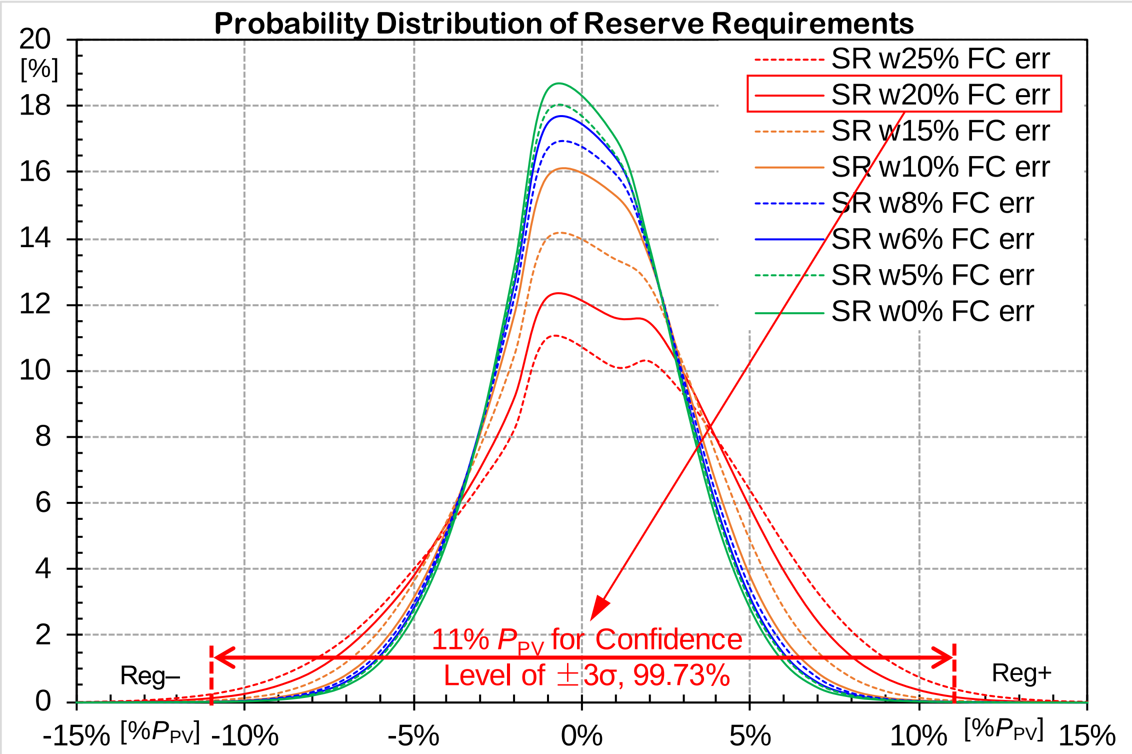


Figure 54 - Probability distribution of reserve requirements

A confidence level 99.73% (±3σ) servers as the criterion to quantify the reserve quantum. Based on ½ dispatch interval and 20% forecast error, a reserve quantum equivalent to 11% of installed solar capacity is required to reach the required confidence level. The reserve provisions to reach the required confidence level are summarised in Table 3.

Table 3 Confidence level of difference forecast error settings

Cases	Reserve Provision [%P_{PV}]	Confidence Level [%]
Forecast Errors 25%	12.0	99.668
Forecast Errors 20%	**11.0**	**99.739**
Forecast Errors 15%	10.0	99.787
Forecast Errors 10%	9.0	99.765
Forecast Errors 08%	9.0	99.813
Forecast Errors 06%	8.0	99.636
Forecast Errors 05%	8.0	99.656
Forecast Errors 00%	**8.0**	**99.709**

As shown in Table 3, with ½ hour dispatch interval, a spinning reserve equivalent to 8% of total PV installation capacity is required even without forecast error. This is related to natural characteristics of solar irradiance, i.e. its output power ramps continuously during each dispatch interval. Furthermore, the reserve requirement stays at 8% till 6% forecast error level.

In Germany and Spain, the vRE prediction error is about 5% system wide. However, improving forecast precision to such a level requires long-term historical operation data for model training. In PLEXOS simulations, a reserve quantum of 11 percent of installed solar capacity is used, assuming independent forecast error of 20% from each location.

To maintain reliable operation of power system, the reserve requirements are modelled for PLEXOS studies as hard constraints:

- Spinning reserve (SR)

- o Raise SR from 0:00 to 8:00am and from 6:00pm to 12:00 midnight = biggest online generator (1000MW) + load variations (200MW), totalling 1 200 MW
- o Down SR from 0:00 to 8:00am and from 6:00pm to 12:00 midnight = load variations (200MW)
- o Raise SR from 8:00am to 6:00pm = biggest online generator (1000MW) + load variations (200MW) + 11% installed PV capacity. e.g. 1 464 MW for scenario with 2 400 MW PV.
- o Down SR from 8:00am to 6:00pm = load variations (200MW) + 11% installed PV capacity. e.g. 464 MW for scenario with 2 400 MW PV.

- System total reserves
    - o Raise spinning reserve + the (next) biggest generator (coal, 1 000MW) + the biggest CCGT block (1 000MW).

The reserve constraints above are summarised in Table 4.

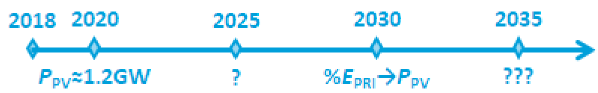
Table 4 Reserve requirement for PLEXOS simulation

Time	Spinning Reserves [MW]		Total Reserves [MW]
	RAISE	DOWN	
00:00 – 08:00	1,200	200	3,200
08:00 – 18:00	1,200 + 11%*P_{PV}	200 + 11%*P_{PV}	3,200 + 11%*P_{PV}
18:00 – 00:00	1,200	200	3,200

4.3 Long-term capacity planning studies

The proposed study years and solar penetration scenarios over the study horizon are:

- 2018, Now, installed PV are known, the load and generation data are very certain;
- 2020, estimated 1.2 GW PV, the load and generation data are quite certain;



- 2025, intermediate step to meet 2030 renewable target, conventional generators are planned;
- 2030, test scenarios of 5, 10, 15, 20, 30, 40, 50, 60 and 70 % PV related to the maximum demand;
- 2035, prospects, similar test scenarios as 2030.

Based on the forecasted demand data, the resulted PV capacity and in percentage of peak demand of the study year are summarised in Table 5. The peak demand values are chosen as the average of the top 24 hours in LDC study.

Table 5 Projected PV capacity for study years

YEAR	Peak[71] [MW]	Trough [MW]	5%	10%	15%	20%	30%	40%	50%	60%	70%
			Solar PV Capacity in [MW], for various Penetration Levels in 2030								
2020	**19,058**	**9,222**	**1,200**	**2,400**							
		Actual [%] of Peak Load:	*6.3%*	*12.6%*							
2025	**20,774**	**10,376**	**1,200**	**2,400**	**2,875**	**3,425**	**4,550**	**5,675**	**6,775**	**7,900**	**9,025**
		Actual [%] of Peak Load:	*5.8%*	*11.6%*	*13.8%*	*16.5%*	*21.9%*	*27.3%*	*32.6%*	*38.0%*	*43.4%*
2030	**22,345**	**10,847**	**1,200**	**2,400**	**3,350**	**4,450**	**6,700**	**8,950**	**11,150**	**13,400**	**15,650**
		Actual [%] of Peak Load:	*5.4%*	*10.7%*	*15.0%*	*19.9%*	*30.0%*	*40.1%*	*49.9%*	*60.0%*	*70.0%*
2035	**23,573**	**11,538**	**1,200**	**2,400**	**3,550**	**4,700**	**7,050**	**9,450**	**11,800**	**14,150**	**16,500**
		Actual [%] of Peak Load:	*5.1%*	*10.2%*	*15.1%*	*19.9%*	*29.9%*	*40.1%*	*50.1%*	*60.0%*	*70.0%*

The starting point is year 2020 with base case of 1,200 MW solar and high growth case of 2,400 MW solar, then progressing to 2030 targets with a linear growth manner as shown in Figure 55.

[71] The peak is calculated as the average of the top 24 hours of annual peak demands taken from the load duration curve.

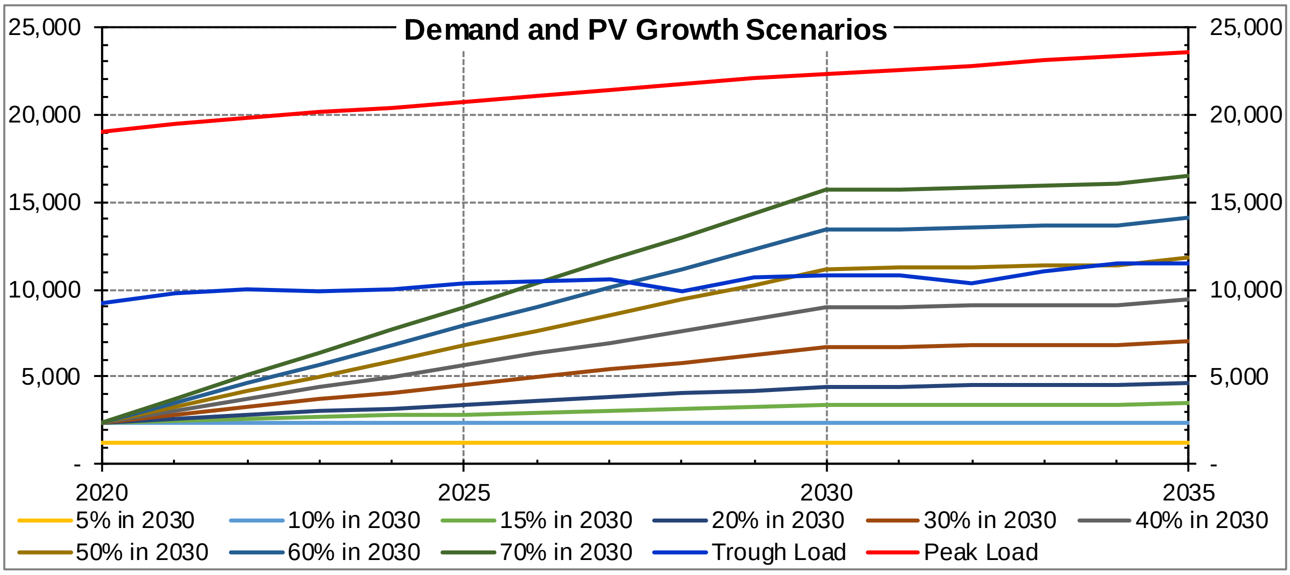


Figure 55 - Demand and solar growth scenarios for study years

For the planning horizon from 2020 to 2035, planned new and retiring conventional generators, the forecasted ½ hourly demand and solar power of test scenarios are modelled in PLEXOS for long-term generation capacity planning simulations, refer to the workflow in Figure 43.

To achieve comparable conventional generation capacity on the specific study years of 2025, 2030 and 2035. The simulations have been scheduled in 3 overlapping 6-year LT runs, e.g. 2020 – 2025, 2025 – 2030 and 2030 – 2035. The conventional generators are grown based on least cost optimisations.

4.3.1 LT results of year 2020 and 2025

Ae discussed in the previous text, the conventional generators have been planned till 2025. The LT simulations of 2020 (Table 6) and 2025 (Table 7) did not grow any new capacity. The additional solar capacities improve slightly the generation system reliability – reduce the already low LOLE days.

Table 6 LT and reliability results of year 2020

2017	*Total generation capacity:*	*24,112 MW*	
2020	**Actual PV / Peak Load:**	**6%[B] PV**	**13% PV**
	Total Generation Capacity[MW]:	**27,108**	**28,308**
Peak load	Solar install capacity	1,200	2,400
19,058 MW	Retired Conventional Generators	-1,944	-1,944
Trough load	Planned Conventional Generators	3,740	3,740
9,222 MW	Additional from PLEXOS LT	-	-
	Reliability LOLE (days):	**0.06**	**0.04**

Table 7 LT and reliability results of year 2025

2025	**Actual PV / Peak Load:**	**6% PV**	**12% PV**	**14% PV**	**16% PV**	**22% PV**	**27% PV**	**33% PV**	**38% PV**	**43% PV**	**80% PV**
	Total generation capacity[MW]:	**28,441**	**29,641**	**30,116**	**30,666**	**31,791**	**32,916**	**34,016**	**35,141**	**36,266**	**43,841**
	Added Solar capacity:	-	-	475	1,025	2,150	3,275	4,375	5,500	6,625	14,200
Peak load	Retired Conventional Generators:	-4,077	-4,077	-4,077	-4,077	-4,077	-4,077	-4,077	-4,077	-4,077	-4,077
20,774 MW	Planned Conventional Generators:	5,410	5,410	5,410	5,410	5,410	5,410	5,410	5,410	5,410	5,410
Trough load	New Gas from PLEXOS LT:	-	-	-	-	-	-	-	-	-	-
10,376 MW	New Coal from PLEXOS LT:	-	-	-	-	-	-	-	-	-	-
	Reliability LOLE (days):	**0.02**	**0.02**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**

4.3.2 LT results of year 2030

The study year 2030 is our target year of solar penetration levels, the LT result is detailed in Table 8 and is plotted in Figure 56 below. The solar penetration levels and reduction of conventional generation capacity are all normalise to the peak demand of the year. The reductions new conventional capacities are effective from 5 to 20 percent penetration; and become less effective from 25 to 40 percent penetration with rising LOLE; no reduction of conventional capacity post 40 percent penetration with slightly reduced LOLE.

Table 8 LT and reliability results of year 2030

2030	Actual PV / Peak Load:	5% PV	11% PV	15% PV	20% PV	30% PV	40% PV	50% PV	60% PV	70% PV
	Total generation capacity[MW]:	**27,444**	**28,344**	**29,194**	**30,094**	**32,144**	**34,294**	**36,494**	**38,744**	**40,994**
	Added Solar capacity:	-	-	475	1,025	2,150	3,275	4,375	5,500	6,625
Peak load	Retired Conventional Generators:	-7,529	-7,529	-7,529	-7,529	-7,529	-7,529	-7,529	-7,529	-7,529
22,345 MW	Planned Conventional Generators:	132	132	132	132	132	132	132	132	132
Trough load	New Interconnections:	600	600	600	600	600	600	600	600	600
10,847 MW	New Gas from PLEXOS LT:	4,400	4,100	4,000	3,800	3,600	3,500	3,500	3,500	3,500
	New Coal from PLEXOS LT:	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400
	Total conventional capacity:	26,244	25,944	25,844	25,644	25,444	25,344	25,344	25,344	25,344
	Reliability LOLE (days):	**0.72**	**0.77**	**0.73**	**0.80**	**0.85**	**0.88**	**0.85**	**0.83**	**0.82**

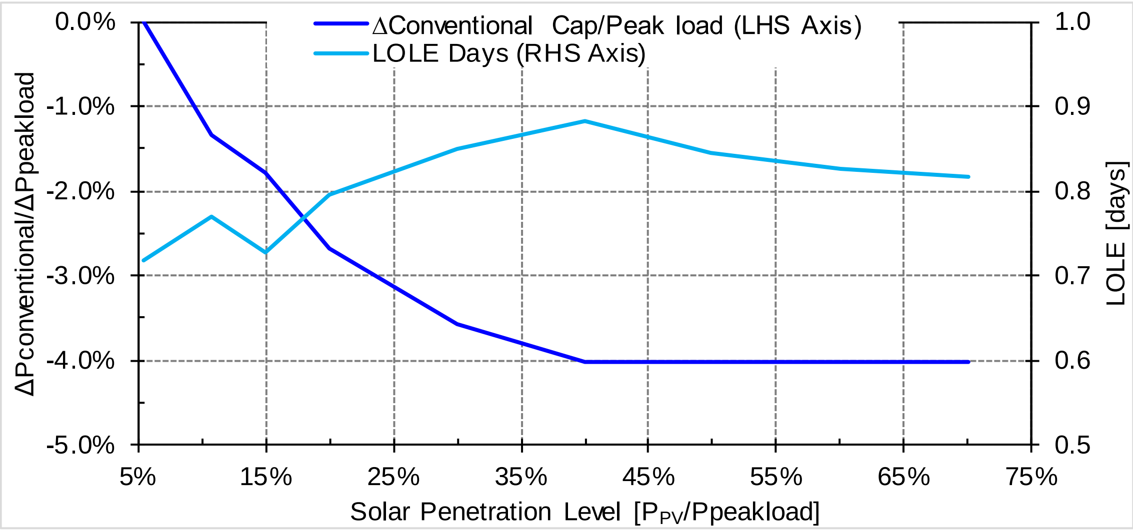


Figure 56 – Reduction of conventional capacity and LOLE vs penetration level 2030

4.3.3 LT results of year 2035

The LT results of 2035 are based on least cost optimisation rather than reliability, e.g. based on the grown conventional capacities the computed LOLE days are much less than the 1 day criterion. The LT results are tabulated in Table 9. Although the new grew conventional capacity were the same for all penetration levels, the total capacity of conventional generator reduces as the based capacity at 2030 were different. The pattern of conventional capacity reduction is similar (Figure 57), e.g. capacity reduces for penetration below 40%, and stay at the same value from 40% PV to 70% PV.

Table 9 LT and reliability results of year 2035

2035	Actual PV / Peak Load:	5% PV	10% PV	15% PV	20% PV	30% PV	40% PV	50% PV	60% PV	70% PV
	Total generation capacity[MW]:	**29,944**	**30,844**	**31,894**	**32,844**	**34,994**	**37,294**	**39,644**	**41,994**	**44,344**
	Added Solar capacity:	-	-	200	250	350	500	650	750	850
Peak load	Retired Conventional Generators:	-3,500	-3,500	-3,500	-3,500	-3,500	-3,500	-3,500	-3,500	-3,500
23,573 MW	Planned Conventional Generators:	-	-	-	-	-	-	-	-	-
Trough load	New Interconnections:	-	-	-	-	-	-	-	-	-

2035	Actual PV / Peak Load:	5% PV	10% PV	15% PV	20% PV	30% PV	40% PV	50% PV	60% PV	70% PV
11,538 MW	New Gas from PLEXOS LT:	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500
	New Coal from PLEXOS LT:	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500
	Total conventional capacity:	28,744	28,444	28,344	28,144	27,944	27,844	27,844	27,844	27,844
	Reliability LOLE (days):	**0.44**	**0.46**	**0.41**	**0.45**	**0.49**	**0.52**	**0.50**	**0.50**	**0.49**

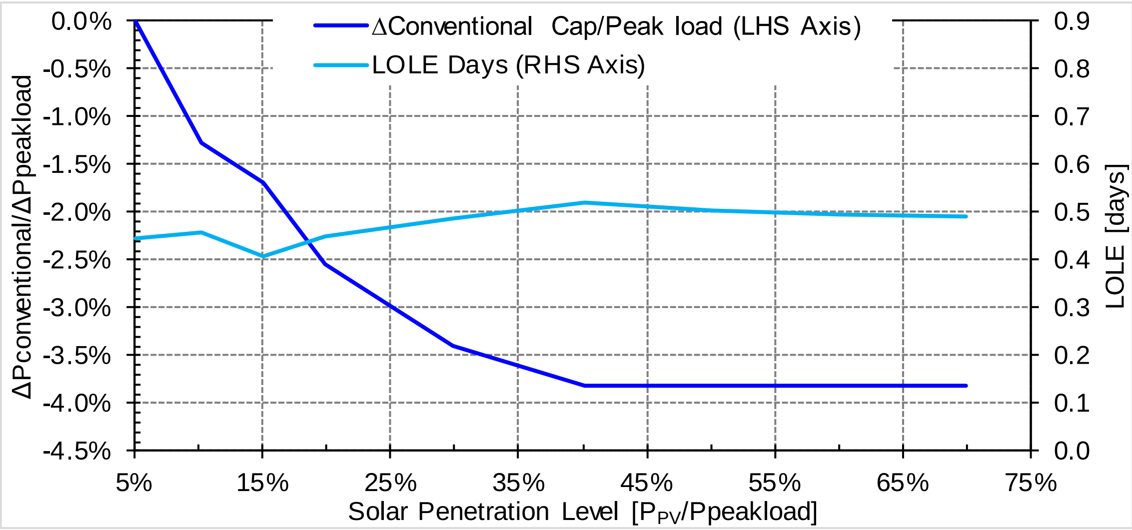


Figure 57 – Reduction of conventional capacity and LOLE vs penetration level 2035

4.4 Mid and short-term operation investigations

With the reserve requirements from 4.2 and the generation mix of each study year at each solar penetration level computed in 4.3, detailed investigations into the mid-term and short-term operations are perform in this section. The study methodology is per Figure 44 to compute the dispatch schedules for each of the study year and the given solar penetration levels. The key inputs to the simulations are:

- the ½ hourly load data, derived from the demand forecasts;
- the grown conventional generators corresponding to each penetration levels, their cost parameters, and fuel cost.
- unit maintenance schedules, and the constraints ramp rates, minimum up/down time, start-up and shutdown profiles are set as hard constraints.
- Spinning and total reserve requirements as per Table 4 are set as hard constraints.
- the combined ½ hourly solar power time-series scaled to a penetration level and their costs.

The scheduling simulations are performed with PLEXOS on ½ hour interval for the whole study, with look day ahead while computing the optimal solutions. The solar generation is modelled as fixed profile generator.

The simulations test firstly the ability of the grown conventional generation portfolio to meet the scheduling constraints, especially on the ramping capability. In case of scheduling constraints not met, part of the grown generators is altered to faster response but less economic types.

Once all hard constraints are met, the simulated full year schedules, total generation cost and emission data are used to quantify the costs impacts and benefits of solar generation. For the study year 2020, two (2) solar penetration scenarios were simulated. For the study year 2025, 2030 and 2035, nine (9) solar penetration scenarios were simulated each year.

In the simulation results, the cost of electricity of the base case is slightly lower than the actual cost due to the removal of minimum gas constraints to obtain optimisation solutions at high solar penetration. Therefore, the result analysis focus on the differences compared with the base case to quantify the influence of different solar penetration levels.

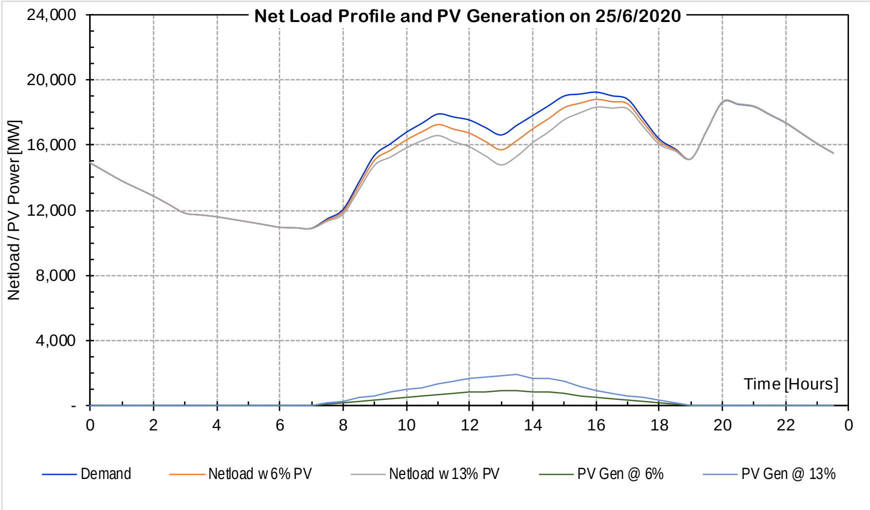
4.4.1 Study results of year 2020

For year 2020, two scenarios are studied: a base case with 1.2 GW solar and a high-growth case with 2.4 GW.

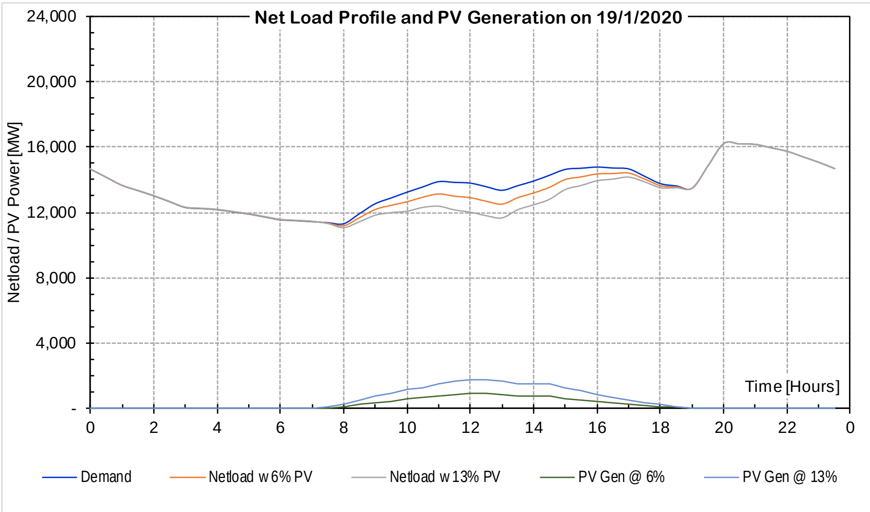
4.4.1.1 Netload profile

For the given two scenarios, netload analysis is conducted to observe PV impact on a system level. As plotted in Figure 58 (a), on a peak demand day, the PV outputs reduce the noon netload, but with limited impact – without drastic change in the load profile. The impact on an off-peak Sunday is also limited per Figure 58 (b). During a low-demand public holiday shown in Figure 58 (c), the noon netload becomes lower than usual morning trough. However, the conventional generators still serve about 80% of the system demand.

(a) Peak demand day



(b) Off-peak demand day



(c) Lowest demand day

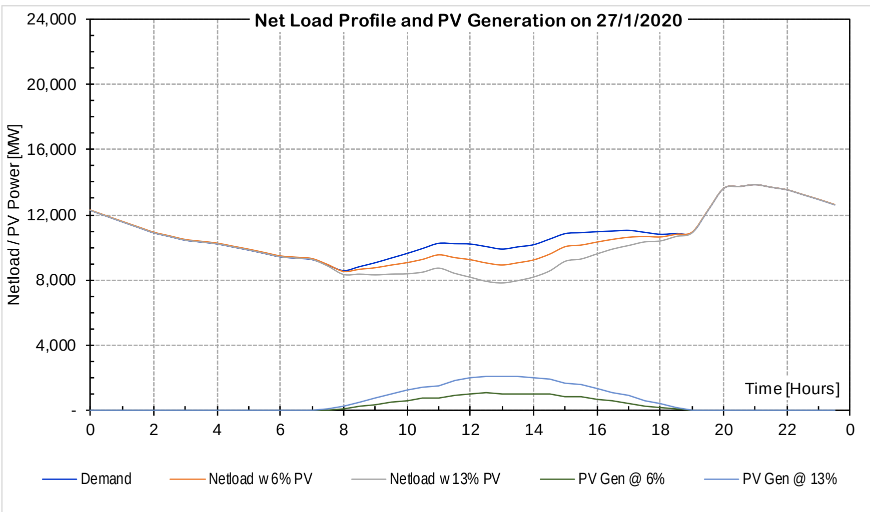


Figure 58 - Netload profiles on peak(a), off-peak(b) and lowest(c) demand days in 2020

The load profile changes of a typical week and a holiday week can be observed in Figure 59 and Figure 60 respectively. For both base case and high-growth case, no significant impact to operation ae observed.

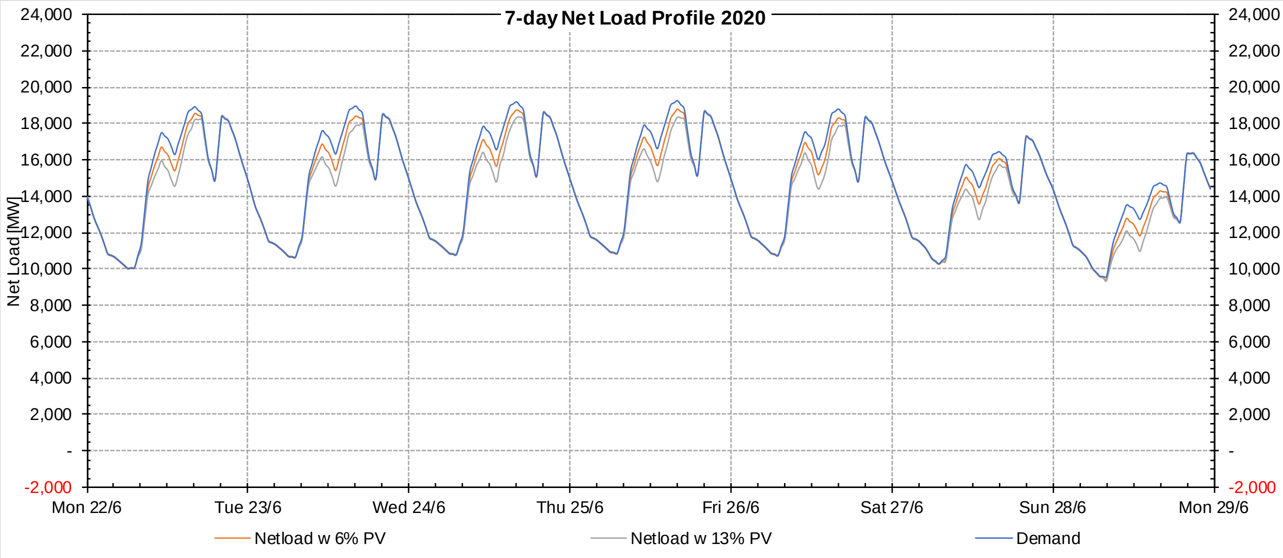


Figure 59 - Netload profile of a normal week in 2020 with tested penetration levels

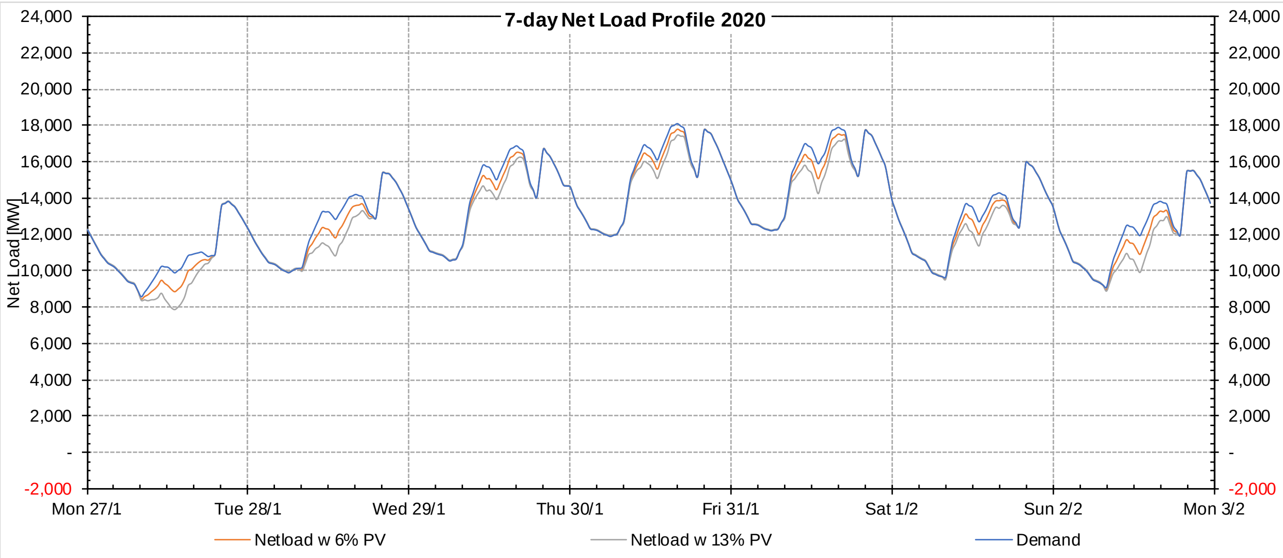


Figure 60 - Netload profile of a holiday week in 2020 with tested penetration levels

4.4.1.2 Netload duration

The full-year netload data is processed into netload duration curve (netLDC) to have a macro understanding the impact of solar Figure 61. In the system operation space, conventional generators are expected to cycle daily along the netload duration curve. The top-left part of the curve dominates the required capacity of the conventional generators, while the bottom-right part calls for flexibility of these generators.

The solar penetration of 6% (1,200 MW) and 13% (2,400 MW) will:

- reduce the peak demand by 409 MW and 536 MW reading at the 24th hour[72] of the netLDC. and
- reduce trough load by 124 MW and 760 MW respectively.

In both scenarios, the solar generations do not cause significant challenge to the grid system operations.

[72] The readings are taken at the LOLE hours, lowering the demands of the top 24 hours have most significant impact on the capacity requirement of conventional generators

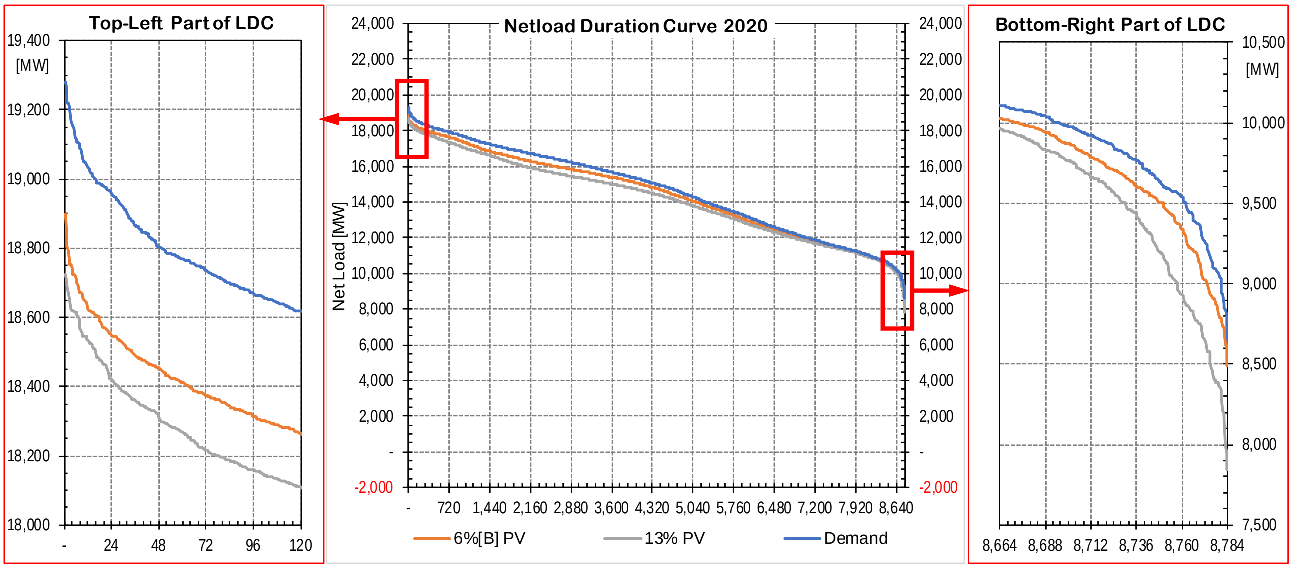


Figure 61 - Netload duration curve for 2020

4.4.1.3 Dispatch simulation

The entire year simulation results from PLEXOS on study year 2020 are summarised in Table 10. By adding solar generation capacity in the grid, system reliability is improved with reduced unserved energy and a lower LOLE value. However, total system cost also rises due to higher solar energy price and an increment in variable system cost to balance the solar fluctuations. The cost of solar balancing mainly comes from the generators, which provides additional reserve capacity and/or operates at less economical points to accommodate more solar generation.

Other social and environmental impacts including HHI and CO_2 emission are summarised in Table 10 as well. When more solar power is scheduled to contribute to the total generation, the HHI reduces, indication of a diverse energy portfolio. CO_2 emission reduced by 0.98% because of contribution from green energy.

The capacity and energy share of each generation category is plotted in Figure 62. While solar PV capacity expands from 4.4% to 8.5%, its energy share only increases from 1.6% to 3.3%. In other words, majority of energy still relies on conventional generation plants using gas and coal.

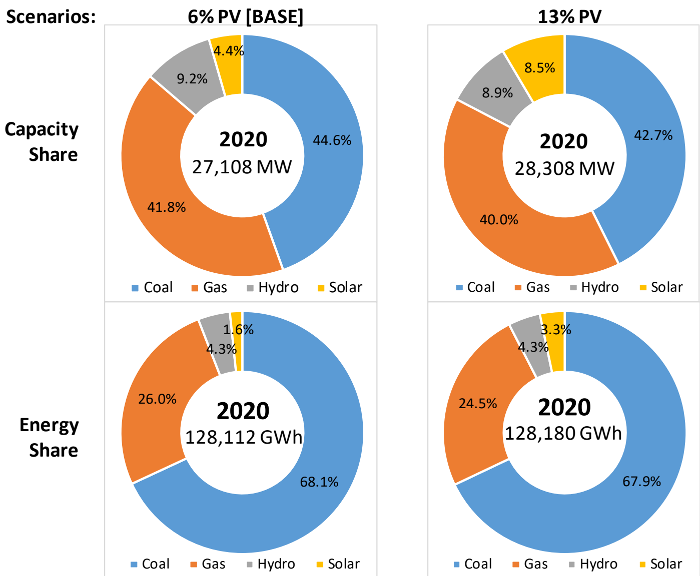


Figure 62 - Capacity and energy share of year 2020

An example of dispatch on a low demand day is shown in Figure 63. The additional solar generations mainly affect the less economic gas generation plants most of the time. On very low demand period with high solar output, a small ramp down of coal generators is observed.

Table 10 Result summary for year 2020

2017	**Total generation capacity:**	**24,112 MW**

2020	**Actual PV / Peak Load:**	**6%[B] PV**	**13% PV**
	Total Generation Capacity[MW]:	**27,108**	**28,308**
Peak load	*Solar install capacity*	*1,200*	*2,400*
19,058 MW	*Retired Conventional Generators*	*-1,944*	*-1,944*
Trough load	*Planned Conventional Generators*	*3,740*	*3,740*
9,222 MW	*Additional from PLEXOS LT*	-	-
Energy	**Reliability LOLE (days):**	**0.06**	**0.04**
128,414 GWh	Unserved Energy (GWh):	*301.47*	*233.84*
Predicted Sales	Solar Curtailment (GWh):	-	-
116,734 GWh	**Total System Cost (Million):**	**27,614**	**28,001**
	Fixed	*9,314*	*9,314*
	Variable	*18,300*	*18,687*
	Cost of Electricity (RM/MWh):	**236.55**	**239.87**
	Scenario/Base[%]	*100%*	*101.40%*
	Increment including [1]+[2], Scenario-Base[%]	*Base*	*+1.40%*
	[1] Cost due to balance of solar[73]		*+0.46%*
	[2] Cost due to higher solar energy price		*+0.94%*
	Additional Solar Curtailment Penalty (Million)[74]:	**0.00**	**0.00**
	HHI:	**0.53**	**0.52**
	CO2 Emission (thousand tonnes):	**95,298**	**94,366**
		Base	*-0.98%*

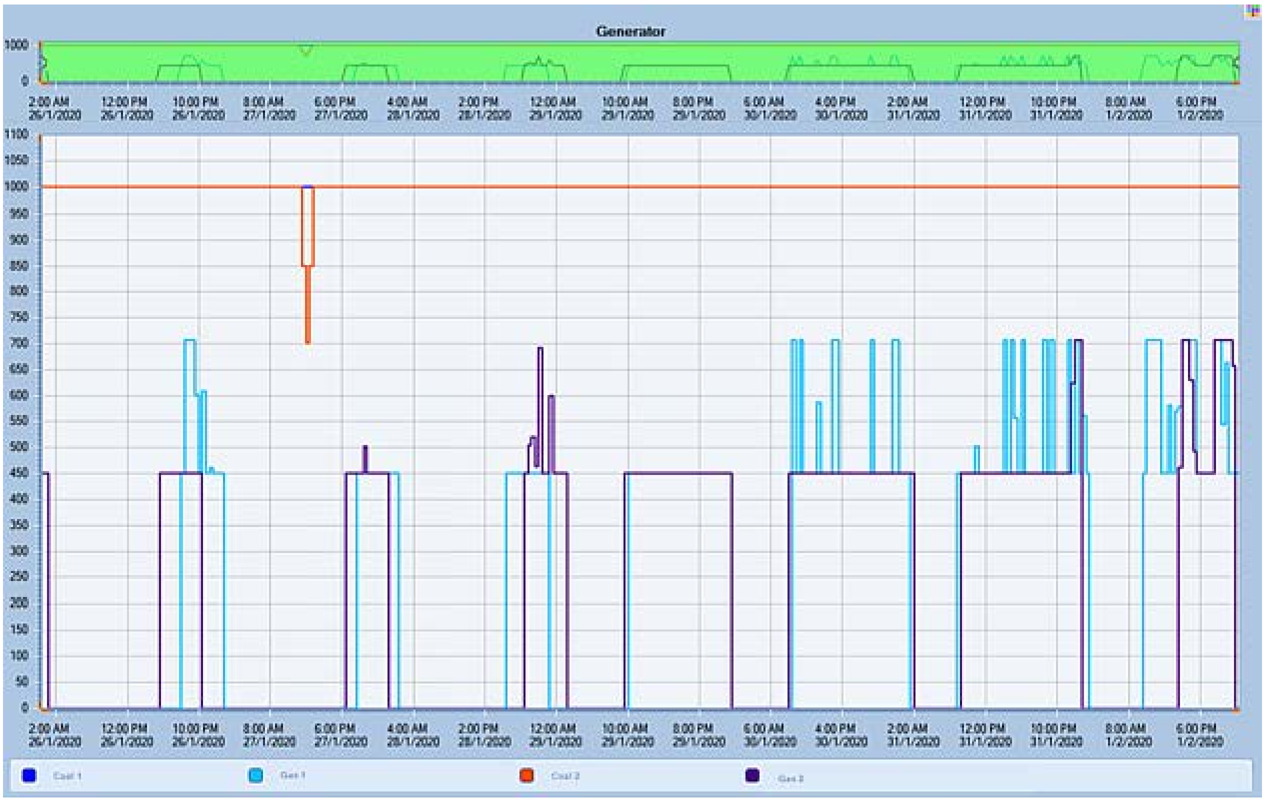


Figure 63 – Dispatch of gas and coal generators on a low demand day

[73] Cost increases due to conventional generators operate at less efficient point.
[74] Additional penalty when PLEXOS decides to curtail solar in searching for optimal solution.

4.4.2 Study results of year 2025

Year 2025 is the intermediate step towards 2030 targets. Nine (9) cases of PV capacity, ranging from 6% (base case) to 43% penetration are simulated. The capacities solar and conventional generation for all tested scenarios are listed in Table 11.

Table 11 Capacity planning summary for scenarios in year 2025

Actual PV / Peak Load	6% PV [B]	12% PV	14% PV	16% PV	22% PV	27% PV	33% PV	38% PV	43% PV
Total generation capacity:	28,441	29,641	30,116	30,666	31,791	32,916	34,016	35,141	36,266
Solar Capacity	1,200	2,400	2,875	3,425	4,550	5,675	6,775	7,900	9,025
Conventional Generators	27,241	27,241	27,241	27,241	27,241	27,241	27,241	27,241	27,241

4.4.2.1 Netload profile analysis

The netload profiles during daylight hours are modified with increased solar penetration as shown in Figure 64. When solar penetrations are above 16 percent, the afternoon peaks become lower than evening peak, which becomes dominant in capacity planning, as illustrated in Figure 64. On peak demand days, the noon trough load is still higher than that of early morning.

On low-demand days with high solar penetration, the solar generation could significantly reduce the netload at noon period Figure 65, thus the numbers of online conventional generators. The system stability might have issues due to low inertia and governor responses during contingent events.

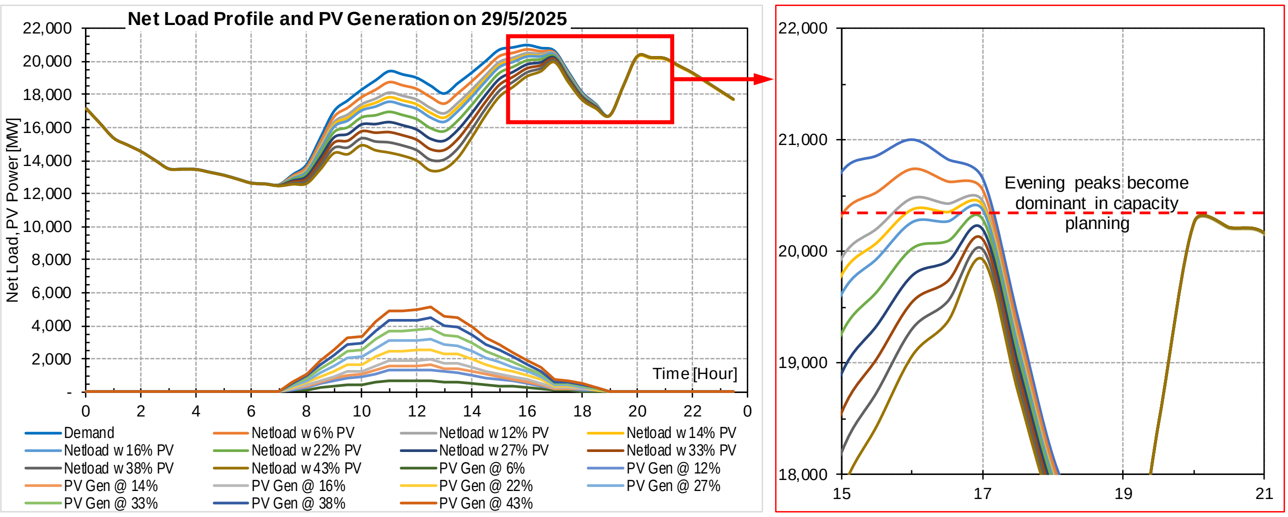
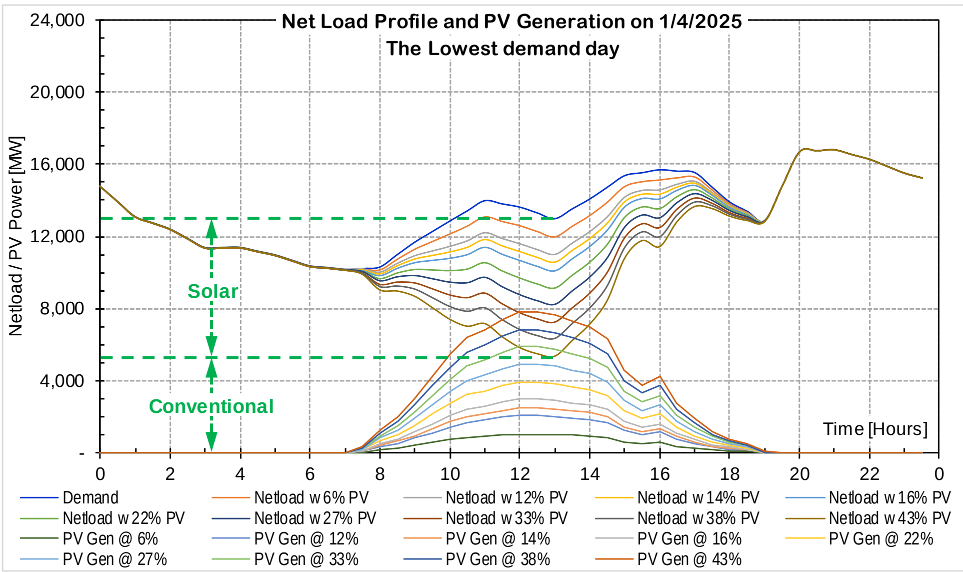
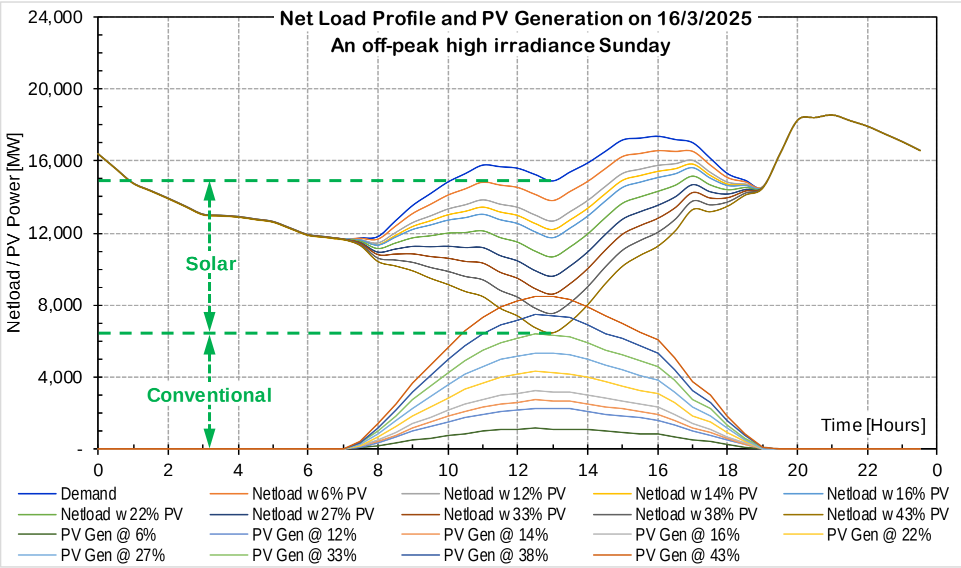


Figure 64 - Netload profile and PV output on peak-demand weekday



(a) Netload profiles for lowest demand day in 2025



(b) Netload profiles for an off-peak Sunday in 2025

Figure 65 - Netload profile on the lowest demand(a) and off-peak (b) days

Dispatch for the 43% PV case on the off-peak Sunday noon with high solar is tabulated in Table 12, and visualised in Figure 66. The solar generation supplies 57% of total demand. In the event of generator tripping, the system might not have sufficient inertia and governor response to stabilise the system frequency. Therefore, the system stability needs to be further investigated in PSS®E stability simulations in later studies.

Table 12 Dispatch on an off-peak Sunday with 43% PV case

16/3/25	Total demand: 14,907 MW		Solar Power: 8,435 MW (57%)		Conventional: 6,472 MW (43%)		
Generators	JMAE_U1	JMAH_U1	JMAH_U2	JMJG_U2	JMJG_U3	JMJG_U4	JMJG_U5
P_{MAX} [MW]	1,080	700	700	690	690	1,010	1,000
P_{GEN} [MW]	700	400	400	345	345	710	721
P_{MIN} [MW]	432	280	280	276	276	404	400
Generators	PKLG_U3_Coal	PKLG_U4_Coal	PKLG_U5_Coal	PKLG_U6_Coal	TBIN_U1	TBIN_U2	TBIN_U4
P_{MAX} [MW]	283	282	465	466	700	700	1,000
P_{GEN} [MW]	220	220	380	380	400	400	850
P_{MIN} [MW]	113.2	112.8	186	186.4	280	280	400

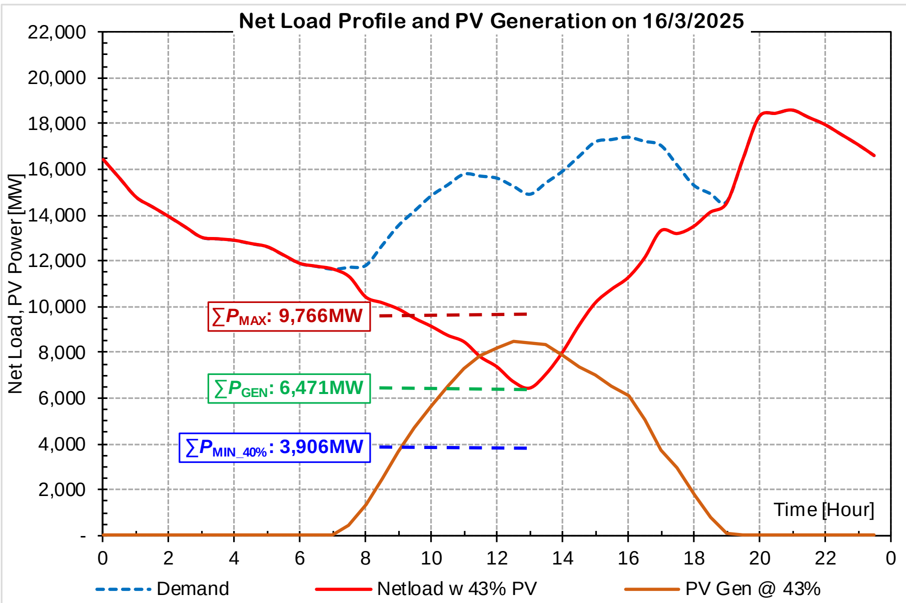


Figure 66 - Netload profile and generator dispatch of an off-peak Sunday noon

Netload profiles of a normal week in 2025 and a holiday week are plotted in Figure 67 and Figure 68. The netload ramps increase drastically with increased solar penetration level.

As shown in Figure 67, comparing to the original morning load ramp approx. 7,000 MW in magnitude, the new evening peaks exceeds the morning ramp up rate starting from 27% PV penetration. For the 43% PV case, the afternoon to evening netload ramps with magnitude of approximately 10,000 MW to 12,500 MW (eq. 48% to 60% maximum demand of the year) are frequently observed.

To provide sufficient load following capacity, greater flexibility from conventional generation units is required. For example, conventional generators are expected to cycle daily in higher magnitudes (10-12.5 GW) from 1 to 8 pm with 43% PV case. Greater flexibilities include:

- the ability to operate at lower minimum load points, thus providing wider range of available power control;
- shorter start up time for the machine to reach minimum load point;
- larger power output ramp, which enables faster response to changes in netload profile.

Measures to improve conventional generator flexibility is discussed in Section 5.3.

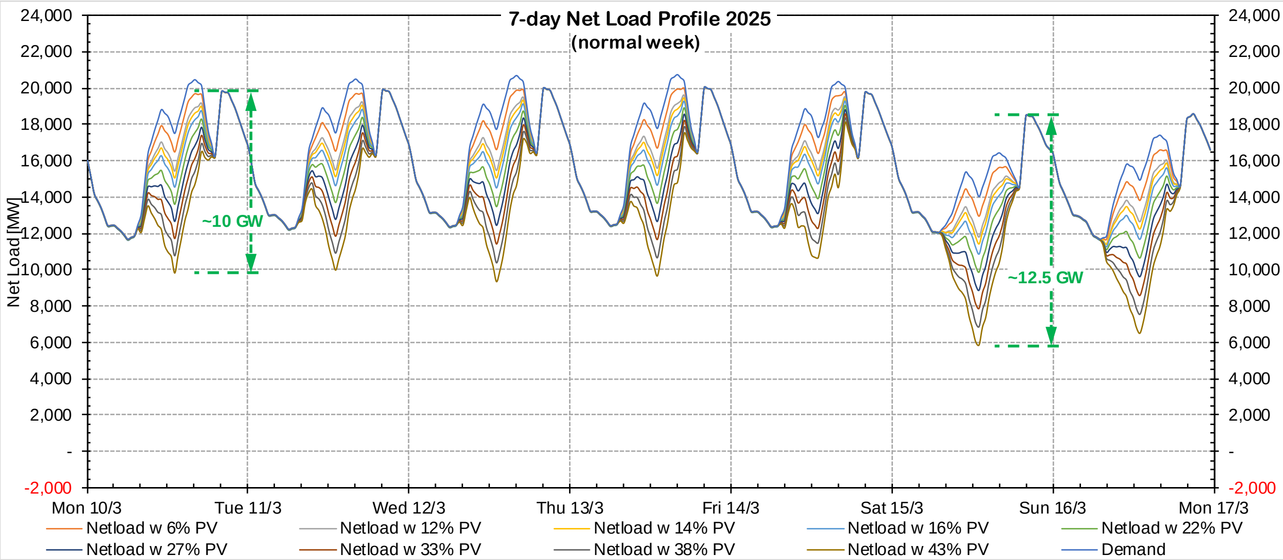


Figure 67 – Netload profile of a normal week in 2025 with tested penetration levels

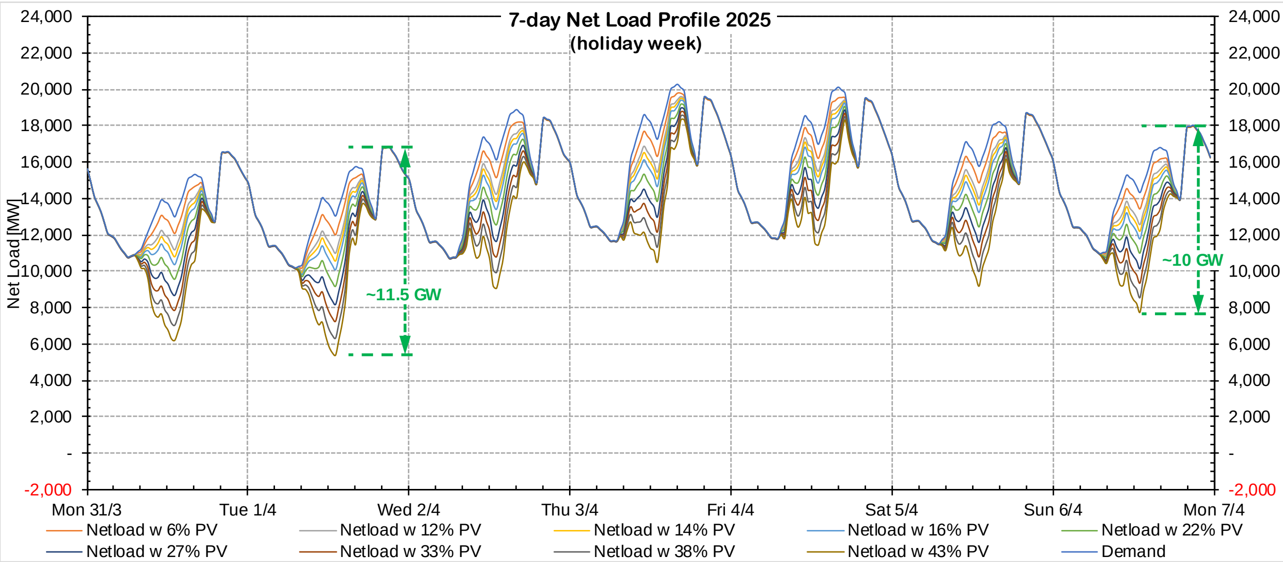


Figure 68 - Netload profile of a holiday week in 2025 with tested penetration levels

4.4.2.2 Netload duration

The full-year netload data is processed into netLDC to have a macro understanding the impact of solar (Figure 69). In the system operation space, conventional generators are expected to cycle daily along the netload duration curve. The top-left part of the curve dominates the required capacity of the conventional generators, while the bottom-right part calls for flexibility of these generators.

The solar penetration of 6% (1,200 MW) and 12% (2,400 MW) will reduce: the peak demand by 429 MW and 593 MW reading at the 24th hour of the netLDC; and trough load by 124 MW and 760 MW respectively.

Penetrations above 16% result in evening peaks, and have negligible effect on the reduction of peak demand or the required capacity of new conventional generation. Penetrations above 22% will significantly reduce the trough, up to 4,790 MW at 43% PV case.

The solar generation at high penetration levels cause significant challenges to the grid system operations.

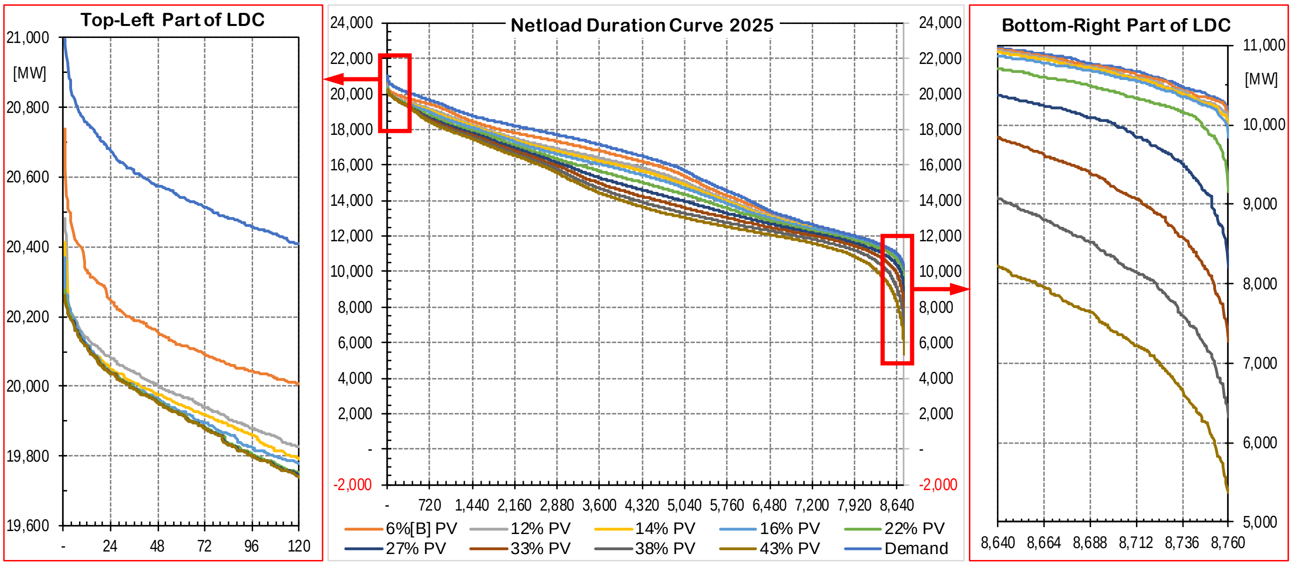


Figure 69 - Netload duration curves for year 2025 with tested penetration levels

Two sets of simulation studies are conducted in PLEXOS for the year 2025, with and without the gas constraint (800 MMSCFD) and with 10 scenarios in each set from base case 6% PV to 43%, and additional case of 80%.

4.4.2.3 Dispatch simulation without gas constraints

The key simulation results without gas constraint are illustrated in Figure 70, including CO_2 emission reductions and incremental cost of electricity as compared with the 6%PV base case, and the solar energy share. The system wide capacity and energy share is indicated in Figure 71.

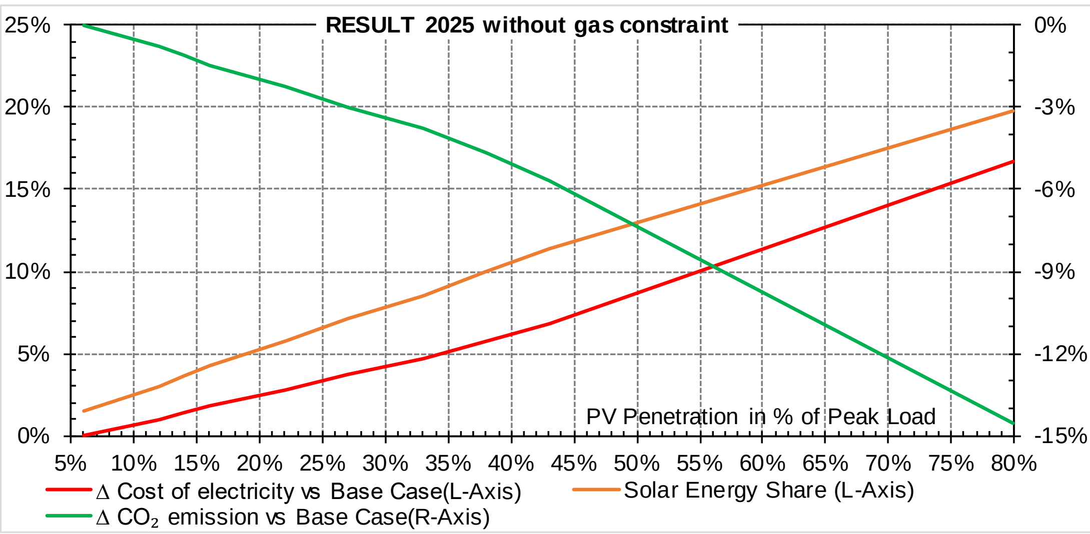


Figure 70 – Result summary of year 2025 without gas constraint

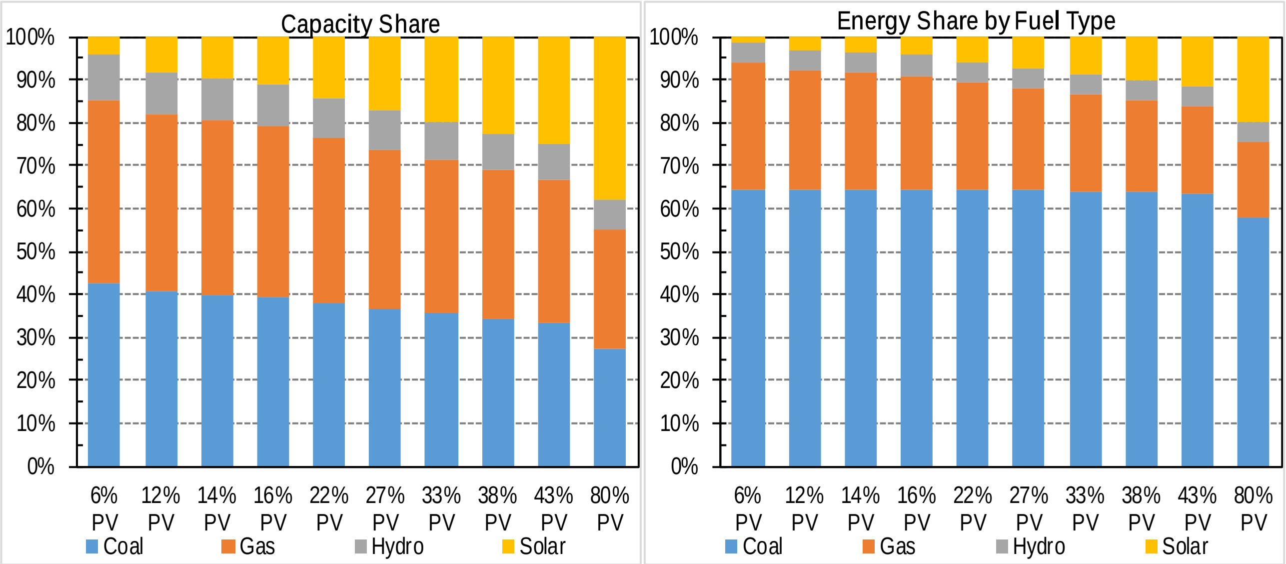


Figure 71 – Capacity and energy share for year 2025 without gas constraint

The detailed numbers are tabulated in Table 13, with the contribution from solar PV, the system unserved energy decreases with higher PV penetrations. However, in 43% PV case, solar curtailment is observed, and very severe curtailment (1670 GWh, eq. 601.57 million ringgit) is observed with 80% pentation. The HHI index reduces from 0.5 to 0.46, and CO_2 emission is reduced by 5.67% with 43% PV case.

Table 13 Result summary for year 2025 without gas constraints

Peak load: 20,774 MW	**Trough load: 10,376 MW**	**Generation: 139,259 GWh**	**Predicted Sales: 126,786 GWh**

Actual PV / Peak Load:	**6% PV**	**12% PV**	**14% PV**	**16% PV**	**22% PV**	**27% PV**	**33% PV**	**38% PV**	**43% PV**	**80% PV**
Total generation capacity[MW]:	**28,441**	**29,641**	**30,116**	**30,666**	**31,791**	**32,916**	**34,016**	**35,141**	**36,266**	**43,841**
Added Solar capacity:	-	-	*475*	*1,025*	*2,150*	*3,275*	*4,375*	*5,500*	*6,625*	*14,200*
Retired Conventional Generators:	*-4,077*	*-4,077*	*-4,077*	*-4,077*	*-4,077*	*-4,077*	*-4,077*	*-4,077*	*-4,077*	*-4,077*
Planned Conventional Generators:	5,410	5,410	5,410	5,410	5,410	5,410	5,410	5,410	5,410	5,410
New Gas from PLEXOS LT:	-	-	-	-	-	-	-	-	-	-
New Coal from PLEXOS LT:	-	-	-	-	-	-	-	-	-	-
Reliability LOLE (days):	**0.02**	**0.02**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
Total System Cost (Million):	**30,266**	**30,564**	**30,684**	**30,825**	**31,117**	**31,413**	**31,718**	**32,031**	**32,362**	**35,348**
Fixed	*8,557*	*8,557*	*8,557*	*8,557*	*8,557*	*8,557*	*8,565*	*8,557*	*8,557*	*8,557*
Variable	*21,709*	*22,007*	*22,127*	*22,268*	*22,560*	*22,856*	*23,153*	*23,474*	*23,805*	*26,791*
Unserved Energy (GWh):	*111*	*80*	*73*	*66*	*58*	*52*	*42*	*46*	*45*	*40*
Solar Curtailment (GWh):	-	-	-	-	-	-	-	0.05	2.35	*1,670.6*
Cost of Electricity (RM/MWh):	**238.92**	**241.22**	**242.15**	**243.25**	**245.54**	**247.87**	**250.25**	**252.73**	**255.34**	**278.89**
Scenario/Base[%]	*100%*	*100.96%*	*101.35%*	*101.81%*	*102.77%*	*103.74%*	*104.74%*	*105.78%*	*106.87%*	*116.73%*
Increment including [1]+[2] Scenario-Base[%]	*Base*	*+0.96%*	*+1.35%*	*+1.81%*	*+2.77%*	*+3.74%*	*+4.74%*	*+5.78%*	*+6.87%*	*+16.73%*
[1] Cost due to balance of solar[75]		*+0.12%*	*+0.17%*	*+0.25%*	*+0.41%*	*+0.60%*	*+0.82%*	*+1.07%*	*+1.37%*	*+5.90%*
[2] Cost due to higher solar energy price		*+0.84%*	*+1.18%*	*+1.56%*	*+2.35%*	*+3.15%*	*+3.92%*	*+4.71%*	*+5.50%*	*+10.83%*
Additional Solar Curtailment Penalty (Million)[76]**:**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.02**	**0.84**	**601.57**
HHI:	**0.50**	**0.50**	**0.49**	**0.49**	**0.48**	**0.48**	**0.47**	**0.47**	**0.46**	**0.41**
CO2 Emission (thousand tonnes):	**99,231**	**98,446**	**98,133**	**97,773**	**97,027**	**96,250**	**95,456**	**94,578**	**93,609**	**84,830**
Increment, Scenario-Base[%]	*Base*	*-0.79%*	*-1.11%*	*-1.47%*	*-2.22%*	*-3.00%*	*-3.80%*	*-4.69%*	*-5.67%*	*-14.51%*

With growing PV capacity, total variable system cost increases as results of high solar energy price and balancing of solar causing conventional unit operating at lower efficiency point. The cost of electricity

[75] Cost increases due to conventional generators operate at less efficient point.

[76] Additional penalty when PLEXOS decides to curtail solar in searching for optimal solution.

increases by 6.87% at 43%PV case, or 16.73% with 80% PV case. Total system cost increment due to provision of solar reserve (11% of PV capacity) range from 0.01% to 0.12% from 6% PV to 80% PV.

The dispatch schedules of a coal generator under different PV scenarios is shown in Figure 72. Up to 22% PV case, the dispatch schedule for this period does not show any differences. However, for 27% PV and above, the schedule power output from this coal generator decreases with the increase of solar penetration.

Figure 73 shows the dispatch of the same coal generator on a high demand day and a low demand day. On the high demand day, the coal generator is dispatch to as base load generator throughout the day. However, during low demand days, when the PV penetration is above 27%, the scheduled power output is lower during peak solar generation hours. With the highest penetration test (43% PV), the schedule power output dropped to its minimum power 300 MW during high solar generation hours.

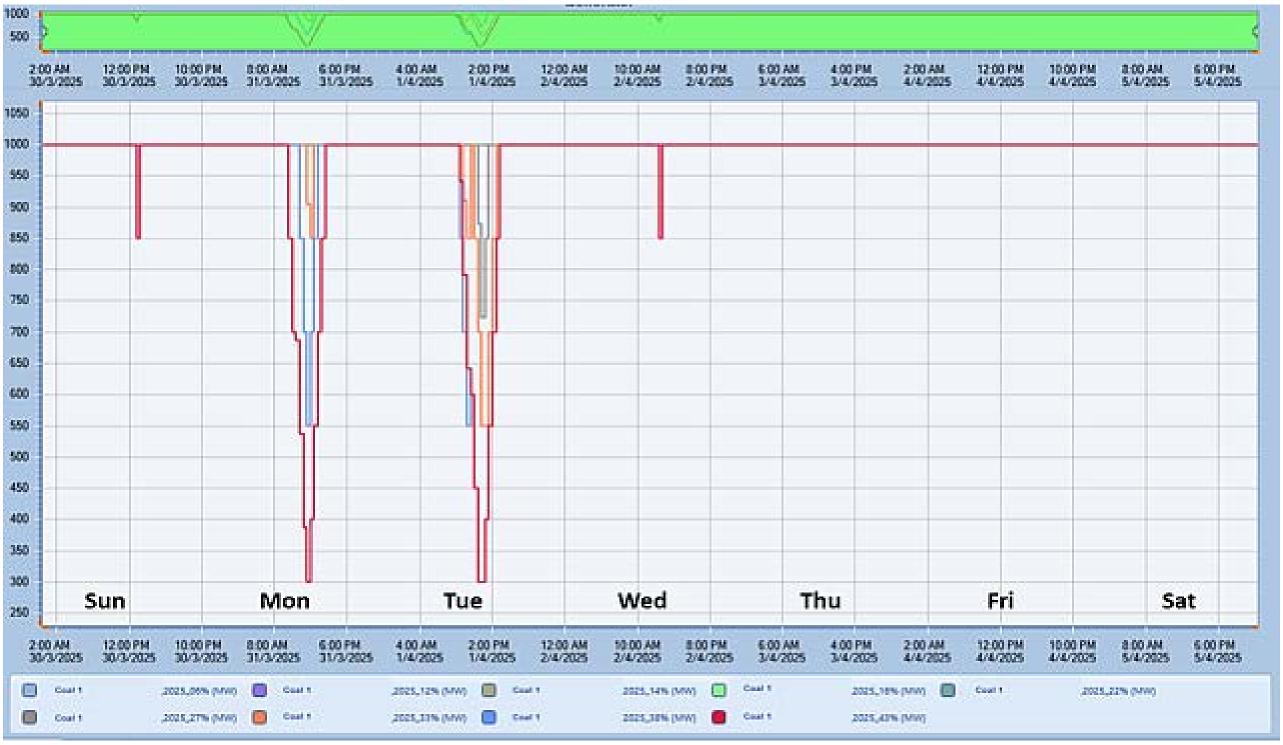


Figure 72 - Dispatch of a coal generator over a sample week

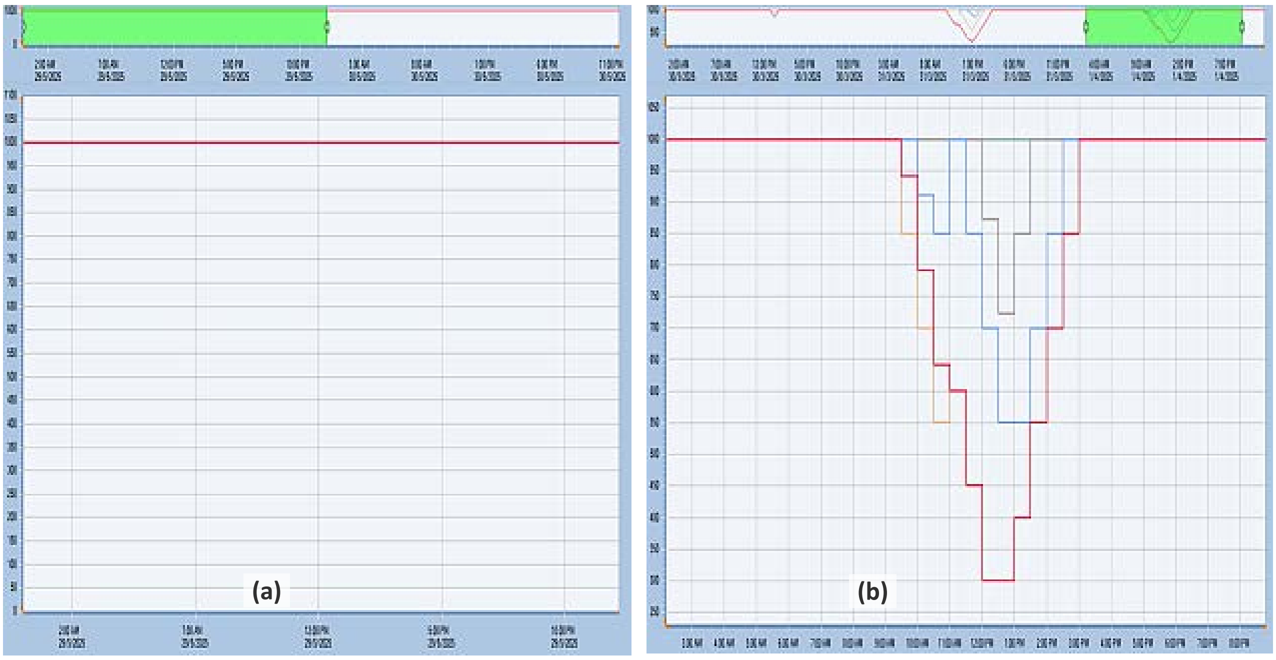


Figure 73 - Dispatch of a coal generator on: (a) a high demand day, (b) a low demand day

An example of the dispatch schedule of a gas generator over a sample week is plotted in Figure 74, and the dispatch on a high and low demand day is plotted in Figure 75. One can observe that relatively less economic gas generators are significantly affected by increasing solar penetration in a fully economic based unit commitment optimisation.

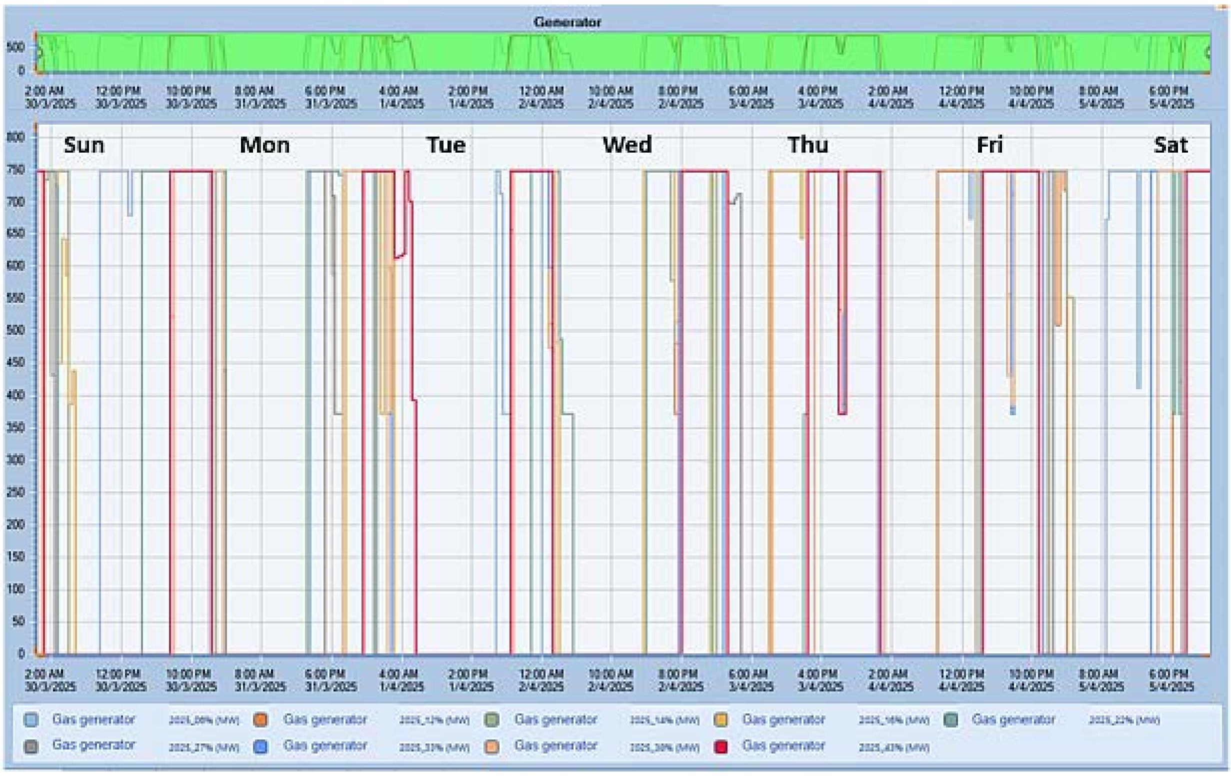
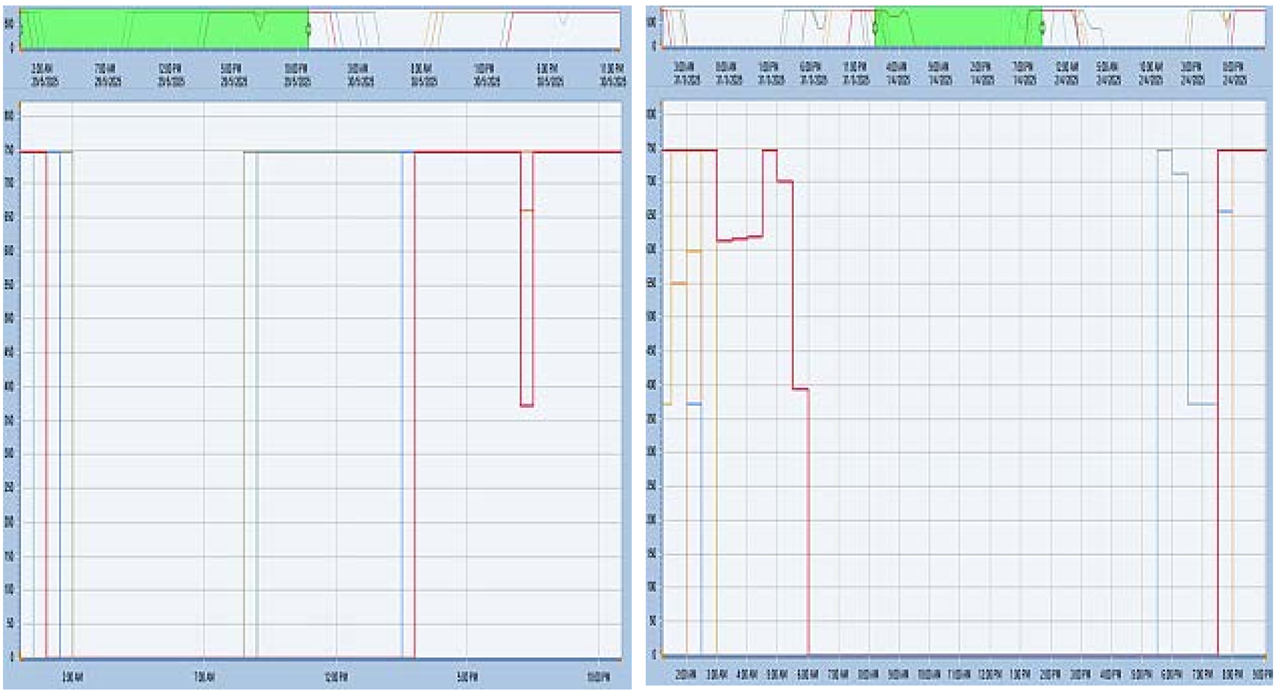


Figure 74 - Dispatch of a gas generator over a sample week



(a) (b)

Figure 75 - Dispatch of a gas generator on (a) the high demand day and (b) the low demand day

4.4.2.4 Dispatch simulation with gas constraints

The key simulation results with gas constraint are illustrated in Figure 76, including CO_2 emission reductions, incremental cost of electricity, and solar energy share as compared to the base case. The system wide capacity and energy share is indicated in Figure 77.

The detailed numbers are tabulated in Table 14, with the contribution from solar PV, the system unserved energy decreases with higher PV penetrations. In 43% PV case, solar curtailment is observed, and severe curtailment (748.06 GWh, eq. 269.38 million ringgit) is observed with 80% pentation. The HHI index reduces from 0.47 to 0.38, and CO_2 emission is reduced by 13.42% with 43% PV case.

With growing PV capacity, total variable system cost increases as results of high solar energy price and balancing of solar causing conventional unit operating at lower efficiency point. The cost of electricity increases by 9.65% at 43%PV case, or 20.23% with 80% PV case. Total system cost increment due to provision of solar reserve (11% of PV capacity) range from 0.53% to 9.6% from 12% PV to 80% PV as compared with 6% PV base case.

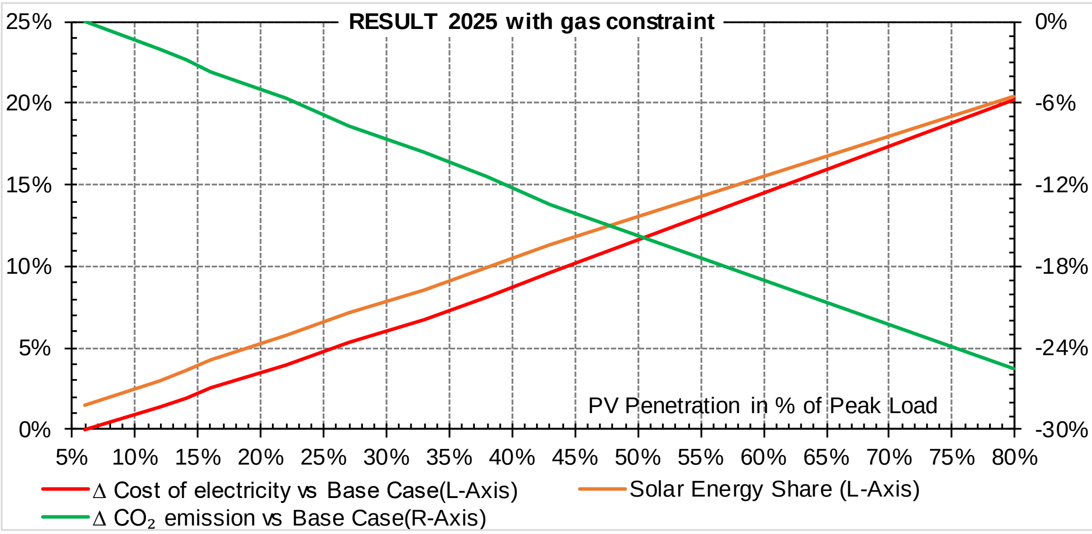


Figure 76 – Result summary of year 2025 with gas constraint

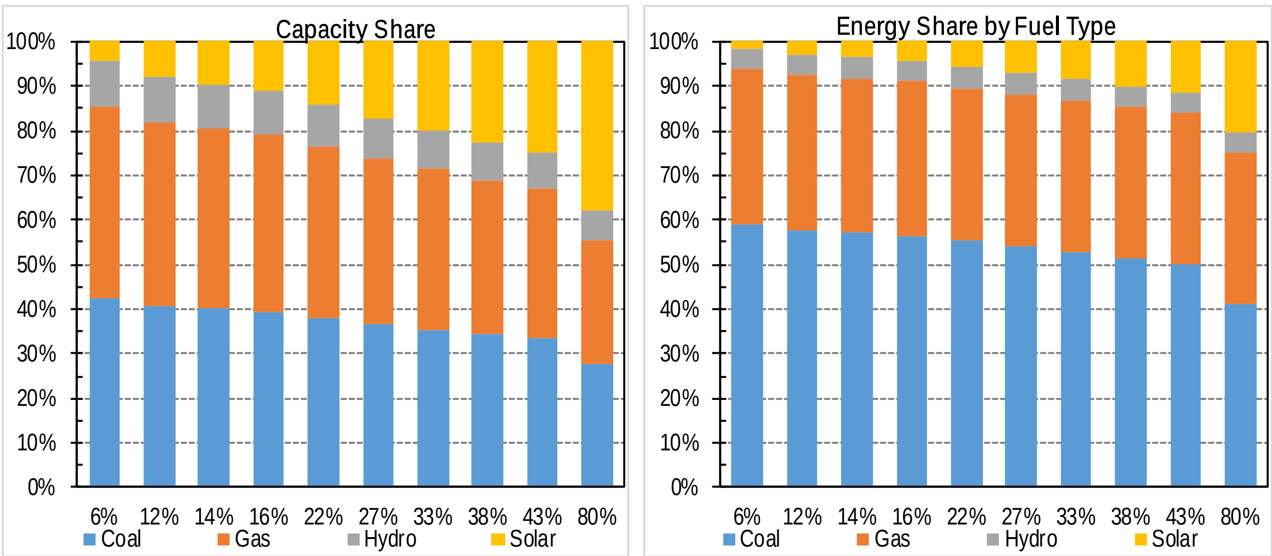


Figure 77 – Capacity and energy share for year 2025 with gas constraint

Table 14 Result summary for year 2025 with gas constraints

Peak load: 20,774 MW	Trough load: 10,376 MW	Generation: 139,259 GWh	Predicted Sales: 126,786 GWh

Actual PV / Peak Load:	6% PV	12% PV	14% PV	16% PV	22% PV	27% PV	33% PV	38% PV	43% PV	80% PV
Total generation capacity[MW]:	**28,441**	**29,641**	**30,116**	**30,666**	**31,791**	**32,916**	**34,016**	**35,141**	**36,266**	**43,841**
Added Solar capacity:	-	-	*475*	*1,025*	*2,150*	*3,275*	*4,375*	*5,500*	*6,625*	*14,200*
Retired Conventional Generators:	*-4,077*	*-4,077*	*-4,077*	*-4,077*	*-4,077*	*-4,077*	*-4,077*	*-4,077*	*-4,077*	*-4,077*
Planned Conventional Generators:	*5,410*	*5,410*	*5,410*	*5,410*	*5,410*	*5,410*	*5,410*	*5,410*	*5,410*	*5,410*
New Gas from PLEXOS LT:	-	-	-	-	-	-	-	-	-	-
New Coal from PLEXOS LT:	-	-	-	-	-	-	-	-	-	-
Reliability LOLE (days):	**0.02**	**0.02**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
Total System Cost (Million):	**30,806**	**31,233**	**31,403**	**31,611**	**32,034**	**32,464**	**32,899**	**33,342**	**33,796**	**37,060**
Fixed	*8,557*	*8,557*	*8,557*	*8,557*	*8,557*	*8,557*	*8,565*	*8,557*	*8,557*	*8,557*
Variable	*22,249*	*22,676*	*22,846*	*23,054*	*23,477*	*23,907*	*24,335*	*24,785*	*25,239*	*28,503*
Unserved Energy (GWh):	*114*	*81*	*75*	*68*	*58*	*53*	*43*	*48*	*47*	*41*
Solar Curtailment (GWh):	-	-	-	-	-	-	-	*0.09*	*0.10*	*748.06*
Cost of Electricity (RM/MWh):	**243.19**	**246.50**	**247.83**	**249.46**	**252.78**	**256.16**	**259.57**	**263.08**	**266.66**	**292.40**
Scenario/Base[%]	*100%*	*101.36%*	*101.91%*	*102.58%*	*103.94%*	*105.33%*	*106.74%*	*108.18%*	*109.65%*	*120.23%*
Increment including [1]+[2], Scenario-Base[%]	*Base*	*+1.36%*	*+1.91%*	*+2.58%*	*+3.94%*	*+5.33%*	*+6.74%*	*+8.18%*	*+9.65%*	*+20.23%*
[1] Due to balance of solar[77]		*+0.53%*	*+0.75%*	*+1.04%*	*+1.63%*	*+2.24%*	*+2.89%*	*+3.55%*	*+4.24%*	*+9.60%*
[2] Due to higher solar energy price		*+0.83%*	*+1.16%*	*+1.54%*	*+2.31%*	*+3.09%*	*+3.85%*	*+4.63%*	*+5.40%*	*+10.64%*
Additional Solar Curtailment Penalty (Million)[78]:	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.03**	**0.04**	**269.38**
HHI:	**0.47**	**0.46**	**0.45**	**0.44**	**0.43**	**0.42**	**0.40**	**0.39**	**0.38**	**0.33**
CO2 Emission (thousand tonnes):	**94,547**	**92,672**	**91,943**	**91,038**	**89,192**	**87,349**	**85,516**	**83,715**	**81,862**	**70,483**
Increment, Scenario-Base[%]	*Base*	*-1.98%*	*-2.75%*	*-3.71%*	*-5.66%*	*-7.61%*	*-9.55%*	*-11.46%*	*-13.42%*	*-25.45%*

4.4.2.5 Result comparison with and wihout gas constraint

As shown in Figure 78, the increase of cost of electricity is more significant when minimum gas constraint is in place, as more gas generation is scheduled online by reducing the output from more economic coal generators. The HHI index is naturally improved with more energy from gas generation. The gas constraint helps further reduction of CO_2 emission due to less carbon content in gas fuel.

It is also observed that with gas constraint in place, solar curtailment is reduced for the same penetration, e.g. 0.1 GWh with gas constraint versus 2.35 GWh without gas constraint at 43% PV case, and 748.06 GWh versus 1670.56 GWh at 80% PV case. The system with more online gas generators is more flexible.

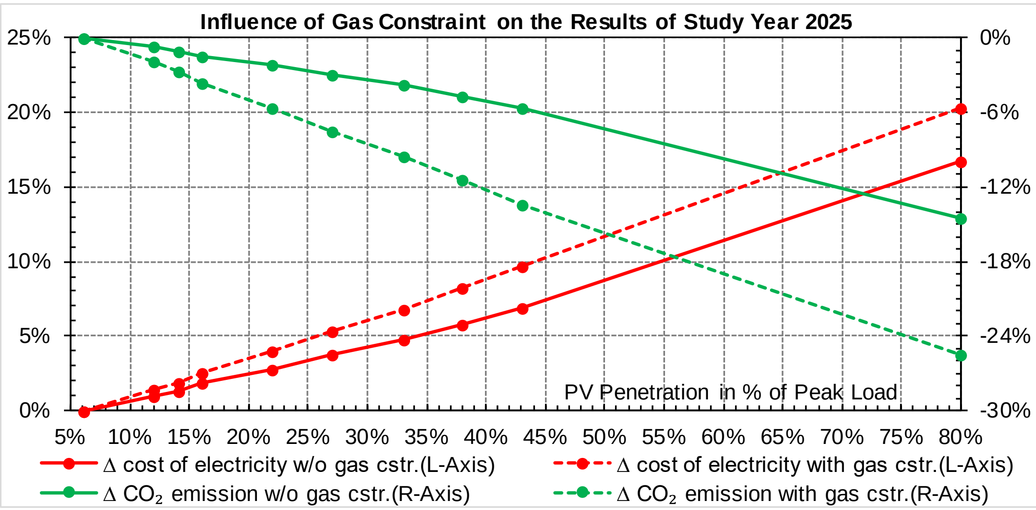


Figure 78 – Comparison of results with and without gas constraint

[77] Cost increases due to conventional generators operate at less efficient point.
[78] Additional penalty when PLEXOS decides to curtail solar in searching for optimal solution.

Comparisons of the gas constraint on system operation with all the tested solar penetrations are shown in Figure 79. Without gas constraint, the solar generation displaces the energy of gas generators and the energy share coal generation is not affected until 43% PV case. With the gas constraint, the solar generation displaces the energy from coal generators instead of the less economic gas generators, and gas energy share is kept constantly around 34%. The latter explains the high incremental cost of electricity with the gas constraint, and the further reduction of CO_2 emissions.

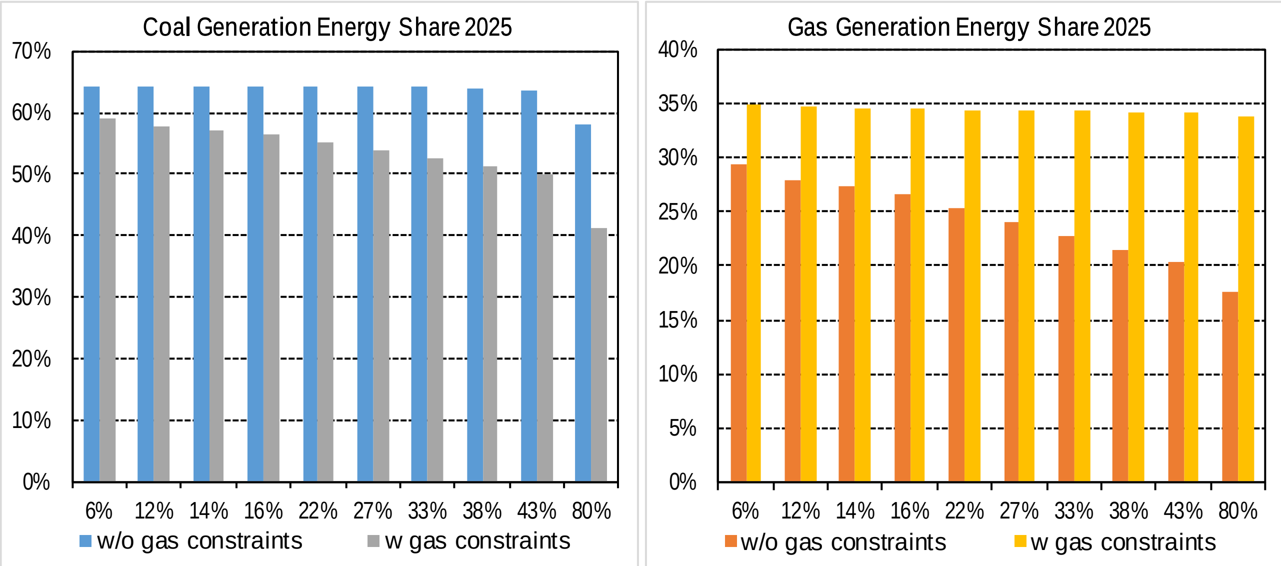


Figure 79 – Influence of gas constraint on Coal and Gas energy share

4.4.3 Results of study year 2030

Total nine (9) cases of PV capacity, ranging from 5% (base case) to 70% penetration are simulated for the year 2030. The capacities solar and conventional generation for all tested scenarios are listed in Table 15.

Table 15 Capacity planning summary for scenarios in year 2030

Actual PV / Peak Load	5% PV	11% PV	15% PV	20% PV	30% PV	40% PV	50% PV	60% PV	70% PV
Total generation capacity:	27,444	28,344	29,194	30,094	32,144	34,294	36,494	38,744	40,994
Solar Capacity	1,200	2,400	3,350	4,450	6,700	8,950	11,150	13,400	15,650
Conventional Generators	26,244	25,944	25,844	25,644	25,444	25,344	25,344	25,344	25,344

4.4.3.1 Netload profile

The Figure 80 (a) illustrates the netload profiles of the lowest demand day (4/2, 2nd day of CNY), where negative netload is observed. On an off-peak Sunday Figure 80 (b), with 40% PV penetration, the solar supplies 57% of the demand, leading to low system inertia and governor response. System stability issues are to be investigated in PSS®E. The netload profile of high demand day (Figure 81) illustrates the mid-day peak becomes load trough while the evening peak becomes dominant on generation capacity planning.

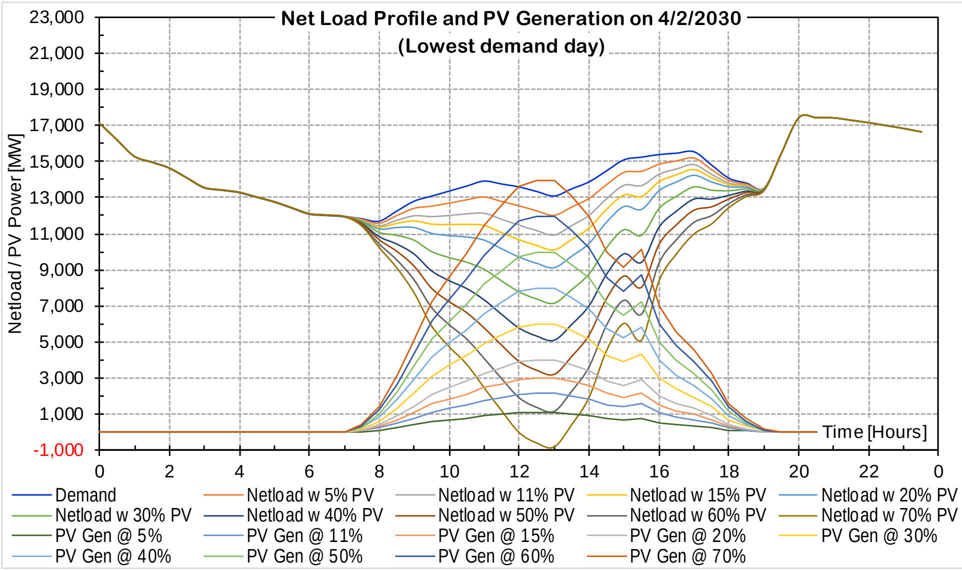
The netload profiles of sample weeks are plotted in Figure 82 and Figure 83, where massive afternoon netload ramps in the magnitude of 15-17 GW (67-76% of the peak demand) are observed with high solar penetration, comparing to the original morning load ramp approx. 8 GW in magnitude. System operation is extremely challenging. For example, conventional generators are expected to cycle daily in higher magnitudes (15-17 GW) from 1 to 8 pm with 70% PV case.

To provide sufficient load following capacity, the unit commitment must curtail the solar output so that more conventional generators can be scheduled online and fulfil the minimum stable power output.

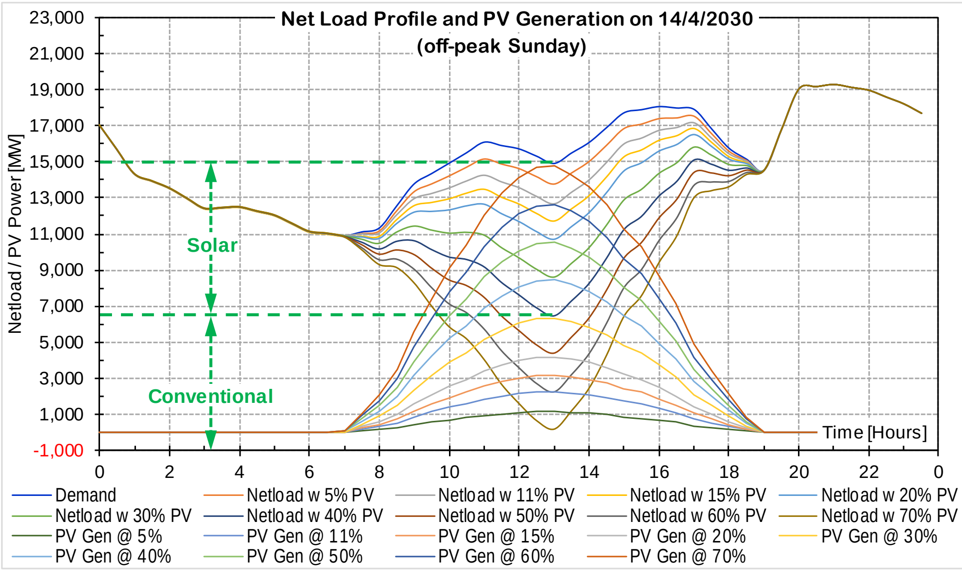
To avoid solar curtailments, greater flexibility from conventional generation units is required:

- the ability to operate at lower minimum load points, thus providing wider range of available power control;
- shorter start up time for the machine to reach minimum load point;

- larger power output ramp, which enables faster response to changes in netload profile.



(a)



(b)

Figure 80 - Netload profiles lowest demand day (a) and an off-peak day (b) in 2030

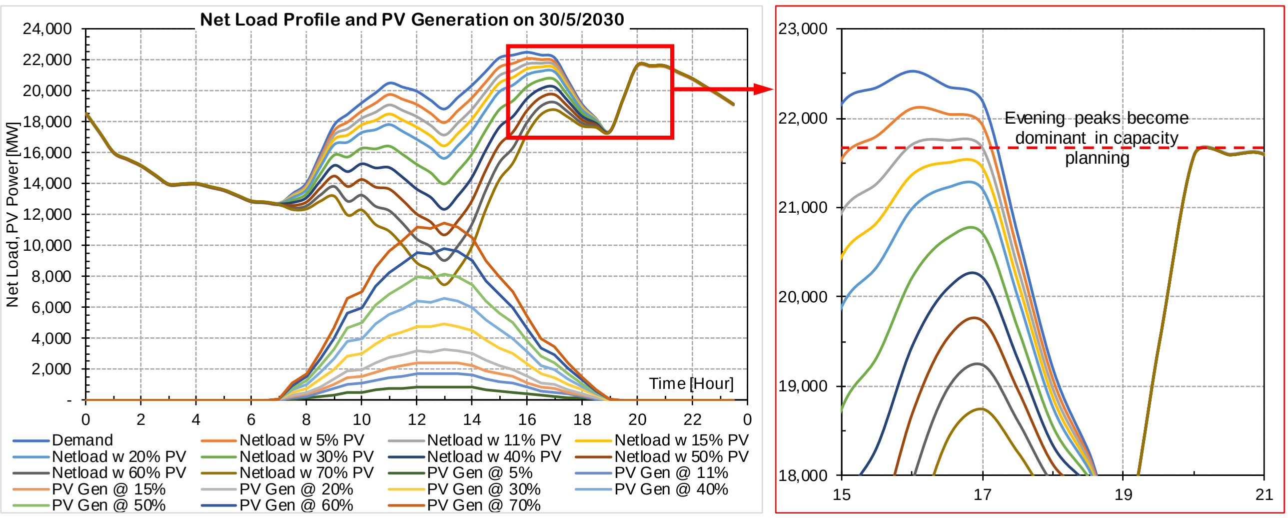


Figure 81 - Netload profiles on a peak demand day (30/5/2030)

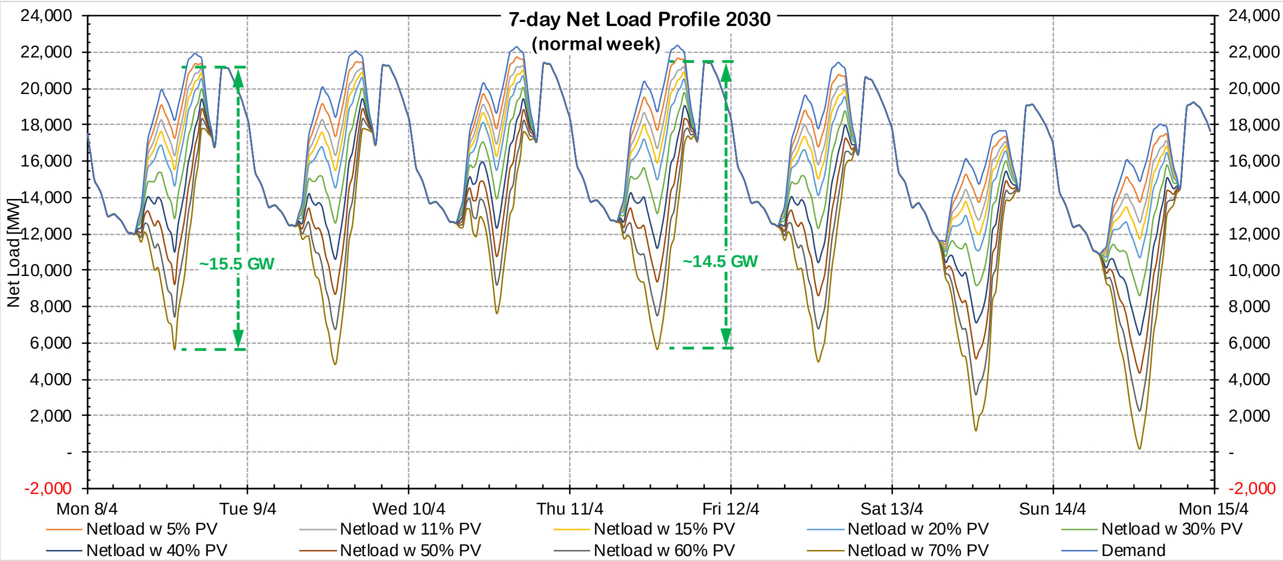


Figure 82 - Netload profiles of a normal week in 2030 with tested penetration levels

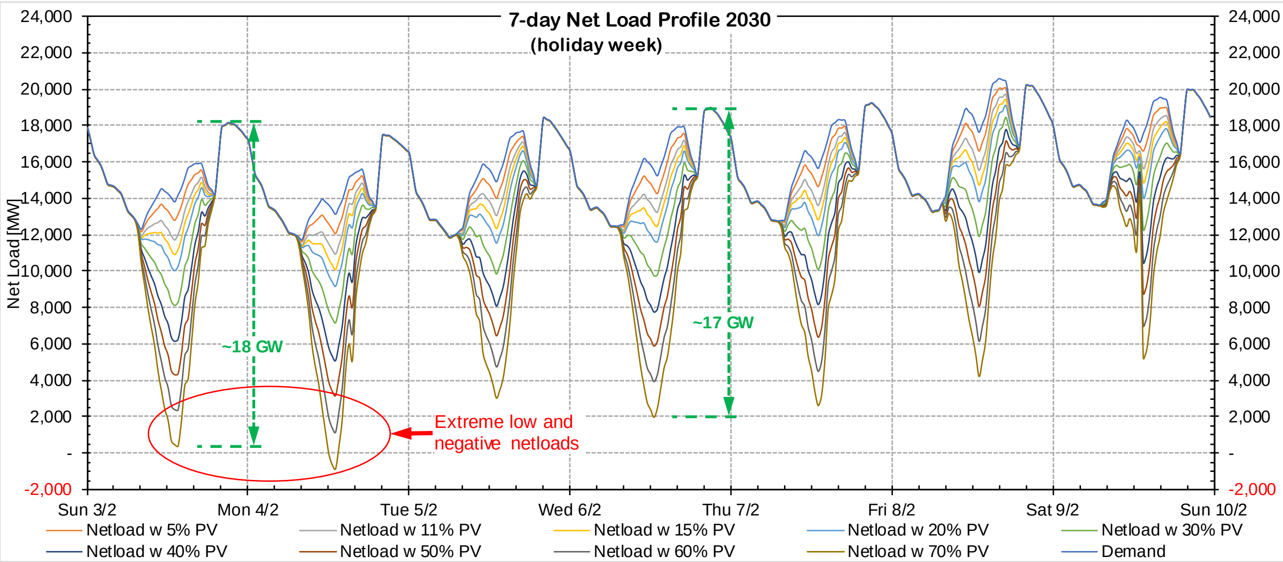


Figure 83 - Netload profiles of a holiday week in 2030 with tested penetration levels

4.4.3.2 Netload duration

The full-year netload data is processed into netLDC (Figure 84) to have a macro understanding the impact of solar. In the system operation space, conventional generators are expected to cycle daily along the netload duration curve. The top-left part of the curve dominates the required capacity of the conventional generators, while the bottom-right part calls for flexibility of these generators.

Penetration of 5% and 11% will reduce the peak demand by 442MW and 726MW respectively read at the 24th hour of the netLDC, significantly reduce the required new capacity.

Penetrations above 20% will significantly reduce the trough, up to 8,714 MW at 70% PV. The system flexibility is extremely challenged, e.g. conventional generators are expected to cycle daily in high magnitudes (15-17 GW from 1 to 8 pm) with 70% PV case. Negative netload can also be observed in Figure 84 (right window).

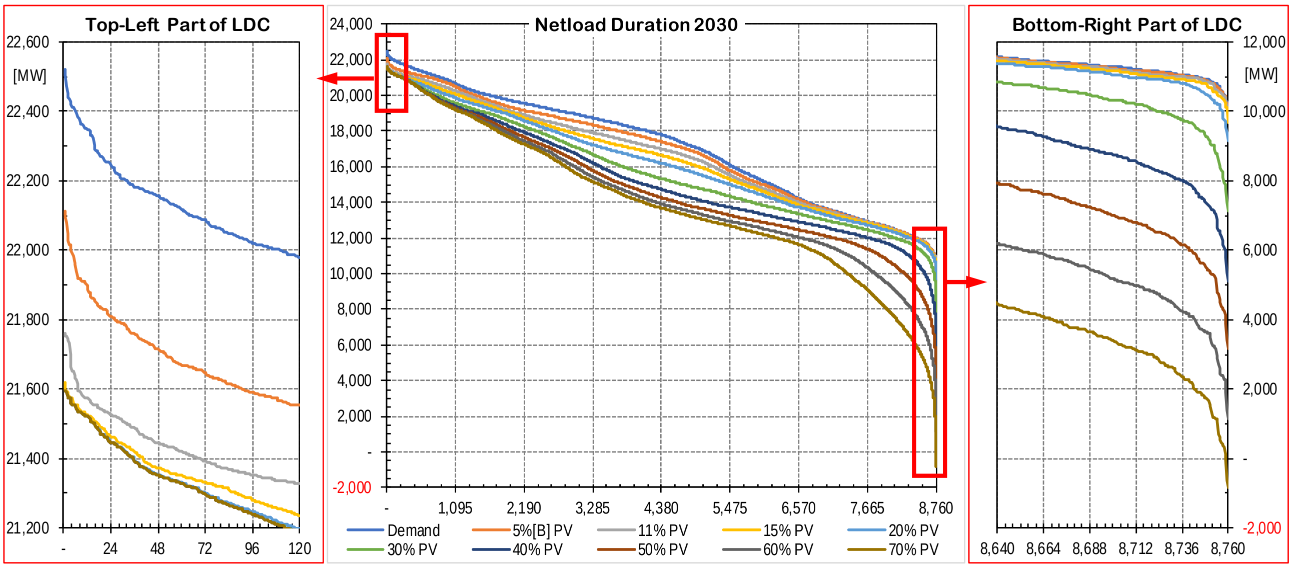


Figure 84 - Netload duration curves for year 2030

4.4.3.3 Dispatch simulations

The key simulation results are illustrated in Figure 85, including CO_2 emission reductions, incremental cost of electricity, and solar energy share as compared to the base case. Unlike the study years 2020 and 2025 where conventional generators have already been planned up, the conventional generators of study year 2030 are grown from the LT simulations. One can observe that solar generation contributes: effectively to capacity planning at lower penetration levels up to 20%; less significant from 20% to 40% penetration; and 'zero' above 40% penetration.

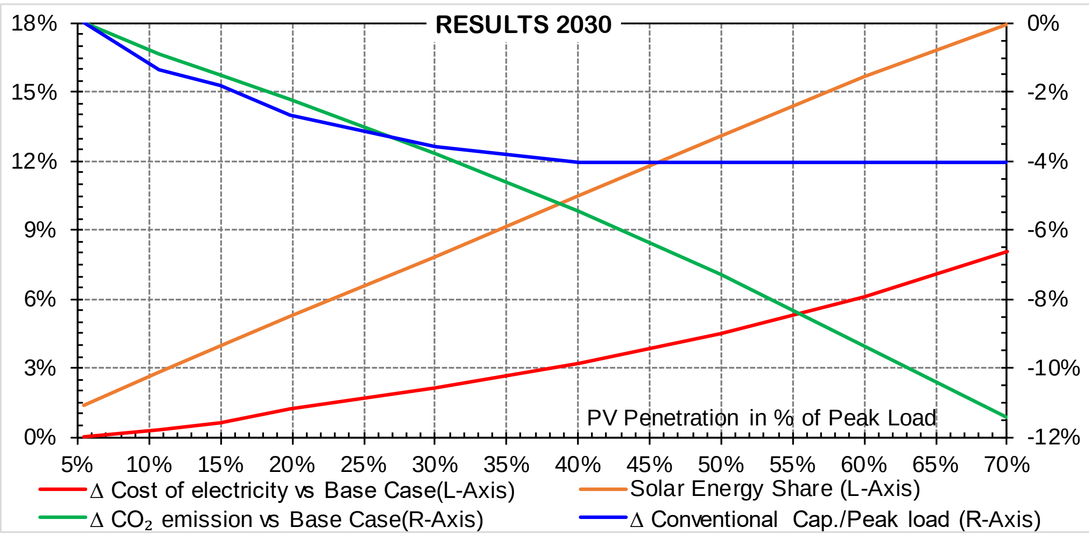


Figure 85 – Result summary for year 2030

The detailed numbers are tabulated in Table 16. Based on the long-term capacity planning results, the gas/coal generation capacity various from case to case. Nonetheless, LOLE is in the range of 0.72-0.88 days. As the conventional generation capacity varies, both the fixed and the variable costs are different for the tested cases. While fixed cost fluctuates around 8,050 million RM, variable increases with solar penetration, due to higher cost of solar energy and the balancing of solar power output. The cost of electricity increases by 8.06% with 70% PV as compared to the 5% PV base case.

The capacity share and energy share by fuel type are plotted in Figure 86. With more diverse of fuel types, the HHI index reduces from 0.44 to 0.37. The CO_2 emission is reduced by 11.45% from 5% PV to 70% PV case.

Solar curtailments start at 40% PV case for very small amount 0.43 GWh, and increase with higher penetration reaching 629 GWh (eq. 226.4 million ringgit) at 70% PV.

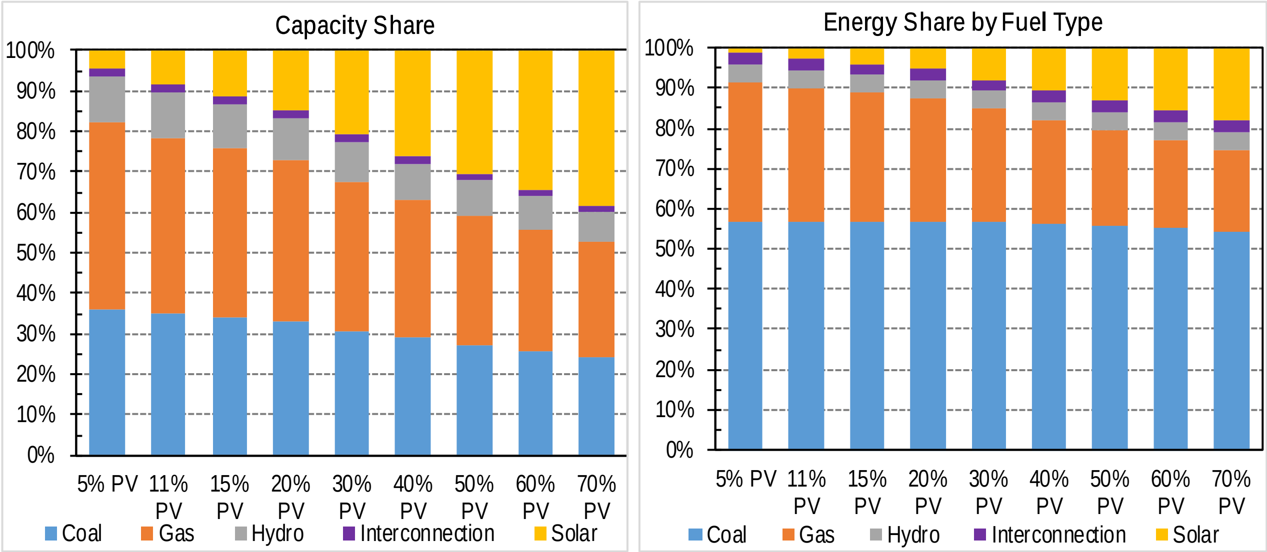


Figure 86 - System capacity share and energy share by fuel type

Table 16 System cost summary for year 2030

Peak load: 22,345 MW	**Trough load: 10,847 MW**	**Generation: 149,445 GWh**	**Predicted Sales: 135,996 GWh**

Actual PV / Peak Load:	**5% PV**	**11% PV**	**15% PV**	**20% PV**	**30% PV**	**40% PV**	**50% PV**	**60% PV**	**70% PV**
Total generation capacity[MW]:	**27,444**	**28,344**	**29,194**	**30,094**	**32,144**	**34,294**	**36,494**	**38,744**	**40,994**
Added Solar capacity:	-	-	*475*	*1,025*	*2,150*	*3,275*	*4,375*	*5,500*	*6,625*
Retired Conventional Generators:	*-7,529*	*-7,529*	*-7,529*	*-7,529*	*-7,529*	*-7,529*	*-7,529*	*-7,529*	*-7,529*
Planned Conventional Generators:	*132*	*132*	*132*	*132*	*132*	*132*	*132*	*132*	*132*
New Interconnections:	*600*	*600*	*600*	*600*	*600*	*600*	*600*	*600*	*600*
New Gas from PLEXOS LT:	*4,400*	*4,100*	*4,000*	*3,800*	*3,600*	*3,500*	*3,500*	*3,500*	*3,500*
New Coal from PLEXOS LT:	*1,400*	*1,400*	*1,400*	*1,400*	*1,400*	*1,400*	*1,400*	*1,400*	*1,400*
Reliability LOLE (days):	**0.72**	**0.77**	**0.73**	**0.80**	**0.85**	**0.88**	**0.85**	**0.83**	**0.82**
Total System Cost (Million):	**35,744**	**35,844**	**35,967**	**36,165**	**36,483**	**36,863**	**37,347**	**37,913**	**38,624**
Fixed	*8,087*	*8,064*	*8,057*	*8,062*	*8,047*	*8,040*	*8,040*	*8,040*	*8,040*
Variable	*27,656*	*27,780*	*27,910*	*28,103*	*28,436*	*28,823*	*29,307*	*29,873*	*30,585*
Unserved Energy (GWh):	*509*	*559*	*543*	*594*	*599*	*593*	*558*	*534*	*515*
Solar Curtailment (GWh):	-	-	-	-	-	0	16	150	629
Cost of Electricity (RM/MWh):	**263.82**	**264.66**	**265.53**	**267.10**	**269.45**	**272.25**	**275.75**	**279.88**	**285.09**
Scenario/Base[%]	*100%*	*100.32%*	*100.65%*	*101.24%*	*102.14%*	*103.20%*	*104.52%*	*106.09%*	*108.06%*
Increment, Scenario-Base[%]	*Base*	*+0.32%*	*+0.65%*	*+1.24%*	*+2.14%*	*+3.20%*	*+4.52%*	*+6.09%*	*+8.06%*
[1] Due to balance of solar[79]		*-0.25%*	*-0.36%*	*-0.29%*	*-0.46%*	*-0.46%*	*-0.17%*	*0.34%*	*1.25%*
[2] Due to higher solar energy price		*+0.57%*	*+1.01%*	*+1.53%*	*+2.59%*	*+3.65%*	*+4.69%*	*+5.75%*	*+6.81%*
Additional Solar Curtailment Penalty (Million)[80]:	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.16**	**5.84**	**53.95**	**226.40**
HHI:	**0.44**	**0.43**	**0.43**	**0.42**	**0.41**	**0.40**	**0.39**	**0.38**	**0.37**
CO2 Emission (thousand tonnes):	**96,020**	**95,183**	**94,572**	**93,892**	**92,395**	**90,788**	**89,009**	**87,020**	**85,021**
Increment, Scenario-Base[%]	*Base*	*-0.87%*	*-1.51%*	*-2.22%*	*-3.78%*	*-5.45%*	*-7.30%*	*-9.37%*	*-11.45%*

[79] Cost increases due to conventional generators operate at less efficient point.

[80] Additional penalty when PLEXOS decides to curtail solar in searching for optimal solution.

The dispatch of a coal generator over a sample week is shown in Figure 87. As with increased PV penetration, the schedule power output of this coal generator is reduced during the day time with high solar generation. With a 70% penetration, the generator output during peak solar hours drops to its minimum power.

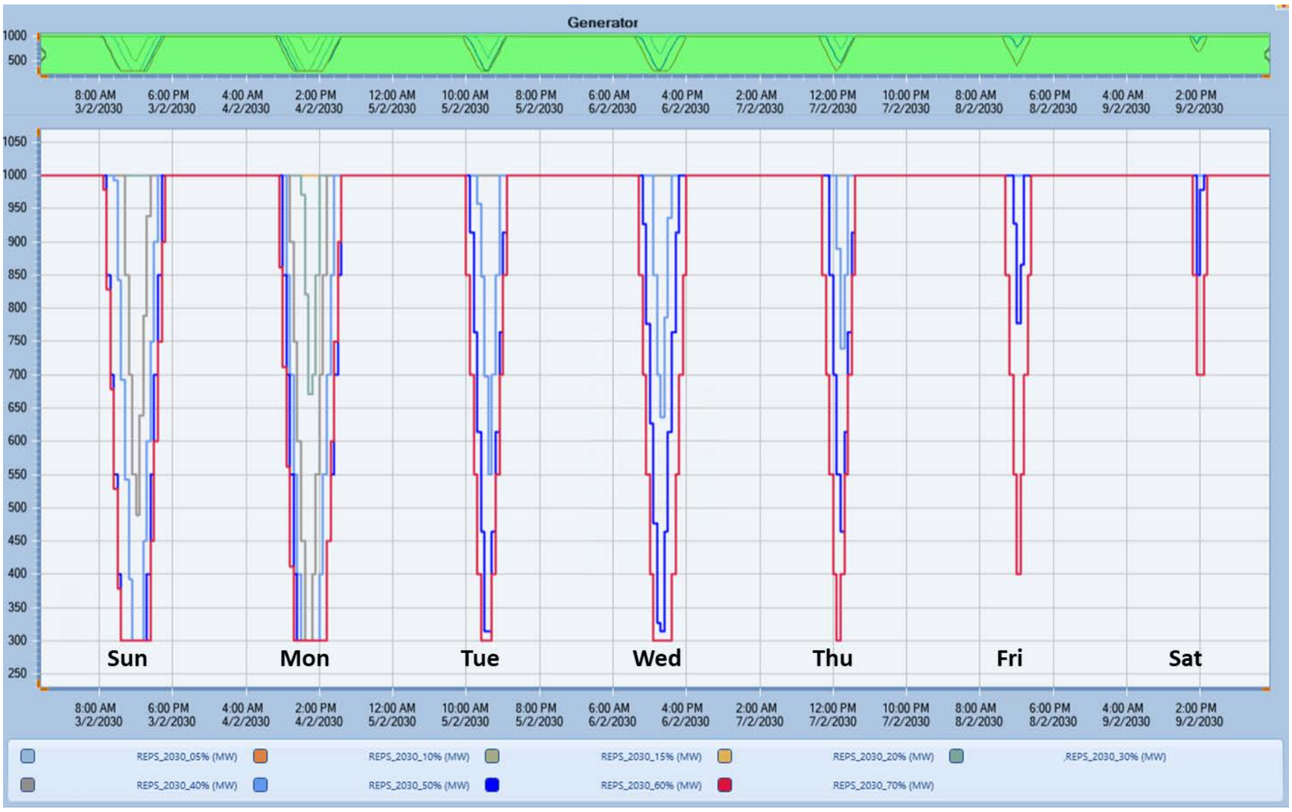
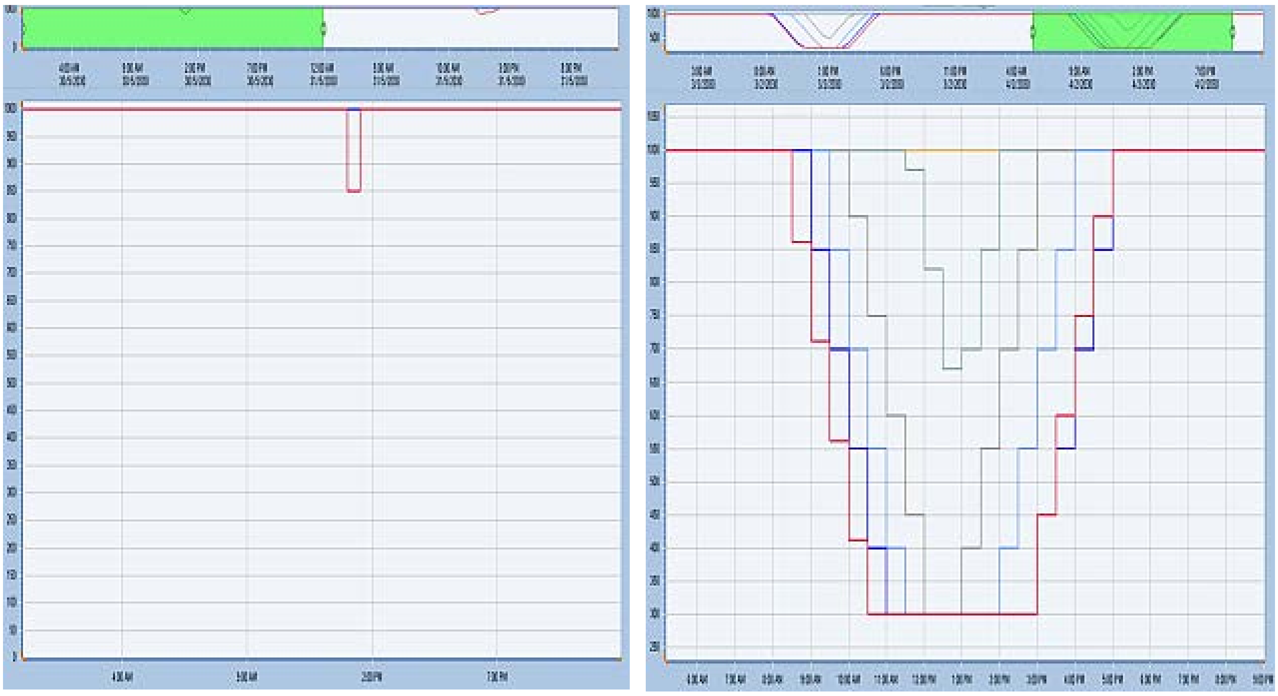


Figure 87 - Dispatch of a coal generator over a sample week

The dispatch of coal generator on a high-demand day and a low-demand day are shown in Figure 88. The influence of solar is insignificant on high demand day, the generator output reduced to 850 MW for half an hour with 70% PV case only (Figure 88(a)). While on off-peak demand day with high solar, the coal generator output reduces in bigger magnitude and longer duration with increased penetration (Figure 88(a)).



(a) (b)

Figure 88 - Dispatch of a coal generator on (a) a high demand day and (b) a low demand day

An example of the dispatch schedule of a gas generator over a sample week is plotted in Figure 89, and the dispatch on a high and low demand day is plotted in Figure 90. One can observe that relatively less economic gas generators are significantly affected by increasing solar penetration in a fully economic based unit commitment optimisation.

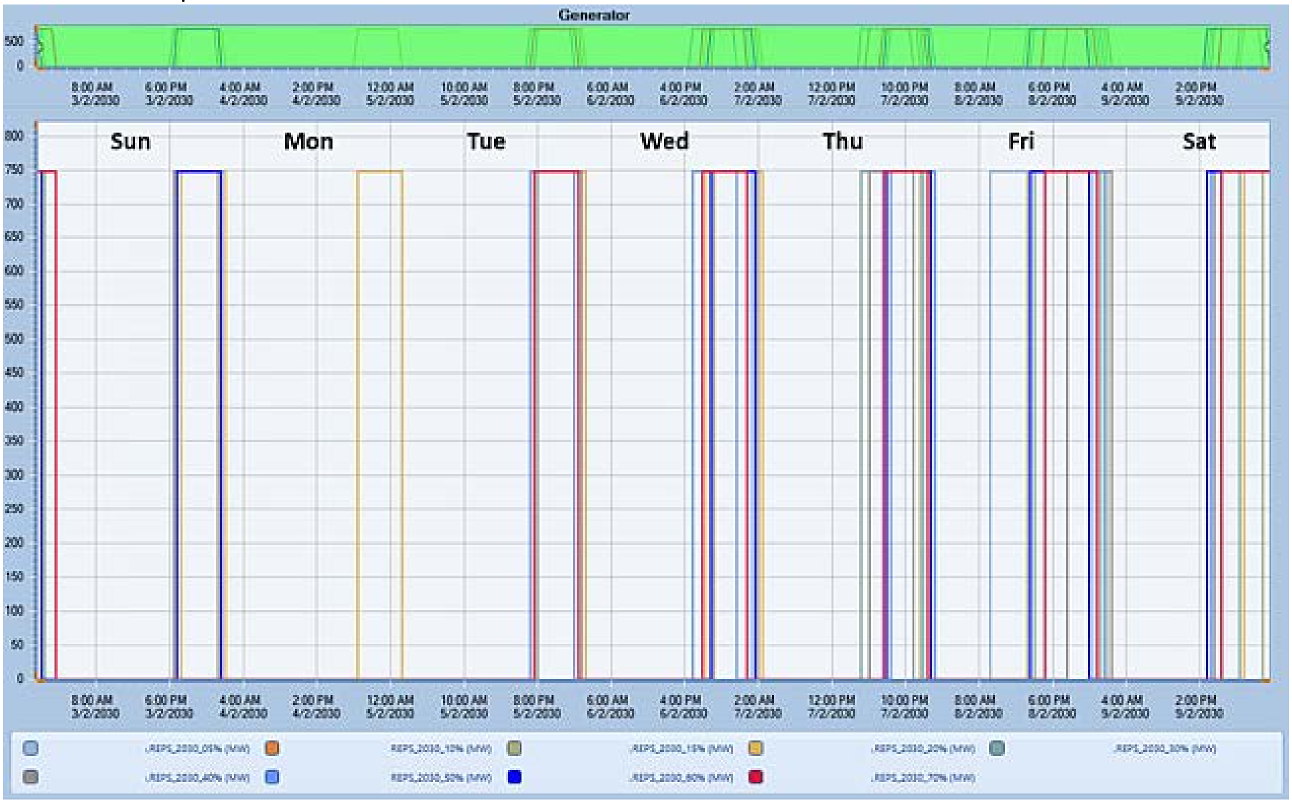
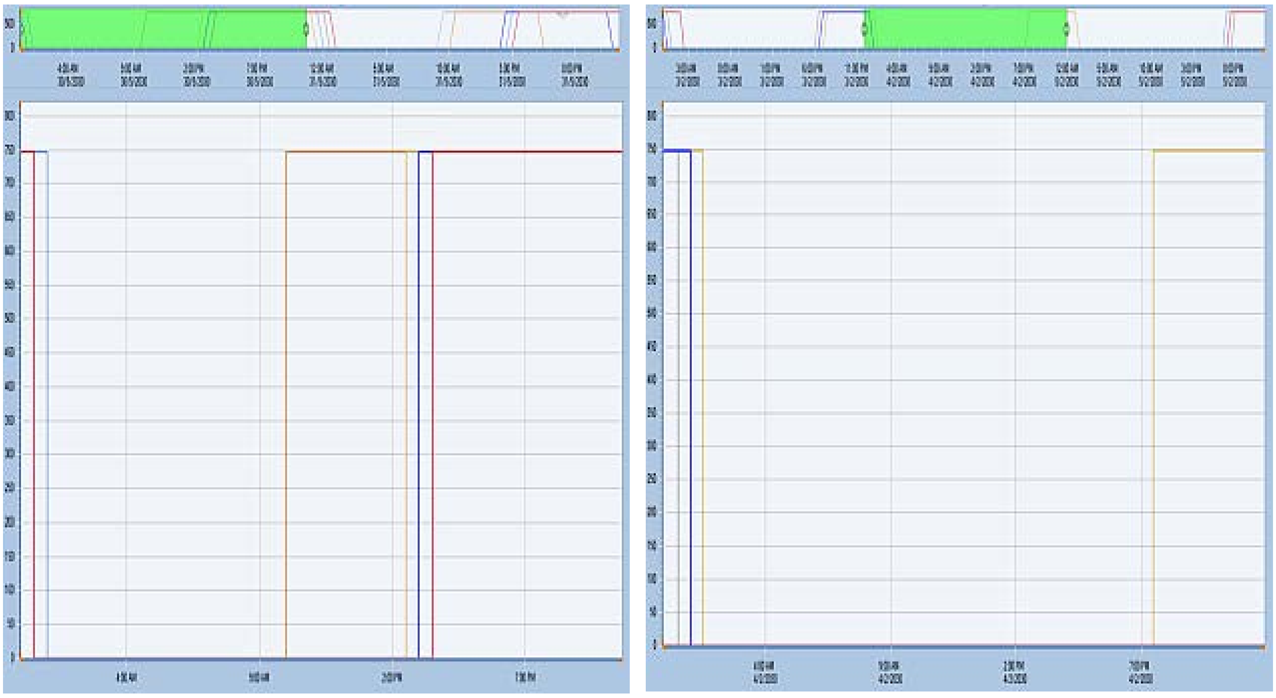


Figure 89 - Dispatch of a gas generator over a sample week



(a) (b)

Figure 90 - Dispatch of a gas generator on (a) the high demand day and (b) the low demand day

4.4.4 Results of study year 2035

Total nine (9) cases of PV capacity, ranging from 5% (base case) to 70% penetration are simulated for the year 2030. The capacities solar and conventional generation for all tested scenarios are listed in Table 18.

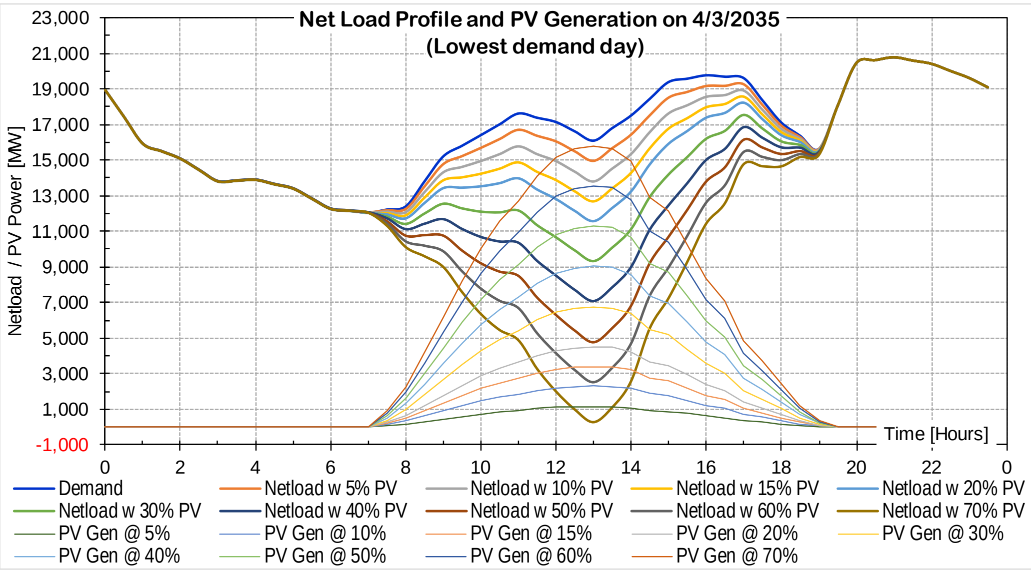
Table 17 Capacity planning summary for year 2035

Actual PV / Peak Load	5% PV	10% PV	15% PV	20% PV	30% PV	40% PV	50% PV	60% PV	70% PV
Total generation capacity:	29,944	30,844	31,894	32,844	34,994	37,294	39,644	41,994	44,344
Solar Capacity	1,200	2,400	3,550	4,700	7,050	9,450	11,800	14,150	16,500
Conventional Generators	28,744	28,444	28,344	28,144	27,944	27,844	27,844	27,844	27,844

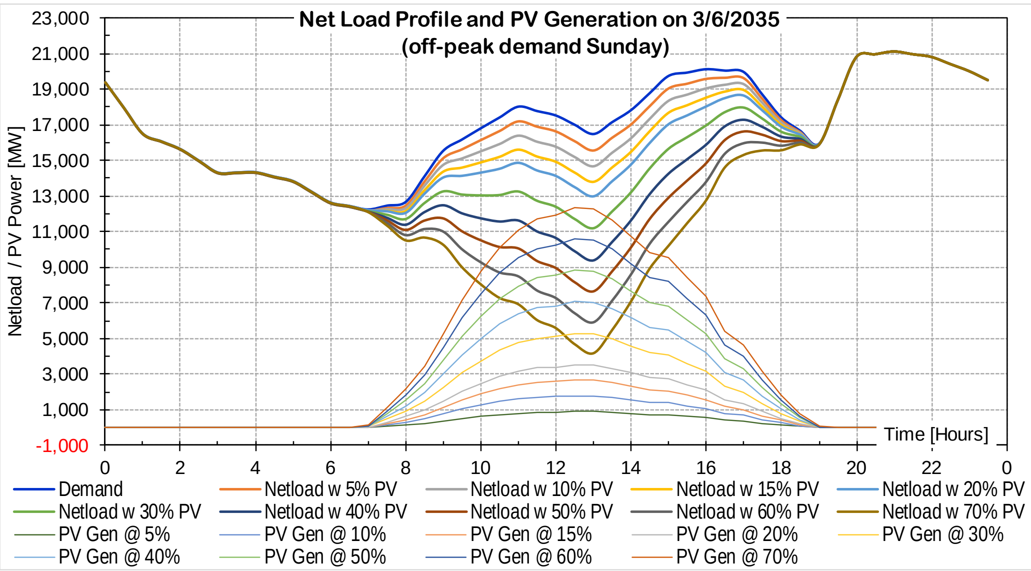
4.4.4.1 Netload profile

The Figure 91 (left) illustrates the netload profiles of the lowest demand day, where almost zero netload is observed. On an off-peak Sunday Figure 91 (right), The situation is very similar to that 2030. The netload profile of high demand day (Figure 92) illustrates the mid-day peak becomes load trough while the evening peak becomes dominant on generation capacity planning.

The netload profiles of sample weeks are plotted in Figure 93 and Figure 94, where massive afternoon netload ramps are observed with high solar penetration. System operation is extremely challenging.



(a)



(b)

Figure 91 - Netload profiles on (a) the lowest demand day and (b) an off-peak Sunday

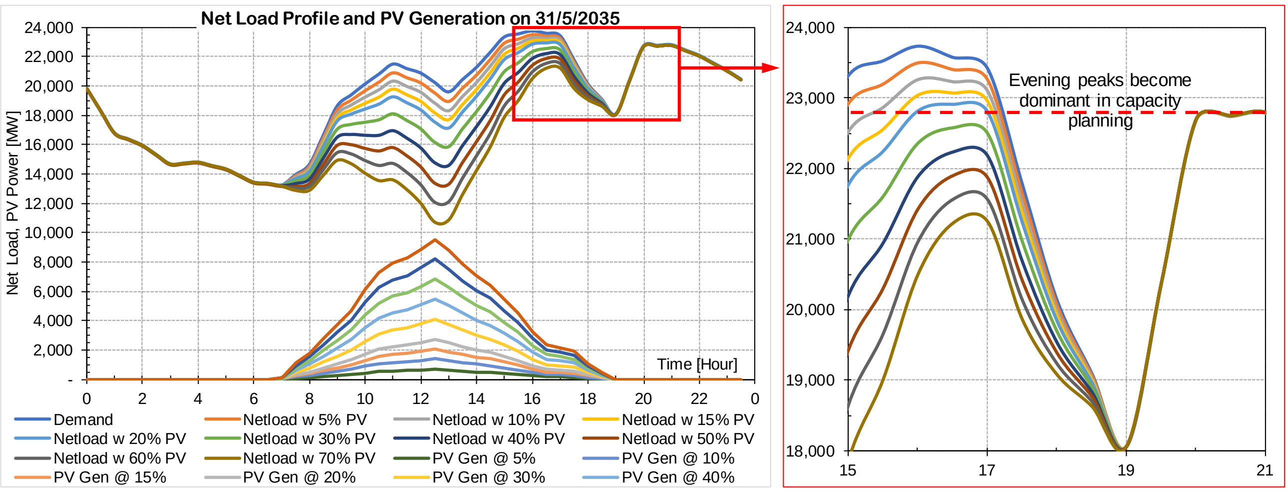


Figure 92 - Netload profiles on the peak demand day

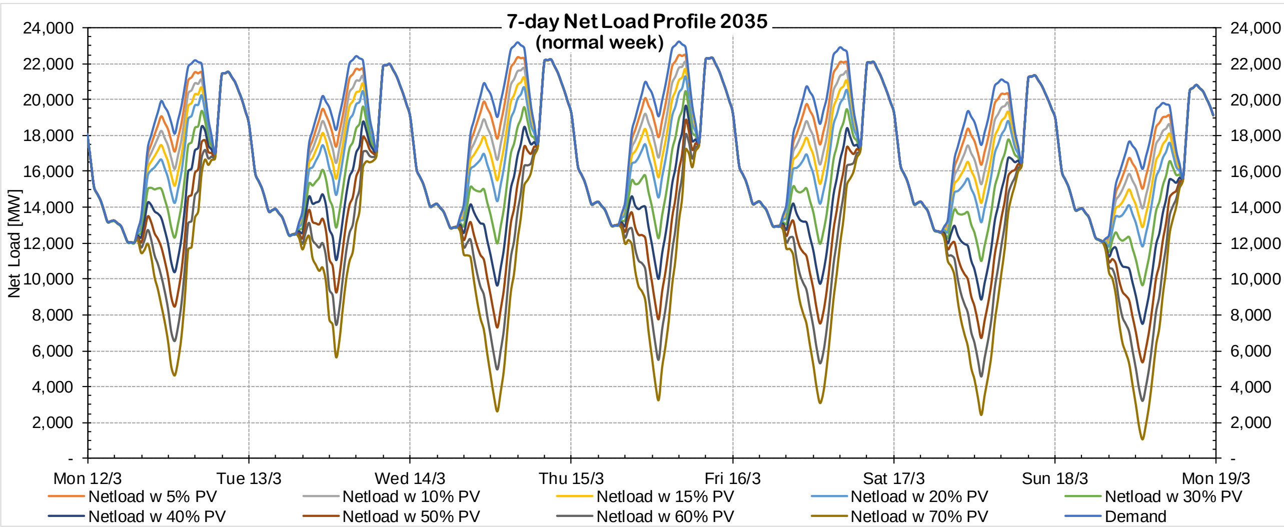


Figure 93 - Netload profiles for a normal week in 2035

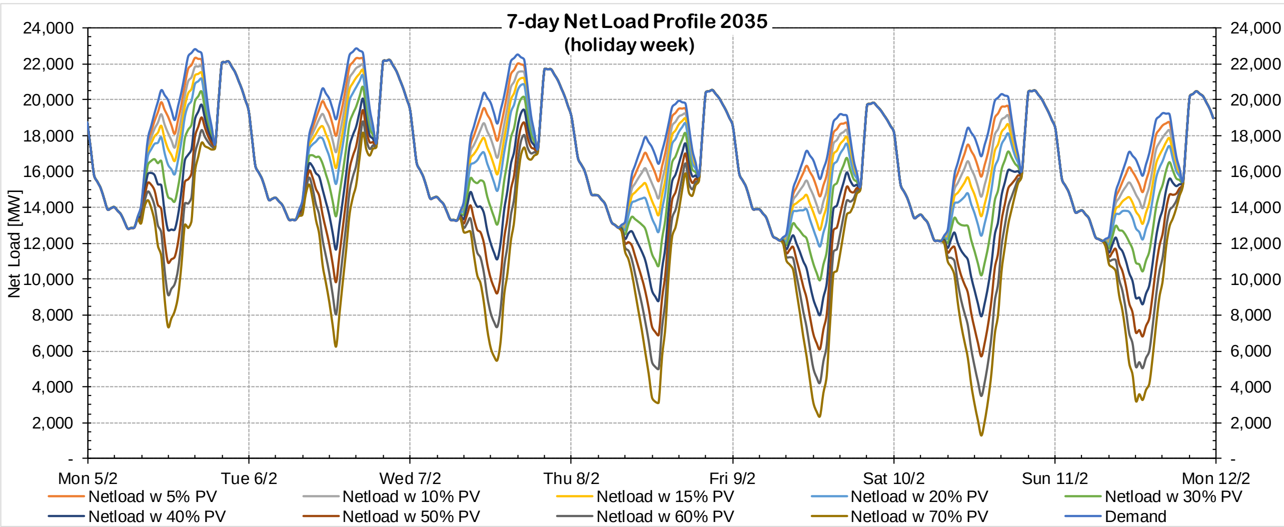


Figure 94 - Netload profiles for a low demand week in 2035

4.4.4.2 Netload duration

The full-year netload data is processed into netLDC (Figure 93) to have a macro understanding the impact of solar. In the system operation space, conventional generators are expected to cycle daily along the netload duration curve. The top-left part of the curve dominates the required capacity of the conventional generators, while the bottom-right part calls for flexibility of these generators.

Penetration of 5% and 10% will reduce the peak demand by 440 MW and 769 MW respectively read at the 24th hour of the netLDC, significantly reduce the required new capacity.

Penetrations above 20% will significantly reduce the trough, up to 9145 MW at 70% PV. The system flexibility is extremely challenged, e.g. conventional generators are expected to cycle daily in high magnitudes (15-17 GW from 1 to 8 pm) with 70% PV case. Almost zero netload can also be observed in Figure 95 (right window).

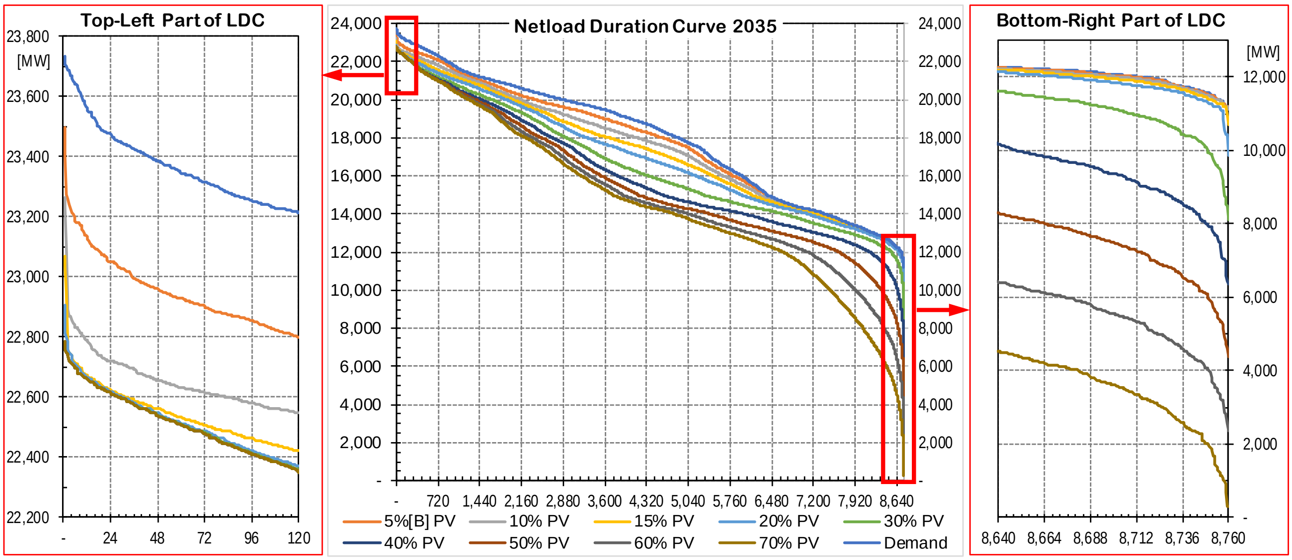


Figure 95 - Netload duration curves with tested penetration rates in 2035

4.4.4.3 Dispatch simulations

The key simulation results are illustrated in Figure 96, including CO_2 emission reductions, incremental cost of electricity, and solar energy share as compared to the base case. The conventional generators of study year 2035 are grown from the LT simulations. The solar generation contributes effectively to capacity planning at lower penetration levels up to 20%; less significant from 20% to 40%; and 'zero' above 40% penetration.

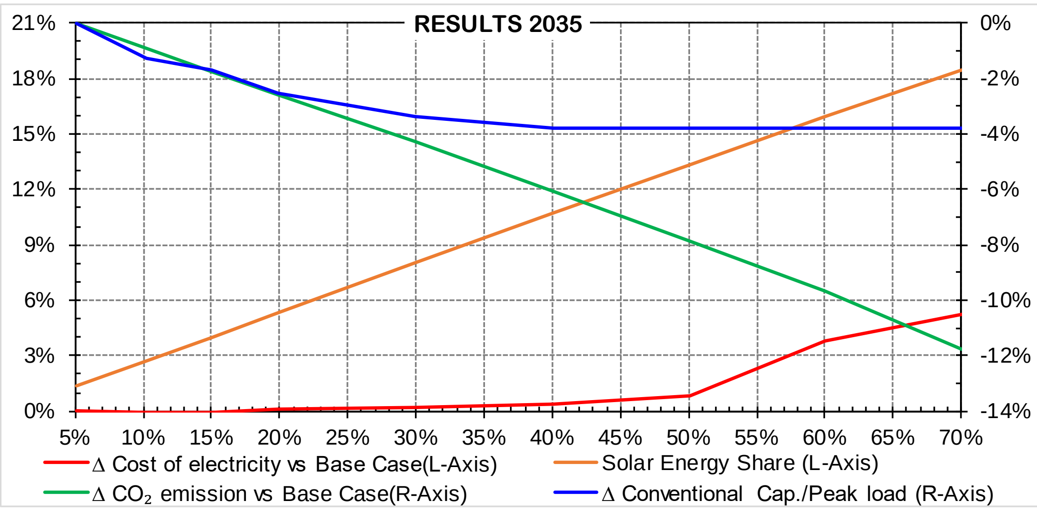


Figure 96 – Result summary for year 2035

The cost of electricity increases in very small magnitude till 50% penetration, and the sharp increases at 60% PV and 70% PV are due to relaxed reserve constraints. PLEXOS cannot get the converged solution for 60% and 70% PV with hard reserve constraint. To get the system cost for comparison, the reserve constraints are changed to soft constraint in PLXOLS for 60% and 70% PV.

The detailed numbers are tabulated in Table 18. Based on the long-term capacity planning results, the gas/coal generation capacity various from case to case. Nonetheless, LOLE is in the range of 0.44-0.52 days. As the conventional generation capacity varies, both the fixed and the variable costs are different for the tested cases. The variable cost increases with solar penetration, mainly due to higher cost of solar energy. The cost of electricity increases by 5.2% with 70% PV as compared to the 5% PV base case.

The capacity share and energy share by fuel type are plotted in Figure 97. With more diverse of fuel types, the HHI index reduces from 0.44 to 0.33. The CO_2 emission is reduced by 11.79% from 5% PV to 70% PV case.

Solar curtailments start at 50% PV case for very small amount 1 GWh, and increase with higher penetration reaching 322 GWh (eq. 115.9 million ringgit) at 70% PV. The curtailment is less than that of 2030 at the same penetration levels, mainly due to relaxation of reserve constraints.

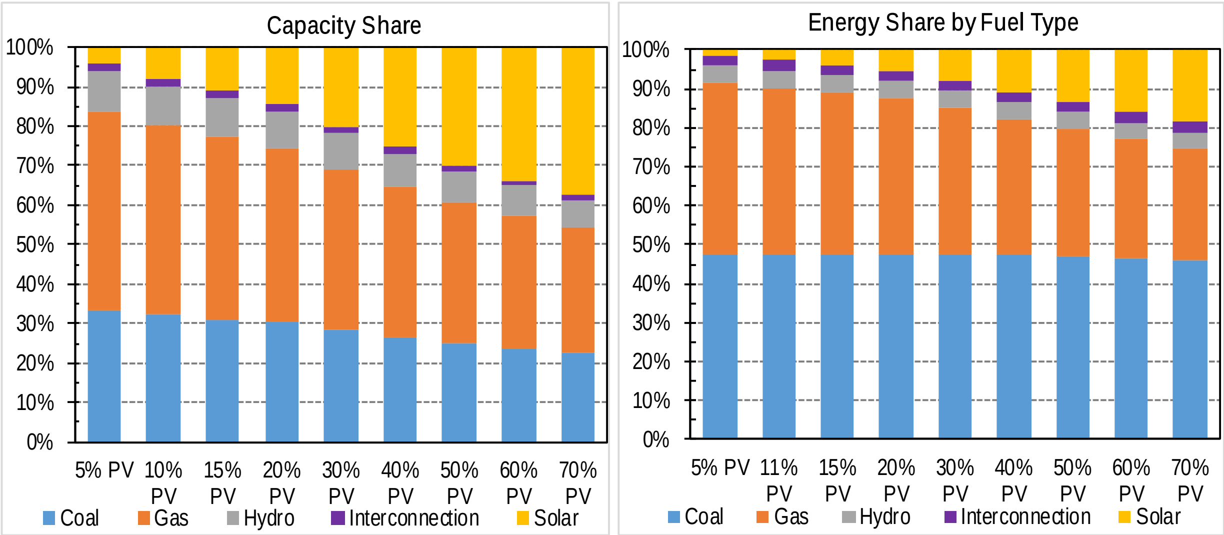


Figure 97 - Capacity share and energy share by fuel type for year 2035

Table 18 Result summary for year 2035

Peak load: 23,573 MW	**Trough load: 11,538 MW**	**Generation: 157,106 GWh**	**Predicted Sales: 143,290 GWh**

Actual PV / Peak Load:	**5% PV**	**10% PV**	**15% PV**	**20% PV**	**30% PV**	**40% PV**	**50% PV**	**60% PV**	**70% PV**
Total generation capacity[MW]:	**29,944**	**30,844**	**31,894**	**32,844**	**34,994**	**37,294**	**39,644**	**41,994**	**44,344**
Added Solar capacity:	-	-	*200*	*250*	*350*	*500*	*650*	*750*	*850*
Retired Conventional Generators:	*-3,500*	*-3,500*	*-3,500*	*-3,500*	*-3,500*	*-3,500*	*-3,500*	*-3,500*	*-3,500*
Planned Conventional Generators:	-	-	-	-	-	-	-	-	-
New Interconnections:	-	-	-	-	-	-	-	-	-
New Gas from PLEXOS LT:	*2,500*	*2,500*	*2,500*	*2,500*	*2,500*	*2,500*	*2,500*	*2,500*	*2,500*
New Coal from PLEXOS LT:	*3,500*	*3,500*	*3,500*	*3,500*	*3,500*	*3,500*	*3,500*	*3,500*	*3,500*
Reliability LOLE (days):	**0.44**	**0.46**	**0.41**	**0.45**	**0.49**	**0.52**	**0.50**	**0.50**	**0.49**
Total System Cost (Million):	**41,551**	**41,501**	**41,513**	**41,575**	**41,613**	**41,704**	**41,890**	**43,264**	**43,834**
Fixed	*6,340*	*6,317*	*6,310*	*6,315*	*6,300*	*6,292*	*6,292*	*6,292*	*6,292*
Variable	*35,211*	*35,184*	*35,204*	*35,260*	*35,313*	*35,411*	*35,598*	*36,972*	*37,541*
Unserved Energy (GWh):	*396*	*432*	*414*	*461*	*463*	*456*	*431*	*1*	*4*
Solar Curtailment (GWh):	-	-	-	-	-	-	1	44	322
Cost of Electricity (RM/MWh):	**290.78**	**290.51**	**290.55**	**291.08**	**291.35**	**291.97**	**293.23**	**301.94**	**305.92**
Scenario/Base[%]	*100%*	*99.91%*	*99.92%*	*100.10%*	*100.20%*	*100.41%*	*100.84%*	*103.84%*	*105.20%*
Increment, Scenario-Base[%]	*Base*	*-0.09%*	*-0.08%*	*+0.10%*	*+0.20%*	*+0.41%*	*+0.84%*	*+3.84%*	*+5.20%*
[1] Due to balance of solar[81]		*-0.45%*	*-0.77%*	*-0.93%*	*-1.53%*	*-2.03%*	*-2.29%*	*0.01%*	*0.68%*
[2] Due to higher solar energy price		*+0.35%*	*+0.70%*	*+1.04%*	*+1.73%*	*+2.44%*	*+3.14%*	*+3.83%*	*+4.53%*
Addl. Solar Curtailment Penalty (Million)[82]:	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.51**	**15.79**	**115.93**
HHI:	**0.42**	**0.41**	**0.40**	**0.39**	**0.38**	**0.36**	**0.35**	**0.34**	**0.33**
CO2 Emission (thousand tonnes):	**90,081**	**89,238**	**88,488**	**87,768**	**86,226**	**84,629**	**83,002**	**81,385**	**79,460**
Increment, Scenario-Base[%]	*Base*	*-0.94%*	*-1.77%*	*-2.57%*	*-4.28%*	*-6.05%*	*-7.86%*	*-9.65%*	*-11.79%*

[81] Cost increases due to conventional generators operate at less efficient point.

[82] Additional penalty when PLEXOS decides to curtail solar in searching for optimal solution.

The dispatch schedule of a coal generator over a sample week for penetration rate of 60% and 70% is plotted in Figure 98, which illustrates the scheduled generator power output is greatly decreased during high solar generation hours with such penetration rates. Dispatch schedules for 50% solar generation and below are plotted in Figure 99.

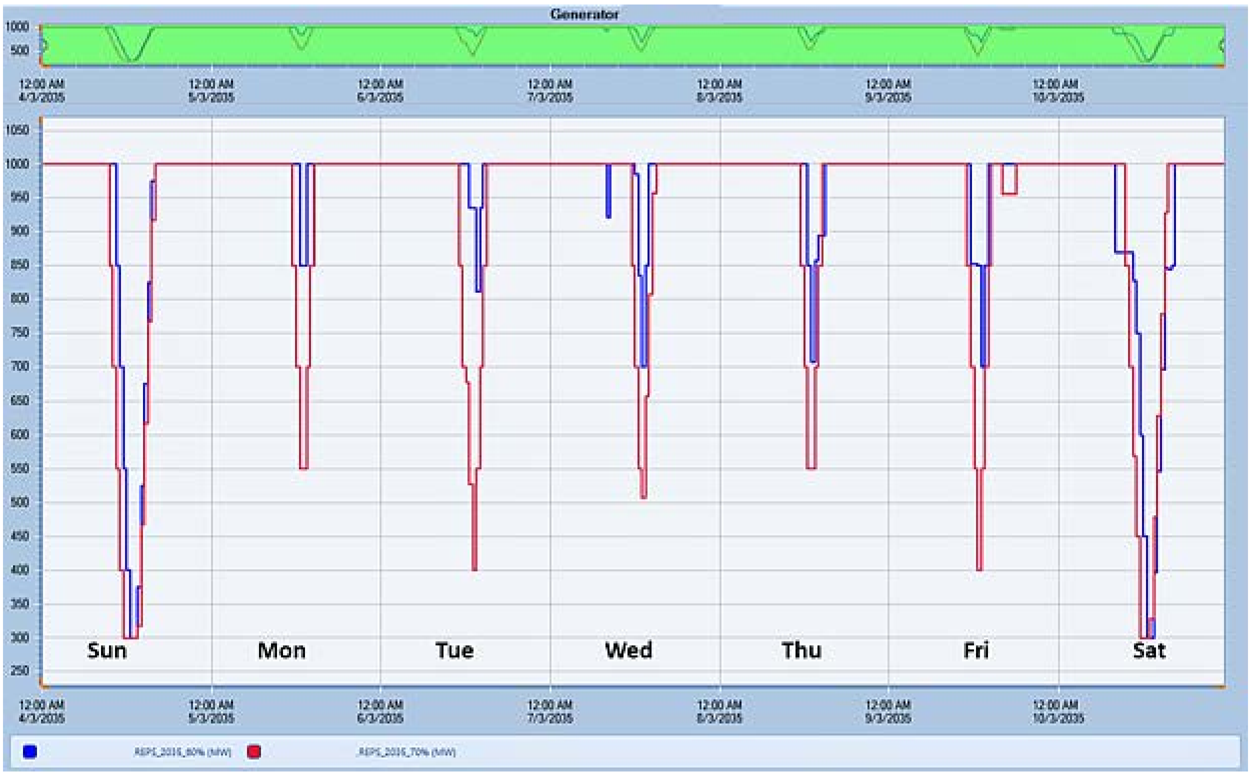


Figure 98 - Dispatch of a coal generator over a sample week with 60% and 70% solar in 2035

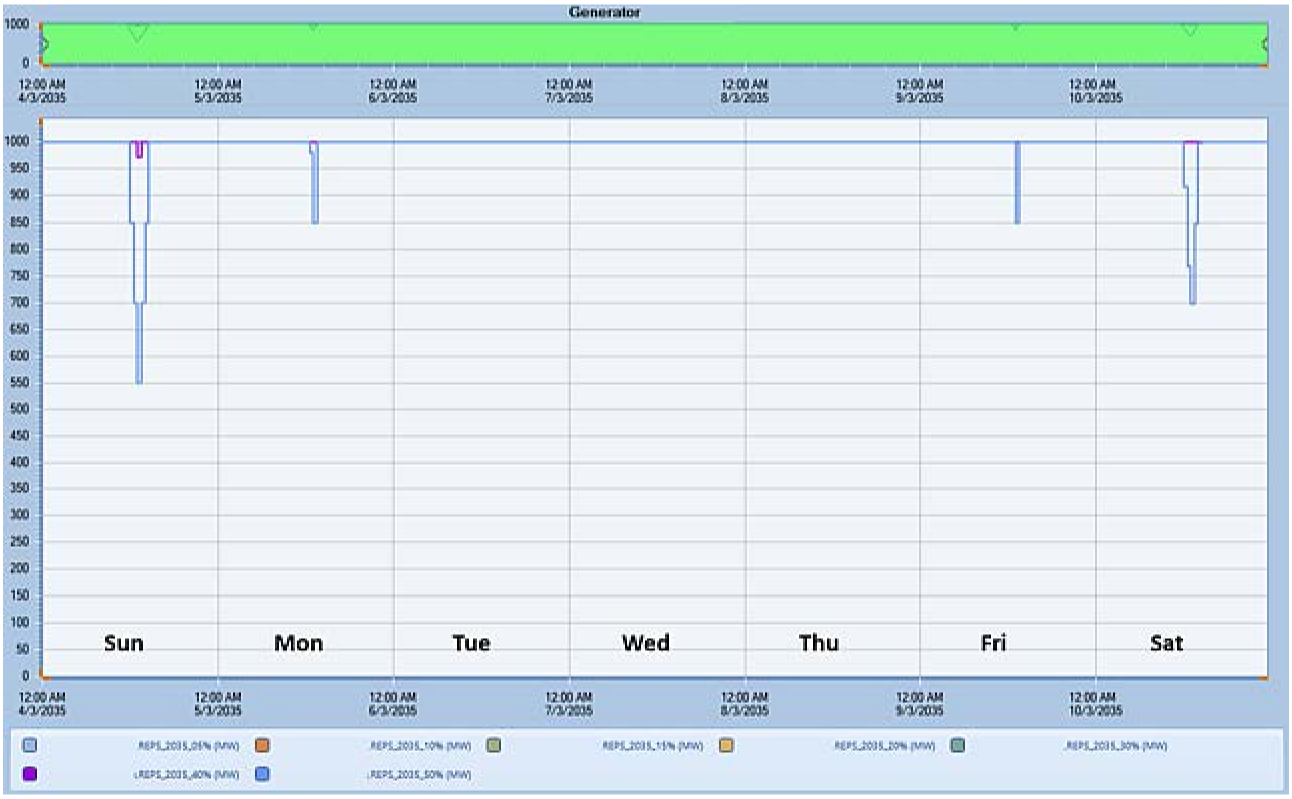
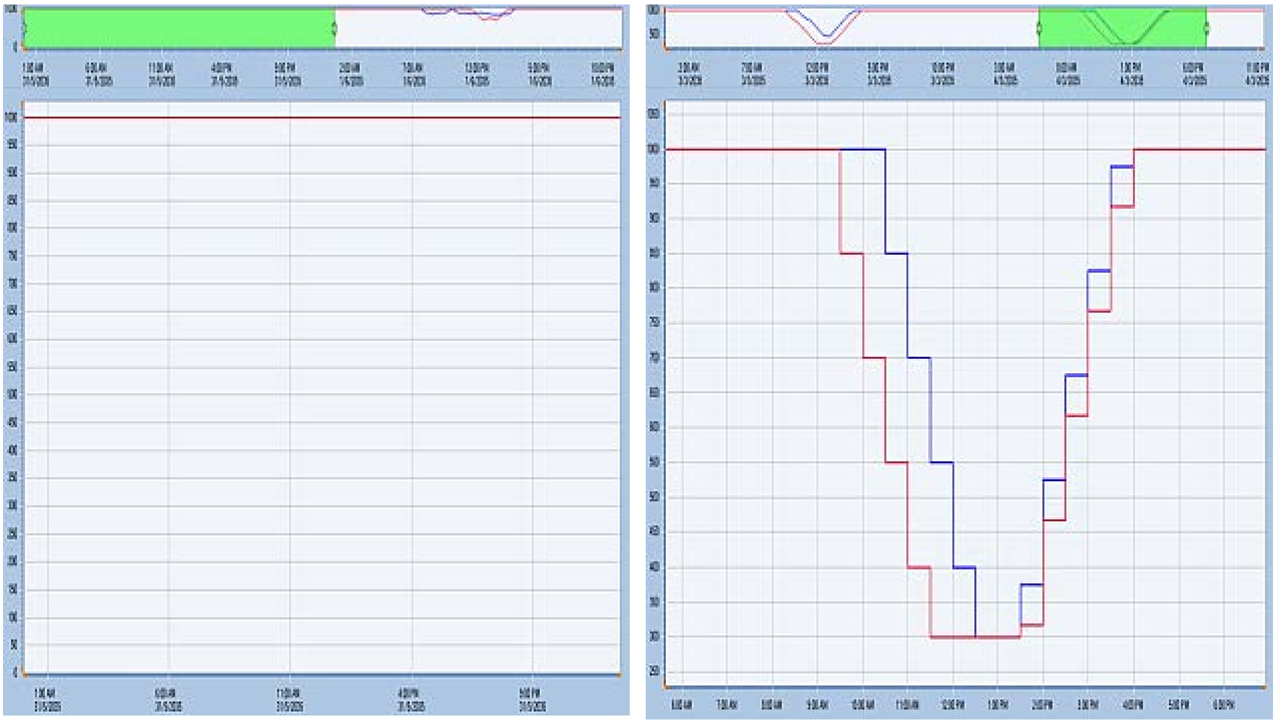


Figure 99 - Dispatch of a coal generator over a sample week 5-50% penetration in 2035

Dispatch schedules for a coal generator with 60-70% PV and 5-50% PV for one day are plotted in Figure 100 and Figure 101 respectively. Schedules on the high demand days are plotted on the left side of both figures, and are not influenced by PV penetration. Compared to low demand days in Figure 101(b) with lower penetration, more drastic schedule changes can be obverse in 60-70% cases in Figure 100(b).

The dispatch of a gas generator over a sample week is shown from Figure 102 and Figure 103. One day dispatch on a high and low demand day is summarise in Figure 104 and Figure 105.



(a) (b)

Figure 100 - Dispatch of a coal generator with 60% and 70% solar generation on (a) a high demand day and (b) a low demand day

(a) (b)

Figure 101 - Dispatch of a coal generator with 5-50% PV penetration on (a) a high demand day and (b) a low demand day

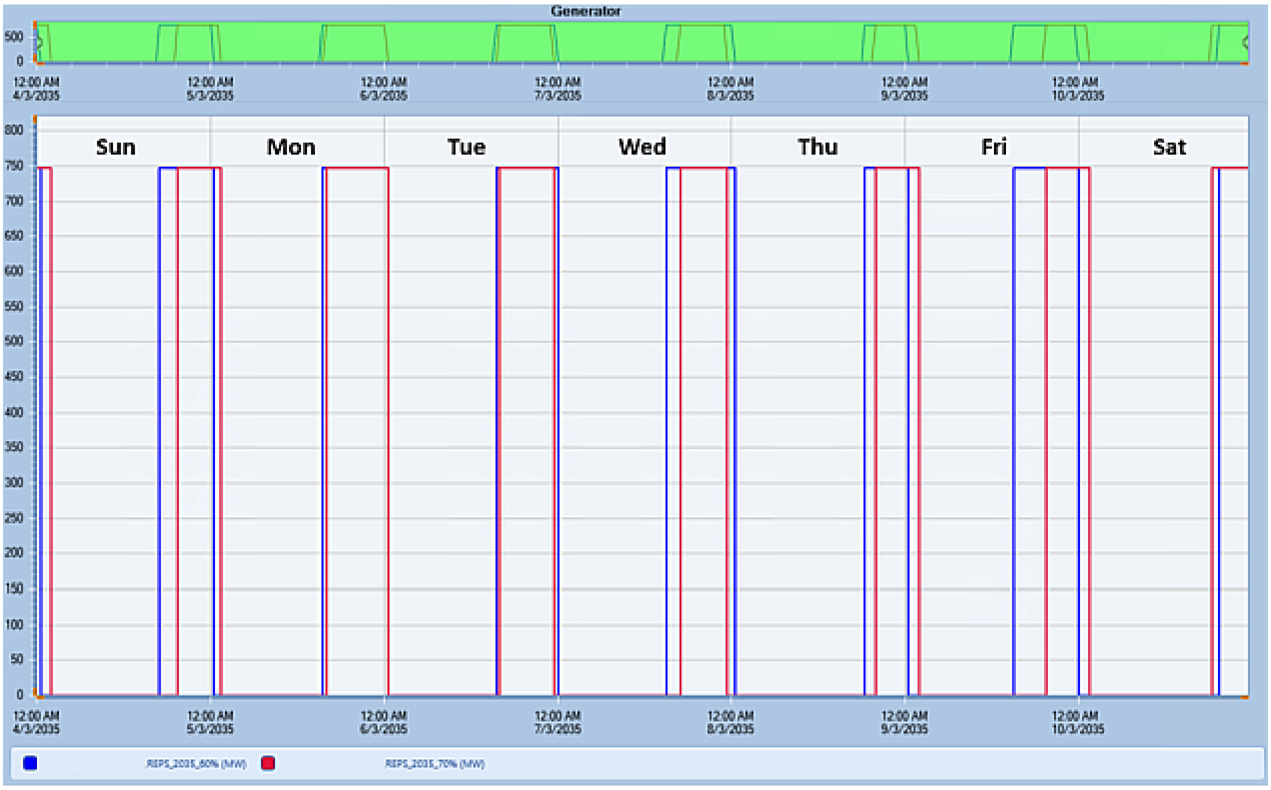


Figure 102 - Dispatch of a gas generator over a sample week with 60-70% PV generation

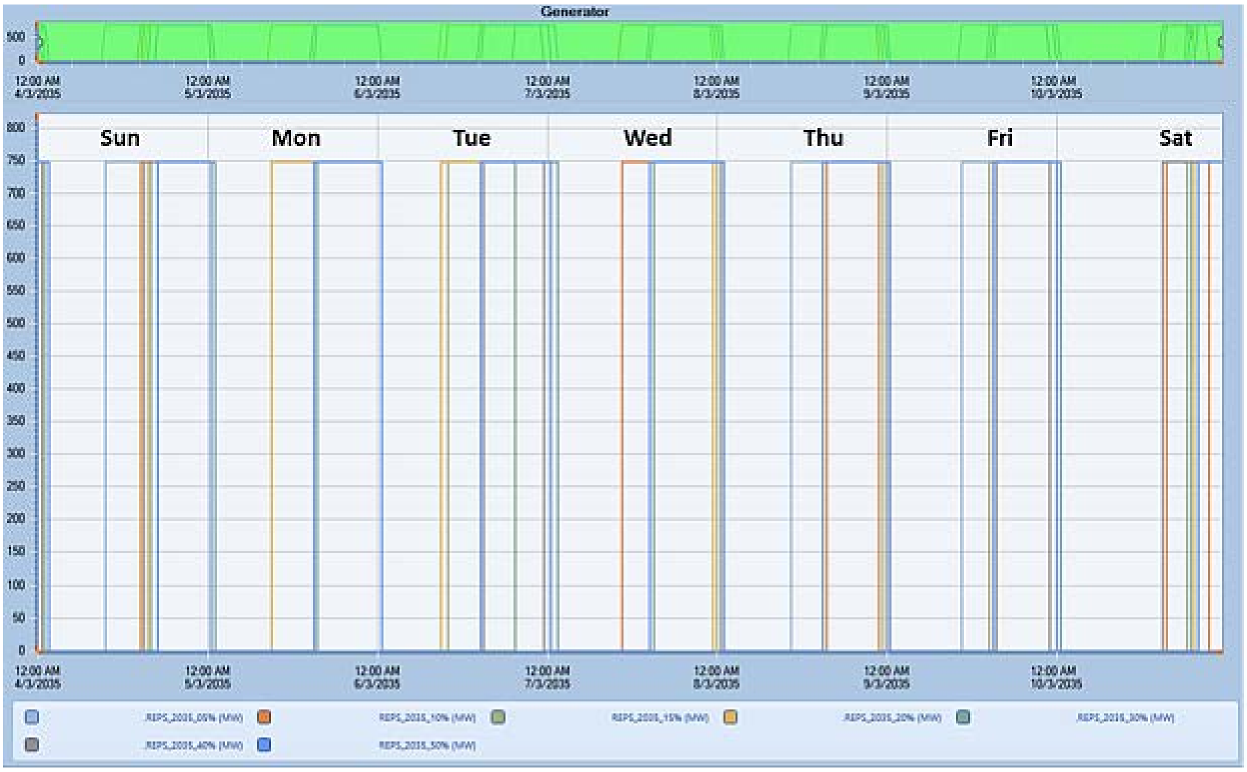
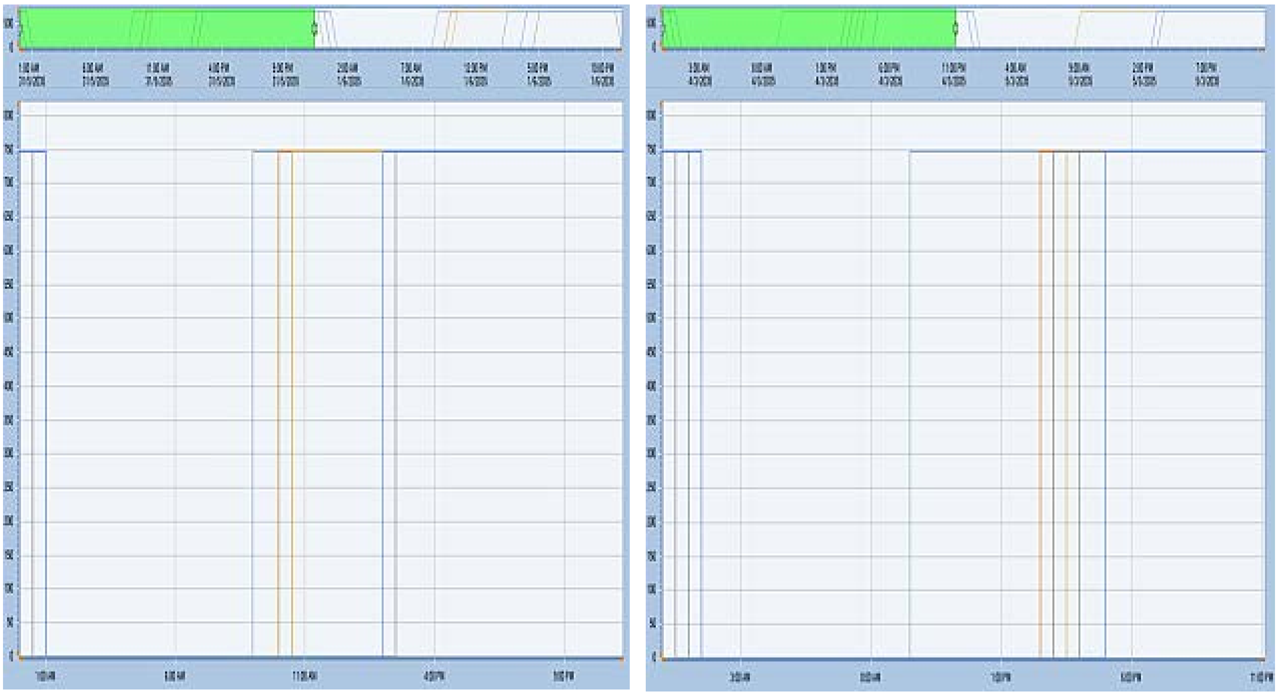


Figure 103 - Dispatch of a gas generator over a sample week with 5-50% PV generation

(a) (b)

Figure 104 - One day dispatch of a gas generator with 60-70% PV on (a) a high demand day and (b) a low demand day



(a) (b)

Figure 105 - Dispatch of a gas generator with 5-50% PV on (a) a high demand day and (b) a low demand day

4.5 Transmission system adequacy and Stability investigations

DNV GL has conducted power system studies in PSS®E to verify the impact of increased solar penetration on the transmission network.

4.5.1 Transmission system adequacy assessment

With high PV penetration levels, existing power flow patterns maybe significantly modified. The influencing factors include: the changes on the dispatch of conventional generators, the output variations of PV power from various locations and different time. To assess the adequacy of the grid transmission backbone, quasi-dynamic power flow simulations were conducted.

The total solar capacity is distributed back to the 15 locations, and connected to the 132kV bus of key 275/132kV substations as illustrated in Figure 106. The Table 19 shows the 9,025 MW PV distribution plan for study year 2025. The injected solar power follows the whole year profile of that respective location. The dispatch of conventional generators is per PLEXOS output. The interior branches of subsystem consist 275 kV and 500 kV buses are monitored.

Table 19 - PV generation connection details for 9025 MW in 2025

Total Solar	KEDAH			PERAK			KL-NS-MALACCA			PAHANG			KELANTAN		JOHOR
9,025 MW	Kangar	Alor Setar	Sungai Petani	Taiping	Ipoh	Bidor	Klang	Seremban	Melaka	Pekan	Gambang	Kuala Dungun	Kuala Krai	Pasir Mas	Kulai
Distribution	7.9%	7.9%	7.9%	6.3%	6.3%	6.3%	8.9%	8.9%	8.9%	5.8%	5.8%	5.8%	4.3%	4.3%	4.9%
Rated Power [MW]	**711**	**711**	**711**	**569**	**569**	**569**	**805**	**805**	**805**	**520**	**520**	**520**	**384**	**384**	**441**
Bus Numbers	61101	61111	61115	63153	63138	63123	51002	51079	96103	74110	74136	75102	75117	75101	97100
132kV buses of	61165		61116		63155		51004	96131	96126		74137	75104	75131		97106
275/132kV S/S			62101				51006	96142				75126			97108
			62104				51015	96158							97114
			62114				51023								97133
			62137				51030								97137
							51041								97154
							51063								97164
							51072								97165
							51075								97170
							51081								97175
							51087								97189
							51095								
							51103								
	356	711	119	569	284	569	58	201	403	520	260	173	192	384	37
	356	-	119	-	284	-	58	201	403	-	260	173	192	-	37
	-	-	119	-	-	-	58	201	-	-	-	173	-	-	37
	-	-	119	-	-	-	58	201	-	-	-	-	-	-	37
	-	-	119	-	-	-	58	-	-	-	-	-	-	-	37
	-	-	119	-	-	-	58	-	-	-	-	-	-	-	37
	-	-	-	-	-	-	58	-	-	-	-	-	-	-	37
	-	-	-	-	-	-	58	-	-	-	-	-	-	-	37
	-	-	-	-	-	-	58	-	-	-	-	-	-	-	37
	-	-	-	-	-	-	58	-	-	-	-	-	-	-	37
	-	-	-	-	-	-	58	-	-	-	-	-	-	-	37
	-	-	-	-	-	-	58	-	-	-	-	-	-	-	37
	-	-	-	-	-	-	58	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	58	-	-	-	-	-	-	-	-

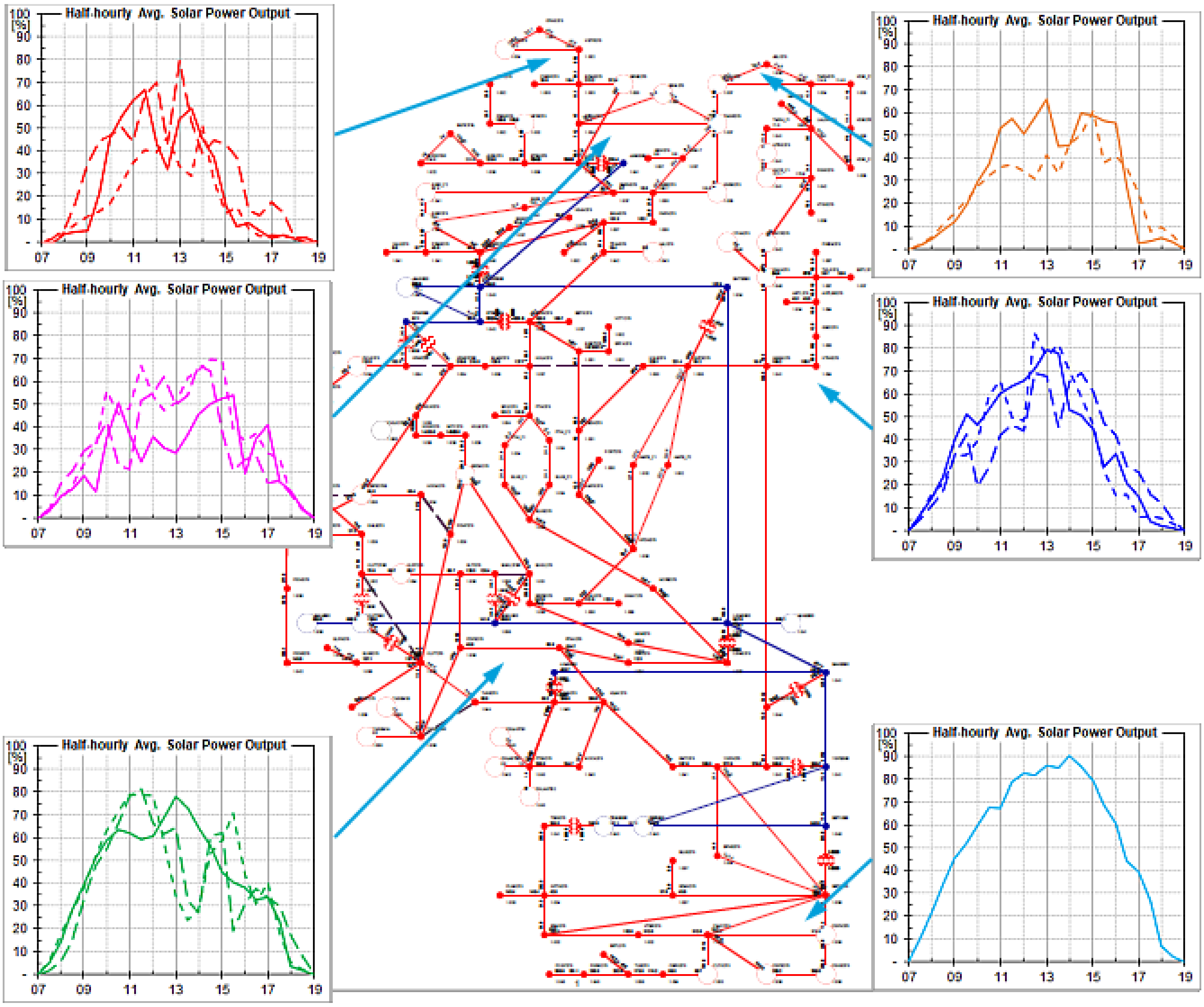


Figure 106 - Grid transmission backbone and PV connection points

4.5.1.1 Simulation result of study year 2025

Sample simulation outputs are shown in Figure 107 and Figure 108. The complete reseults are tabulated in Table 31. The power flow results are processed into average, maximum and the standard deviation in percentage of their rating A.

For the full year simulations, only one transformer KPAR 500/275kV X1 was slightly overloaded for 4 hours above its rating A, e.g. 118% with 5% PV and reduced to 107% with 43% PV (Figure 108). The X2 connected to KPAR275R bus in the same station was less loaded, e.g. 82% with 5% PV and reduced to 95% with 43% PV. It can be observed that the increase of PV penetration level has negligible impact on the loading of backbone or reduces the loading (Figure 109).

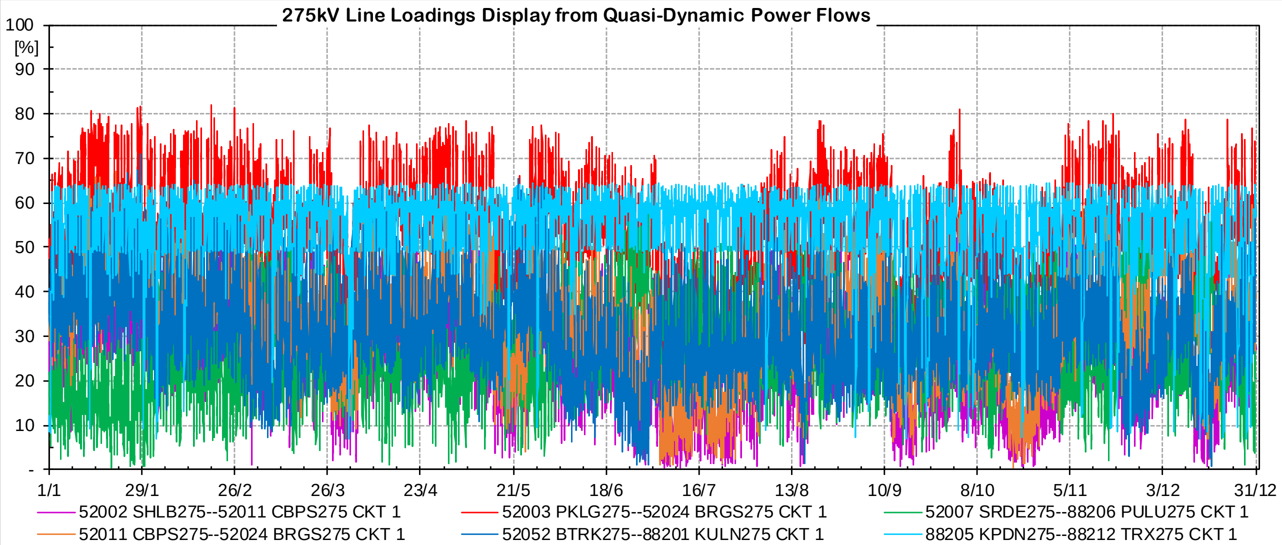


Figure 107 - Full year loading of selected 275kV transmission lines

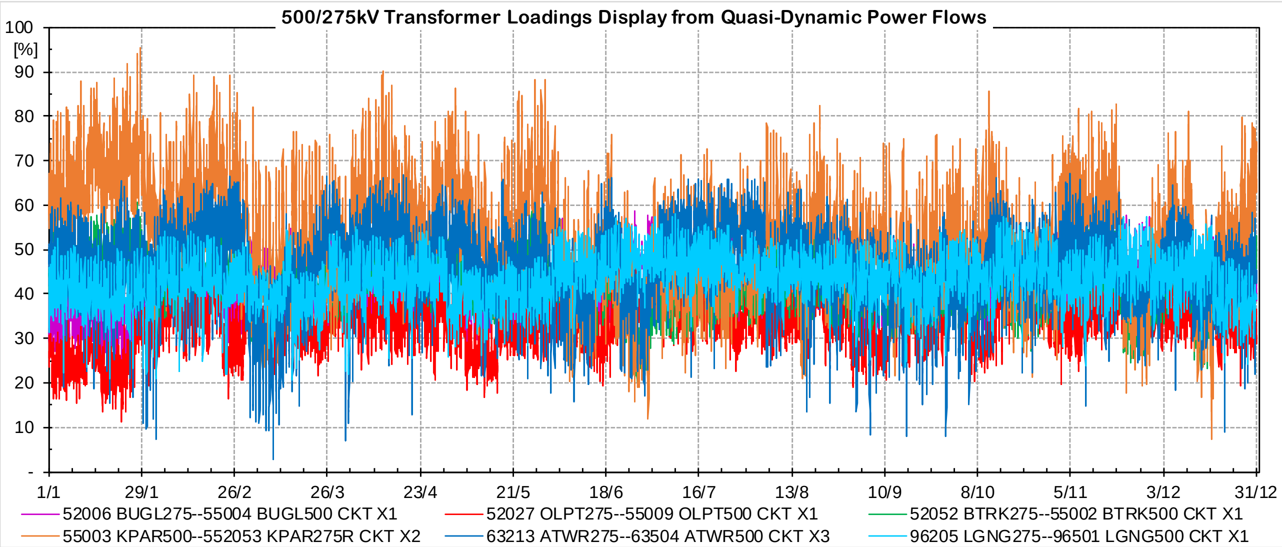


Figure 108 – Full year loading of selected 500/275kV inter-bus transformers

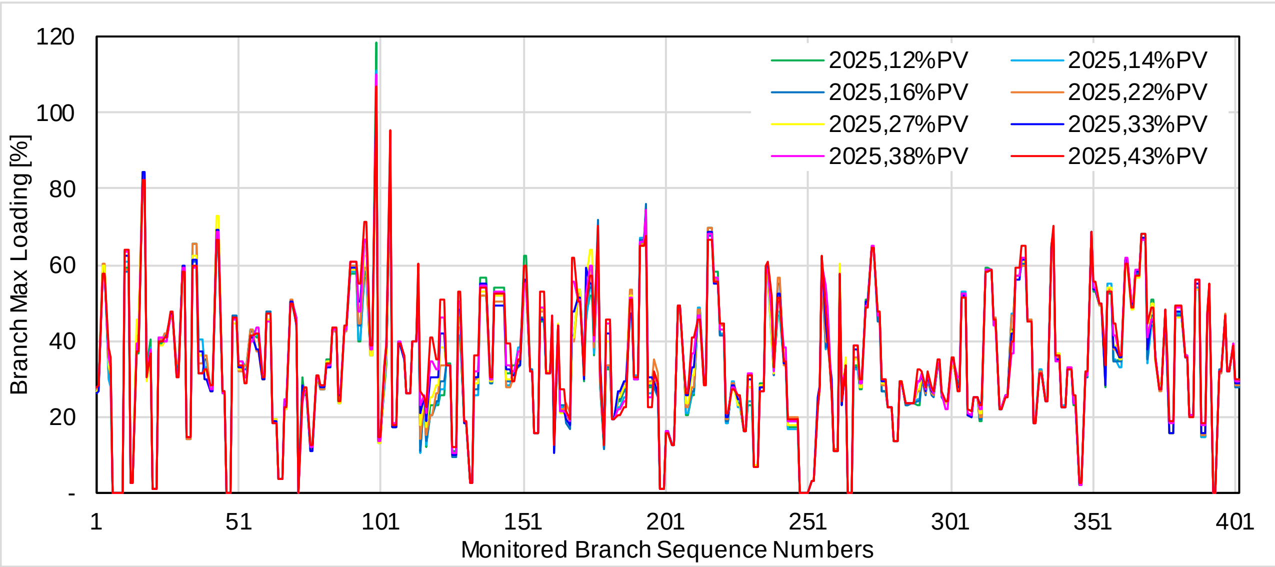


Figure 109 – Branch maximum loadings under different PV penetration levels

4.5.1.2 Simulation result of study year 2030

In year 2030, PV curtailment occurs after a 40% penetration level. Therefore, the PV generation output is adjusted to exclude the amount of curtailed power. The power flow results are processed into average, maximum and the standard deviation in percentage of their rating A and tabulated in Table 32. For the full year simulations, no overload is observed on the backbone, as shown in Figure 110.

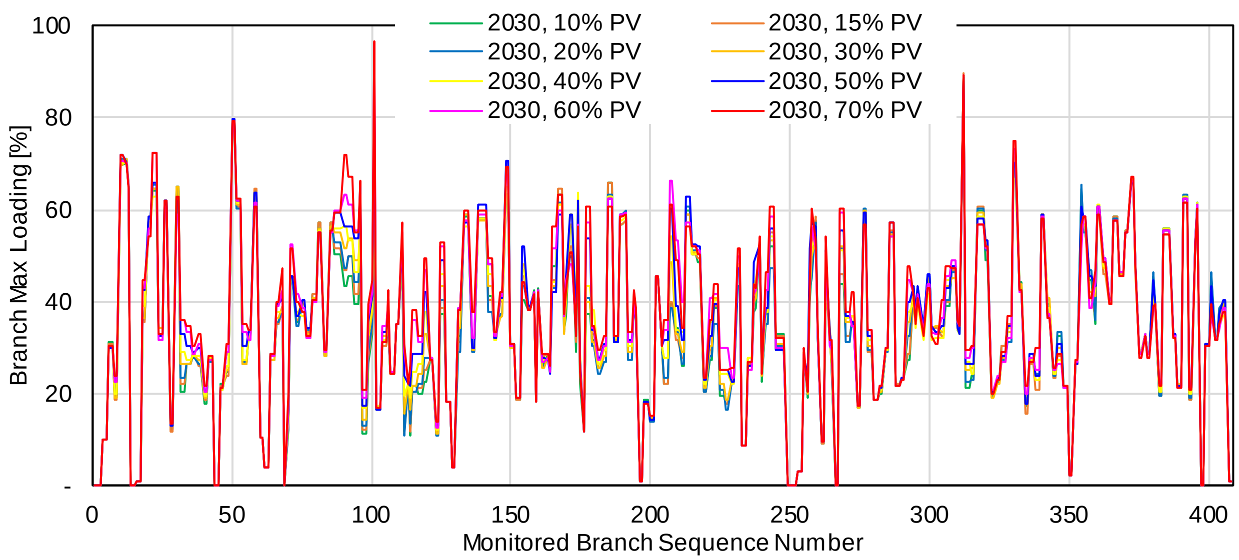


Figure 110 – Backbone bus maximum loading percentage under different PV penetration rates

4.5.2 System stability tests

The system must remain stable with credible category B events without loss of demand or cascading outages. The dynamic voltage excursion must be with the limits of lower bound 0.7 p.u. for not more than 400ms, and upper bound 1.2 p.u. for not more than 30s.

The scenario screening is conducted to select the most representative snapshots to be tested in PSS®E. The most concerned snapshots are off-peak demand weekends with high solar outputs, when many conventional generators are pushed offline, resulting in low primary frequency response and low system inertia.

For transient stability assessments at each PV penetration level, total 23 category B event are chosen:

- 7 cases with three-phase fault at high voltage side of step-up transformer for 0.1s, followed by loss of a generator.
- 16 cases with three-phase fault at 500 kV bus for 0.1s, followed by loss of a 500kV transmission line

As requested, a half-hour load-frequency control simulation with solar continuous ramps is also tested, where system frequency bias and parameters is estimated based on TNB documents, modelled in the AGC controller, and linked to grid model in PSS®E.

4.5.2.1 Results of study year 2025

For year 2025, the weekends with solar output above 90% installed capacity are filtered (Table 33). The snapshot of 13:00 Sun 16 Mar 2025 with 14,907 MW demand and PV power outputs at 93.5% their rated capacities is chosen for stability tests. The dispatched generators are listed in Table 20, we can observe the numbers of online generators decrease with the PV penetration level, especially gas generators.

Based on the schedules, category B events are simulated, and the results are summarised in Table 21 for all contingency simulations for study year 2025. Fault bus voltage, angel separation and frequency are monitored. The green ticks represent the monitored quantity is within the limits, the red crosses indicate violations, and the yellow crosses for approaching the limits.

Rotor angle separation are within the limits for all test cased and solar penetration levels, indicating a strong transmission system. No violation is observed for penetration up to 27% PV; frequency violations are observed starting from 33% PV penetration for loss of biggest online generator; and voltage violations are observed for 43% PV. The stability tests clearly indicate the challenge with high penetration.

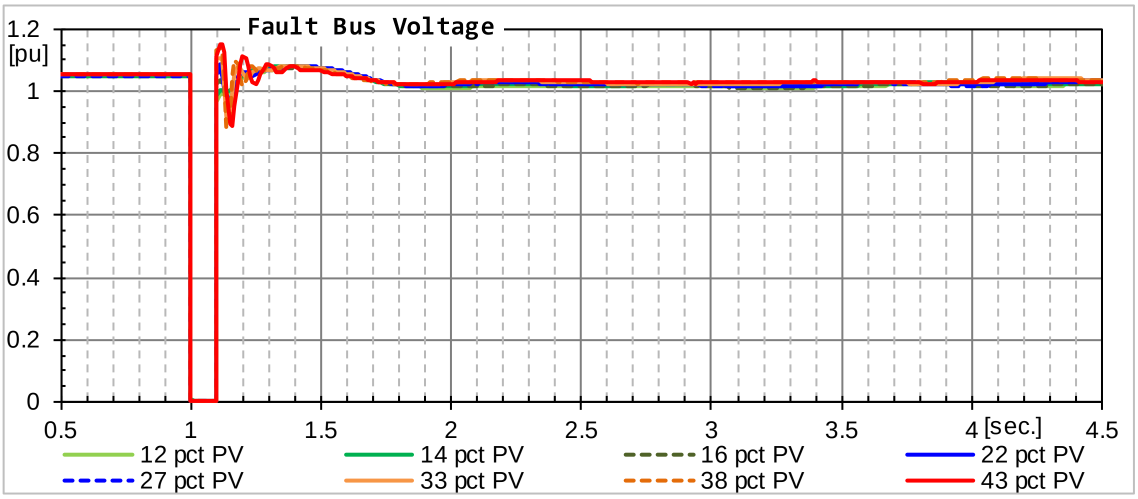
Table 20 List of online generators for tested PV penetration levels (13:00 Sun 16 Mar 2025)

Bus#	Gen Name	Type	P_{MAX}	P_{GEN} at different PV Penetration Levels							
				12%	14%	16%	22%	27%	33%	38%	43%
51903	TADMAX_U1 21.000	Gas	500	-	250	-	-	-	-	-	-
59013	PKLG_U3 20.000	Coal	283	255	255	255	255	200	200	180	150
59014	PKLG_U4 20.000	Coal	282	254	254	254	254	200	200	-	-
59015	PKLG_U5 22.000	Coal	465	419	419	419	419	380	360	250	250
59016	PKLG_U6 22.000	Coal	466	419	419	419	419	380	360	250	-
59036	JMAH_U1 20.000	Coal	700	665	665	665	665	650	577	450	360
59037	JMAH_U2 20.000	Coal	700	665	665	665	665	650	577	450	360
59043	JMHE_U1 26.000	Coal	1080	1000	1000	1000	1000	1000	1000	950	850
61910	YAN_U1 21.000	Gas	500	380	375	360	360	250	-	-	-
61911	YAN_U2 21.000	Gas	500	380	375	360	360	250	-	-	-
63901	BSIA_U1 11.000	Hydro	22	-	-	-	3	3	3	3	-
63902	BSIA_U2 11.000	Hydro	23	-	-	-	3	3	3	3	-
63903	BSIA_U3 11.000	Hydro	23	-	-	-	3	3	3	3	-
63904	TMGR_U1 13.800	Hydro	82	29	20	24	28	30	30	30	30
63905	TMGR_U2 13.800	Hydro	86	20	-	-	-	30	-	-	-
63938	JMJG_U2 23.000	Coal	690	656	656	656	656	656	577	535	500
63939	JMJG_U3 23.000	Coal	690	656	656	656	656	656	577	535	500
63940	JMJG_U4 27.000	Coal	1010	960	960	960	960	960	960	960	850
63941	JMJG_U5 27.000	Coal	1000	950	950	950	950	950	950	950	850
75931	PGAU_U1 16.000	Hydro	150	-	-	-	-	-	30	-	-
75932	PGAU_U2 16.000	Hydro	150	-	-	-	-	30	30	-	-
75933	PGAU_U3 16.000	Hydro	150	-	-	-	-	30	30	-	-
75934	PGAU_U4 16.000	Hydro	150	-	-	-	-	30	30	-	-
96921	AGJHGT1 15.000	Gas	747	672	-	-	-	-	-	-	-
96923	AGJHGT2 15.000	Gas	747	-	672	-	-	-	-	-	-
97937	SIPP GT1 15.000	Gas	720	600	-	370	360	-	-	-	-
97938	SIPP GT2 15.000	Gas	720	600	600	648	360	-	-	-	-
97961	TBIN_U1 26.000	Coal	700	665	665	665	665	665	577	535	500
97962	TBIN_U2 26.000	Coal	700	665	665	665	665	665	577	535	500
97964	TBIN_U4 27.000	Coal	1000	950	950	950	950	950	950	950	850
97971	RAPIDGT11 22.000	Gas	369	295	270	280	-	-	-	-	-
97973	RAPIDGT21 22.000	Gas	369	295	270	280	-	-	-	-	-
97975	RAPIDST31 15.750	Gas	286	229	209	217	-	-	-	-	-

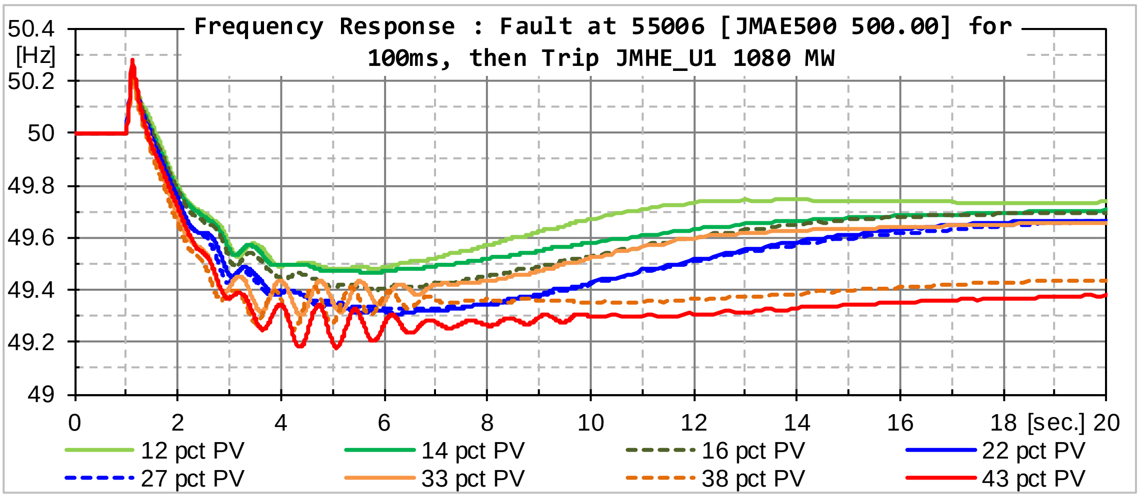
Table 21 System stability test results under various PV penetration rates for study year 2025

CASE	FAULT BUS	LOST GEN / LINE	12%PV			14%PV			16%PV			22%PV			27%PV			33%PV			38%PV			43%PV		
			VOLT	ANGL	FREQ	VOLT	ANGL	FREQ	VOLT	ANGL	FREQ	VOLT	ANGL	FREQ	VOLT	ANGL	FREQ	VOLT	ANGL	FREQ	VOLT	ANGL	FREQ	VOLT	ANGL	FREQ
1	52003 PKLG275	PKLG_U5 465 MW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2	55005 JMAH500	JMAH_U1 700 MW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3	55006 JMAE500	JMHE_U1 1080 MW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗	✓	✓	✗
4	63505 JMJG500	JMJG_U2 690 MW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗
5	63505 JMJG500	JMJG_U4 1010 MW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗	✗	✓	✗
6	597534 TBIN500R	TBIN_U1 700 MW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
7	97534 TBIN500	TBIN_U4 1000 MW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗	✓	✓	✗
8	63504 ATWR500	ATWR500-JMJG500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗
9	63504 ATWR500	ATWR500-BNTS500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗
10	96528 BAHS500	BAHS500-AGJH500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
11	96528 BAHS500	BAHS500-YGPE500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
12	97502 BBTU500	BBTU500-YGPE500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
13	97502 BBTU500	BBTU500-TBIN500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
14	74502 BNTS500	BNTS500-LGNG500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
15	55002 BTRK500	BTRK500-KPAR500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
16	55002 BTRK500	BTRK500-ATWR500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
17	55004 BUGL500	BUGL500-OLPT500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓
18	55004 BUGL500	BUGL500-LGNG500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓
19	61523 JJNG500	JJNG500-ATWR500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗	✓	✓
20	55006 JMAE500	JMAE500-LGNG500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
21	55005 JMAH500	JMAH500-OLPT500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
22	96501 LGNG500	LGNG500-BAHS500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓
23	97511 YGPE500	YGPE500-TBIN500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

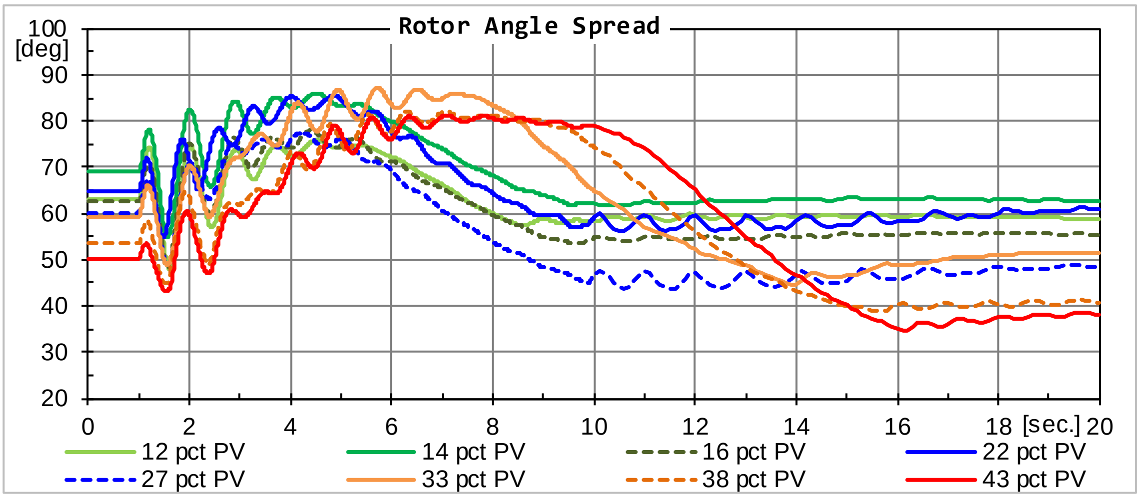
For the case No. 3, fault is induced at 55006 [JMAE500 500.00] for 100ms, then trip JMHE_U1 1080 MW. The post event voltage recovery is within limits for all scenarios in Figure 111(a), the rotor angles stabilise after a short period of oscillation as in Figure 111(c). Frequency violations (below 49.3Hz) are observed for 33%, 38%, and 43% PV penetration in Figure 111(b).



(a)



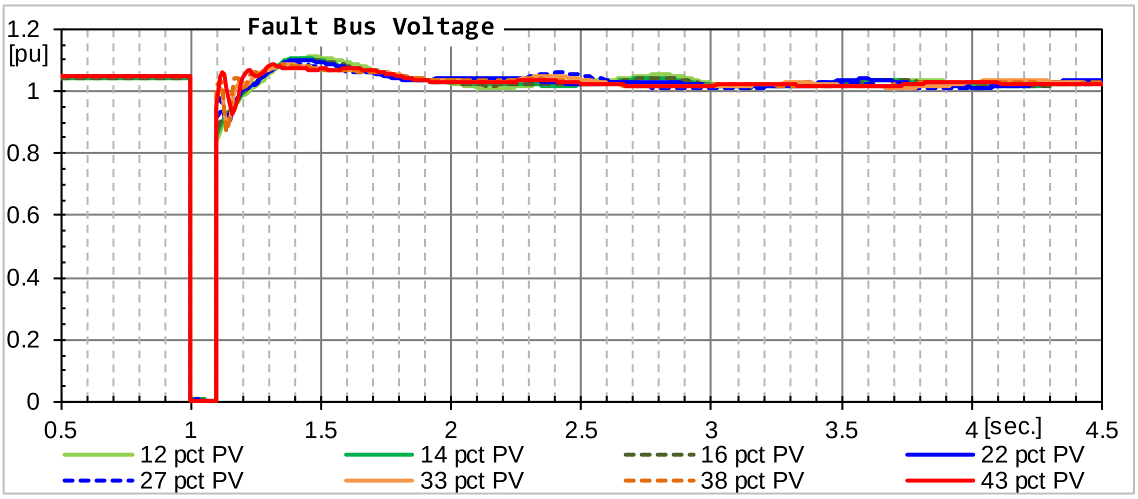
(b)



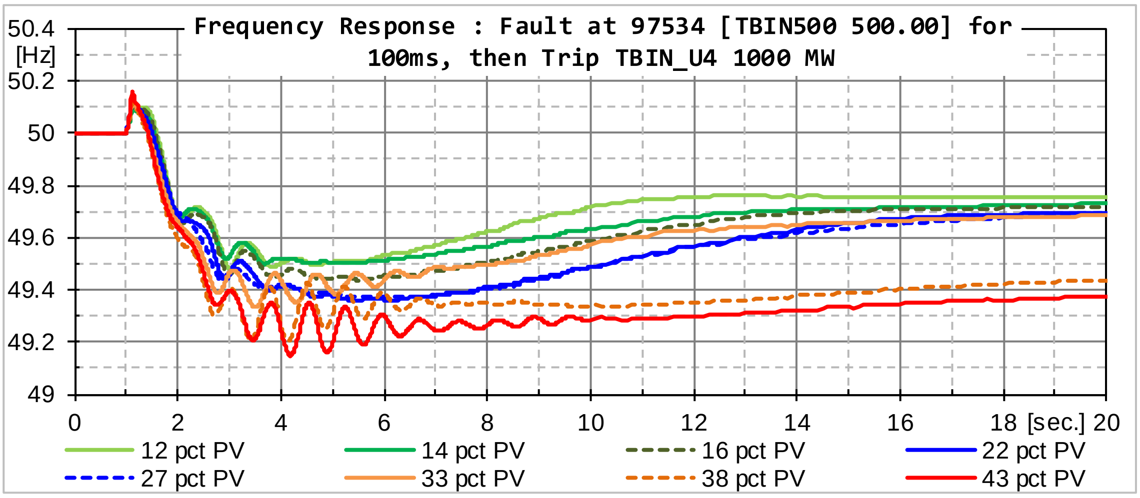
(c)

Figure 111 – Case No. 3 (a) Fault bus voltage, (b) frequency, and (c) rotor angle

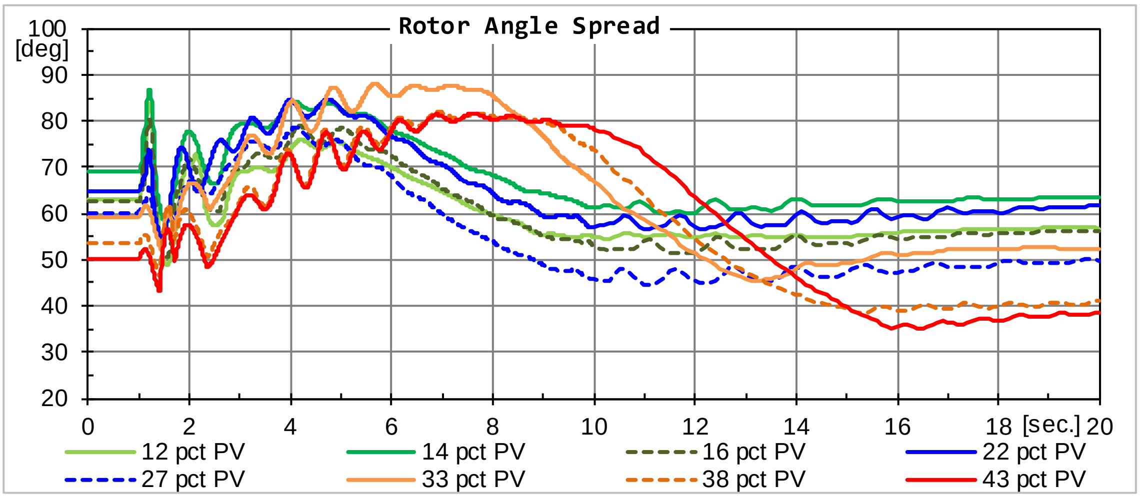
Similar conditions happened with loss of generator case No. 7, where fault at 97534 [TBIN500 500.00] for 100ms, then trip TBIN_U4 1000 MW. Voltages are stable for all scenarios, while frequency deviation for 33%, 38% and 43% PV entered load-shedding zone (49.3Hz). The rotor angle stable after a short period of oscillation. The results are plotted in Figure 112.



(a)



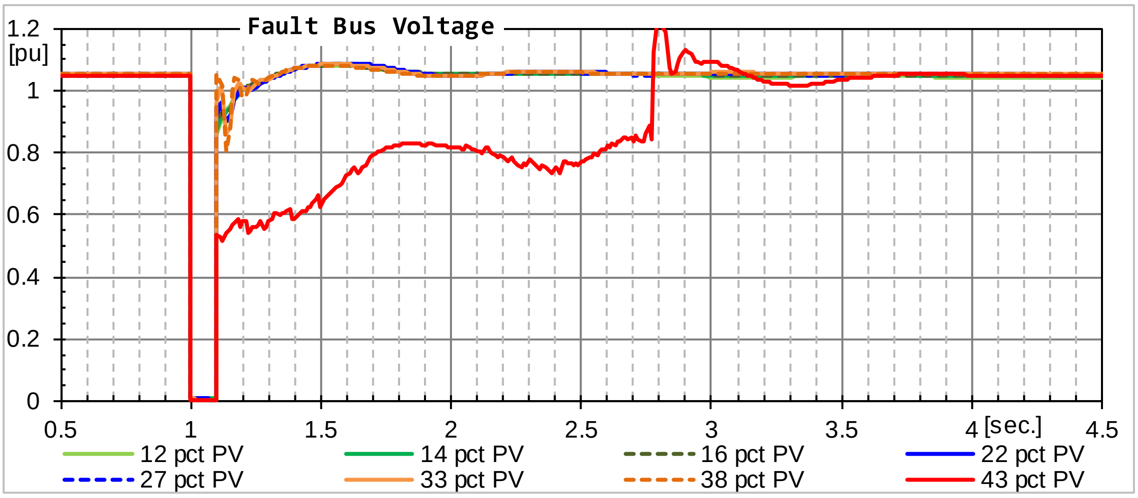
(b)



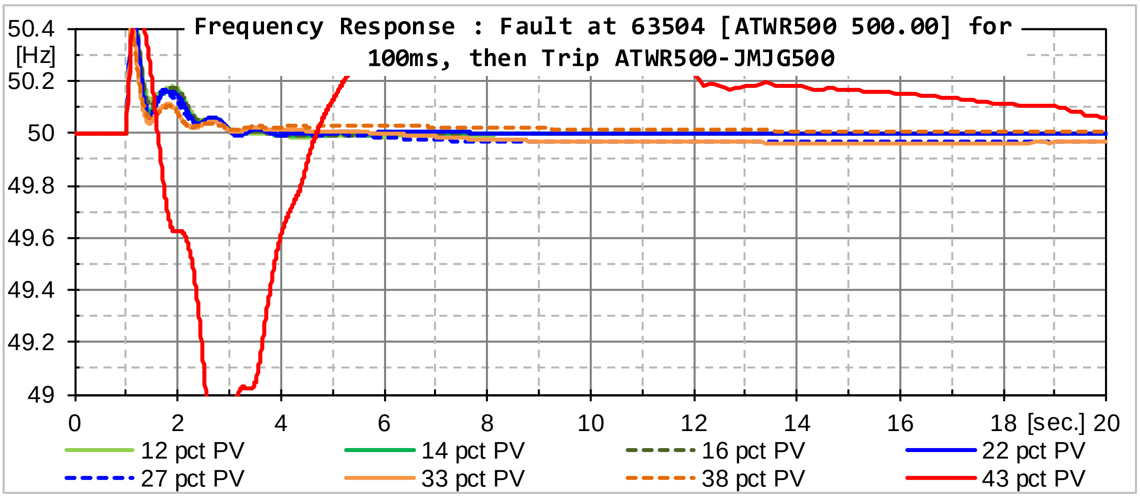
(c)

Figure 112 – Fault bus voltage (a), frequency (b), and rotor angle (c) of case No. 7

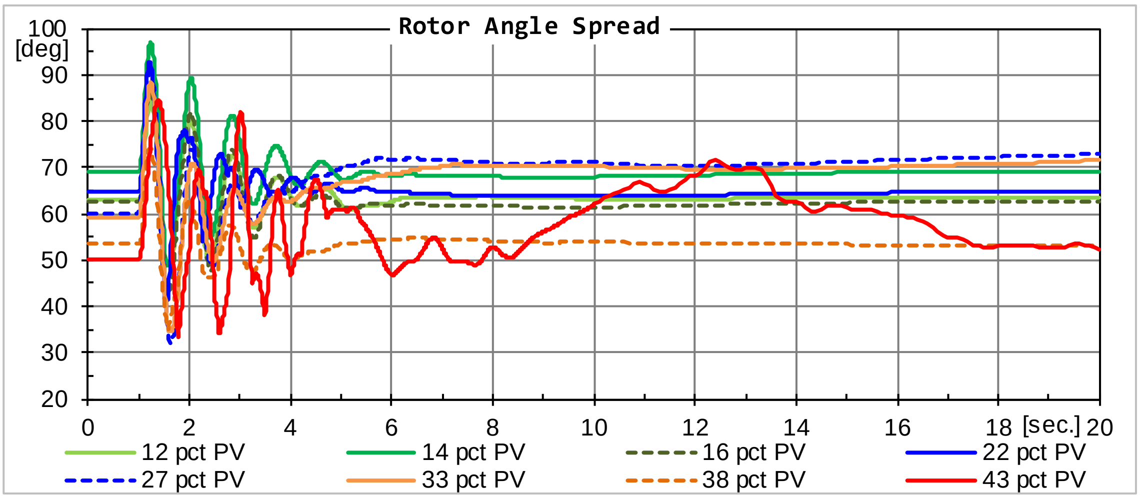
For loss of line event of case No. 8 (fault at 63504 [ATWR500 500.00] for 100ms, then trip ATWR500-JMJG500). The voltage remains stable for all scenarios except 43% PV, where post event voltage did not recover successfully, leading to large frequency deviations. Result profiles are plotted in Figure 113.



(a)



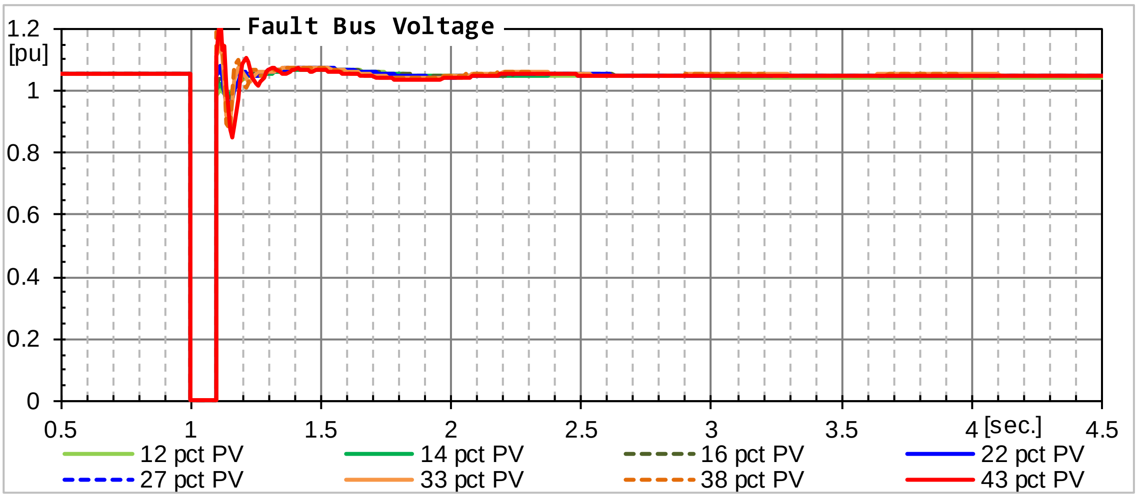
(b)



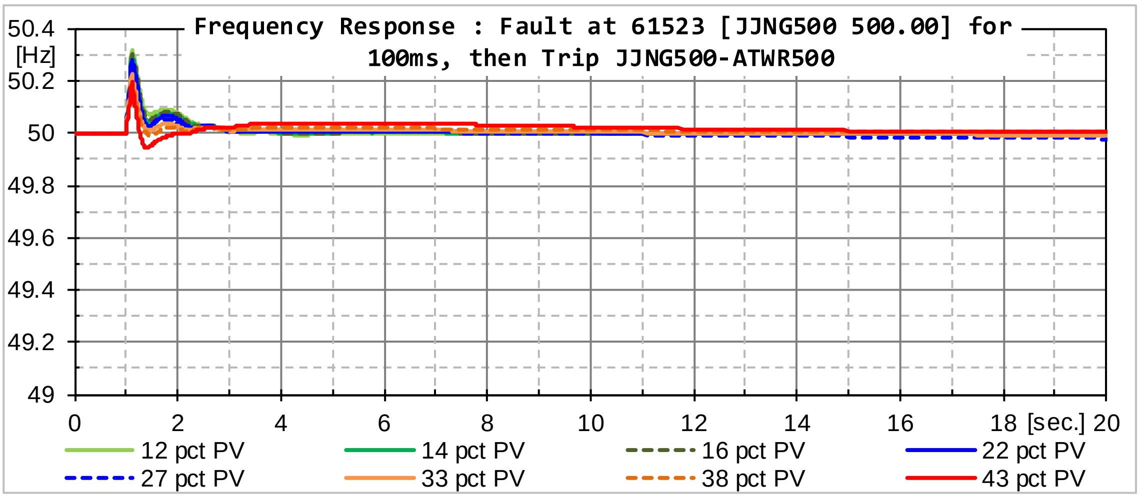
(c)

Figure 113 – Fault bus voltage (a), frequency (b), and rotor angle (c) of case No. 8

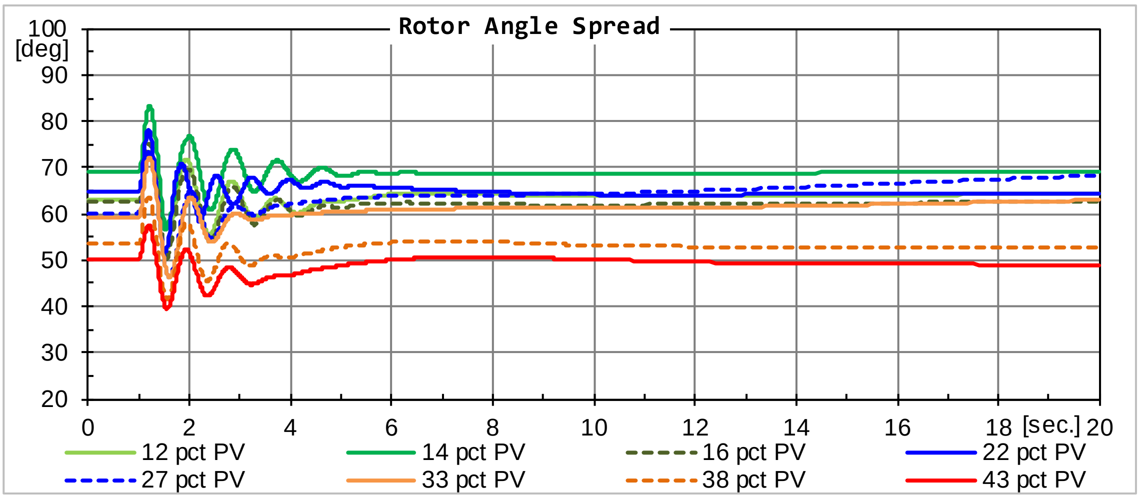
For loss of line event of case No. 19 (fault at 61523 [JJNG500 500.00] for 100ms, then trip JJNG500-ATWR500), voltage remains stable for all scenarios except 38% and 43 % PV, frequency stable, and angle stable after a short period of resonances. Result profiles are plotted in Figure 114.



(a)



(b)



(c)

Figure 114 – Fault bus voltage (a), frequency (b), and rotor angle (c)of case No. 19

The AGC test is performed for a 30-minute window with large solar power fluctuation (21/5/2025 13:30). The test is conducted in PSS®E and automated with Python codes. The AGC mechanism is provided by TNB, and some parameters are tuned via system tests. The overall testing configuration is illustrated in Figure 115.

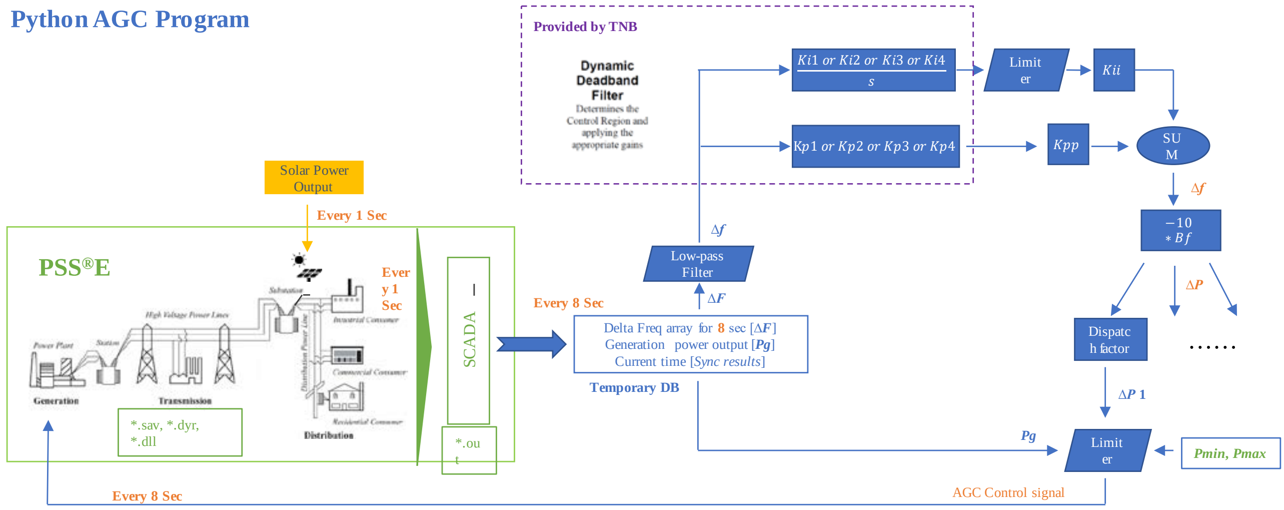


Figure 115 – AGC test setup with PSS®E in Python

The tested solar power penetration rate is set as 27%, which is the highest PV penetration level after curtailment with no transient stability issues as tested in Table 21. In the selected window, total solar generation decreases by around 10% of the total installed capacity, as shown in Figure 116.

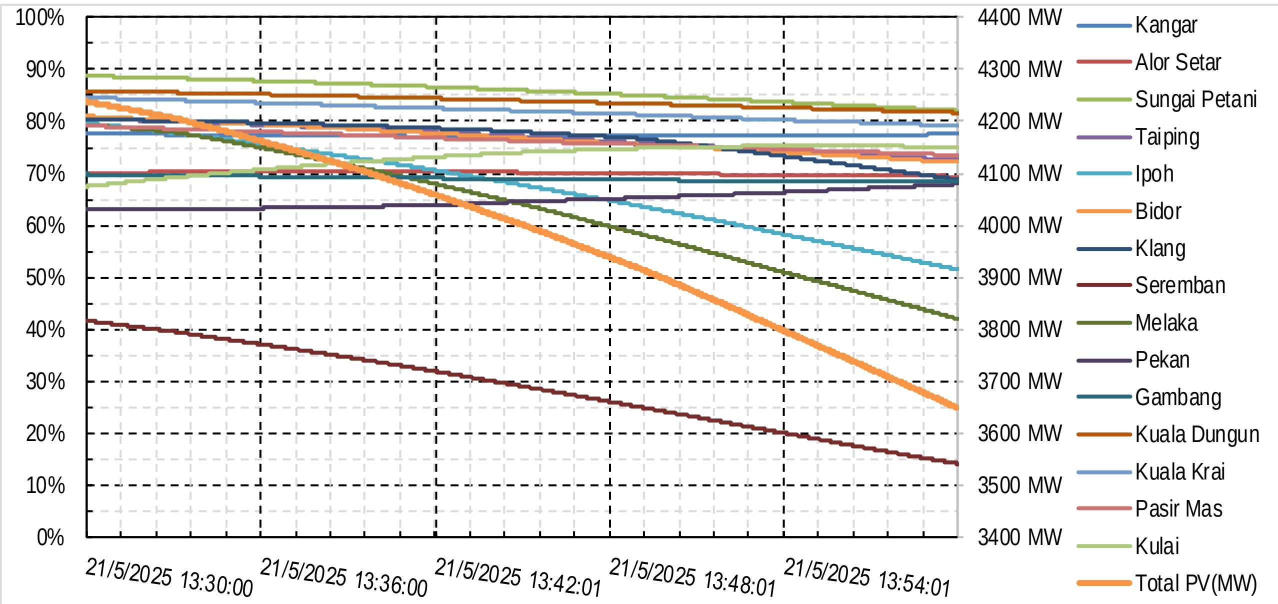


Figure 116 – Individual and total solar generation fluctuation for AGC testing window

The AGC dispatch list is as follows: Hydro#1 186MW, Hydro#2 186MW, Hydro#3 150MW, Hydro#4 150MW, Hydro#5 150MW, Hydro#6 150MW, SSGT#1 500MW, SSGT#2 500MW, SSGT#3 500MW, SSGT#4 500MW. The resulted system frequency profile is plotted in Figure 117, where the frequency deviations remain within the range of ±0.2 Hz.

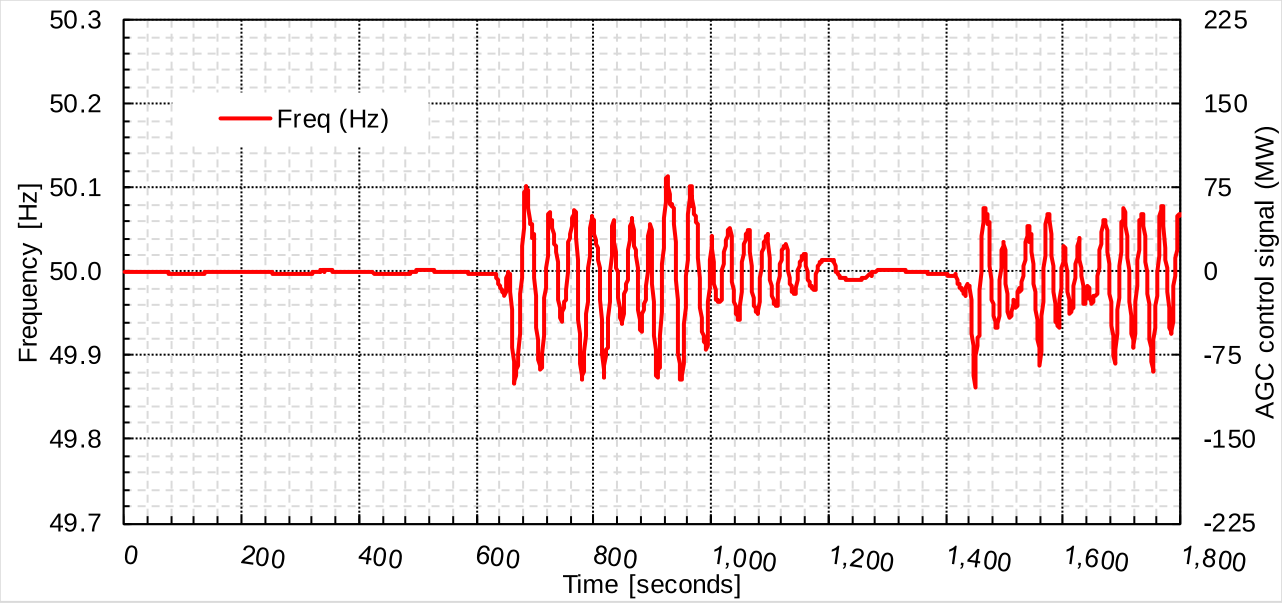


Figure 117 – System frequency response for the 30-min AGC testing window

4.5.2.2 Results of study year 2030

For year 2030, sample snapshot is chosen as 13:00 Sun 14 Apr 2030 with 15,700 MW demand. For the snapshots with 50%, 60% and 70% PV scenario, the scheduled curtailment occurs, after curtailment the actual solar generation are 43%, 43% and 42% respectively. The dispatched generators are listed in Table 22.

Based on the schedules, category B events are simulated, and the results are summarised in Table 23 for all contingency simulations for study year 2030. Fault bus voltage, angel separation and frequency are monitored. The green ticks represent the monitored quantity is within the limits, the red crosses indicate violations, and the yellow crosses for approaching the limits.

Rotor angle separation are within the limits for all test cased and solar penetration levels, indicating a strong transmission system. No violation is observed for penetration up to 30% PV; frequency violations are observed starting from 40% PV penetration for loss of biggest online generator; and short-term voltage overshooting are observed starting from 40% PV. The stability tests clearly indicate the challenge with high penetration.

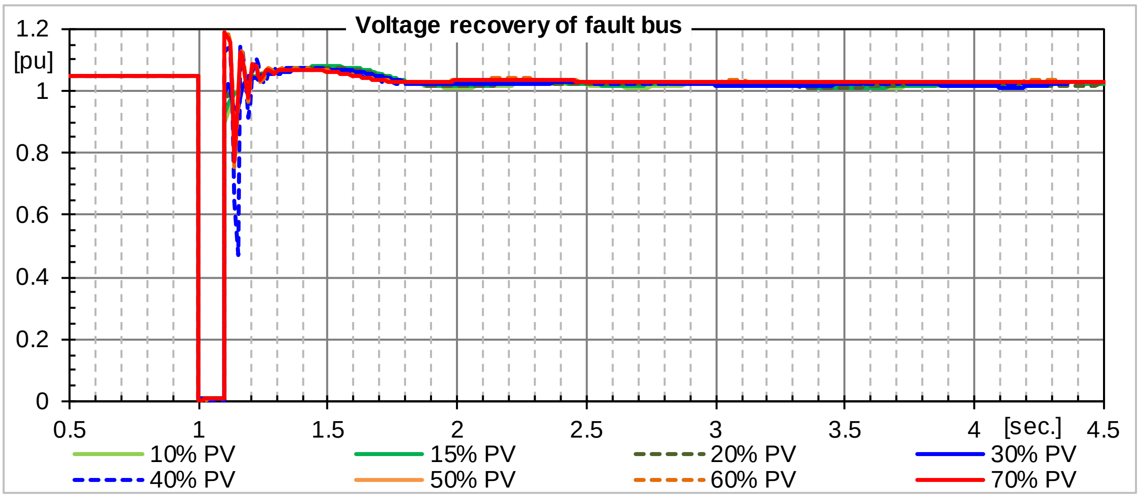
Table 22 List of online generators for tested PV penetration levels (13:00 Sun 14 Apr 2030)

Bus#	Gen Name	Type	P_{MAX}	P_{GEN} at different PV Penetration Levels							
				After curtailment:					43%	43%	42%
				10%	15%	20%	30%	40%	50%	60%	70%
51905	TADMAX_U3 21.000	Gas	500	400	-	-	-	-	-	-	-
59018	N30COAL1 20.000	Coal	700	600	600	600	600	600	600	600	600
59019	N30COAL2 20.000	Coal	700	600	600	600	-	-	-	-	-
59020	PKLW_U1 21.000	Gas	500	450	450	-	-	-	-	-	-
59036	JMAH_U1 20.000	Coal	700	600	600	600	600	600	600	600	600
59037	JMAH_U2 20.000	Coal	700	600	600	600	600	-	-	-	-
59043	JMHE_U1 26.000	Coal	1079.5	900	900	900	900	900	900	900	900
59044	JMHE_U2 26.000	Coal	1079.5	900	900	900	900	-	-	-	-
63901	BSIA_U1 11.000	Hydro	22	10	10	10	-	-	-	-	-
63902	BSIA_U2 11.000	Hydro	23	10	10	10	-	-	-	-	-
63903	BSIA_U3 11.000	Hydro	23	10	10	10	-	-	-	-	-
63904	TMGR_U1 13.800	Hydro	82	30	30	30	30	30	30	30	30
63922	CEND_U1 11.000	Hydro	9	8	8	-	-	-	-	-	-
63923	CEND_U2 11.000	Hydro	9	8	8	-	-	-	-	-	-
63924	CEND_U3 11.000	Hydro	9	8	8	-	-	-	-	-	-
63925	CEND_U4 11.000	Hydro	7	6	6	-	-	-	-	-	-
63934	N30SSGT1 21.000	Gas	500	400	400	320	180	150	-	-	110
63935	N30SSGT2 21.000	Gas	500	400	400	320	180	-	-	-	-
63938	JMJG_U2 23.000	Coal	690	600	600	600	600	600	600	600	600
63939	JMJG_U3 23.000	Coal	690	600	600	600	600	230	230	300	230
63940	JMJG_U4 27.000	Coal	1010	900	900	900	900	900	900	900	900
63941	JMJG_U5 27.000	Coal	1000	900	900	900	900	900	550	700	900
74911	UJLI_U1 11.000	Hydro	186	100	19	19	19	19	19	19	19
74912	UJLI_U2 11.000	Hydro	186	100	19	19	19	19	19	19	19
75931	PGAU_U1 16.000	Hydro	150	100	15	15	15	15	15	15	15
75932	PGAU_U2 16.000	Hydro	150	100	15	15	15	15	15	15	15
75933	PGAU_U3 16.000	Hydro	150	100	15	15	15	15	15	15	15
75934	PGAU_U4 16.000	Hydro	150	100	15	15	15	15	15	15	15
96913	N30SSGT3 21.000	Gas	500	400	400	-	-	-	-	-	-
97961	TBIN_U1 26.000	Coal	700	600	600	600	600	600	600	600	600
97962	TBIN_U2 26.000	Coal	700	600	600	600	-	-	-	-	-
97963	TBIN_U3 26.000	Coal	700	600	600	600	-	-	-	-	-
97964	TBIN_U4 27.000	Coal	1000	900	900	900	900	900	900	900	900

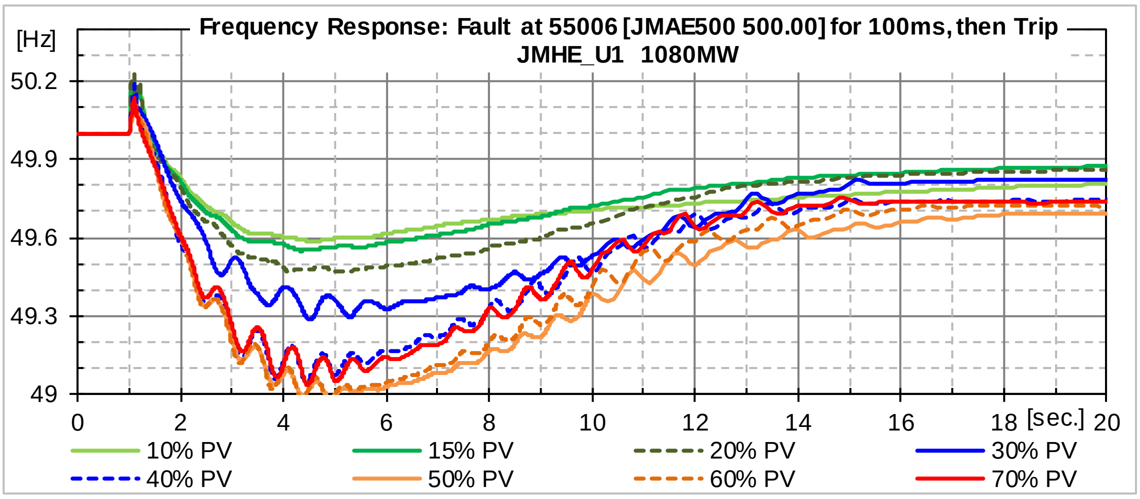
Table 23 System stability test results under various PV penetration rates for study year 2030

																		After Curtailment:	43%PV			43%PV			42%PV		
				10%PV			15%PV			20%PV			30%PV			40%PV			50%PV			60%PV			70%PV		
CASE	FAULT BUS		LOST GEN / LINE	VOLT	ANGL	FREQ	VOLT	ANGL	FREQ	VOLT	ANGL	FREQ	VOLT	ANGL	FREQ	VOLT	ANGL	FREQ	VOLT	ANGL	FREQ	VOLT	ANGL	FREQ	VOLT	ANGL	FREQ
1	52003	PKLG275	PKLG_U5 465 MW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2	55005	JMAH500	JMAH_U1 700 MW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3	55006	JMAE500	JMHE_U1 1080 MW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	×	✓	✓	×	✓	✓	×	×	✓	×
4	63505	JMJG500	JMJG_U2 690 MW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	×	✓	✓	×	✓	✓	×	✓	✓
5	63505	JMJG500	JMJG_U4 1010 MW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	×	✓	✓	×	✓	✓	×	×	✓	×
6	597534	TBIN500R	TBIN_U1 700 MW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
7	97534	TBIN500	TBIN_U4 1000 MW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	×	✓	✓	×	✓	✓	×	×	✓	×
8	63504	ATWR500	ATWR500-JMJG500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	×	✓	✓	×	✓	✓	×	✓	✓
9	63504	ATWR500	ATWR500-BNTS500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	×	✓	✓	×	✓	✓	×	✓	✓
10	96528	BAHS500	BAHS500-AGJH500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
11	96528	BAHS500	BAHS500-YGPE500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
12	97502	BBTU500	BBTU500-YGPE500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
13	97502	BBTU500	BBTU500-TBIN500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
14	74502	BNTS500	BNTS500-LGNG500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
15	55002	BTRK500	BTRK500-KPAR500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
16	55002	BTRK500	BTRK500-ATWR500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
17	55004	BUGL500	BUGL500-OLPT500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
18	55004	BUGL500	BUGL500-LGNG500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
19	61523	JJNG500	JJNG500-ATWR500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	×	✓	✓	×	✓	✓	×	✓	✓
20	55006	JMAE500	JMAE500-LGNG500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
21	55005	JMAH500	JMAH500-OLPT500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
22	96501	LGNG500	LGNG500-BAHS500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
23	97511	YGPE500	YGPE500-TBIN500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

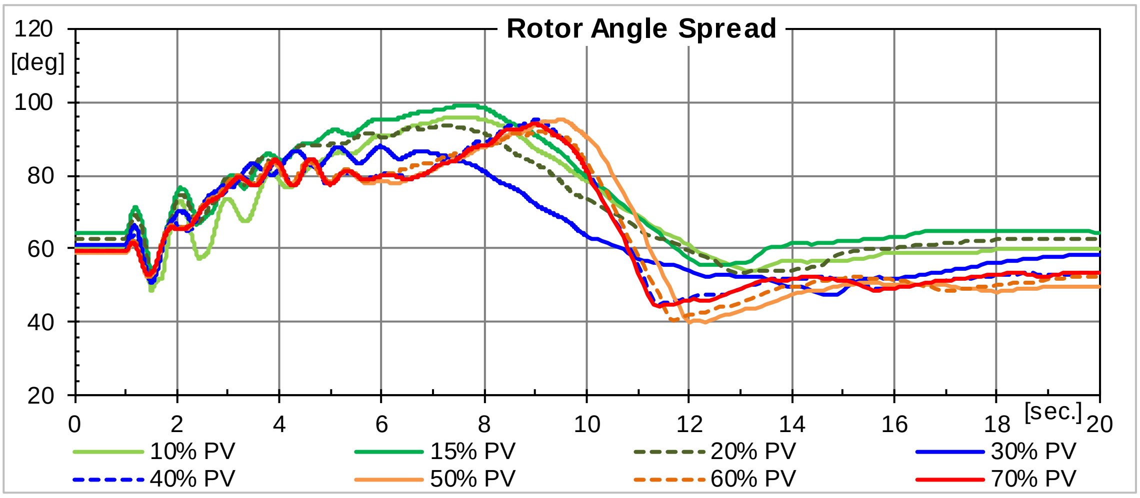
For case No. 3, fault is induced at 55006 [JMAE500 500.00] for 100ms, then trip JMHE_U1 1080 MW. Rotor angle stabilises after a short period of oscillation as in Figure 118(c). Voltage is stable for all scenarios but transient overshooting can be observed with 40% and 42% (70% capacity) in Figure 118(a). Frequency violations are observed for 40% PV and above even with scheduled curtailment for 50%, 60% and 70%PV penetration as shown in Figure 118(b).



(a)



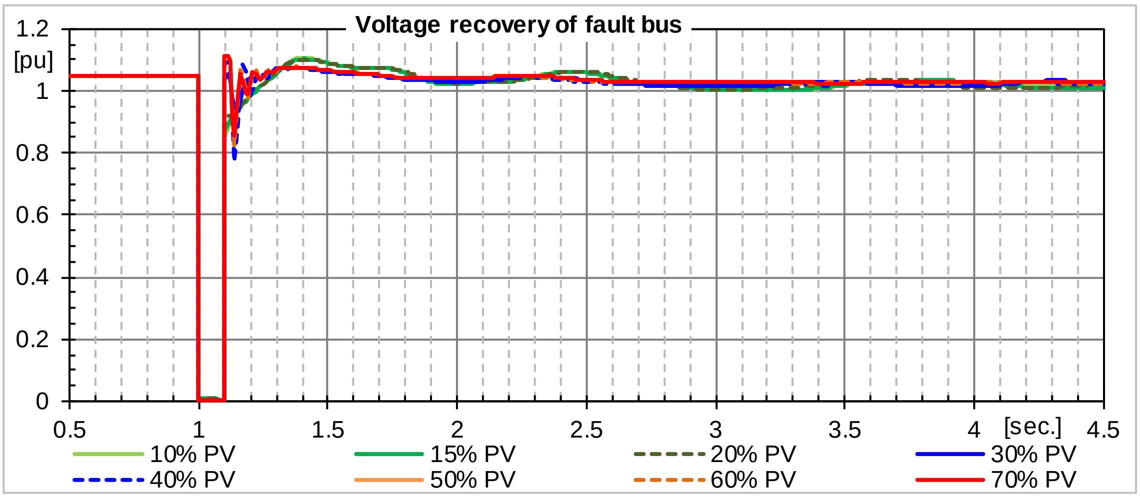
(b)



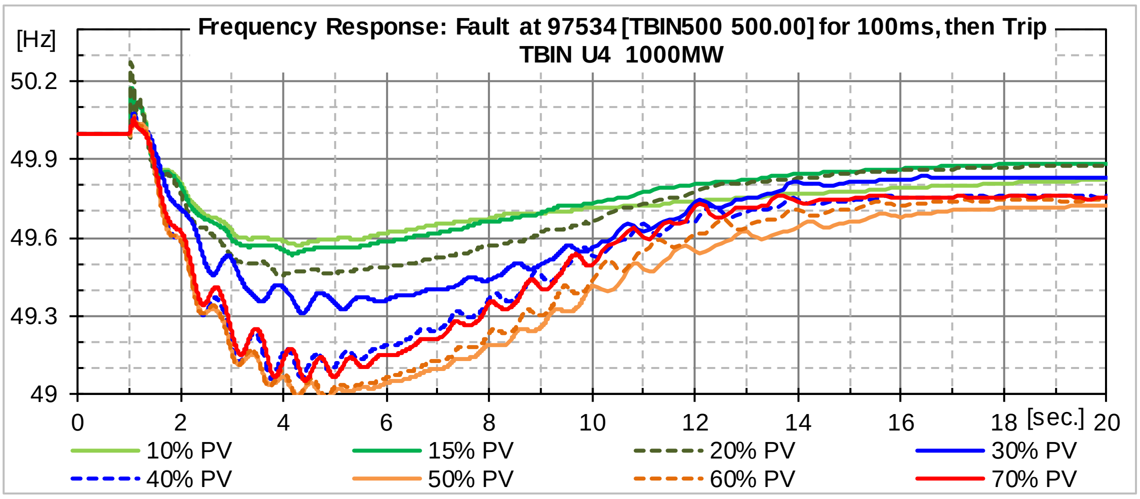
(c)

Figure 118 – Fault bus voltage (left), frequency (middle), and rotor angle (right) profiles for case No. 3

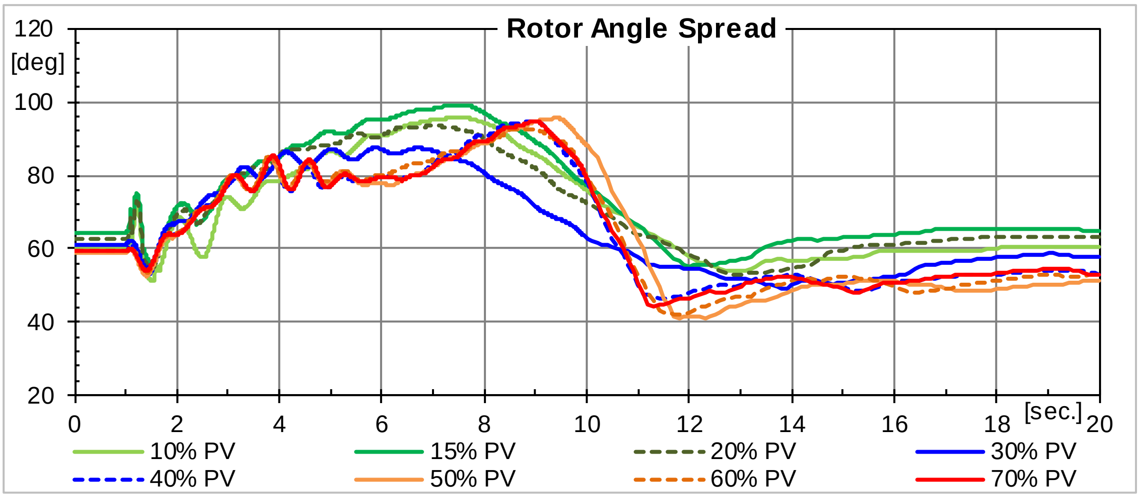
Similar results happened with case No. 7, where fault at 97534 [TBIN500 500.00] for 100ms, then trip TBIN_U4 1000 MW. The results are plotted in Figure 119.



(a)



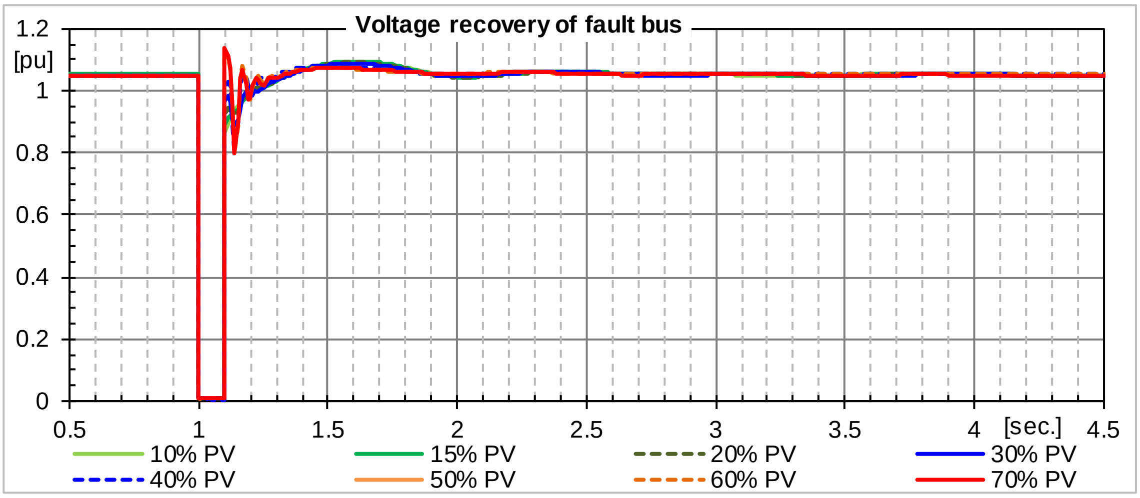
(b)



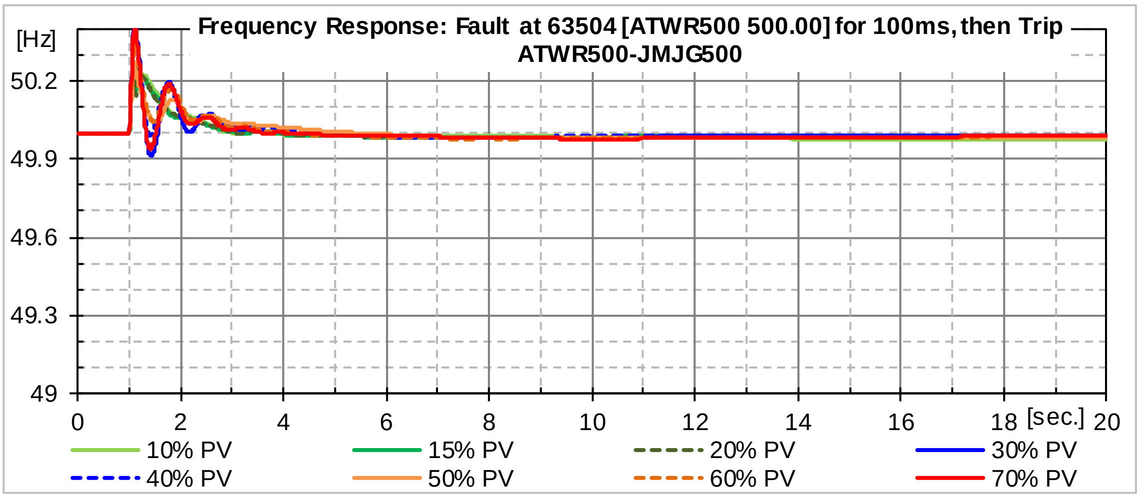
(c)

Figure 119 – Fault bus voltage (a), frequency (b), and rotor angle (c) profiles for case No. 7

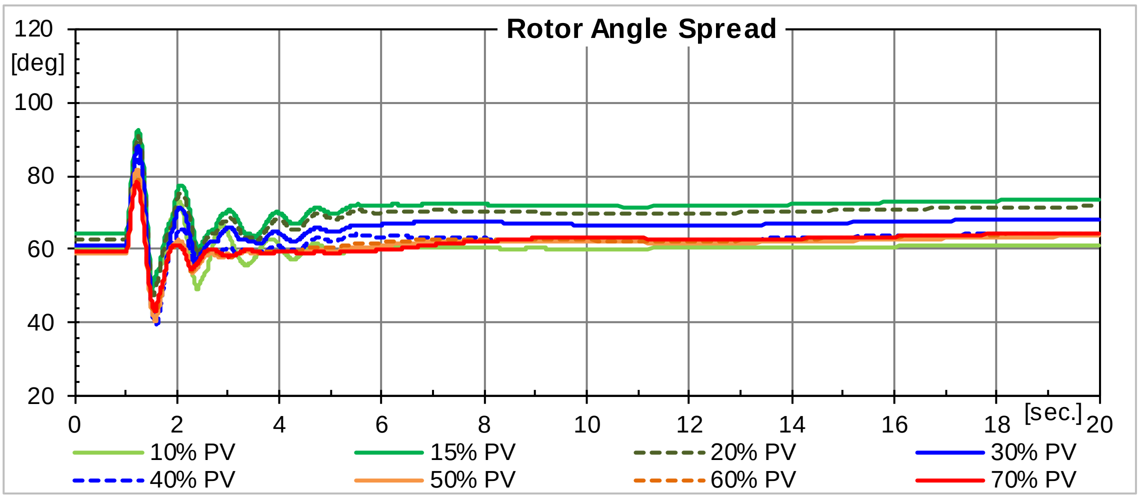
For loss of line event of case No. 8 (fault at 63504 [ATWR500 500.00] for 100ms, then trip ATWR500-JMJG500), voltage, frequency, and rotor angel remains stable. Only voltage with 40% and above PV penetration shows transient overshooting. The simulation results are plotted in Figure 120.



(a)



(b)



(c)

Figure 120 – Fault bus voltage (left), frequency (middle), and rotor angle (right) profiles for case No. 8

AGC tests have been performed for a 30-minute window with large solar power fluctuation (9/9/2030 10:30). System AGC is tested at 30% PV penetration, which is the recommended level within technical limit. Total solar generation increases by around 10% of installed PV capacity, as shown in Figure 121.

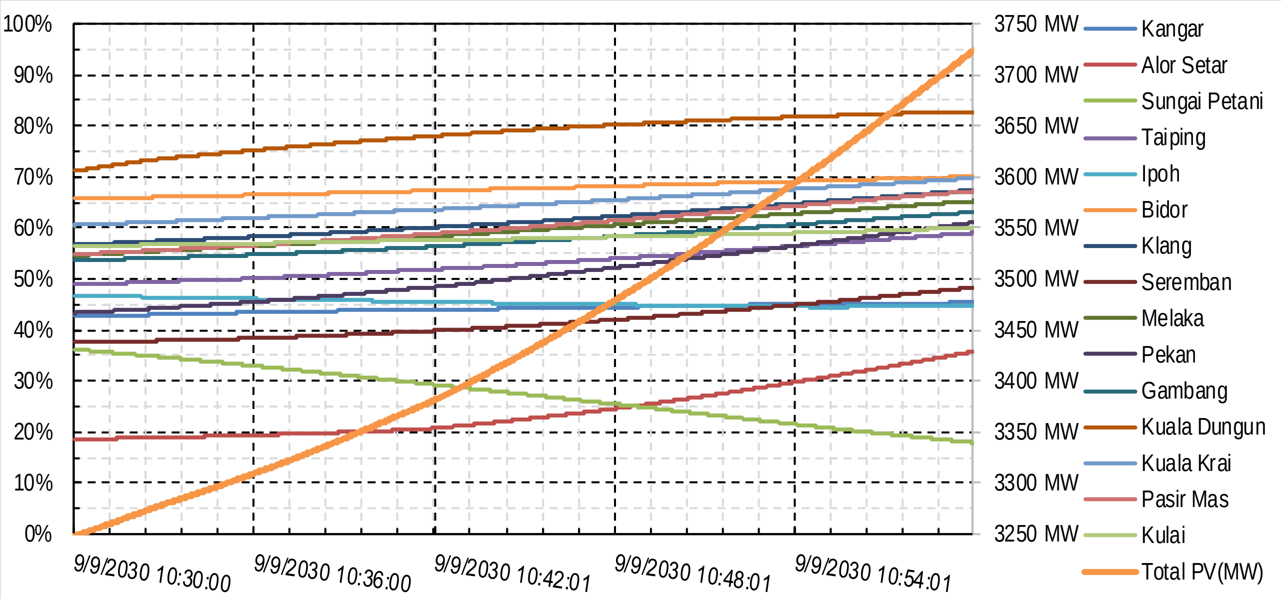


Figure 121 – Individual and total solar generation fluctuation in 30-min AGC testing window

TNB AGC scheme is implemented and unavailable parameters are assumed based on system tests. AGC units dispatch list is as follows: Hydro#1 186MW, Hydro#2 186MW, Hydro#3 150MW, Hydro#4 150MW, Hydro#5 150MW, Hydro#6 150MW, SSGT#1 500MW, SSGT#2 500MW, SSGT#3 500MW, SSGT#4 500MW. The resulted system frequency profile is plotted in Figure 122, the frequency deviations remain in the range of ±0.2 Hz.

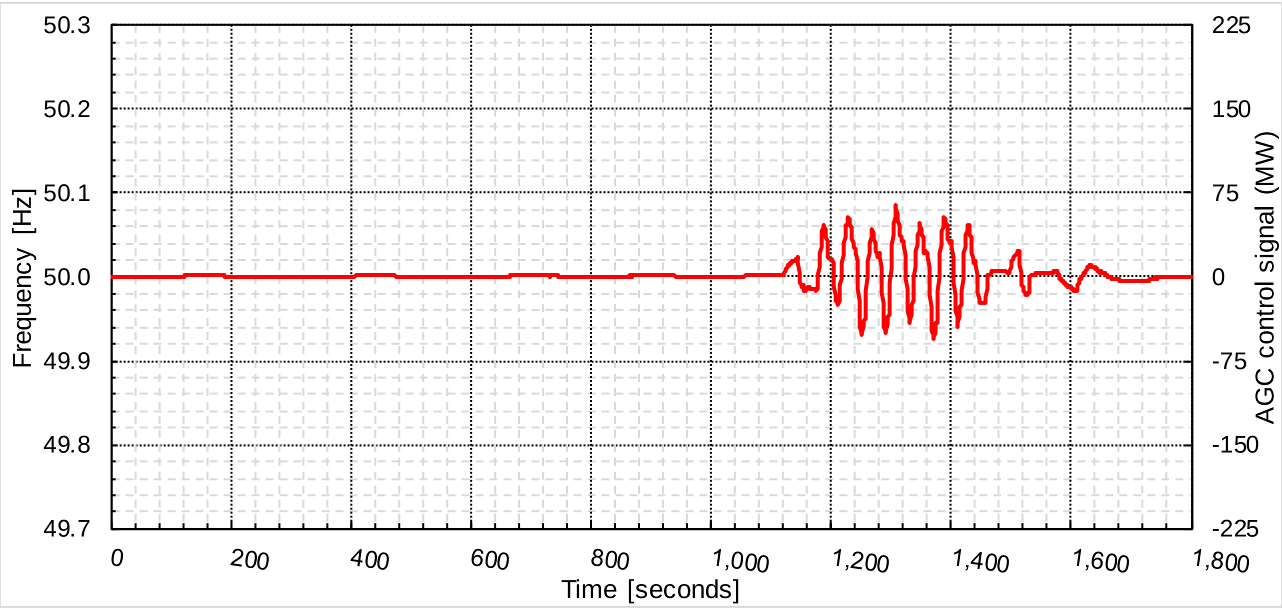


Figure 122 – System frequency profile in the 30-min AGC testing window

4.6 Establish the solar capacity credit

As the penetration level of PV increases, the system reliability improves with additional solar generation, resulting in a smaller LOLE value. However, the amount of reliability improvement does not increase proportionally with the installed solar capacity. Since VRE power output is constantly fluctuating and intermittent, its contribution to the total system generation capacity cannot be represented directly by the nameplate capacity of the PV panels. Therefore, the "capacity credit" of solar generation is required to quantify the amount of capacity impact of PV on the system, as illustrated in Figure 123.

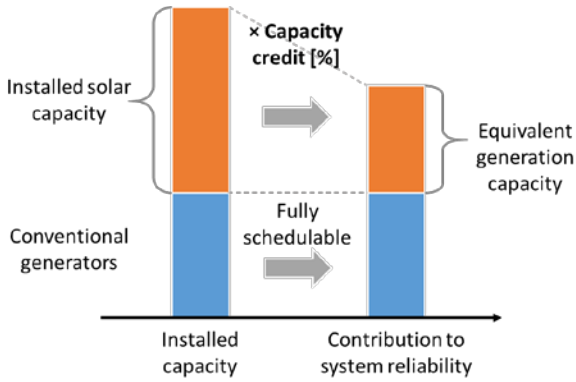


Figure 123 – Equivalent capacity of solar generation

Capacity credit of PV is evaluated by the effective load carrying capability (ELCC) of the variable solar generation. It can be represented quantitatively as the equivalent generation capacity in terms of contribution towards overall system reliably.

To conduct capacity credit analysis of PV, the original PV capacity in the system is removed and gradually replaced by benchmark units (conventional generators). The system LOLE is assessed throughout the procedure until its value equals to the level with original amount PV penetration. The PV capacity credit is calculated as the equivalent capacity of conventional generators installed to achieve the same level of system reliability, divided by the installed solar nameplate capacity (%).

The capacity credit of PV in Malaysia Peninsular system is evaluated by PLEXOS PASA simulation. PLEXOS utilizes an improved LDC (load duration curve) method to solve for system LOLE, with consideration of user-defined generator forced outage rate and maintenance schedule. We built case studies with 5-10-15-20-30-40-50-60-70% PV penetration rates, and conducted simulations to evaluate the equivalent amount of PV generation. The evaluation criterion is to maintain a same LOLE level as the 0% PV case. The final amount of added generation is regarded as the credited capacity of PV. Our analysis provides a conservative estimation of solar capacity credit since the FOR is not considered in the benchmark generation unit. Using benchmark unit with FOR will result in higher capacity value.

The 11-year simulation results from year 2025 to 2035 are summarised in Figure 124. In general, the capacity credit of PV decreases with the increase of installed PV capacity. However, the rate of increase decreases when more PV capacity is integrated in the system. In other words, the load-carrying ability is not proportional to the total PV capacity. This is also due to the altered netload pattern. When the evening peak becomes dominant, PV penetration no longer contributes to system overall capacity.

There have been studies evaluated wind generation capacity credit in the USA[83] as well as Europe[84]. Although the general trend of decrease is similar to solar in Peninsular system, the capacity credit of wind varies greatly through time and locations from 5% to 40% for different systems. The overall fitting result for Peninsular system is shown in Figure 124. The fitted 3rd order polynomial formulation and its R^2 value are displayed in

[83] M. Milligan and K. Porter, "*Determining the Capacity Value of Wind: An Updated Survey of Methods and Implementation*". National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy08osti/43433.pdf. June 2008.

[84] R. Gross, P. Heptonstall, D. Anderson, T. Green, M. Leach, and J. SKea, "*The Costs and Impacts of Intermittency: An assessment of the evidence on the costs and impacts of intermittent generation on the British electricity network*". http://www.uwig.org/0604_Intermittency_report_final.pdf. March 2006.

the plot. For Peninsular system, a R^2 value of 0.9869 means that the variance (expected squared deviation from the mean) of the fitting errors is 98.69% less than the variance of the simulated solar capacity credits. That is, the 3rd polynomial fitting method can provide reasonably accurate solar capacity credit values for future system capacity planning, regardless of the various load and solar generation profiles of different years. This is due to the relatively stable load and solar irradiance profile in Malaysia Peninsular.

As shown in Figure 124, the solar capacity credit declines rapidly as penetration level increases, e.g. for the 20% penetration, the capacity credit is 17.2%, it reduces to 13.1% at 30% penetration and to 10.3% at 40% penetration.

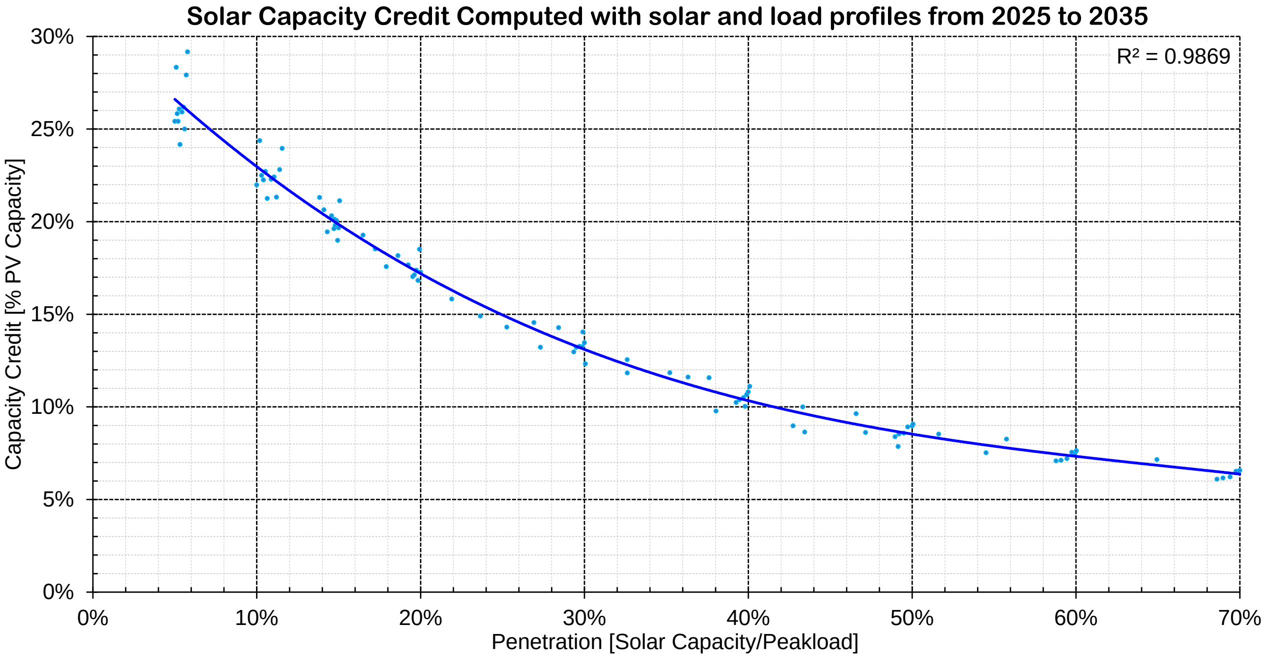


Figure 124 – Solar capacity credit for Peninsular Malaysia system

5 DISCUSSIONS ON THE CHALLENGES AND POSSIBLE MITIGATIONS

This study has been conducted with:

- the chronological load data from 2020 to 2035 forecasted based on historical load data.
- the generators' minimum stable powers and ramp rates from respective PPAs, which indicate the big coal generators (690-1010MW) have a P_{MIN} in the range of 30-35% and per minute ramp 0.5-2% of their rated power. The minimum stable powers of big coal generators are lower than that of the CCGTs (in the range of 40-50%).
- the reserve requirements have been computed with short-term solar forecasts for each location are available with independent forecast errors of ±20% (±2σ).
- all solar generators fulfil the technical requirements for large scale solar generators, i.e. the solar generators have been modelled at 132kV sub-transmission level.

The fundamental tenets of power system planning and operation call for:

- the ability to plan sufficient generation to meet future demand economically and reliably;
- the ability to reliably forecast loads and variable renewable generations;
- the ability to balance instantaneously the load with generation; and
- the resilience of the system to withstand credible contingent events without cascading loss of loads or generations.

Apart from the expected electricity generation cost increases, these fundamental requirements are challenged at high solar penetration levels.

Generation Capacity Planning	The solar generate power during daylight hours, as solar penetration increase the existing afternoon peaks become lower than the evening peaks, which become dominant in capacity planning. This phenomenon leads to rapid decline of solar capacity credit as the penetration level increases: 23% at 10% penetration, 17.2% at 20%, and 13.1% at 30%. Starting from 40% penetration, further increases of solar install capacity does not result on reduction of conventional capacity. Duplicated generation capacity investments are added to the generation system, and increases the generation cost.
Load Forecast	The forecast for variable renewable generations is new to system operators, and depends on the accuracy of locational weather predictions. In the context of land preciousness, large amount solar deployment is expected in the distribution level, e.g. small scale rooftop installations. The control centre sees only the netloads (load – distributed solar generation). The historical load data will be distorted, and the future load forecast would encounter greater errors. To maintain the reliable operation of power system, additional reserves are required to cope with expected forecast errors.
Generation and Load Balancing	Due to the solar continuous ramping expected forecast errors, additional regulation reserve quantum equal to 11% of solar install capacity is required. The requirement becomes significant at high penetration, e.g. 690MW for 30% penetration in 2025 in comparison to the current frequency regulation reserve quantum of 200MW. At high penetration level, the solar generation results in noon troughs and subsequent very high magnitude netload ramps in the afternoon. To prepare for the afternoon ramps, more conventional generators are scheduled online. These conventional generators operate at low thermal efficiency points, results in increased overall per MWh fuel cost. On the other hand, solar curtailment occurs to satisfy the minimum stable power of the online conventional generators. Due these two reasons, the 50-70% penetration were schedule curtailed to a level of 43% in low demand days.

Resilience of the Power System	In off-peak weekends with high irradiance, the numbers of online conventional generators reduce as penetration level increase, resulting in reduced system inertia and primary (governor) response. The frequency stability is challenged in case loss of the biggest online generator (category B events). As the online conventional generators reduces at high penetration level, the post-event voltage recovery become increasing volatile.

The mitigation measures discussed in following text of this section are mainly based on the practices of Germany, who has successfully integrated renewable at large scale while maintaining the reliability of the grid system.

5.1 Policy and guidelines

5.1.1 Discussions

In Germany, high level of wind and solar energy integration induces large amount of power fluctuation – 114.6% of peak load in 2016. To accommodate more and more RES, a proper cross-border balancing market is required to cope with the high fluctuations. The balancing market incorporated frequency regulation resources for primary, secondary, and tertiary frequency control. The reserve quantum is chosen to achieve a 99.95% confidence level, which considers generation plant outage rate distribution; solar, wind and load forecast error in the calculation.

The current balancing market practices weekly tendering with 12 hour-products. For primary frequency control, the reserve capacity is contracted 1 week ahead; the secondary frequency control, several days ahead; and 10-12 hours ahead for tertiary frequency control products. There are 37 competitive balancing service providers to the grid control cooperation (GCC). The German electricity market (EPEX Spot) operates an intra-day market that is closed 15 minutes before delivery, allowing participants to balance any forecasted deviations in their production and consumption.

The stablity tests show post event voltage recovery issues with high penetration levels during off-peak high-irradiance periods, when limited generators are online providing voltage support.

The Malaysia Grid Code and Guidelines on LSS PV Plant to Electricity Networks set out comprehensive technical and operational requirements for solar PV installation of capacity ≥1000kW. However, these important requirements are not applicable for installation of capacity <1000kW.

In the context of land preciousness, significant amount solar deployment is expected in the distribution level, e.g. small-scale rooftop installations. The potential impacts of these small scale solar installation to the grid system and operation are generally similar to LSS, plus localised impacts to the low-voltage network, e.g.

- the control centre sees only the netloads (load – distributed solar generation). The historical load data will be distorted, and the future load forecast would encounter greater errors. Thus, more frequency regulation reserves are required.
- the balancing of load with generation due to lack of visibility and forecast on the distributed small scale solar generations.
- voltage control issues of low voltage networks with significant amount solar installations, e.g. residential area with low noon demand.
- in case of a severe fault, e.g. 3-phase or LLG, on the transmission system, a large area with significant amount of the distributed solar generations could experience very low voltage. Significant amount of solar generation could trip on low voltage if not equipped with LVRT function.
- in case of load rejection, the difficulties on frequency control if large amount of distributed solar generator does not have automatic overfrequency power reduction function.
- the effectiveness of underfrequency load-shedding scheme becomes time/irradiance dependent, e.g. shedding a residential area at noon might have actually tripped generation.

As the total installed capacity become large, controllability and observability of these distributed small solar generations become essential for system planning and operation.

5.1.2 Possible Mitigations

In high penetration scenarios, a cross-border day-ahead market enables the trading of surplus VRE generations amount interconnected control areas, and a balancing market for primary, secondary, and tertiary frequency control reserves. An intra-day spot market within the control area enable the participants to balance any forecasted deviations in their production and consumption.

The post event voltage recovery issues could be improved by the dynamic reactive current injection from solar inverters. For example, the German grid code calls for voltage support from renewable generators based on requirements shown in Figure 125.

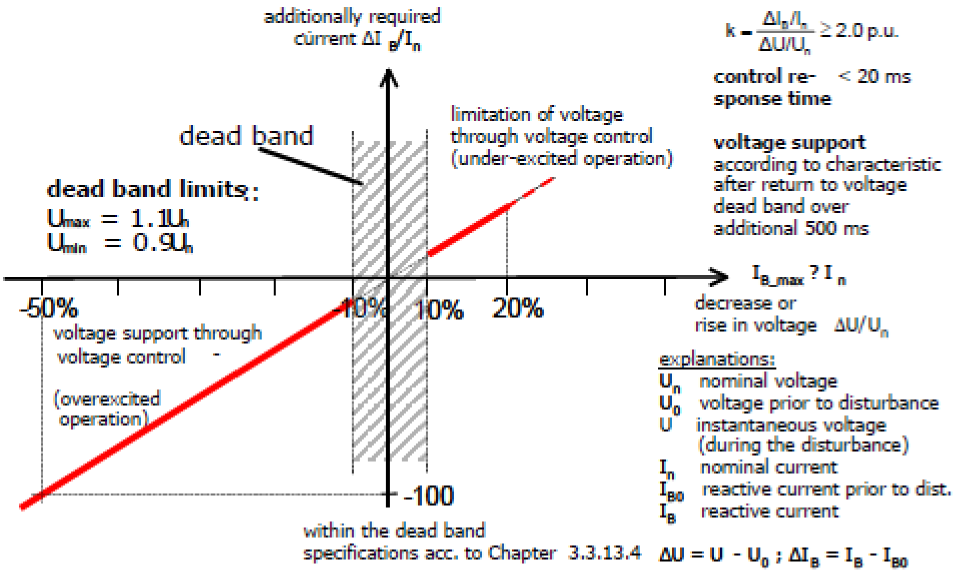


Figure 125 – German grid code requirement for voltage support from renewable generators

In Germany, 95% of renewables are connected on the distribution network. For example, the installed PV capacity in Germany totals 41,300 MW, and 73% of that capacity is on building rooftops. This poses a challenge to the system operator, since the TSO has very little information about the infeed of VRE generation on the distribution network. Additionally, since 2014, subsidies for RES started to phase out and future RES is expected to be market-based. Consequently, this high number of small generation units/market participants at medium/low voltage network must be automated and quipped with communication devices to enhance the system controllability and observability. As a result, the updated EEG requires solar PV with installed capacity 30 kWp and above must have energy management function and centrally controlled by the distribution system operators, as detailed in Table 24.

Table 24 Updated energy management requirements in EEG 2012 for distributed solar PV installations

Installed PV Capacity	EEG 2009	EEG 2012
$P_{MAX} \geq 100$ kWp	Energy management - remotely controlled	Energy management – remotely controlled
30kWp ≤ $P_{MAX} \geq 100$ kWp	No energy management requirements	Energy management – remotely controlled
$P_{MAX} < 30$ kWp	No energy management requirements	Either remotely controlled or fixed 70% feed-in limitation

Apart from the energy management requirements, automatic control functions are required for all distributed solar installations:

- Low-Voltage Ride-Through capability.
- negative/positive control power, i.e. reduction/release of active power according to a 40% per Hz P(f) droop characteristics;

- minimum reactive power capability from 0.95 leading to 0.95 lagging. Capability of reactive power Q(U) control and Q set-point by the distribution system operator.

In large amount of small scale solar deployment scenario, similar technical and operational requirements should apply to the small scale solar installations. The distribution management system could be enhanced to monitor and control these small scale solar generations.

5.2 Deployment of technology

5.2.1 Discussions

In this study, the system planning and operation are challenged with high solar penetrations:

1) Evening peaks become dominant in long-term capacity expansion planning,
2) Very high magnitude netload ramps from afternoon to evening,
3) Scheduled curtailments in low demand days with high irradiance due to reliability constraints, and
4) Insufficient inertia and governor response in case loss of the biggest online generator.

These issues are mainly due to the correlation between the fixed-hour solar generation profile of and the demand profile.

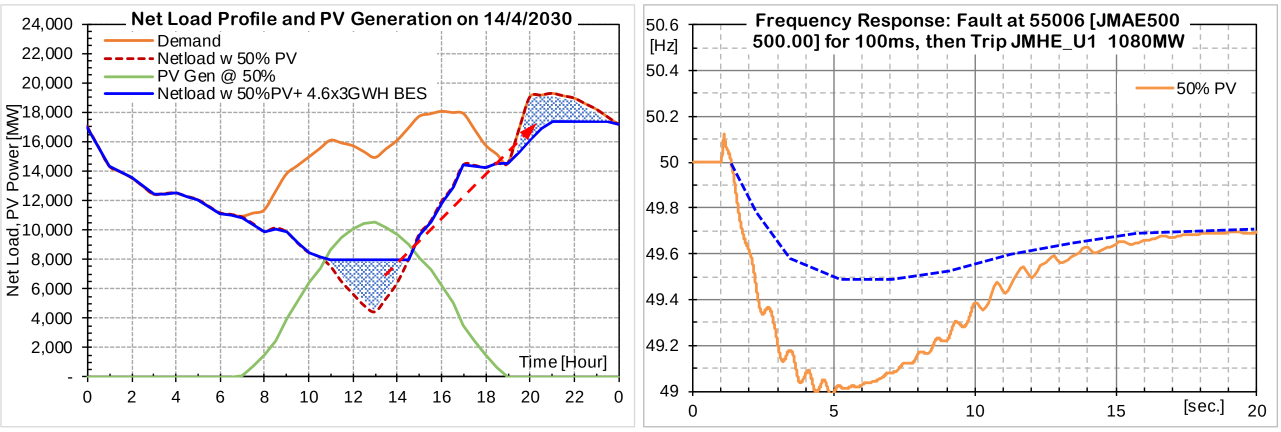
Various technologies are being developed and deployed to mitigate the variable renewable generation impacts to power system planning and operation. Of these developments, the battery energy storage (BES) technology has been the most promising one. A recent paper[85] published by Fraunhofer Germany pointed out the power system roadmap for further PV integration: time frame up to 2025, focus on “Creating flexibility”; and time frame up to 2050, focus on “Storage”.

5.2.2 Possible Mitigations

Based on current BES price, the long-term capacity planning did not pick up the BES candidate from the least cost optimisation simulations. However, with the expected large-scale deployment of electric vehicles (EV), significant price reductions of batteries are expected.

The BES applications for variable renewable integrations varies from power output smoothing, shifting the energy produced in low demand periods to the peak periods, compensate the VRE forecast errors, to provide fast-response frequency regulation services, and synthetic inertia response.

For the off-peak Sunday 14 April 2030 discussed in the study, with 3.6GW x 2.3Hour BES, the netload profile of 50% PV case (11,150MW) can be modified as shown in Figure 126 (a).



(a) **(b)**

Figure 126 Illustrative BES Applications: (a) netload profile conditioning, (b) inertia response

The modification of netload profile bring multiple benefits.

- During the noon periods:
  - avoiding solar energy curtailment;

[85] Recent Facts about Photovoltaics in Germany, July 2018, Fraunhofer Institute for Solar Energy Systems ISE

- allow more conventional generators go online to improve system stability;
  - reduced the reserve requirement of the conventional generators, so that they can operate at more efficient set-point.
- In the event of severe frequency deviations, the BES provide effectively synthetic inertia response to mitigate the frequency drop as shown in Figure 126 (a).
- During the evening periods:
  - bring down evening peaks so that less conventional generation capacity is required, benefit the capacity planning.
  - mitigate the sharp evening ramps, ease the ramping requirement of conventional generators.

Although the BES brings numerous technical benefits, the high investment cost of the batteries and associated balance-of-plant equipment such as converters, transformers and switchgears remains the drawback for large scale deployment. The batteries life time is also a major concern, especially when they are deployed for energy shifting purpose that involve daily deep cycles.

5.3 Generation mitigation

5.3.1 Discussions

With increasing amount of power fluctuation brought to the grid by vRE, system operation requires larger and faster regulation reserve, i.e. demanding more power control capacity from conventional generation units such as more flexible power plants, peakers, and pump storage system.

The pumped hydro storage plant can provide additional power balancing capacity and primary, secondary, and tertiary frequency control services. The pumped hydro storage plant is similar to the BES but response in a slower manner. Peakers are commonly open-cycle gas-turbine or combustion engine driven generation units that provide replacement reserves.

For conventional power plants, although majority of the capacity is to carry system base load, there are ways to enhance the flexibility of plant operation. Plant upgrade measures for 3 key parameters (minimum load level, start-up time, and ramp rate) are summarised in Table 25.

Table 25 Measures for improvements for conventional power plants

Measures	Systems	Min Load	Start-up Time	Ramp Rate	Limits
Indirect firing	Coal Mills & Bunker	✓		✓	Fire Stability
Switching from multi to single coal mill operation		✓			Water-steam circuit
Control system upgrade	Control system	✓	✓	✓	Fire stability, thermal stress
Auxiliary firing with dried lignite burner	Boiler, burners ignition fuel supply	✓		✓	Fire stability, boiler design
Thermal energy storage for feed water pre-heating	Water-steam system	✓			N.A.
Repowering			✓	✓	N.A.
Turbine design, thin-walled components	Turbine		✓	✓	Mechanical, thermal stress

5.3.2 Possible mitigations

The coal generators' minimum stable powers and ramp rates from respective PPAs indicate the big coal generators (690-1010MW) have a P_{MIN} in the range of 30-35% and per minute ramp up to 2% of their rated power. Hence, the flexible measures could not gain much additional benefits.

The pumped hydro storage plant, depends on available lower and upper reservoirs, could be a good candidate for high solar penetration scenarios.

5.4 Grid mitigation

5.4.1 Discussions

Interconnection with neighbouring grids to enable mutual support and to widen the balance area with cross border electricity trading have been proven for large scale VRE integration.

By interconnecting the grids, the reserves could be shared among the power system operators, so that the generation plants in each grid can be operated more economically.

In contingent events, all generators from the interconnect grids will provide both inertia and governor responses, results in much less frequency deviations.

With established cross-border electricity market trading mechanisms, surplus VRE generation in one control area could exported to neighbouring system, thus avoid curtailments and improve economic operation of interconnected grids.

5.4.2 Possible mitigations

The Peninsular system is interconnected with Singapore and Thailand, and will be interconnected with Sumatra system of Indonesia. The HVDC connection with Thailand currently operates in DC mode for import fixed amount of power, and is technically possible to operate in AC mode to provide certain amount of primary reserves. The AC connection with Singapore are for mutual support in case of contingencies. Future submarine DC connection with Sumatra is planned for import of electricity from Indonesia.

The grid infrastructure is available. However, these interconnections have not been fully utilised for trading of electricity or balancing of VRE due to lack of regional electricity market, which is one of the key strategies of HAPUA.

5.5 System operation and reserve allocation

5.5.1 Discussions

A main portion of the additional frequency regulation reserves is due to the 'clear-sky-ramp' of solar generation, i.e. the continuously ramping of solar output versus the average power within the half-hour dispatch interval. The deviations can only be reduced by shorten dispatch interval.

In the scenario of large amount of small-scale and rooftop solar deployment, the load data seen from national load dispatch centre could be distorted due to lack of visibility on these small generators. The Virtual Power Plant and Aggregator topology are deployed to monitor and control the distributed small VRE generators in Germany and Spain. The latest developments of Advanced Distribution Management System (ADMS) are capable fulfil the monitor and control requirements as well the localised VRE forecast.

5.5.2 Possible Mitigations

System operators with high vRE penetration, German TSOs and REE Spain, adopted 15-minute dispatch interval, which is recommended for high penetration scenarios.

For the large amount of small-scale and rooftop solar deployment scenarios, implementation of VRE monitoring, control and forecast functions in the ADMS can greatly improve the observability and controllability. And subsequently preserve the accuracy of load data and provide VRE forecast to the NLDC for load forecasting and scheduling.

5.6 VRE forecast methodology/improvement

5.6.1 Discussions

Implementing and improving the VRE forecast methodology is crucial for a reliable system operation and more economical dispatch of conventional generators. System operators with high vRE penetration, e.g. German TSOs and REE Spain, adopted sophisticated renewable forecast system that can accurately forecast the output from vRE for scheduling. The accuracy of such forecast system continuously improves over time, and reduces the reserve quantum due to vRE forecast errors.

The VRE forecast systems are based on numerical weather predictions, and the methodology and measures for improvements are summarised in Table 26.

Table 26 RE forecast methodology and improvement measures

	Germany	Spain	Improvement measures
Prediction methodology	Combine forecasted power from commercial providers with weighted experience by 50Hertz (7 providers for wind[86] power, 5 providers for PV[87]). Energy production is also estimated for system reliability.	SIPREOLICO forecasts hourly wind power output for individual wind farm. Prediction method is based on neural networks (NN) with more than 800 NN, providing probabilistic interval outputs. Sipresolar uses NN and analogous days method, providing 15, 50 and 85 percentile predictions.	Combine wind prediction from multiple locations. Combine various types of vRE output (wind + solar).
Input data	Commercial power output forecast. Online measurements of: ▪ Wind speed and direction. ▪ Solar radiation. ▪ Temperature.	Numerical weather prediction model (NWP). Real production measurements. Forecast data: ▪ Wind speed and direction forecast. ▪ Solar radiation. ▪ Cloudiness.	Higher spatial resolution grid. Increase the update frequency of the NWP. Use satellite images to improve short-term forecast. Consider dust and other aerosols data in radiation prediction.
Prediction horizon	Day-ahead: up to 96 hours Short-term: up to 8 hours	Up to 240 hours	
Prediction accuracy	One day ahead root mean square error: 2-6% weekly	Mean absolute error/installed capacity: 1-4%	Can be improved with larger historical database or more advanced prediction models.

5.6.2 Possible Mitigations

The grid control centre can monitor and control the transmission connected LSS plants, including the irradiance sensors installed within the LSS facility. System-wide solar power forecast is required for reliable and economic operation of the system, especially the day-ahead and intraday rolling forecast.

For the large amount of small-scale and rooftop solar deployment scenarios, the ADMS can perform the forecast.

[86] 7 providers for wind forecast: EnergyMeteoSystems, IWES, EuroWind, MeteoGroup, WEPROG, Meteologica, Prognos Energy
[87] 5 providers for solar forecast: EnergyMeteoSystems, Meteocontol, Enercast, EnergyWeather, Meteologica

6 SUMMARY AND RECOMMENDATIONS

6.1 Key Summaries

The key summaries of the study are illustrated in Figure 127 with increases of solar penetration level. The system is technically capable to accommodate solar penetration up to 30% with increased cost of electricity. Post event frequency deviation are observed with penetration from 30% to 40%, this could be mitigated by dispatch more conventional units – more costly schedules. Starting from 40% penetration, scheduled solar curtailments occur on off-peak demand noon periods of weekends and public holidays, and severe solar curtailments are observed for 60% and 70% PV scenarios. For penetration level above 43%, both post event frequency and voltage stability issues are observed.

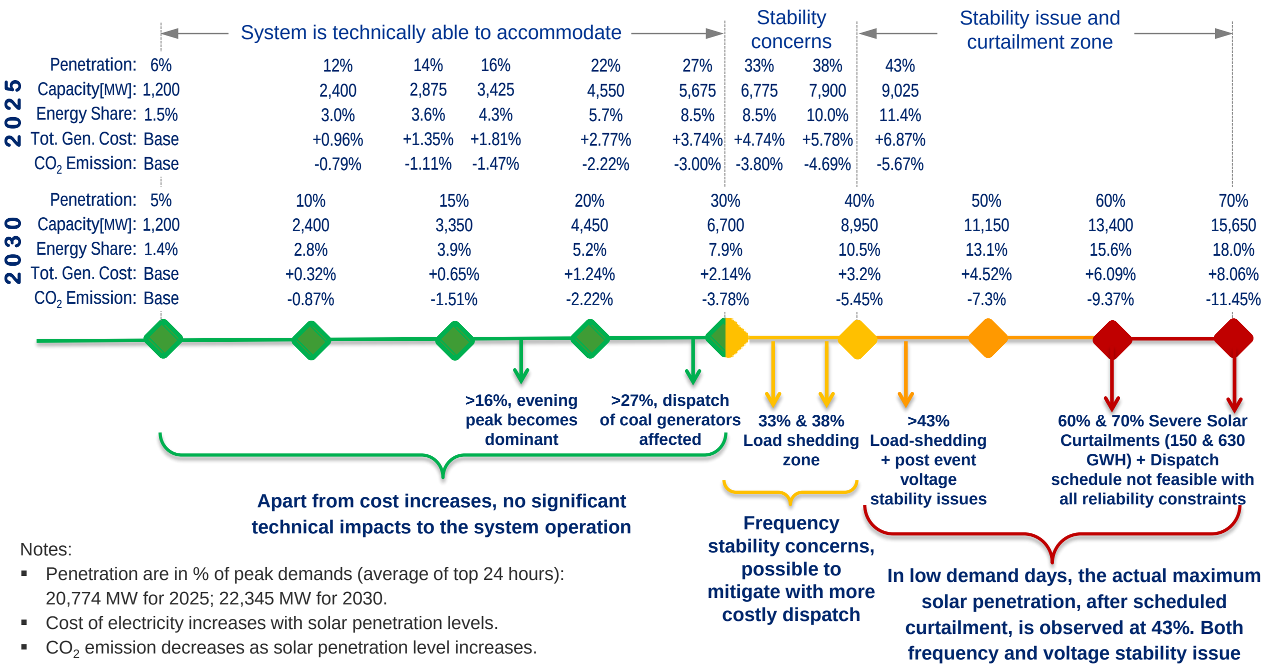


Figure 127 – Summary: Peninsular Malaysia energy transition

6.1.1 Solar variability and reserve requirement

The combined solar power output of the whole Peninsular Malaysia is smoothed out, high frequency and high magnitude power fluctuations are not observed.

With ½ hour dispatch interval, a spinning reserve equivalent to at least 8% of total PV installation capacity is required even without forecast error.

Based on 20% forecast error of individual locations and 99.73% confidence level, additional spinning reserves of 11% of installed solar capacity is required for Peninsular system.

Result summary is in Figure 128. Please refer to Section 4.2.5 for further details.

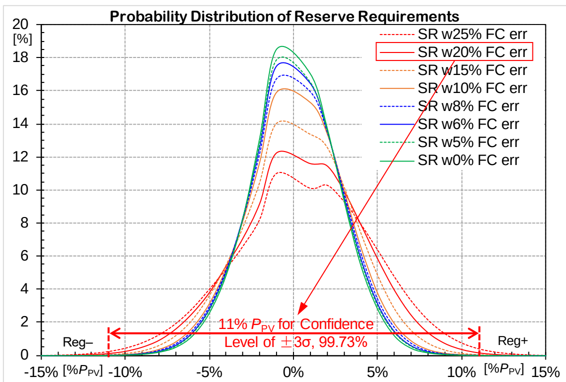


Figure 128 – Summary: probability distribution of reserve requirements

6.1.2 Long-term capacity expansion planning

The ability of solar to replace new conventional capacity largely depends on the matching between the fixed solar generation profile and the load profile.

The solar generation reduces the noon peaks to a level lower than evening peaks at penetration level of 20%.

The reductions new conventional capacities are effective from 5 to 20 percent penetration; become less effective from 25 to 40 percent penetration with rising LOLE; no reduction of conventional capacity post 40 percent penetration with slightly reduced LOLE.

The results are shown in Figure 129, refer to Section 4.3 for details.

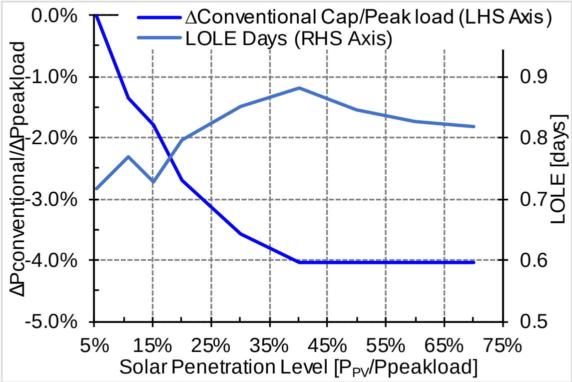


Figure 129 – Summary: Capacity planning for solar penetration levels

6.1.3 Mid/short-term operations

With increased solar penetration levels, solar energy share increases, CO_2 emission reduces and the cost of electricity increases. The 70% PV case results in solar energy share 18%; CO_2 reduction of 11.45% and cost of electricity increase of 8.06% comparing with the 5% PV base case.

Starting from 40% penetration, technical curtailments of solar occur in off-peak demand weekends and public holidays. At higher penetration, the actual solar power after scheduled curtailments remains at 43%.

Simulations results of year 2030 are summarised in Figure 130. Details for all study years are in Section 4.4.

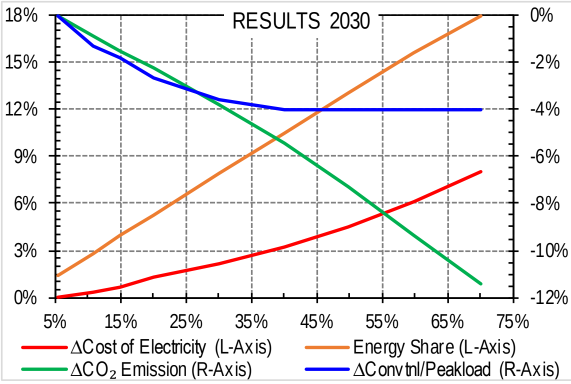


Figure 130 – Summary: Mid/short term simulation results for year 2030

As shown in sample netload profiles in a day in 2030 in Figure 131, the netload profiles are moderately modified up to 20% penetration, helping to reduce morning netload ramps while not increasing the afternoon ramps.

Starting 30% penetration, the noon troughs become lower than early morning trough, resulting in increased netload ramps during afternoons and sunsets.

At higher penetrations, very low or even negative noon netloads are observed during off-peak weekends and public holidays, where technical curtailments occur.

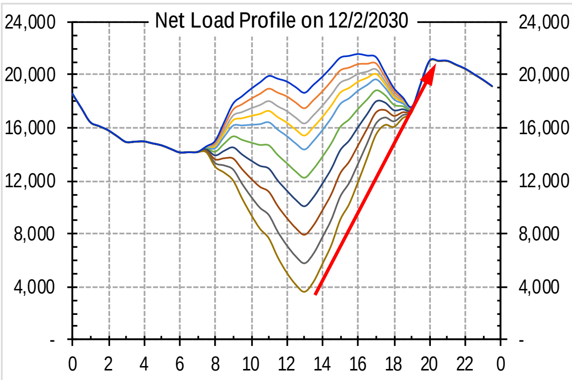


Figure 131 – Summary: netload profiles on a sample day in year 2030

As shown in the netLDCs for year 2030 in Figure 132, the solar generation reduces the peak loads at lower penetration levels up to 20% PV, after which the evening peaks become higher and the peak load reduction effect become insignificant.

Penetrations above 20% significantly reduce the trough loads, up to 8,714 MW with 70% PV.

The high solar penetration levels require flexible operations of the conventional generators, which are required cycle daily between the top-left and bottom-right corners of the netload duration curve.

Details of netload studies for all simulated years are in Section 4.4.

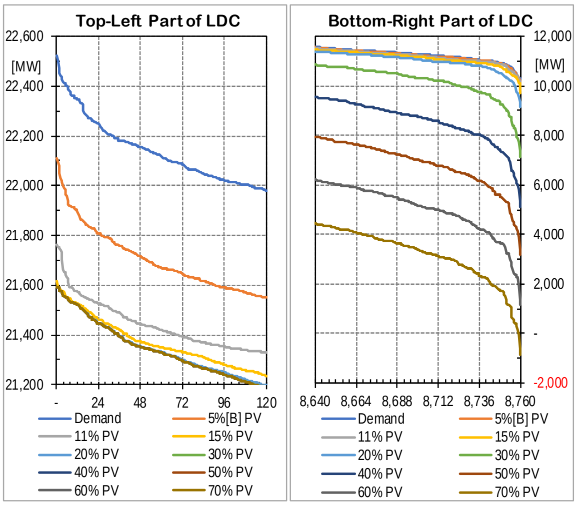


Figure 132 – Summary: netLDC for year 2030

6.1.4 Grid adequacy and system stability

The solar installations are connected to 132kV sub-transmission and distribution voltage levels, and are distributed across the Peninsular Malaysia.

Increased solar penetrations tend to slightly reduce the loadings of the transmission backbone system. Overall, the impact of solar generation is insignificant, as shown in Figure 133.

The quasi-dynamic power flow results of year 2025 and 2030 show the planned transmission backbone are adequate for all penetration levels.

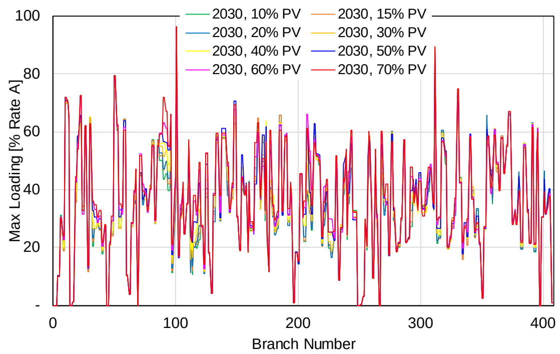


Figure 133 – Summary: backbone branch loading test

At high penetration levels, the system stability is challenged during high-irradiance off-peak weekends and public holidays, when the many conventional generators go offline to give way to solar generation. During these periods, the solar generations of 50-60-70 % PV cases are firstly curtailed to a level of 43%.

Shown in Figure 134, large frequency deviations, below the load-shedding frequency of 49.3Hz, are observed with 40% and above penetration with loss of the biggest online generator due to insufficient inertia and governor responses.

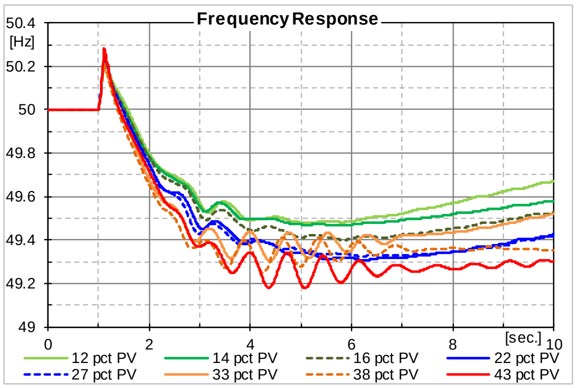


Figure 134 – Summary: system frequency response

6.1.5 Solar capacity credit

The capacity credits are computed based on ELCC method with load and solar profiles from 2025 to 2035 and normalised with installed solar capacity in percentage of the peak load of the year. The calculation results are shown in Figure 135.

The capacity credit of solar decreases rapidly with increased penetration levels. At 5% penetration, a 27% of the installed capacity can be treated as conventional generation; reduces to 17.2% with 20% PV and to 10% at 40% PV.

The average solar capacity credit represents the contribution from each installed PV unit towards the regional capacity requirements/reliability requirement. The credit value can serve as a reference capacity during future long-term planning.

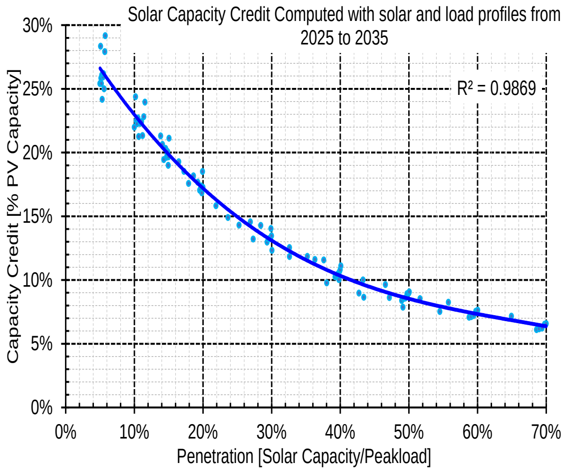


Figure 135 – Summary: solar capacity credit results

6.2 Recommendations

6.2.1 Penetration level based on current system and operation practices

The study results are evaluated on three aspects:

- Reliability: system frequency stability with credible contingent events.
- Affordability: incremental cost of electricity
- Environment Sustainability: contribution towards CO_2 emission reduction

Numerical results for the above three criteria are normalized to scores on a scale of 0 to 10, and plotted in the energy trilemma for various solar penetration levels in Figure 136.

The three scores are of equal importance, and the total sum/overall scores corresponding to each penetration level are illustrated in Figure 137.

According to system stability test results, the system remains reliable/stable for penetration up to 30%, which promotes environment sustainability but reduces affordability. Considering all the three dimensions, the penetration level of 20% brings the most benefits.

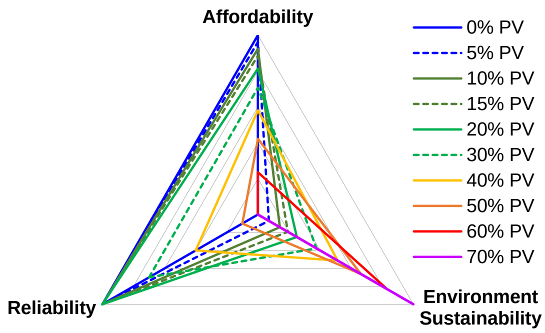


Figure 136 – Summary: energy trilemma

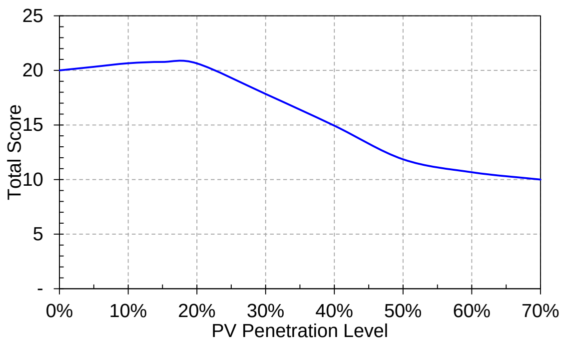


Figure 137 – Summary: overall scores for PV penetration assessment

Penetrations 30-40% stretch further the system towards sustainability while compromise the affordability. It could potentially impact the stability of the system under contingent events. This can be mitigated with more costly dispatch of conventional generators, thus further increases the cost of electricity or reduced affordability.

As discussed in Section 4.2.5, additional reserve capacity with the size of 11% of the installed PV generation capacity shall be provided by the system. Without sufficient reserve capacity, drastic fluctuations in PV output power might cause severe issues in system frequency stability.

Penetration above 40% resulted in scheduled curtailments, e.g. penetration of 50-70% are curtailed to a level of 43% during off-peak weekends and public holidays to fulfil the reserve constraints. Even after the scheduled curtailments, system under contingent condition shows frequency and voltage stability issues due to reduced inertia and governor response from online conventional generators.

6.2.2 Measures to enable higher renewable penetration

6.2.2.1 Interconnection standards (Grid Codes)

The current Malaysia grid codes have well cover the tehcnical requirements on large scale solar installations. The impact of the small scale solar installations to the system is similar to large scale. Hence, the core technical requirements should be extended to the small scale solar installations, including low-voltage ride through, reactive power range[88] and voltage regulation support, and overfrequency response.

The stablity tests show post event voltage recovery issues with high penetration levels during off-peak high-irradiance periods, when limited generators are online providing voltage support. This could be partially improved by the reactive current injection from solar inverters. For example, the German grid code calls for voltage support from renewable generators based on requirements stated in Figure 138.

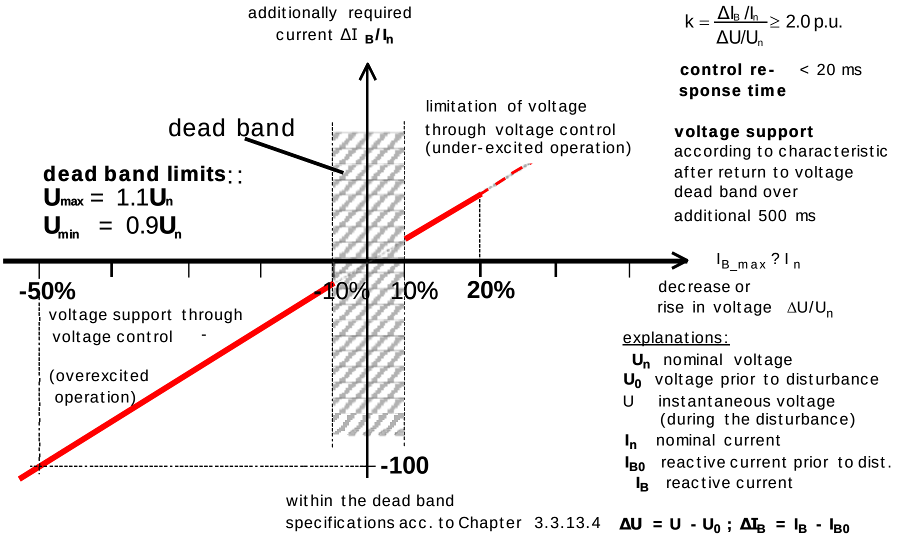


Figure 138 – German grid code requirement for voltage support from renewable generators

6.2.2.2 Wider balance area with interconnection

To achieve these penetration levels while maintaining stability of the system, interconnections with neighbouring system enabling electricity trading are required. During off-peak demand periods, part of the solar generation could be exported, and more conventional generators can go online to provide sufficient inertia and governor response. A strong interconnection enables the neighbouring generators participate in inertia and governor response during a contingent event.

6.2.2.3 Operation improvement

The reserve requirements / constraints significantly impact on scheduling with high solar penetrations. The reserve analysis of study has been conducted based on half-hour dispatch interval and non-correlated solar power forecast error of 20% (2σ) on individual locations.

Shorter dispatch interval: a significant part of the reserve requirement come from the solar 'clear-sky ramps', which can only be reduced with shorter dispatch interval. System operators with high vRE penetration, German TSOs and REE Spain, moved to 15-minute dispatch interval, which is recommended for high penetration.

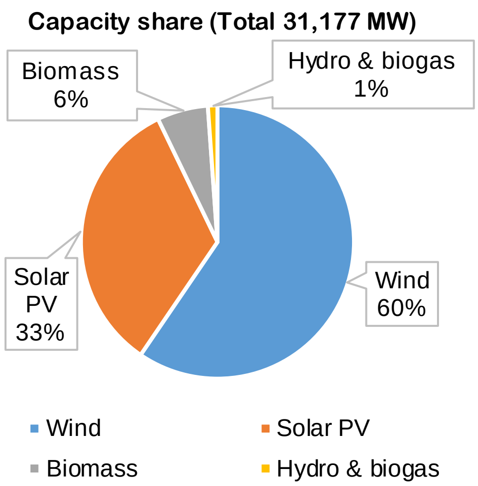
[88] The reactive power range could be less stringent comparing to LSS, UK and Europe codes call for 0.95 lagging and leading power factor.

Renewable forecast system: system operators with high vRE penetration, German TSOs and REE Spain, adopted sophisticated renewable forecast system that can accurately forecast the output from vRE for scheduling. The accuracy of such forecast system continuously improves over time, and reduces the reserve quantum due to vRE forecast errors. Such forecast system is need now allowing fine-tuning and accuracy improvements for high penetration in the future.

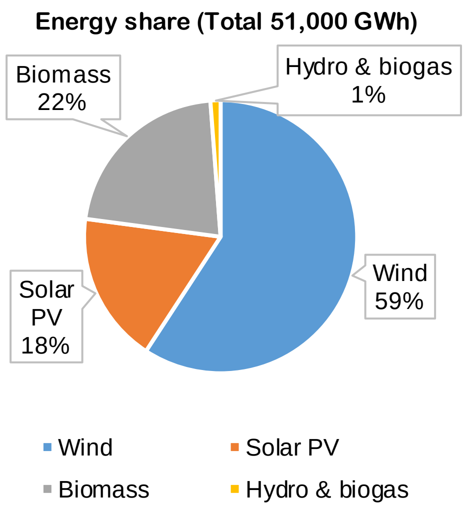
6.2.2.4 Diversified renewable portfolio

The solar generation is available during daylight hours and generate full power for a short period at noon, resulting in relatively low capacity factor and ineffective to increase the renewable energy share of the system. The solar installed capacities of 20% and 40% of peak load in 2030 result in an energy share of 5.23% and 10.52% only, where the 40% solar case poses challenges to system stability. To achieve higher share of renewable energy, a diversified renewable portfolio (hydroelectric, bioenergy and other forms) is recommended.

The renewable portfolio of 50Hertz system generated 51,000 GWh (53%) of the total 96,000 GWh electricity consumption. The renewable portfolio as illustrate in Figure 139.



(a)



(b)

Figure 139 – (a) Capacity share of RES in 50Hertz system; (b) Energy share of RES in 50Hertz system

The comparisons of capacity and energy shares illustrates the benefits of a diversified renewable portfolio to achieve high renewable energy share. Furthermore, the biomass, hydro and biogas generators are dispatchable.

7 DATA TABLES

This section contains the detailed data of the study.

Table 27 Installed generation capacity of surveyed countries (states)

	Global	Germany	Spain	Hawaii	California	Australia	China	India	Thailand	Philippines	Malaysia
Installed Capacity (2016)	[GW]	[GW]	[GW]	[GW]	[GW]	[GW]	[GW]	[GW]	[GW]	[GW]	[GW]
Total installed capacity	6,429.67	197.14	105.28	3.02	84.00	51.0897	1,645.69	317.73	41.56	21.42	28.90
Non-RE	4,413.37	93.88	53.38	2.02	45.47	33.42	1,087.52	225.11	32.91	14.47	22.31
Hydropower	1,096.00	5.60	20.35	0.02	14.00	7.31	332.11	44.48	2.54	3.62	6.09
Biomass, Biogas, Biodiesel	112.00	7.35	1.50	0.19	1.33	0.83	-	9.18	3.45	0.45	0.17
Geothermal	13.50	-	-	0.03	2.69	0.00	-	-	0.00	1.92	-
Concentrating solar (CSP)	4.80	-	-		1.25	0.00	-	0.20	-	-	-
Wind power	487.00	49.59	23.07	0.20	5.64	4.33	148.64	28.87	0.51	0.43	-
Solar PV	303.00	40.72	6.97	0.55	13.62	5.20	77.42	9.89	2.15	0.54	0.33
Capacity Share (2016)	Global	Germany	Spain	Hawaii	California	Australia	China	India	Thailand	Philippines	Malaysia
Non-RE	68.6%	47.6%	50.7%	67.1%	54.1%	65.4%	66.1%	70.8%	79.2%	67.5%	77.2%
Dispatchable RE	19.1%	6.6%	20.8%	8.0%	22.9%	15.9%	20.2%	17.0%	14.4%	28.0%	21.6%
Variable RE	12.3%	45.8%	28.5%	25.0%	22.9%	18.7%	13.7%	12.2%	6.4%	4.5%	1.1%

Table 28 Electricity production share of surveyed countries (states)

Electricity Production Share	Global	Spain	Germany	California	Hawaii	Australia	China	India	Philippines	Thailand	Malaysia
Non-RE	75.5%	59.3%	66.4%	64.3%	74.2%	83.8%	75.2%	83.6%	75.8%	92.0%	87.2%
Hydropower	16.6%	14.9%	3.8%	11.9%	0.6%	7.0%	19.7%	10.5%	8.9%	2.0%	11.8%
Biomass (Biogas, Biodiesel)	2.0%	2.6%	8.7%	2.3%	5.2%	1.3%	-	1.2%	0.8%	4.8%	0.7%
Other RE (Geoth, CSP, Ocean)	0.4%	-	-	4.4%	2.9%	-	-	-	12.2%	-	-
Solar PV	1.5%	18.2%	6.9%	8.1%	7.4%	2.8%	1.1%	1.1%	1.2%	1.0%	0.2%
Wind	4.0%	5.0%	14.3%	9.1%	9.6%	5.1%	4.0%	3.7%	1.1%	0.2%	-
Non-RE	75.5%	59.3%	66.4%	64.3%	74.2%	83.8%	75.2%	83.6%	75.8%	92.0%	87.2%
Dispatchable RE	19.0%	17.5%	12.4%	18.5%	8.8%	8.3%	19.7%	11.7%	21.9%	6.8%	12.5%
Variable RE	5.5%	23.2%	21.2%	17.2%	17.0%	7.9%	5.1%	4.8%	2.3%	1.2%	0.2%

Table 29 Historical Wind capacity growth of surveyed countries (states)

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	CAGR*
Installed Wind Capacity (MW)											

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	CAGR*
Australia	1,249	1,441	1,703	1,864	2,127	2,561	3,221	3,797	4,234	4,327	14.8%
California	1,734	1,799	2,090	2,230	3,184	5,152	5,152	5,387	5,671	5,671	14.1%
China	6,031	12,174	17,672	31,468	48,171	63,129	76,771	96,619	129,638	148,983	42.8%
Germany	22,183	23,815	25,692	27,180	29,060	31,304	34,660	39,193	44,670	49,747	9.4%
Hawaii	62	62	62	62	92	206	206	206	206	206	14.3%
India	7,845	9,655	10,926	13,065	16,084	18,421	20,150	22,465	25,088	28,875	15.6%
Philippines	33	33	33	33	33	33	33	337	427	427	32.9%
Spain	14,820	16,555	19,176	20,693	21,529	22,789	22,958	22,975	22,943	22,992	5.0%
Thailand	1	1	5	6	7	112	223	225	234	507	99.8%
Wind Annual Growth Rate											
Australia		15.4%	18.2%	9.5%	14.1%	20.4%	25.8%	17.9%	11.5%	2.2%	
California		3.7%	16.2%	6.7%	42.8%	61.8%	-	4.5%	5.3%	-	
China		101.9%	45.2%	78.1%	53.1%	31.1%	21.6%	25.9%	34.2%	14.9%	
Germany		7.4%	7.9%	5.8%	6.9%	7.7%	10.7%	13.1%	14.0%	11.4%	
Hawaii		-	-	-	48.7%	124.5%	-	-	-	-	
India		23.1%	13.2%	19.6%	23.1%	14.5%	9.4%	11.5%	11.7%	15.1%	
Philippines		-	-	-	-	-	-	921.2%	26.7%	-	
Spain		11.7%	15.8%	7.9%	4.0%	5.9%	0.7%	0.1%	-0.1%	0.2%	
Thailand		-	400.0%	20.0%	16.7%	1500.0%	99.1%	0.9%	4.0%	116.7%	

*CAGR: Compound Annual Growth Rate, calculated as $(MW_{2016}/MW_{2007})^{1/9}$-1

Table 30 Historical Solar capacity growth of surveyed countries (states)

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	CAGR*
Installed Solar Capacity (MW)											
Australia	70	82	105	399	1,394	2,432	3,255	4,004	4,357	5,202	61.4%
California	366	376	420	446	597	1,044	3,362	5,806	7,062	8,619	42.0%
China	198	253	431	958	3,478	7,018	17,748	28,388	43,538	77,788	94.2%
Germany	4,170	6,120	10,564	17,552	25,037	32,641	36,335	38,234	39,786	40,986	28.9%
Hawaii	5	14	26	45	85	200	358	447	564	674	74.5%
India	4	10	12	37	563	1,277	2,269	3,144	5,271	9,658	137.6%
Malaysia	7	9	11	13	14	32	138	203	262	333	53.6%
Philippines	1	1	1	1	1	1	1	22	132	542	101.3%

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	CAGR*
Spain	739	3,389	3,488	3,921	4,352	4,646	4,785	4,787	4,856	4,871	23.3%
Thailand	32	32	37	49	79	377	824	1,299	1,420	2,149	59.6%
Solar Annual Growth Rate											
Australia		17.1%	28.0%	280.0%	249.4%	74.5%	33.8%	23.0%	8.8%	19.4%	
California		2.6%	11.7%	6.4%	33.8%	74.8%	222.1%	72.7%	21.6%	22.1%	
China		27.8%	70.4%	122.3%	263.0%	101.8%	152.9%	60.0%	53.4%	78.7%	
Germany		46.8%	72.6%	66.1%	42.6%	30.4%	11.3%	5.2%	4.1%	3.0%	
Hawaii		200.0%	94.1%	70.6%	90.6%	134.2%	79.5%	24.8%	26.2%	19.5%	
India		150.0%	20.0%	208.3%	1421.6%	126.8%	77.7%	38.6%	67.7%	83.2%	
Malaysia		28.6%	22.2%	18.2%	7.7%	128.6%	331.3%	47.1%	29.1%	27.1%	
Philippines		-	-	-	-	-	-	2100.0%	500.0%	310.6%	
Spain		358.6%	2.9%	12.4%	11.0%	6.8%	3.0%	0.0%	1.4%	0.3%	
Thailand		-	15.6%	32.4%	61.2%	377.2%	118.6%	57.6%	9.3%	51.3%	

*CAGR: Compound Annual Growth Rate, calculated as $(MW_{2016}/MW_{2007})^{1/9}-1$

Table 31 Filtered transmission backbone loadings [≥55%] of 2025

From Bus [#, Name kV]	To Bus [#, Name kV]	CKT ID	Rate A	2025,12%PV			2025,14%PV			2025,16%PV			2025,22%PV			2025,27%PV			2025,33%PV			2025,38%PV			2025,43%PV		
				Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]
101 PKLW275	552011 CBPS275B	3	683	24	60	12	24	60	12	23	58	12	22	60	12	22	60	12	21	57	12	20	57	11	20	58	11
101 PKLW275	552011 CBPS275B	4	683	24	60	12	24	60	12	23	58	12	22	60	12	22	60	12	21	57	12	20	57	11	20	58	11
52002 SHLB275	52011 CBPS275	1	683	24	60	11	23	61	11	24	58	11	23	59	11	24	62	10	24	63	10	24	63	11	24	64	11
52002 SHLB275	52011 CBPS275	2	683	24	60	11	23	61	11	24	58	11	23	59	11	24	62	10	24	63	10	24	63	11	24	64	11
52003 PKLG275	52024 BRGS275	1	1000	54	83	11	53	84	11	53	82	11	53	83	11	53	84	11	53	85	11	53	83	11	53	82	11
52003 PKLG275	52024 BRGS275	2	1,000	54	83	11	53	84	11	53	82	11	53	83	11	53	84	11	53	85	11	53	83	11	53	82	11
52006 BUGL275	55004 BUGL500	X1	1,050	44	59	6	44	59	6	43	59	6	43	59	6	42	59	6	42	60	6	41	59	6	41	58	6
52006 BUGL275	55004 BUGL500	X2	1,050	44	59	6	44	59	6	43	59	6	43	59	6	42	59	6	42	60	6	41	59	6	41	58	6
52007 SRDE275	88206 PULU275	1	683	33	66	9	33	66	9	32	61	9	31	66	9	30	62	9	29	62	9	28	59	9	27	60	10
52007 SRDE275	88206 PULU275	2	683	33	66	9	33	66	9	32	61	9	31	66	9	30	62	9	29	62	9	28	59	9	27	60	10
52011 CBPS275	52024 BRGS275	1	683	32	67	12	32	65	12	32	65	12	32	68	12	32	73	12	32	69	11	32	69	11	33	67	11
52011 CBPS275	52024 BRGS275	2	683	32	67	12	32	65	12	32	65	12	32	68	12	32	73	12	32	69	11	32	69	11	33	67	11
52052 BTRK275	55002 BTRK500	X1	750	41	58	6	41	58	6	41	60	6	42	60	6	42	59	6	42	59	6	42	61	6	42	61	6
52052 BTRK275	55002 BTRK500	X2	750	41	58	6	41	58	6	41	60	6	42	60	6	42	59	6	42	59	6	42	61	6	42	61	6
52052 BTRK275	55002 BTRK500	X3	750	41	58	6	41	58	6	41	60	6	42	60	6	42	59	6	42	59	6	42	61	6	42	61	6
52052 BTRK275	88201 KULN275	1	683	26	58	8	26	57	8	27	58	8	28	59	9	29	62	9	30	66	10	30	67	10	31	71	11
52052 BTRK275	88201 KULN275	2	683	26	58	8	26	57	8	27	58	8	28	59	9	29	62	9	30	66	10	30	67	10	31	71	11

From Bus [#, Name kV]	To Bus [#, Name kV]	CKT ID	Rate A	2025,12%PV			2025,14%PV			2025,16%PV			2025,22%PV			2025,27%PV			2025,33%PV			2025,38%PV			2025,43%PV		
				Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]
52053 KPAR275	55003 KPAR500	X1	750	45	118	19	44	111	19	44	109	19	42	107	19	40	104	19	39	108	19	39	110	19	38	107	19
55003 KPAR500	552053 KPAR275R	X2	750	48	82	11	48	82	11	49	85	11	50	86	11	51	89	11	51	91	11	52	93	11	53	95	12
62212 BTBN275	62215 NPRI275	1	683	25	62	10	25	55	10	24	55	10	24	54	10	24	55	11	23	56	11	23	55	11	23	60	12
62212 BTBN275	62215 NPRI275	2	683	25	62	10	25	55	10	24	55	10	24	54	10	24	55	11	23	56	11	23	55	11	23	60	12
63204 PAPN275	63208 KKSR275	1	487	15	42	7	14	41	8	14	41	8	13	40	8	13	41	8	13	48	8	13	55	8	13	62	8
63204 PAPN275	63208 KKSR275	2	487	15	42	7	14	41	8	14	41	8	13	40	8	13	41	8	13	48	8	13	55	8	13	62	8
63206 TMGR275	75208 PGAU275	1	487	23	52	9	23	55	9	23	54	9	22	59	9	22	64	9	21	55	9	21	60	9	21	57	9
63206 TMGR275	75208 PGAU275	2	487	23	52	9	23	55	9	23	54	9	22	59	9	22	64	9	21	55	9	21	60	9	21	57	9
63207 KNRG275	63208 KKSR275	1	487	16	63	9	16	64	9	16	72	9	16	61	10	16	63	10	16	66	10	16	63	10	16	70	11
63213 ATWR275	63504 ATWR500	X1	750	49	65	6	48	67	6	48	67	6	47	66	6	46	65	7	45	66	7	44	66	8	42	65	9
63213 ATWR275	63504 ATWR500	X2	750	49	65	6	48	67	6	48	67	6	47	66	6	46	65	7	45	66	7	44	66	8	42	65	9
63213 ATWR275	63504 ATWR500	X3	750	51	75	6	50	71	6	50	76	6	49	73	7	49	74	7	48	70	8	47	74	8	46	68	9
74206 KAWA275	96228 BAHS275	1	683	39	70	11	38	70	11	37	68	11	35	70	12	33	69	13	31	69	13	29	68	14	28	66	14
74206 KAWA275	96228 BAHS275	2	683	39	70	11	38	70	11	37	68	11	35	70	12	33	69	13	31	69	13	29	68	14	28	66	14
74208 BNTS275	74502 BNTS500	X1	1050	42	58	5	42	57	5	42	56	5	42	56	5	41	57	5	40	55	5	40	56	5	39	55	6
74208 BNTS275	74502 BNTS500	X2	1,050	42	58	5	42	57	5	42	56	5	42	56	5	41	57	5	40	55	5	40	56	5	39	55	6
75201 TMRH275	75206 JELI275	1	574	19	58	8	19	58	8	18	55	9	18	57	9	17	57	9	16	60	9	16	58	10	16	60	10
75201 TMRH275	75208 PGAU275	2	574	20	59	8	19	58	8	19	56	9	18	58	9	18	58	9	17	61	10	17	59	10	16	61	10
75206 JELI275	75208 PGAU275	1	574	21	60	9	21	60	9	20	58	9	20	59	9	19	59	9	18	62	10	18	60	10	17	62	10
75216 PGWI275	175202 KNYR_F1	1	587	10	54	8	10	57	8	10	56	8	11	58	8	11	61	8	11	57	8	12	55	9	12	58	9
88205 KPDN275	88212 TRX275	1	500	55	65	8	54	65	8	54	65	8	54	65	9	55	65	8	55	65	8	55	65	8	54	65	8
88205 KPDN275	88212 TRX275	2	500	55	65	8	54	65	8	54	65	8	54	65	9	55	65	8	55	65	8	55	65	8	54	65	8
96205 LGNG275	96501 LGNG500	X1	750	46	59	5	46	58	5	45	59	5	45	58	5	45	58	5	44	58	5	44	59	5	43	58	6
96205 LGNG275	96501 LGNG500	X2	750	46	59	5	46	58	5	45	59	5	45	58	5	45	58	5	44	58	5	44	59	5	43	58	6
96205 LGNG275	96501 LGNG500	X3	750	47	59	6	47	59	6	47	59	6	46	59	6	46	59	6	45	59	6	45	59	6	44	59	6
96220 PDPS275	596201 TJGS275R	1	683	8	57	8	8	57	8	7	57	7	7	57	7	7	57	7	6	56	6	6	57	7	6	59	6
96220 PDPS275	596201 TJGS275R	2	683	8	57	8	8	57	8	7	57	7	7	57	7	7	57	7	6	56	6	6	57	7	6	59	6
96224 KLMK275	96227 RTAU275	1	683	28	60	14	28	60	14	27	60	14	26	60	14	24	61	14	23	61	14	21	62	14	20	65	14
96224 KLMK275	96227 RTAU275	2	683	28	60	14	28	60	14	27	60	14	26	60	14	24	61	14	23	61	14	21	62	14	20	65	14
96255 AGJH275	96555 AGJH500	X1	1,050	40	65	16	39	65	16	38	65	16	36	66	16	35	64	16	34	65	17	33	65	16	32	65	17
96255 AGJH275	96555 AGJH500	X2	1,050	41	64	14	41	66	14	40	65	14	40	67	13	38	66	14	40	69	13	38	68	14	39	70	13
97203 YGPN275	97212 BBTU275	1	683	32	69	14	32	69	14	31	69	14	30	68	14	28	69	15	26	68	15	24	69	14	23	69	14
97205 PGPS275	97206 PGGS275	1	650	36	60	19	36	61	19	36	61	19	34	61	19	33	60	19	31	61	19	29	62	19	28	60	19
97205 PGPS275	97206 PGGS275	2	650	36	60	19	36	61	19	36	61	19	34	61	19	33	60	19	31	61	19	29	62	19	28	60	19
97206 PGGS275	97235 PGPN275	1	683	34	57	18	34	58	18	34	58	18	32	58	18	31	57	18	29	58	18	28	59	18	27	57	18
97206 PGGS275	97235 PGPN275	2	683	34	57	18	34	58	18	34	58	18	32	58	18	31	57	18	29	58	18	28	59	18	27	57	18
97207 KTBR275	97208 PMJY275	1	683	40	67	20	39	68	20	39	67	20	37	67	20	35	67	20	33	67	20	31	67	19	29	68	18
97207 KTBR275	97208 PMJY275	2	683	40	67	20	39	68	20	39	67	20	37	67	20	35	67	20	33	67	20	31	67	19	29	68	18

From Bus [#, Name kV]	To Bus [#, Name kV]	CKT ID	Rate A	2025,12%PV			2025,14%PV			2025,16%PV			2025,22%PV			2025,27%PV			2025,33%PV			2025,38%PV			2025,43%PV		
				Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]
97232 GPTH275	97234 TBIN275	1	683	31	54	8	31	54	8	31	54	8	32	56	8	32	53	8	33	55	8	34	56	8	35	56	8
97232 GPTH275	97234 TBIN275	2	683	31	54	8	31	54	8	31	54	8	32	56	8	32	53	8	33	55	8	34	56	8	35	56	8

Table 32 Filtered transmission backbone loadings [≥55%] of 2030

From Bus [#, Name, kV]	To Bus [#, Name, kV]	CKT ID	Rate A	2030, 10% PV			2030, 15% PV			2030, 20% PV			2030, 30% PV			2030, 40% PV			2030, 50% PV			2030, 60% PV			2030, 70% PV		
				Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]
52003 PKLG275 275	52024 BRGS275 275	3	683	44	70	8	45	71	8	45	71	9	45	70	8	45	70	8	45	72	9	45	71	9	45	72	9
52003 PKLG275 275	52024 BRGS275 275	4	683	44	70	8	45	71	8	45	71	9	45	70	8	45	70	8	45	72	9	45	71	9	45	72	9
52003 PKLG275 275	52053 KPAR275 275	1	1,000	35	70	14	35	70	14	35	71	15	35	71	14	34	70	14	34	70	14	33	70	15	32	70	15
52003 PKLG275 275	52053 KPAR275 275	2	1000	32	65	13	32	65	13	32	66	13	32	65	13	32	65	13	31	65	13	31	65	14	30	65	14
52005 SRDG275 275	52022 PCHP275 275	1	683	26	58	10	25	58	10	26	58	10	25	58	10	24	57	10	24	59	10	24	56	10	23	54	9
52005 SRDG275 275	52022 PCHP275 275	2	683	26	58	10	25	58	10	26	58	10	25	58	10	24	57	10	24	59	10	24	56	10	23	54	9
52005 SRDG275 275	88202 KULS275 275	1	683	28	64	11	27	64	10	29	66	10	29	65	10	29	63	10	30	66	10	30	72	9	30	73	8
52005 SRDG275 275	88202 KULS275 275	2	683	28	64	11	27	64	10	29	66	10	29	65	10	29	63	10	30	66	10	30	72	9	30	73	8
52006 BUGL275 275	55004 BUGL500 500	X1	1,050	39	61	8	39	62	8	39	62	8	39	61	7	38	60	7	38	62	7	37	61	7	37	62	7
52006 BUGL275 275	55004 BUGL500 500	X2	1,050	39	61	8	39	62	8	39	62	8	39	61	7	38	60	7	38	62	7	37	61	7	37	62	7
52007 SRDE275 275	88206 PULU275 275	1	683	34	65	10	33	64	10	33	65	10	31	65	11	30	63	11	29	62	11	28	59	12	27	63	12
52007 SRDE275 275	88206 PULU275 275	2	683	34	65	10	33	64	10	33	65	10	31	65	11	30	63	11	29	62	11	28	59	12	27	63	12
52014 ELMW275 275	52053 KPAR275 275	1	683	47	79	13	47	79	13	47	78	14	47	78	14	47	79	14	46	80	14	46	79	14	44	79	14
52014 ELMW275 275	52053 KPAR275 275	2	683	47	79	13	47	79	13	47	78	14	47	78	14	47	79	14	46	80	14	46	79	14	44	79	14
52014 ELMW275 275	88201 KULN275 275	1	683	33	61	12	33	61	12	33	60	12	33	61	12	33	62	12	33	62	12	32	62	12	31	62	12
52014 ELMW275 275	88201 KULN275 275	2	683	33	61	12	33	61	12	33	60	12	33	61	12	33	62	12	33	62	12	32	62	12	31	62	12
52022 PCHP275 275	52027 OLPT275 275	1	1,000	35	64	10	35	64	10	35	64	10	34	64	10	34	63	9	34	64	9	33	62	9	33	61	9
52022 PCHP275 275	52027 OLPT275 275	2	1,000	35	64	10	35	64	10	35	64	10	34	64	10	34	63	9	34	64	9	33	62	9	33	61	9
52049 PIDH275 275	52051 BTGK275 275	1	683	24	57	13	24	57	13	23	56	13	22	56	13	21	55	13	21	55	14	20	55	14	18	55	15
52049 PIDH275 275	52051 BTGK275 275	2	683	24	57	13	24	57	13	23	56	13	22	56	13	21	55	13	21	55	14	20	55	14	18	55	15
52051 BTGK275 275	552011 CBPS275B 275	1	683	24	57	13	24	57	13	23	56	13	22	56	13	21	55	13	21	55	14	20	55	14	18	55	15
52051 BTGK275 275	552011 CBPS275B 275	2	683	24	57	13	24	57	13	23	56	13	22	56	13	21	55	13	21	55	14	20	55	14	18	55	15
52052 BTRK275 275	55002 BTRK500 500	X1	750	31	50	9	32	52	9	31	53	9	31	55	9	31	56	9	31	59	9	31	60	9	31	59	9
52052 BTRK275 275	55002 BTRK500 500	X2	750	31	50	9	32	52	9	31	53	9	31	55	9	31	56	9	31	59	9	31	60	9	31	59	9
52052 BTRK275 275	55002 BTRK500 500	X3	750	31	50	9	32	52	9	31	53	9	31	55	9	31	56	9	31	59	9	31	60	9	31	59	9
52052 BTRK275 275	63210 TPAH275 275	1	683	10	43	5	11	47	6	11	47	6	12	52	7	13	56	8	15	57	10	16	63	12	18	72	15
52052 BTRK275 275	63210 TPAH275 275	2	683	10	43	5	11	47	6	11	47	6	12	52	7	13	56	8	15	57	10	16	63	12	18	72	15
52053 KPAR275 275	55003 KPAR500 500	X1	750	15	51	11	15	51	11	16	53	11	16	54	11	16	62	11	16	66	11	16	63	11	17	66	12
55003 KPAR500 500	552053 KPAR275R 275	X2	750	15	54	10	16	59	10	19	62	11	21	71	13	24	78	15	27	88	18	30	96	19	32	96	21
61223 JJNG275 275	61523 JJNG500 500	X1	1,050	36	58	7	35	58	8	33	59	8	32	59	10	30	56	10	29	57	11	28	58	12	27	60	12
61223 JJNG275 275	61523 JJNG500 500	X2	1,050	36	58	7	35	58	8	33	59	8	32	59	10	30	56	10	29	57	11	28	58	12	27	60	12

From Bus [#, Name, kV]		To Bus [#, Name, kV]		CKT ID	Rate A	2030, 10% PV			2030, 15% PV			2030, 20% PV			2030, 30% PV			2030, 40% PV			2030, 50% PV			2030, 60% PV			2030, 70% PV		
						Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]	Avg [%]	Max [%]	σ [%]
61223 JJNG275	275	61523 JJNG500	500	X3	1,050	36	58	7	35	58	8	33	59	8	32	59	10	30	56	10	29	57	11	28	58	12	27	60	12
61223 JJNG275	275	62212 BTBN275	275	1	683	38	58	7	37	58	7	36	58	7	35	57	8	33	58	9	32	61	10	31	59	11	29	60	12
61223 JJNG275	275	62212 BTBN275	275	2	683	38	58	7	37	58	7	36	58	7	35	57	8	33	58	9	32	61	10	31	59	11	29	60	12
61223 JJNG275	275	62212 BTBN275	275	3	683	38	58	7	37	58	7	36	58	7	35	57	8	33	58	9	32	61	10	31	59	11	29	60	12
61223 JJNG275	275	62212 BTBN275	275	4	683	38	58	7	37	58	7	36	58	7	35	57	8	33	58	9	32	61	10	31	59	11	29	60	12
62212 BTBN275	275	62215 NPRI275	275	1	683	37	63	10	36	63	10	34	63	10	33	63	11	31	65	12	30	71	13	29	68	14	28	69	14
62212 BTBN275	275	62215 NPRI275	275	2	683	37	63	10	36	63	10	34	63	10	33	63	11	31	65	12	30	71	13	29	68	14	28	69	14
63204 PAPN275	275	63218 BGJH275	275	1	573	35	63	8	34	65	8	32	62	9	30	61	11	28	61	11	27	59	11	27	60	10	28	63	10
63204 PAPN275	275	63218 BGJH275	275	2	573	35	63	8	34	65	8	32	62	9	30	61	11	28	61	11	27	59	11	27	60	10	28	63	10
63206 TMGR275	275	75208 PGAU275	275	1	487	12	56	7	12	52	7	12	50	7	12	57	7	12	59	7	12	59	7	13	48	7	13	51	7
63206 TMGR275	275	75208 PGAU275	275	2	487	12	56	7	12	52	7	12	50	7	12	57	7	12	59	7	12	59	7	13	48	7	13	51	7
63207 KNRG275	275	63208 KKSR275	275	1	487	13	53	8	13	57	8	13	56	9	13	60	9	13	64	10	13	62	10	14	57	10	15	56	11
63213 ATWR275	275	63218 BGJH275	275	1	683	41	66	9	40	66	9	38	63	9	36	63	10	34	63	11	32	62	12	30	63	13	28	61	14
63213 ATWR275	275	63218 BGJH275	275	2	683	41	66	9	40	66	9	38	63	9	36	63	10	34	63	11	32	62	12	30	63	13	28	61	14
63213 ATWR275	275	63504 ATWR500	500	X1	750	29	57	10	28	57	10	30	59	10	28	58	11	28	58	11	27	59	12	27	59	12	26	58	13
63213 ATWR275	275	63504 ATWR500	500	X2	750	29	57	10	28	57	10	30	59	10	28	58	11	28	58	11	27	59	12	27	59	12	26	58	13
63213 ATWR275	275	63504 ATWR500	500	X3	750	29	58	10	29	58	10	30	60	10	29	59	11	28	58	11	28	60	12	27	60	12	26	59	13
74206 KAWA275	275	96228 BAHS275	275	1	683	23	60	10	21	59	10	23	61	11	21	59	11	19	57	11	19	63	10	19	57	10	20	56	9
74206 KAWA275	275	96228 BAHS275	275	2	683	23	60	10	21	59	10	23	61	11	21	59	11	19	57	11	19	63	10	19	57	10	20	56	9
88205 KPDN275	275	88215 AMPG275	275	1	683	28	59	10	27	59	10	27	60	10	26	60	10	25	56	10	24	59	10	23	56	10	23	57	10
88205 KPDN275	275	88215 AMPG275	275	2	683	28	59	10	27	59	10	27	60	10	26	60	10	25	56	10	24	59	10	23	56	10	23	57	10
96202 MCCA275	275	96902 N28SMTRA	275	U1	670	70	89	31	69	90	31	69	89	31	69	89	31	69	89	31	69	89	32	69	89	32	69	89	33
96205 LGNG275	275	96501 LGNG500	500	X1	750	39	60	7	39	61	7	39	60	7	38	60	7	38	58	7	37	58	7	37	57	7	36	57	7
96205 LGNG275	275	96501 LGNG500	500	X2	750	39	60	7	39	61	7	39	60	7	38	60	7	38	58	7	37	58	7	37	57	7	36	57	7
96205 LGNG275	275	96501 LGNG500	500	X3	750	39	60	7	39	61	7	39	60	7	38	60	7	38	58	7	37	58	7	37	57	7	36	57	7
96224 KLMK275	275	96227 RTAU275	275	1	683	26	68	16	24	70	15	26	72	16	24	72	15	23	67	14	23	70	14	22	73	13	23	75	13
96224 KLMK275	275	96227 RTAU275	275	2	683	26	68	16	24	70	15	26	72	16	24	72	15	23	67	14	23	70	14	22	73	13	23	75	13
96255 AGJH275	275	96555 AGJH500	500	X1	1,050	26	59	16	25	59	15	26	59	15	23	59	15	22	59	15	21	59	16	20	59	15	19	58	15
96255 AGJH275	275	96555 AGJH500	500	X2	1,050	26	59	16	25	59	15	26	59	15	23	59	15	22	59	15	21	59	16	20	59	15	19	58	15
97203 YGPN275	275	97213 YGPE275	275	1	683	36	56	6	36	56	6	35	55	6	36	58	6	36	57	6	36	59	6	36	59	6	35	59	7
97203 YGPN275	275	97213 YGPE275	275	2	683	36	56	6	36	56	6	35	55	6	36	58	6	36	57	6	36	59	6	36	59	6	35	59	7
97204 SDAI275	275	97207 KTBR275	275	1	683	23	60	15	25	59	15	24	61	15	26	60	15	28	61	15	28	61	14	29	61	14	27	59	14
97204 SDAI275	275	97207 KTBR275	275	2	683	23	60	15	25	59	15	24	61	15	26	60	15	28	61	15	28	61	14	29	61	14	27	59	14
97205 PGPS275	275	97206 PGGS275	275	1	650	30	59	22	28	59	22	29	58	22	25	58	21	22	58	20	21	58	19	20	58	18	22	58	17
97205 PGPS275	275	97206 PGGS275	275	2	650	30	59	22	28	59	22	29	58	22	25	58	21	22	58	20	21	58	19	20	58	18	22	58	17
97207 KTBR275	275	97208 PMJY275	275	1	683	26	66	15	24	67	14	25	67	14	23	67	13	21	66	12	19	66	11	18	66	10	16	67	10
97207 KTBR275	275	97208 PMJY275	275	2	683	26	66	15	24	67	14	25	67	14	23	67	13	21	66	12	19	66	11	18	66	10	16	67	10
97212 BBTU275	275	97502 BBTU500	500	X1	1,050	33	56	8	34	55	8	33	56	8	34	56	8	35	56	8	36	56	7	36	56	7	35	55	7

From Bus [#, Name, kV]	To Bus [#, Name, kV]	CKT ID	Rate A	2030, 10% PV Avg [%]	Max [%]	σ [%]	2030, 15% PV Avg [%]	Max [%]	σ [%]	2030, 20% PV Avg [%]	Max [%]	σ [%]	2030, 30% PV Avg [%]	Max [%]	σ [%]	2030, 40% PV Avg [%]	Max [%]	σ [%]	2030, 50% PV Avg [%]	Max [%]	σ [%]	2030, 60% PV Avg [%]	Max [%]	σ [%]	2030, 70% PV Avg [%]	Max [%]	σ [%]
97212 BBTU275 275	97502 BBTU500 500	X2	1,050	33	56	8	34	55	8	33	56	8	34	56	8	35	56	8	36	56	7	36	56	7	35	55	7
97212 BBTU275 275	97502 BBTU500 500	X3	1,050	33	56	8	34	55	8	33	56	8	34	56	8	35	56	8	36	56	7	36	56	7	35	55	7
97232 GPTH275 275	97234 TBIN275 275	1	683	40	63	8	41	62	8	40	63	8	41	62	8	42	63	8	42	63	7	42	63	7	41	62	8
97232 GPTH275 275	97234 TBIN275 275	2	683	40	63	8	41	62	8	40	63	8	41	62	8	42	63	8	42	63	7	42	63	7	41	62	8
97234 TBIN275 275	597534 TBIN500R 500	X2	750	39	61	8	40	60	8	39	62	8	40	61	8	41	61	8	41	61	7	41	61	7	40	60	7

Table 33 High solar (≥90%) weekends of study year 2025

PV Penetration	6% PV	12% PV	14% PV	16% PV	22% PV	27% PV	33% PV	38% PV	43% PV	Weekday
PV Capacity [MW]	1,200	2,400	2,875	3,425	4,550	5,675	6,775	7,900	9,025	
25/01/25 12:00	1,128	2,256	2,702	3,219	4,276	5,334	6,368	7,425	8,482	Sat
25/01/25 12:30	1,168	2,336	2,799	3,334	4,429	5,524	6,595	7,690	8,785	Sat
25/01/25 13:00	1,184	2,367	2,836	3,378	4,488	5,598	6,683	7,792	8,902	Sat
25/01/25 13:30	1,172	2,344	2,808	3,345	4,444	5,542	6,617	7,715	8,814	Sat
25/01/25 14:00	1,144	2,287	2,740	3,264	4,337	5,409	6,457	7,530	8,602	Sat
26/01/25 12:00	1,087	2,174	2,604	3,103	4,122	5,141	6,137	7,156	8,175	Sun
26/01/25 12:30	1,091	2,181	2,613	3,113	4,135	5,157	6,157	7,179	8,202	Sun
26/01/25 13:00	1,091	2,182	2,613	3,113	4,136	5,159	6,159	7,181	8,204	Sun
08/02/25 12:00	1,097	2,193	2,627	3,130	4,158	5,186	6,191	7,219	8,247	Sat
08/02/25 12:30	1,133	2,266	2,714	3,234	4,296	5,358	6,396	7,458	8,521	Sat
08/02/25 13:00	1,127	2,254	2,700	3,216	4,273	5,329	6,362	7,418	8,475	Sat
08/02/25 13:30	1,103	2,207	2,643	3,149	4,183	5,218	6,229	7,263	8,298	Sat
22/02/25 12:00	1,101	2,202	2,637	3,142	4,174	5,206	6,215	7,247	8,279	Sat
22/02/25 12:30	1,145	2,290	2,744	3,269	4,342	5,416	6,465	7,539	8,613	Sat
22/02/25 13:00	1,156	2,312	2,770	3,299	4,383	5,467	6,526	7,610	8,694	Sat
22/02/25 13:30	1,167	2,333	2,795	3,330	4,424	5,517	6,587	7,681	8,774	Sat
22/02/25 14:00	1,128	2,255	2,702	3,218	4,276	5,333	6,366	7,423	8,481	Sat
23/02/25 12:30	1,087	2,174	2,605	3,103	4,122	5,141	6,138	7,157	8,176	Sun
23/02/25 13:00	1,131	2,262	2,709	3,228	4,288	5,348	6,385	7,445	8,505	Sun
23/02/25 13:30	1,107	2,214	2,652	3,159	4,197	5,235	6,249	7,287	8,325	Sun
08/03/25 12:30	1,112	2,224	2,664	3,174	4,217	5,259	6,278	7,321	8,364	Sat
08/03/25 13:00	1,089	2,179	2,610	3,109	4,130	5,152	6,150	7,172	8,193	Sat
09/03/25 12:30	1,102	2,204	2,640	3,146	4,179	5,212	6,222	7,256	8,289	Sun
09/03/25 13:00	1,121	2,242	2,686	3,199	4,250	5,301	6,329	7,380	8,430	Sun
15/03/25 12:00	1,090	2,180	2,612	3,111	4,133	5,155	6,154	7,176	8,198	Sat
15/03/25 12:30	1,128	2,256	2,702	3,219	4,276	5,334	6,368	7,425	8,482	Sat
15/03/25 13:00	1,087	2,174	2,604	3,102	4,121	5,140	6,136	7,155	8,174	Sat
16/03/25 12:00	1,092	2,183	2,615	3,115	4,139	5,162	6,163	7,186	8,209	Sun
16/03/25 12:30	1,131	2,261	2,709	3,227	4,287	5,347	6,384	7,444	8,504	Sun

PV Penetration	6% PV	12% PV	14% PV	16% PV	22% PV	27% PV	33% PV	38% PV	43% PV	Weekday
PV Capacity [MW]	**1,200**	**2,400**	**2,875**	**3,425**	**4,550**	**5,675**	**6,775**	**7,900**	**9,025**	
16/03/25 13:00	**1,122**	**2,243**	**2,687**	**3,201**	**4,253**	**5,304**	**6,332**	**7,384**	**8,435**	**Sun**
16/03/25 13:30	1,106	2,212	2,649	3,156	4,193	5,230	6,243	7,280	8,317	Sun
12/04/25 12:30	1,088	2,175	2,606	3,104	4,124	5,144	6,141	7,160	8,180	Sat
12/04/25 13:00	1,090	2,179	2,611	3,110	4,131	5,153	6,152	7,173	8,195	Sat
13/04/25 12:30	1,102	2,203	2,639	3,144	4,177	5,210	6,220	7,252	8,285	Sun
19/04/25 12:00	1,099	2,197	2,632	3,135	4,165	5,195	6,202	7,232	8,262	Sat
19/04/25 12:30	1,107	2,213	2,651	3,159	4,196	5,233	6,248	7,285	8,323	Sat
19/04/25 13:00	1,138	2,275	2,726	3,247	4,314	5,380	6,423	7,490	8,557	Sat
19/04/25 13:30	1,120	2,240	2,684	3,197	4,247	5,298	6,324	7,375	8,425	Sat
20/04/25 12:30	1,082	2,165	2,593	3,089	4,104	5,118	6,110	7,125	8,140	Sun

7.1 Raw Data Files and Simulation Model Files

This study processed large amount of data, which cannot be included in this report. The raw data files and simulation model files used in this study are made available in usb drive. Interested readers may refer to raw data and model files for more details.

Main Folder

GermanySpainVisit	Presentation slides from the site visit		
PresentationSlides	20180512 DataAnaPlexos Workshop.pptx 20181015 GCC at ST.pptx	20180829 PSSE Workshop.pptx 20181018 GSO.pptx	20180830 Steering Committee.pptx
ReportFiles	199104_Tr4_r2_Final Report for the VRE Penetration Study for Peninsular System_release.docx 199104_Tr4_r2_Summary Data Peninsular System.xlsx		
Task1n2 Survey	_Survery Data Summary.xlsx	and various reference files	
Task3 Study Methodolgy			
Task4.1 Solar Growth	PVpentrationMY.kmz		
Task4.2-5 DataAnalysis	Pen0_Load_2017-2036_Interpolated.xlsm Pen3_SolarVariablityStatistics_docRp.xlsm Pen6_Reserve _calc.xlsm	Pen1_pv_pow_calc_final.xlsm Pen4_NetloadDuratnAnalysis_docRp.xlsm Pen7_Summary Data Peninsular System.xlsx	Pen2_SolarVaribilityHalfHouly_docRp.xlsm Pen5_powTS and fcErr.xlsm Pen8_CombineHiResSolar.xlsm
Task4.6 PlexosAssessment	PLEXOS Model and Simulation Result Files	REPS_v18 and its variants, refer to readme.txt in the folder.	
Task4.7 PsseAssessment	2025 gen_schedule.xlsm 2025_Solar_1800_Sec.xlsm	2030 gen_schedule.xlsm 2030_Solar_1800_Sec.xlsm	pssePen2025 (model and simulation results) pssePen2030 (model and simulation results)

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