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Least Cost High Renewable Energy Penetration Scenarios in the Java Bali Grid System

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The falling costs of some key renewable energy technologies in recent years have highlighted possible opportunities to reduce the costs as well as emissions of electricity sectors around the world. With growing deployment of variable renewables such as wind and PV, however, come questions regarding the ability of power systems with high renewable penetrations to reliably meet ever changing demand over its daily and seasonal cycles.

Developing countries, including Indonesia, are targeting a low emission electricity industry without compromising the security of supply and affordability of energy service provision. Currently, renewable energy contributes to less than 10 % of energy production in Indonesia which is dominated by coal and gas power plant. While a high proportion of renewable energy generation in the electricity industry will undoubtedly reduce its carbon emissions, the ability of a high renewable energy system to meet current system reliability requirements and affordability is still to be investigated in the context of Indonesia.

This paper evaluates the potential implications of high renewable energy penetrations in the Java Bali grid system in Indonesia, including significant solar and wind deployment. The open source National Electricity Market Optimizer (NEMO) tool is used to model hourly generation dispatch and find least cost generation investment mixes according to a range of scenarios of future demand growth, fossil fuel limits, emissions limits and carbon pricing. The average electricity cost and industry greenhouse emissions associated with different scenarios of renewable energy penetration, including a 100 percent renewable energy scenario for the year of 2050 are evaluated. There is an evident trade-off between costs and emissions. The impact of incorporating a carbon price and the potential of achieving Indonesia's stated emissions targets are also evaluated. The paper aims to provide insights for policy makers and other stakeholders around options for a future cleaner electricity system in Indonesia.

Keywords: modelling, least cost, high RE penetration, carbon price, emissions target, National electricity market optimizer (NEMO)

1. Introduction

The world now adds more renewable energy generation capacity than fossil fuel capacity annually. The UNEP-Frankfurt School (McCrone et al. 2017) reported that investment in renewable energy over the period from 2010 to 2016 showed an increasing trend, with a record of 138.5 GW capacity addition in 2016. This high uptake is due to increasing global awareness of climate change and the decreasing cost of renewable energy generation to the point where renewables can directly compete against new build fossil fuel generation in a growing number of jurisdictions around the world.

Renewables are increasingly considered to be central to tackling the energy trilemma of energy security, energy equity, and energy sustainability. Renewable energy can improve energy security by reducing dependency on fossil fuel supply from other countries, and the risk of fuel price volatility. Nevertheless, there is concern that high penetrations of only partially predictable and highly variable renewable energy, notably wind and solar photovoltaics (PV), in the electricity grid may threaten reliability and security (Johansson 2013). This threat is particularly relevant in developed countries where the reliability of the existing electricity grid is extremely high such as Australia (Anderson 2016). However, other jurisdictions including many industrialising countries do not have particularly reliable electricity grids at present. In such cases, low cost variable renewable energy may well provide opportunities to improve reliability issues arising from extended periods of insufficient generation, improving both overall energy security and energy equity as more people can access modern energy services. Of course, the inherently low emission intensity of renewable energy will also improve the environmental sustainability of these electricity industries. This paper explores this potential for the main grid of Indonesia.

Studies to model high renewable energy penetration into electricity grids are widely available. Cochran et.al. (Cochran et al. 2014) provides a summary of several existing studies that model and evaluate how high shares of renewables can be integrated into the electricity system to meet the system demand. The studies vary in terms of geographic scope, economic scope, scenario motivation, model used, model framework, and penetration level of renewables. Overall, these studies have found that high penetrations of up to 100% renewable energy are capable of meeting hourly electricity demand of the electricity industries being investigated if the right mix of technologies and locations can be utilised. These studies also conclude that the renewable energy mix for high shares of renewables varies regionally and globally and suggest that region-specific modelling is required to evaluate the potential of renewable technologies.

Several studies regarding sustainable energy development for Indonesia exist. Hasan et al (Hasan et al. 2012) concluded that Indonesia has notable renewable energy potential that should be taken into account by the government. Although Kumar (Kumar 2016) suggested that renewables have the potential to meet electricity demand, he also suggested that a high renewable penetration in Indonesia will increase the cost of electricity production substantially. An optimization study also done by Purwanto et al (Purwanto et al. 2015) for several optimization criteria including economic, environment and adequacy of generation sources provides insights for decision makers, but these studies use a one year time interval and are focussed on the long term future. Dewan Energi Nasional (National Energy Board) of Indonesia also conducted time-step simulations of the Java-Bali grid for a generation mix including renewable energy for the year of 2050 (Abdurrahman 2016), but only incorporated 26% renewable energy.

This study aims to evaluate the capability of a generation mix with high renewable energy penetration (up to 100%) to meet the hourly demand of Indonesia over a year, focussing on the

Java-Bali grid system. Several different scenarios including different renewable energy penetration or fossil limit, reliability standard, cost of generation, and demand growth. This study also explores the impact of incorporating carbon externalities into the electricity system.

The rest of the paper is structured as follows. The following Section 2 describes the present Indonesian electricity industry. The modelling method used in our study is presented in Section 3, with results presented in Section 4 and then discussed in Section 5.

2. Electricity Industry in Indonesia

The electricity industry in Indonesia is currently structured as a traditional vertically integrated electric utility. A single entity is responsible for handling generation, transmission, distribution and retail functions. Perusahaan Listrik Negara (PLN), the only state owned electric company in Indonesia is mandated by the government of Indonesia to provide reliable and affordable supply of electricity for all Indonesian people stretching from Sabang in the West up to Merauke in the East.

Currently, the total installed generation capacity in Indonesia is 52,859 MW with 36,892 MW or 70% are interconnected in Java-Bali system. Most of the generation capacity comes from fossil fuel based units such as coal and gas power plants, with very few renewable energy based generators. Table 1 gives present installed generation capacity in Indonesia and Java – Bali system by fuel source (Corporate Secretary PT PLN (Persero) 2016).

Table 1 Generation capacity by fuel in Indonesia and Java – Bali system

Fuel Type	National		Java – Bali system	
	Capacity (MW)	Percentage	Capacity (MW)	Percentage
Hydro	3566	6.7%	2405.8	6.5%
Coal (Steam)	21087	39.9%	18060.0	49.0%
Gas	20840	39.4%	15768.7	42.7%
Geothermal	551	1.0%	345.0	0.9%
Diesel	6805	12.9%	311.9	0.8%
Solar	8.9	0.02%	0.0	0.0%
Wind	1.0	0.002%	0.3	0.0%
Total	52859	100%	36892	100.0%

More than 90 percent of the generation capacity is fossil fuel based (coal, gas, and a significant fraction of diesel). With this high share of fossil fuel usage in electricity, the Indonesian electricity industry emits around 145 million ton of CO2e green-house gases each year (PT PLN (Persero) 2015).

According to the Indonesian Ministry of Energy and Mineral Resources (Directorate General for Renewable and Conservation Energy 2014) there are significant renewable energy resources in the Java and Bali region, including geothermal, hydro, biomass, wind, and solar, as shown in Table 2.

Table 2 Estimated renewable energy potential in Java and Bali region

Resource	Potential (MW)
Geothermal	10149
Biomass	9215
Hydro	12272
Solar	4.8 kWh/m2/day
Wind	2.5 - 8.0 m/s at 75 metres

3. Methodology

This study uses National Electricity Market Optimizer (NEMO), a modelling and optimization tool originally developed by Elliston and colleagues at the Centre for Energy and Environmental Markets, UNSW to simulate 100% renewable energy scenarios for the Australian National Electricity Market (Elliston et al. 2012). It has since been used in a number of studies of Australia and the Philippines (Elliston et al. 2014)(Enano et al. 2016). NEMO is a python based modelling program which uses a genetic algorithm (GA) to find a least cost capacity mix of generation technology to meet a given chronological demand profile, based on generation cost structure and any constraints.

For this study, NEMO is used to model a least cost generation mix to meet the projected demand in the year of 2050 for the Java-Bali region of Indonesia , when it is assumed that all currently operated generators will be retired. The total cost of generation and CO_2 emissions of the electricity industry are evaluated for different renewable energy penetrations. Sensitivity analyses are conducted for different carbon externalities costs, demand growth, technology cost structure, and coal and gas prices. We also simulate the generation mix to meet Indonesia's UNFCCC INDC[1] emission target established as part of the Paris Agreement.

Inputs for the model include demand data, generation cost data, fuel cost data, renewable energy resources data as follows:

Hourly **demand data** sourced from PT PLN (Persero) Pusat Pengatur Beban Jawa Bali for the Java-Bali system for the year of 2015. In the past 15 years, nationally, annual demand growth varies from 2.1% (2015) to 10.7% (2004) and 6.5% on average (Ministry of Energy and Mineral Resources 2016b; Ministry of Energy and Mineral Resources 2011) while in the future electricity demand is forecasted to grow 7.2% (Ministry of Energy and Mineral Resource 2017). In this model demand is scaled linearly according to annual demand growth scenarios of 3.0%, 5.0%, 7.0%, and 10.0%.
The **generation technology cost structure** consists of capital costs, fixed operation and maintenance (O&M), variable O&M, and fuel costs. For this study we use baseline costs provided in the 2016 Indonesia Energy Outlook report by Indonesia's National Energy Board (Abdurrahman 2016). Costs for 2050 are scaled from the baseline in proportion to the rate of change is costs predicted for each technology by NREL in its 2016 Annual Technology Baseline Report (NREL 2016). The base scenario generation cost structure used in this study is given in Table 3.

Table 3 Generation cost structure for the year of 2050 – Mid scenario ($USD)

Gen Technology	Capital Cost ($/kW)	Fix O&M Cost ($/kW-year)	Variable O&M Cost ($/MWh)	Fuel Cost ($/GJ)
Black Coal	$1,273	$56	$3.8	$2.28
OCGT	$351	$20	$3.8	$10.38
CCGT	$618	$24	$3.8	$10.38
Diesel	$400	$28	$3.8	$16.1
Biomass	$1,996	$97	$6.5	$39
Geothermal	$2,099	$40	$0.7	$0
Hydropower	$2,300	$54	$3.8	$0

[1] United Nations Framework Convention on Climate Change Intended Nationally Determined Contribution

Pumped Hydro Power	$2,760	$64	$4.6	$0
Wind Onshore	$1,447	$28	$0.8	$0
Wind Offshore	$1,721	$105	$0.8	$0
PV Fix Plate	$648	$18	$0.4	$0
CSP w/ Storage	$3,075	$40	$4.0	$0

Fuel cost data required for the simulation are coal price, gas price, and biofuel price. The coal price used in this study is taken from Indonesia's coal reference price issued by ministry of energy and mineral resources for the year of 2015. The gas and biofuel prices are taken from PLN's 2015 statistics report.
Hourly **wind and solar generation** data for 2015 is obtained from www.renewables.ninja, which uses the NASA MERRA 2 weather data for the Indonesia region, with a methodology for PV generation introduced by Pfenninger et.al (Pfenninger & Staffell 2016) and for wind generation a method introduced by Staffel et.al (Staffell & Pfenninger 2016).

The base scenario for this study uses the parameters given below:

- Reliability / unserved energy : 0.006%
- Demand growth : 7.0% per year
- Carbon price : No carbon price
- Coal price : $ 2.28/GJ
- Gas price : $ 10.38/GJ

The base scenario was evaluated for various renewable energy penetrations to find the least cost generation mix, total generation cost and emissions. Sensitivity analysis was then conducted to this set of data to find the impact of demand growth variations, carbon prices between $0 and $60, and greenhouse emission limits in line with Indonesia's international commitments.

4. Results

4.1 Base Scenario Results

NEMO simulations for the base scenario identify a least-cost generation cost for 100 percent renewable energy of $83.1/MWh. There are, of course, no emissions associated with this scenario. The average generation cost and emissions varies for different renewable energy penetrations, as shown in Figure 1, with the capacity mix and energy mix for these varied penetrations given in Figure 2. Simulated total generation capacity is 1241.9 GW with hourly peak demand of 301.6 GW. Total demand energy to be supplied is 2093.7 TWh. It is apparent that the average electricity cost for the 100% renewables case is more than double the fossil fuel dominated scenario. Of course, CO_2 emissions emitted by the generation system increase when the portion of fossil fuel generation increases. For base scenario parameters, different fossil limit values see emissions ranging from 343 $MtCO_2e$ (for fossil limit 0.2) to 1834 $MtCO_2e$ for fossil limit 1.0. The potential trade-off facing policy makers is very apparent.

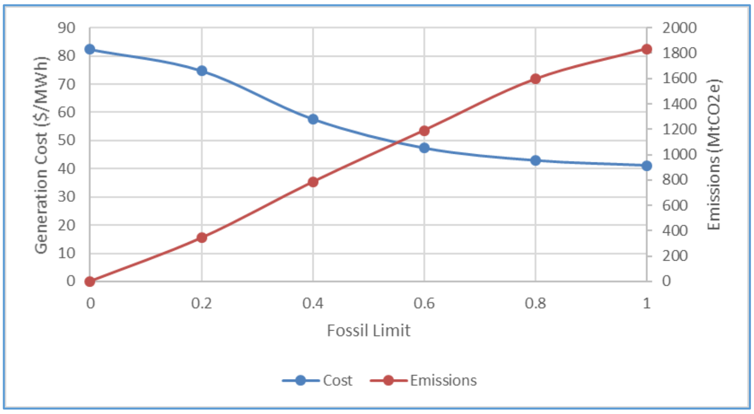


Figure 1 Average generation cost and total annual industry emissions for different fossil limits in the base scenario. Renewable energy penetration is determined by the fossil limit constraint - Fossil limit 0 means 100% renewables, while Fossil limit 1.0 means there is no constraint.

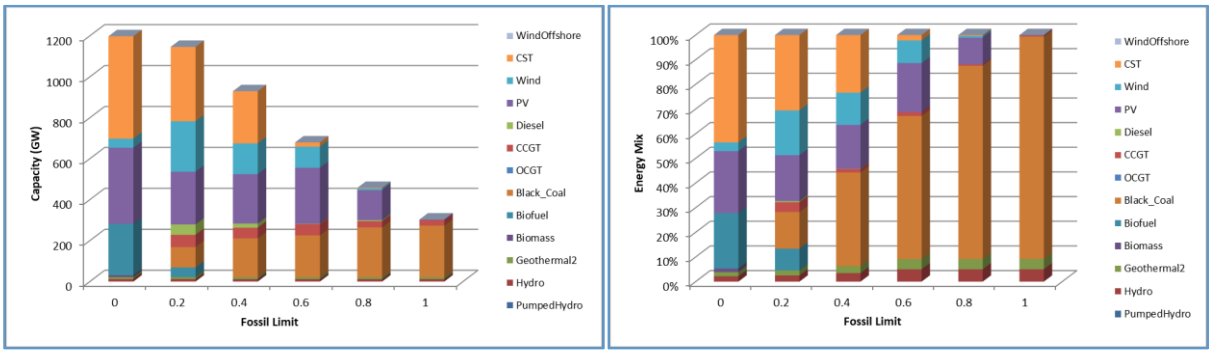


Figure 2 Generation capacity mix (left) and energy mix (right) for different fossil limit

A sample of NEMO's hourly energy dispatch for a 100 percent renewable energy penetration for the base scenario is given in Figure 3. A sample of hourly energy dispatch for a scenario with a combination of renewables and fossil energy generation is given in Figure 4.

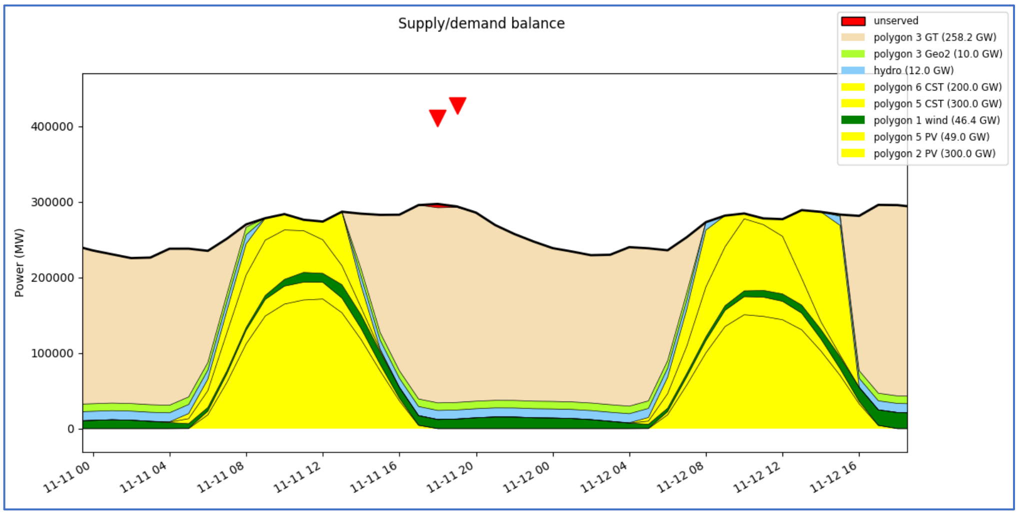


Figure 3 Hourly dispatch of generators – 100 percent renewable energy for the base scenario, over two sunny days.

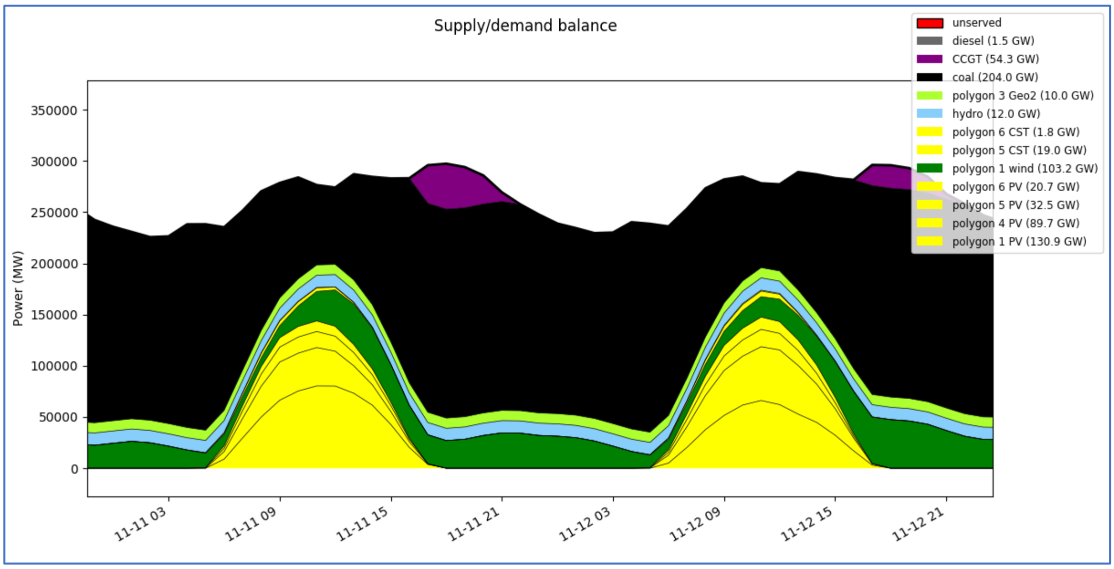


Figure 4 Hourly dispatch of generator – fossil limit 0.6

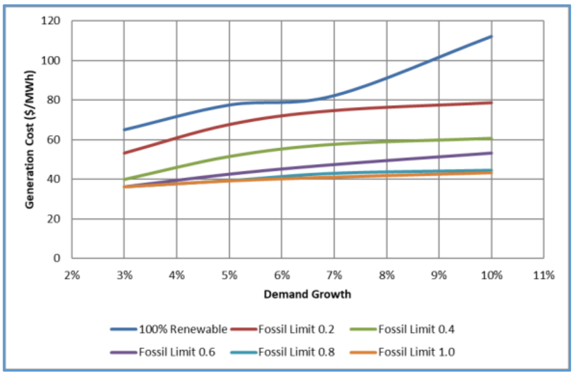
Figure 1 shows that for the 100 percent renewable scenario, both solar PV and concentrating solar thermal (CST) dominate the capacity and energy mix together with biofuel which acts to support solar renewables variability. On the other hand hydro and geothermal only contribute a relatively small portion of energy and capacity mix due to the limited resources available for these options. The total generation capacity far exceeds the peak demand. In comparison, if there are no limits on fossil fuel use then cheap coal fired generation dominates the mix, with CCGT power plant used to meet peak demand

Figure 3 highlights the challenge of meeting demand outside daylight hours with 100% renewables that also sees considerable solar spill in the middle of sunny days. Figure 4 shows how a mix of renewables and fossil fuel plant would likely be dispatched.

4.2 Impact of Demand Growth

Sensitivity analysis were conducted for different renewable energy penetration scenarios in terms of demand growth. Demand energy in the year of 2050 was calculated for 3%, 5%, and 10% annual growth scenarios, 460.6 TWh, 921.1 TWh, and 4689.9 TWh respectively. Peak demand energy in the year of 2050 for 3%, 5%, and 10% scenario are 66.35 GW, 132.7 GW, and 675.56 GW respectively.

The impact of demand growth on generation cost and emissions is given in Figure 5. The impact of demand growth on generation capacity and energy mix is given in Figure 6.



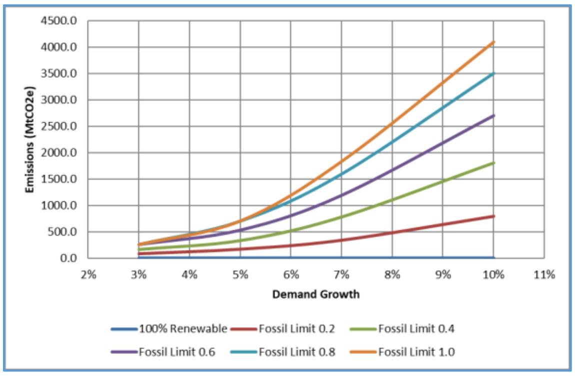


Figure 5 Impact of different demand growth scenarios to average generation cost (left) and total annual industry emission (right) for different fossil limits.

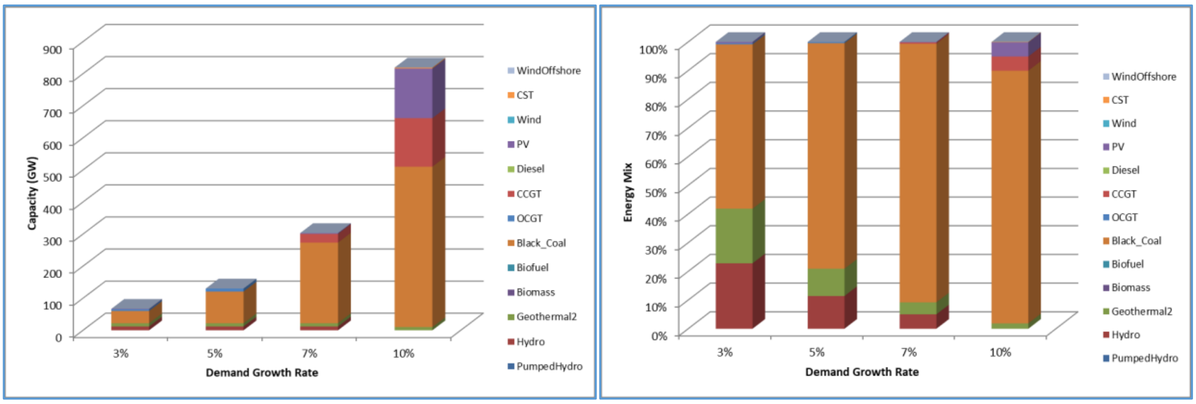


Figure 6 Impact of different demand growth to generation capacity (left) and energy (right) mix, fossil limit 1.

Figure 5 shows that the average generation cost increases as the demand growth rate increases, reflecting the impact of constraints on particular generation technologies, notably geothermal and hydro in the high renewables scenarios. It is clear that high demand growth increases the challenges of high renewables scenarios more than fossil fuel scenarios, although we do not model possible constraints on coal and gas resources or possible price impacts with far greater consumption

In terms of generator capacity and energy mix, Figure 6 also shows that when the demand growth is low, hydro power and geothermal energy resources can still make a significant contribution to the overall energy mix, even in the case where there are no constraints on fossil fuel generation contribution. If demand growth rate is only 3%, 30% renewable energy penetration in the year of 2050 can be easily met only through hydro power and geothermal power.

4.3 Impact of Carbon Price

The introduction of a carbon price is widely argued to be one of the most effective measures to reduce greenhouse emissions from industry including the electricity sector; the OECD suggest carbon taxing as a key policy option for achieving a future low carbon economy (OECD 2015).

The impact of incorporating a carbon price on generation costs and industry emissions for the future Java Bali electricity grid is given in Figure 7 while its impact on generation capacity and energy mix is shown in Figure 8.

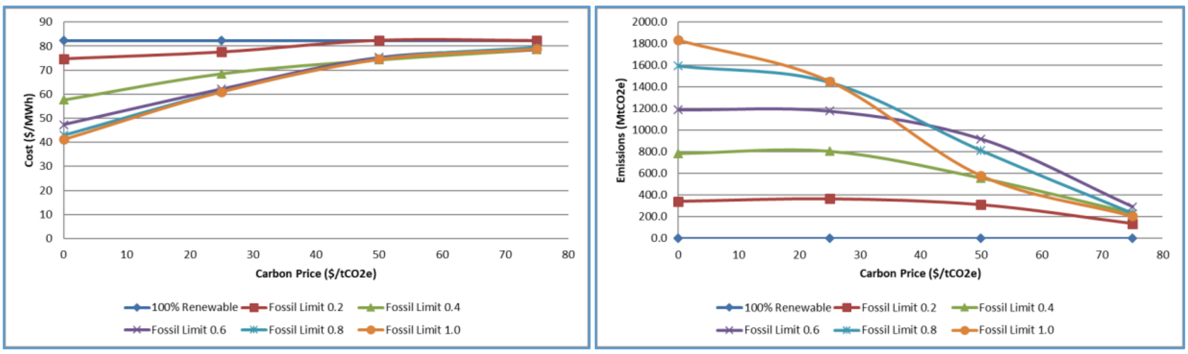


Figure 7. Impact of different carbon price to generation cost (right) and emission (left) for different fossil limit

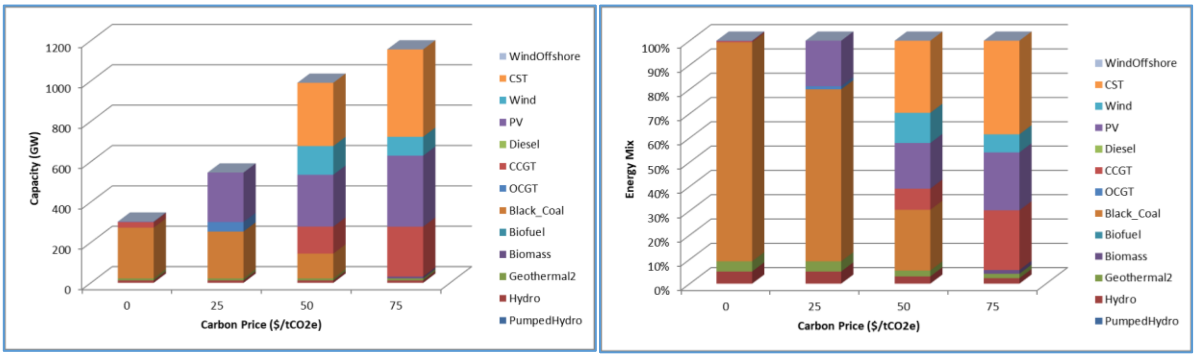


Figure 8 Impact of different carbon price to generation capacity (left) and energy (right) mix, fossil limit 1.0

Incorporating a carbon price into the Java Bali system increased average generation costs for all scenarios other than the 100% renewables case, as shown in Figure 7. Incorporating a \$75/tCO2 carbon price to the no fossil limit scenario increased the generation cost from \$ 41.2/MWh to \$ 78.8/MWh, almost the same as the price for the 20% fossil limit scenario at \$ 82.3/MWh. Figure 7 also shows how electricity industry emissions decrease with a rising carbon price. Introducing a \$75/tCO2 carbon price significantly decreases emissions for the no fossil limit scenario from 1834 MtCO2e to 205 MtCO2e, which is close to emissions for 20% fossil limit scenario without carbon price at 343 MtCO2e.

Figure 8 highlights that with just a \$25/tCO2e carbon price, PV starts to become more economical compared to fossil fuel generation. As the carbon price is increased further, gas power plant starts to replace coal power plant, which indeed totally disappears from the generation mix when a \$75/tCO2e carbon price were introduced.

4.4 Impact of an Emissions Limit

To evaluate the optimum generation mix for delivering the emissions targets of the Indonesian government, three different emissions limit scenarios were simulated. Indonesia aims to reduce its greenhouse gas emissions to 29% of the 2030 business as usual (BAU) level unconditionally and 41% with international help (Indonesia Government 2015). Assuming the 2030 BAU greenhouse gas emissions from the electricity sector is 1669 MtCO2e, a 29% reduction scenario is 1355 MtCO2e, and a 41% reduction is 1271 MtCO2e. Energy generated in Java-Bali system accounts for 74% of total energy generated nationally while emission factor of Java-Bali system is comparatively higher than other grid systems (Ministry of Energy and Mineral Resources 2016a; Corporate Secretary PT PLN (Persero) 2016), thus in this model Java-Bali system is assumed to contribute for 80% of national emissions and emissions limits of 1084 MtCO2e (29% reduction) and 1016 MtCO2e (41% reduction), were applied and compared to BAU (1359 MtCO2e). The total generation cost for these three emissions limit scenarios is given in Figure 9.

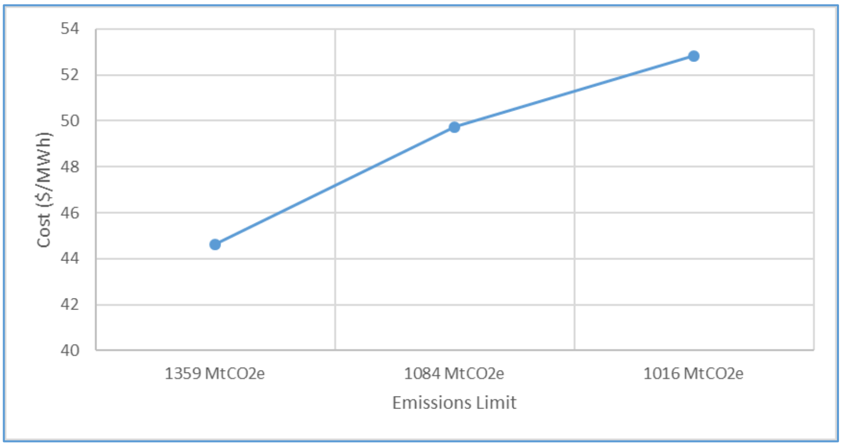


Figure 9 Generation cost for different emissions limit

Generation capacity and energy mix for different emissions target is given in Figure 10.

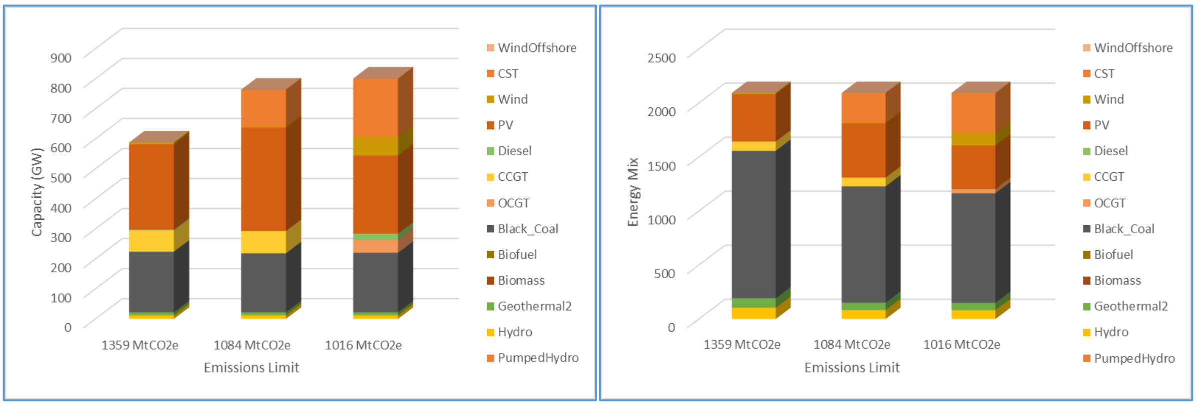


Figure 10 Generation capacity (left) and energy (right) mix for different emission limit scenarios

Figure 9 highlights that the generation cost of Java Bali system increases when the emissions limit became stricter from $ 44.6/MWh to $49.7/MWh for a 29% reduction, and $ 52.8/MWh for a 41% reduction level. To achieve tighter emissions target, portions of renewable energy in the generation system would need to be increased as shown in Figure 10. To achieve the 29% and 41% reduction scenarios, the renewable energy penetrations in the Java Bali system would be 45% and 50% respectively.

5. Discussion and conclusions

From the NEMO simulation results, we can see that incorporating 100 percent renewable energy technologies in the Java-Bali Grid to meet hourly demand of 2050 appears technology possible. It is achieved with a combination of hydro, solar PV, wind, concentrating solar thermal, and gas turbines using biofuel, together with pumped hydro storage. The simulated average generation cost for this scenario was $ 83.1/MWh.

However, the feasibility of implementing 100 percent renewable energy into Java-Bali System needs to be examined further. The 100 percent renewable scenarios, for the base case scenario of demand growth, will have 372 GW of solar photovoltaic, 44 GW of wind power plant, and 500 GW of concentrating solar thermal power plant. To build this amount of PV, wind, and CST power plant might require a total area of 48400 km2 (13000 km2, 15400 km2, 20000 km2 for PV, wind, and CST respectively) (Denholm et al. 2009; Ong et al. 2012).With the total land area of Java and Bali island around 134000 km2, the land requirement for this 100 percent renewable energy scenario takes around 36% of the total land area available. It will be particularly difficult to realize because Java and Bali island are the most populated island in Indonesia so renewables will need to compete with land requirement for settlement, not to mention land requirements for agricultural and other industries.

Simulating a combination of renewable energy and fossil power plant showed how low emission generation in the Java Bali system seems likely to be achieved at the expense of generation costs, for the assumed future generation technology and fuel costs used in this study anyway. This highlights the likely difficulty in balancing the energy trilemma in Java-Bali system. With an equal reliability requirement, higher renewable energy penetrations, while reducing emissions, could well impose higher electricity generation costs, as also highlighted by Kumar in his study (Kumar 2016). Increasing the renewable energy penetration from 0% to 80% almost doubled the average generation cost in our scenarios. This is an outcome of the relatively low wind and PV resources in Java-Bali region, high capital costs for renewable power plant and low capital costs for fossil fuel generators, especially coal power plant, in Indonesia.

Sensitivity analysis for different demand growth showed that the likelihood of achieving high renewable energy penetration into Java-Bali grid increases as demand growth decreases. For 3% demand growth, achieving 80% renewable energy appears entirely possible with hydro and geothermal roles becoming significant. Lower electricity demand growth can help in achieving a lower emission generation system without significant increase in generation cost. For 3% demand growth, incorporating 60% renewable energy penetration into the system only increased the generation cost from \$ 36.2/MWh to \$ 39.9/MWh while for 10% demand growth, incorporating the same renewable energy shares increased generation cost from \$ 43.5/MWh to \$ 78.6/MWh. This result showed the significance of energy efficiency measures in achieving low emissions generation system. Energy efficiency measures can help reduce energy consumption without sacrificing economic growth.

Incorporating a carbon price into the generation system had significant impacts on the least-cost generation cost and generation mix. The impact of the carbon price was particularly noticeable in terms of generator energy mix. The generation mix was altered as soon as a \$25/tCO2 carbon price was implemented, with the proportion of coal power plant reduced and PV generation increased. At a \$50/tCO2e carbon price, CCGT started to replace some portion of energy which was previously generated by coal power plant because of its lower emission intensity. At a \$75/tCO2 carbon price, the situation has completely shifted with coal plant completely disappearing from the generation mix, and the generation system favoured renewable energy at this carbon price.

Implementing a carbon price into the electricity system may help the industry to shift from high emission intensity power generator technology to low emission energy sources without directly putting limits on the fossil generators. The Indonesian Ministry of Finance in its green paper also acknowledged the impact of carbon price in driving energy industry in Indonesia towards lower emission technology (Indonesian Ministry of Finance 2009). However, the planned carbon price to be implemented, which was around \$ 6/tCO2e and increased 5% per annum until 2020, does not seem likely to significantly alter power generation technology by industry players.

Achieving the emission reductions stated in the intended nationally determined contributions (INDC) of Indonesia is not an easy task. To achieve 29% emission reduction from the electricity sector might require a 45% renewable energy penetration into Java-Bali electricity system, and a 50% penetration to achieve 41% emission reduction target. The Renewable energy target recommended by Indonesia's National Energy Board which was 31% in 2050 seems very inadequate in this context. This conclusion is also made in a World Resource Institute working paper that states current energy policy is not adequate to achieve the INDC target and requires enhanced energy policy to support current policy in order to achieve the target (Wijaya et al. 2017). Energy efficiency measures were mentioned as one of the enhancement for current energy policy.

To conclude, while the NEMO simulations provide valuable insights into our options for implementing a low emission Java-Bali grid system, these findings should only be seen as preliminary. Further studies incorporating more low emission generator technologies such as carbon capture and storage, battery storage, and other renewables will be needed to broaden the options. Incorporating demand side management measures may also give contributions in this area.

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