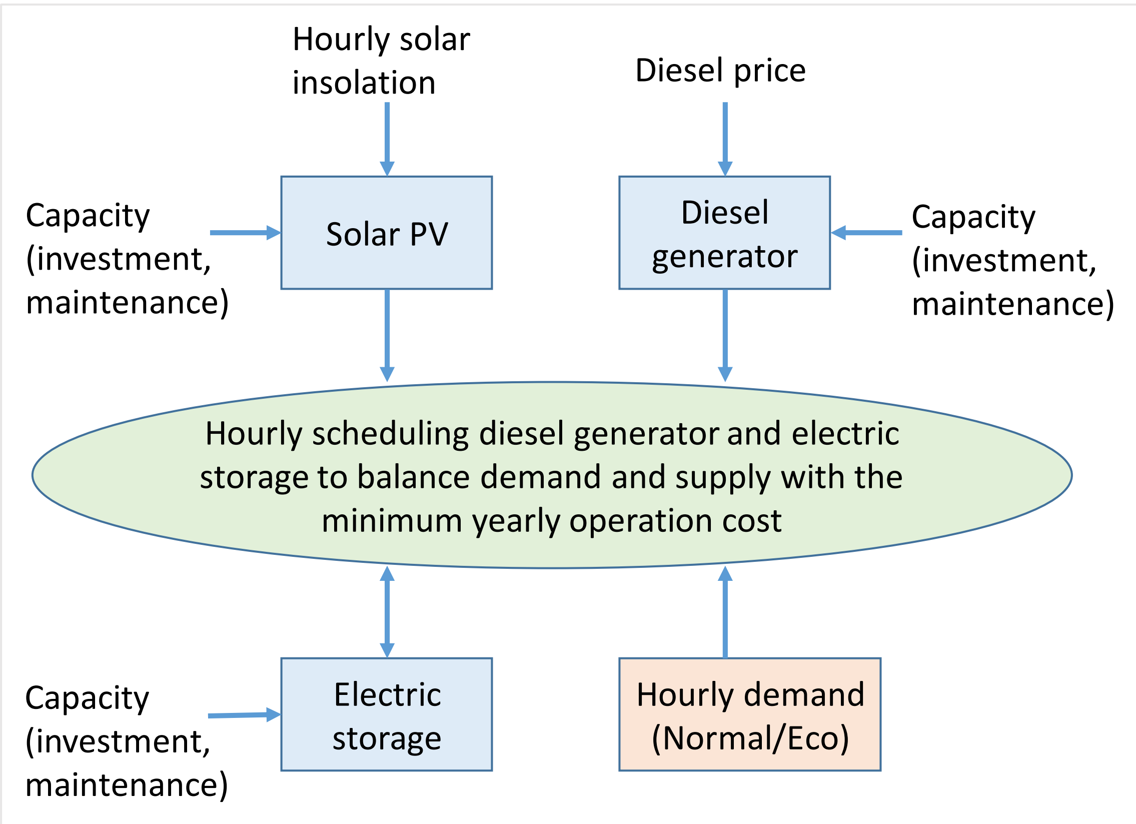
Chapter 3
Seeking Best Mix of Power Generation System for Temburong Eco Town

3.1. Basic Concept of Simulation Model

Operation schedule of diesel generators and electricity storage was simulated to balance demand and supply with minimum operation cost. Two electricity demands (normal and eco) estimated in Chapter 2 were used as inputs of the simulation. Generated electricity in solar photovoltaic (PV) was estimated using a given capacity and observed hourly solar radiation data described in Chapter 1. Diesel generator and electricity storage were operated to balance demand and supply of electricity with given capacities of diesel generator and electricity storage and diesel fuel price. Basic concept of the simulation model is schematically shown in Figure 3.1. The simulation model was formulated as a mixed integer linear mathematical programing (Ikeda, et al., 2012; Ikeda and Ogimoto, 2013; Ikeda and Ogimoto, 2014) and simulated operation schedule of diesel generators and electricity storage with minimum fuel cost of diesel generator. Solar PV, diesel generators, and electricity storage require investment and maintenance costs. Considering fuel, investment, and maintenance costs, levelised cost of energy (LCOE) was estimated for a given mix of power generation system.

Figure 3.1. Basic Concept of Simulation Model



PV = photovoltaic.
Source: Authors.

3.2. Scenario Setting

There are three power sources available in Temburong: (i) existing diesel generator, (ii) solar PV plant, and (iii) electricity storage. We have three different scenarios for diesel generators, i.e. 12MW, 6MW, and 0MW. Capacity of solar PV is in the range of 0MW to 192MW. Stored electricity is in the range of 12MWh to 570 MWh (0MW–95 MW). Tables 3.1 to 3.6 summarise the scenarios. Table 3.7 shows cost assumptions for each power source (Lazard, 2014; Fu et al., 2016).

Table 3.1. Existing Diesel Generators (12MW) + Solar PV + Storage for the Normal Demand

Demand	Normal
Diesel (MW)	12 (number of generators=4)
PV (MW)	0, 9.6, 24.0, 38.4, 52.8, 67.2
Stored electricity (MWh)	24, 42, 60, 78, 90
Rated power of electric storage ((MW)	4, 7, 10, 13, 15

MW = megawatt, MWh = megawatt hour.
Source: Authors.

Table 3.2. Existing Diesel Generators (12MW) + Solar PV + Storage for the Eco Demand

Demand	Eco
Diesel (MW)	12 (number of generators=4)
PV (MW)	0, 4.8, 19.2, 33.6
Stored electricity (MWh)	12, 30, 48, 66
Rated power of electric storage (MW)	2, 5, 8, 11

MW = megawatt, MWh = megawatt hour.
Source: Authors.

Table 3.3. Half of Diesel Generators (6MW) + Solar PV + Storage for the Normal Demand

Demand	Normal
Diesel (MW)	6 (number of generators=2)
PV (MW)	96, 120, 144, 168
Stored electricity (MWh)	150, 180, 210, 240
Rated power of electric storage (MW)	25, 30, 35, 40

MW = megawatt, MWh = megawatt hour.
Source: Authors.

Table 3.4. Half of Diesel Generators (6MW) + Solar PV + Storage for the Eco Demand

Demand	Eco
Diesel (MW)	6 (number of generators=2)
PV (MW)	48, 72, 96, 120
Stored electricity (MWh)	90, 120, 150, 180, 210
Rated power of electric storage (MW)	15, 20, 25, 30, 35

MW = megawatt, MWh = megawatt hour.
Source: Authors.

Table 3.5. Zero Diesel Generator + Solar PV + Storage for the Normal Demand

Demand	Normal
Diesel (MW)	None
PV (MW)	120, 144, 168, 192
Stored electricity (MWh)	450, 480, 510, 540, 570
Rated power of electric storage (MW)	75, 80, 85, 90, 95

MW = megawatt, MWh = megawatt hour.
Source: Authors.

Table 3.6. Zero Diesel Generator + Solar PV + Storage for the Eco Demand

Demand	Eco
Diesel (MW)	None
PV (MW)	96, 120, 144, 168
Stored electricity (MWh)	360, 390, 420, 450, 480
Rated power of electric storage (MW)	60, 65, 70, 75, 80

MW = megawatt, MWh = megawatt hour.
Source: Authors.

Table 3.7. Assumptions for Cost of Each Power Source

	Diesel generator	Solar PV	Electric storage
Status	Existing	Newly Installed	Newly Installed
Initial Cost	0	US$3/W	US$200/kWh
Fuel Cost	US$0.32/liter	0	0
OM Cost	US$15,000/MW/Year	US$15,000/MW/Year	US$20,000/MW/Year

KWh = kilowatt-hour, MW = megawatt, OM = Operations and Maintenance, W = watt.
Source: Authors.

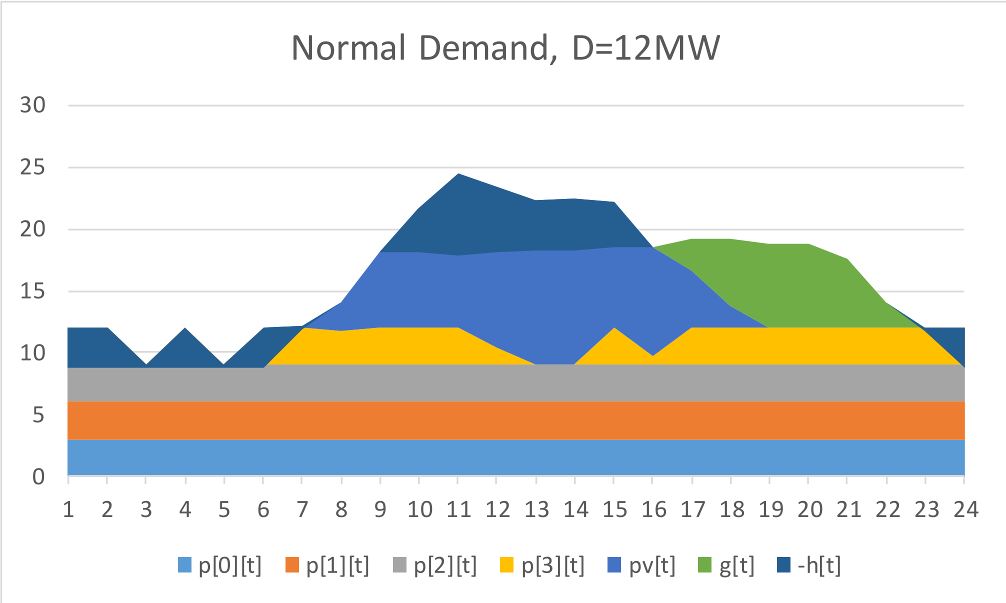
3.3. Comparison of Results among the Scenarios

3.3.1. Demand and Supply Balance

Scheduling diesel generator and electricity storage was simulated for scenarios summarised in Table 3.1 to Table 3.6 for 1 year with 1-hour intervals. The obtained results for demand and supply balance are shown in Figure 3.2 to Figure 3.7. Here 'p[0]', 'p[1]', 'p[2]', and 'p[3]' indicate generated electricity in four diesel generators; 'PV' is generated electricity in solar PV; 'g' and '-h' are discharged electricity from the storage and charged electricity in the storage. Note that '-h' during daytime is surplus electricity from solar PV and is therefore charged in the storage.

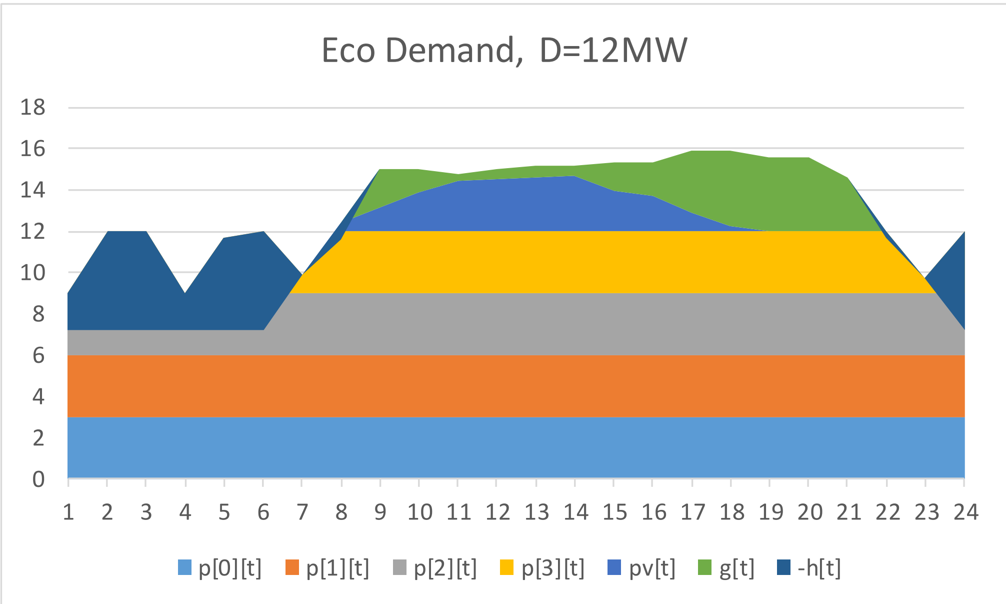
Figure 3.2 shows demand and supply balance in early January for the scenario summarised in Table 3.1. Three diesel generators are operated at rated power and one unit is managed for its generated power to balance demand and supply. In the case of lower solar radiation, solar PV generates electricity for daytime peak and a diesel power charges electricity in the storage at night-time. Figure 3.3 shows demand and supply balance in early January for the scenario summarised in Table 3.2. Three diesel generators are operated at rated power and one unit is managed for its generated power during daytime. Solar PV and diesel power charge their surplus electricity in the storage for night-time use. Figure 3.4 shows demand and supply balance in early January for the scenario summarised in Table 3.3. Solar PV generates a large amount of electricity at daytime and charges surplus electricity in the storage for night-time use. However, in the case of lower solar radiation, two diesel generators are needed at night-time. Figure 3.5 shows demand and supply balance in early January for the scenario summarised in Table 3.4. Solar PV generates a large amount of electricity in daytime and charges surplus electricity in the storage for night-time use. Figure 3.6 and Figure 3.7 show demand and supply balance in early January for the scenario summarised in Table 3.5 and Table 3.6. Solar PV generates a large amount of electricity in daytime and charges surplus electricity in the storage for night-time use.

Figure 3.2. Supply Electricity with D=12MW, PV= 24MW, Storage=78MWh for the Normal Demand



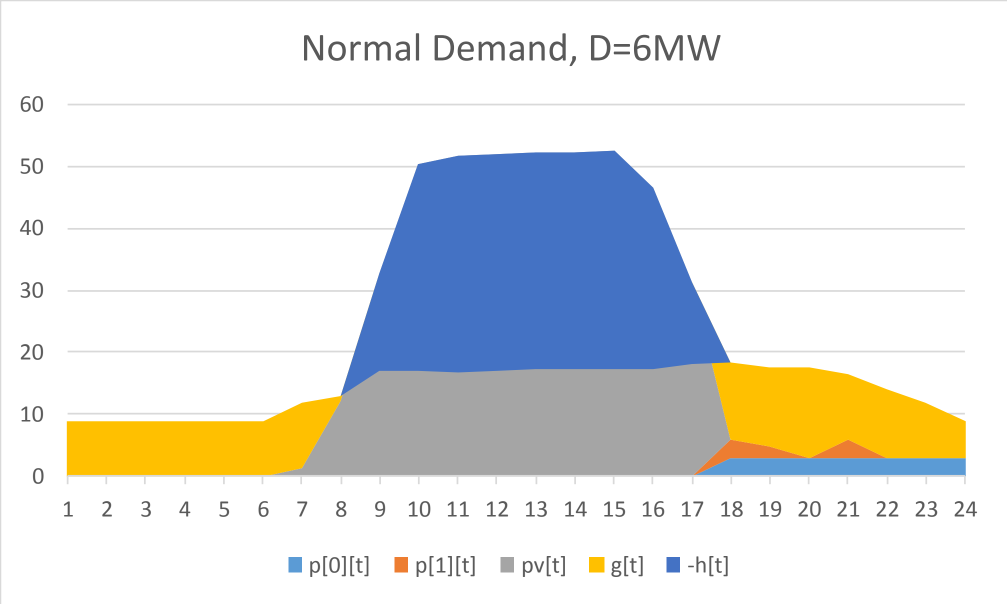
D = capacity of diesel generator, g = discharged electricity from the storage, -h = charged electricity in the storage, MW = megawatt, MWh = megawatt hour, p = generated electricity in diesel generator, PV = generated electricity in solar photovoltaic, t = time in hour.
Source: Authors.

Figure 3.3. Supply Electricity with D=12MW, PV= 4.8MW, Storage=48MWh for the Eco Demand



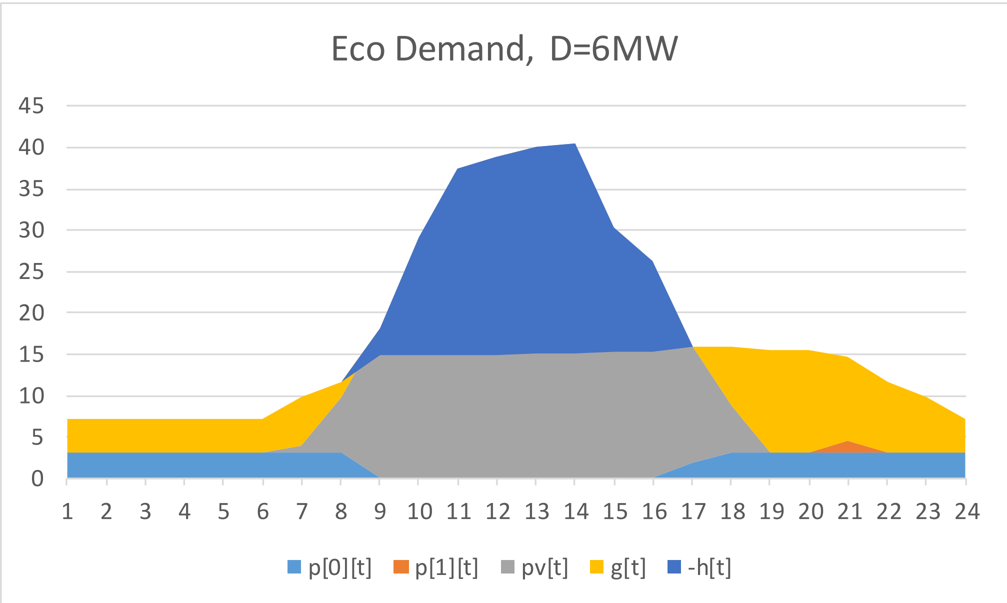
D = capacity of diesel generator, g = discharged electricity from the storage, -h = charged electricity in the storage, MW = megawatt, MWh = megawatt hour, p = generated electricity in diesel generator, PV = generated electricity in solar photovoltaic, t = time in hour.
Source: Authors.

Figure 3.4. Supply Electricity with D=6MW, PV=120MW, Storage=210MWh for the Normal Demand



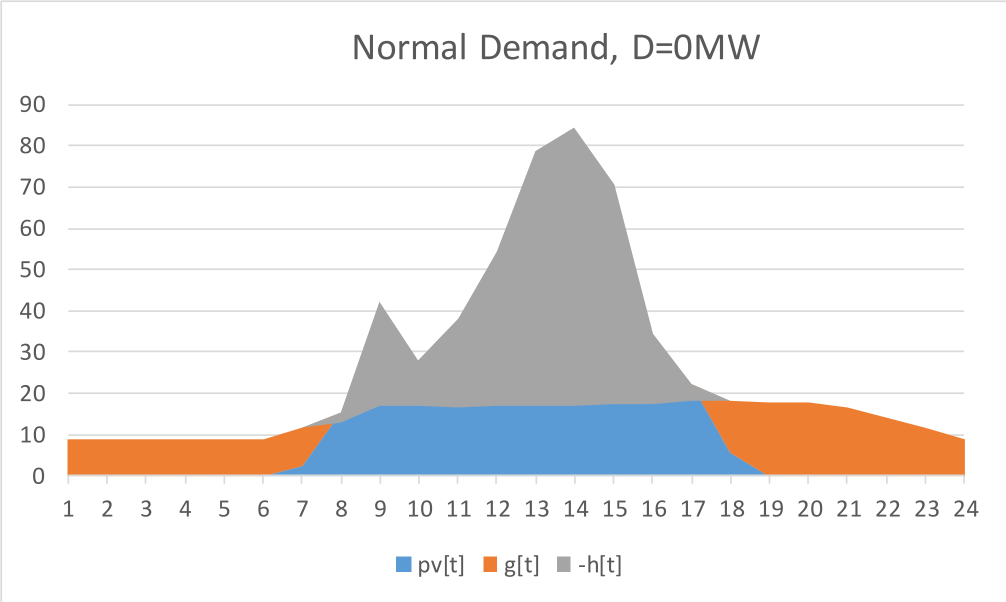
D = capacity of diesel generator, g = discharged electricity from the storage, -h = charged electricity in the storage, MW = megawatt, MWh = megawatt hour, p = generated electricity in diesel generator, PV = generated electricity in solar photovoltaic, t = time in hour.
Source: Authors.

Figure 3.5. Supply Electricity with D=6MW, PV=72MW, Storage=180MWh for the Eco Demand



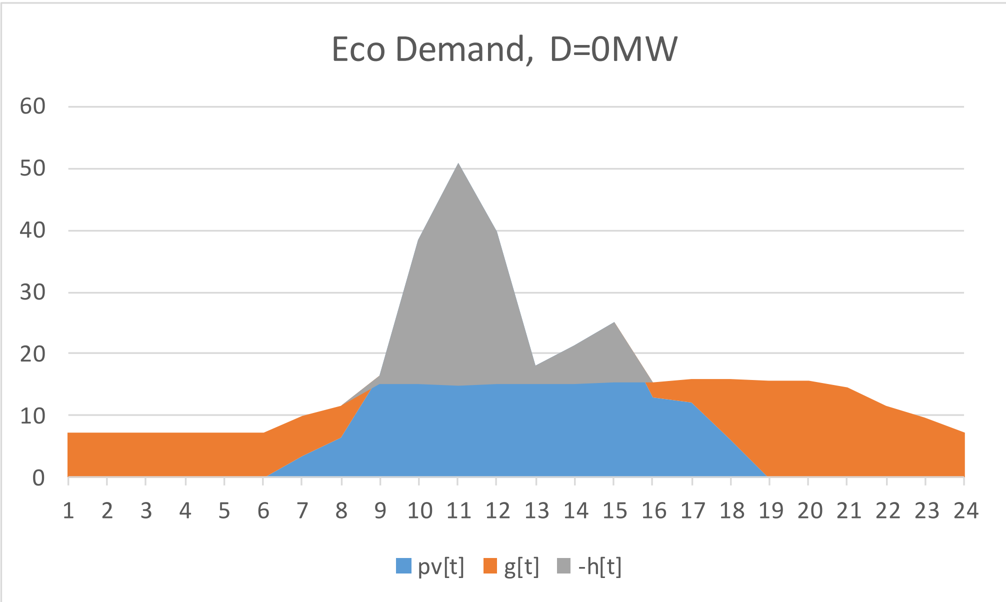
D = capacity of diesel generator, g = discharged electricity from the storage, -h = charged electricity in the storage, MW = megawatt, MWh = megawatt hour, p = generated electricity in diesel generator, PV = generated electricity in solar photovoltaic, t = time in hour.
Source: Authors.

Figure 3.6. Supply Electricity with D=0MW, PV=144MW, Storage=540MWh for the Normal Demand



D = capacity of diesel generator, g = discharged electricity from the storage, -h = charged electricity in the storage, MW = megawatt, MWh = megawatt hour, p = generated electricity in diesel generator, PV = generated electricity in solar photovoltaic, t = time in hour.
Source: Authors.

Figure 3.7. Supply Electricity with D=0MW, PV=120MW, Storage=450MWh for the Eco Demand



D = capacity of diesel generator, g = discharged electricity from the storage, -h = charged electricity in the storage, MW = megawatt, MWh = megawatt hour, p = generated electricity in diesel generator, PV = generated electricity in solar photovoltaic, t = time in hour.
Source: Authors.

3.3.2. Best mix of Power Generation Source

Operation schedule of diesel generators and electricity storage with minimum fuel cost of diesel generator was simulated using the model shown in Figure 3.1, and for the scenarios of solar PV and electricity storage described in Table 3.1 to Table 3.6. LCOE was estimated using the fuel cost obtained in the simulation, investment cost, and maintenance cost described in Table 3.7. The following is the formula for LCOE:

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

where I_t, M_t, F_t, E_t are investment expenditures, operations and maintenance expenditures, fuel expenditures, and electricity generation. Discount rate $r = 5\%$ and life of the system $n = 20$ years are assumed in the calculation of LCOE. The results of LCOE estimations are summarised in Table 3.8 to Table 3.13. The scenarios from which demand supply balance was not obtained for the given capacities of solar PV and electricity storage are indicated by 'infeasible'. Additional results on electricity supply in Temburong Eco Town are described in Annex 3.

The best power mixes are identified in terms of the smallest LCOE and are summarised in Table 3.14 and Table 3.15. Under the condition without diesel generator, combination of solar PV and storage is a technically feasible solution, but large capacities are required for both solar PV and storage.

Table 3.8. LCOE with D=12MW for the Normal Demand (US$/MWh)

PV(MW)\Storage (MWh)	24	42	60	78	90
10	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
24	Infeasible	Infeasible	Infeasible	146	148
38	Infeasible	Infeasible	158	161	163
53	Infeasible	176	177	179	181
67	Infeasible	202	202	202	203

D = capacity of diesel generator, LCOE = levelised cost of energy, MW = megawatt, MWh = megawatt hour, PV = photovoltaic.

Source: Authors.

Table 3.9. LCOE with D=12MW for the Eco Demand (US$/MWh)

PV(MW)\Storage (MWh)	12	30	48	66
0	Infeasible	Infeasible	Infeasible	Infeasible
5	Infeasible	Infeasible	123	127
19	Infeasible	138	141	145
34	Infeasible	158	161	164

D = capacity of diesel generator, LCOE = levelised cost of energy, MW = megawatt, MWh = megawatt hour, PV = photovoltaic.

Source: Authors.

Table 3.10. LCOE with D=6MW for the Normal Demand (US$/MWh)

PV(MW)\Storage (MWh)	150	180	210	240
96	Infeasible	Infeasible	Infeasible	Infeasible
120	Infeasible	Infeasible	299	303
144	Infeasible	344	347	351
168	Infeasible	393	397	401

D = capacity of diesel generator, LCOE = levelised cost of energy, MW = megawatt, MWh = megawatt hour, PV = photovoltaic.

Source: Authors.

Table 3.11. LCOE with D=6MW for the Eco Demand (US$/MWh)

PV(MW)\Storage (MWh)	90	120	150	180	210
48	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
72	Infeasible	Infeasible	Infeasible	245	250
96	Infeasible	289	290	293	297
120	Infeasible	346	347	350	355

D = capacity of diesel generator, LCOE = levelised cost of energy, MW = megawatt, MWh = megawatt hour, PV = photovoltaic.

Source: Authors.

Table 3.12. LCOE with D=0MW for the Normal Demand (US$/MWh)

PV(MW)\Storage (MWh)	450	480	510	540	570
120	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
144	Infeasible	Infeasible	Infeasible	395	400
168	Infeasible	436	441	446	451
192	Infeasible	487	492	497	502

D = capacity of diesel generator, LCOE = levelised cost of energy, MW = megawatt, MWh = megawatt hour, PV = photovoltaic.

Source: Authors.

Table 3.13. LCOE with D=0MW for the Eco Demand (US$/MWh)

PV(MW)\Storage (MWh)	360	390	420	450	480
96	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
120	Infeasible	Infeasible	Infeasible	397	403
144	Infeasible	447	453	459	465
168	Infeasible	509	515	521	526

D = capacity of diesel generator, MW = megawatt, MWh = megawatt hour, PV = photovoltaic.
Source: Authors.

Table 3.14. The Best Power Mixes for the Normal Demand

	Diesel Power Plant: 12MW	Diesel Power Plant: 6MW	No Diesel Power Plant
Solar PV (MW)	24	120	144
Storage (MWh)	78	210	540

MW = megawatt, MWh = megawatt hour, PV = photovoltaic.
Source: Authors.

Table 3.15. The Best Power Mixes for the Eco Demand

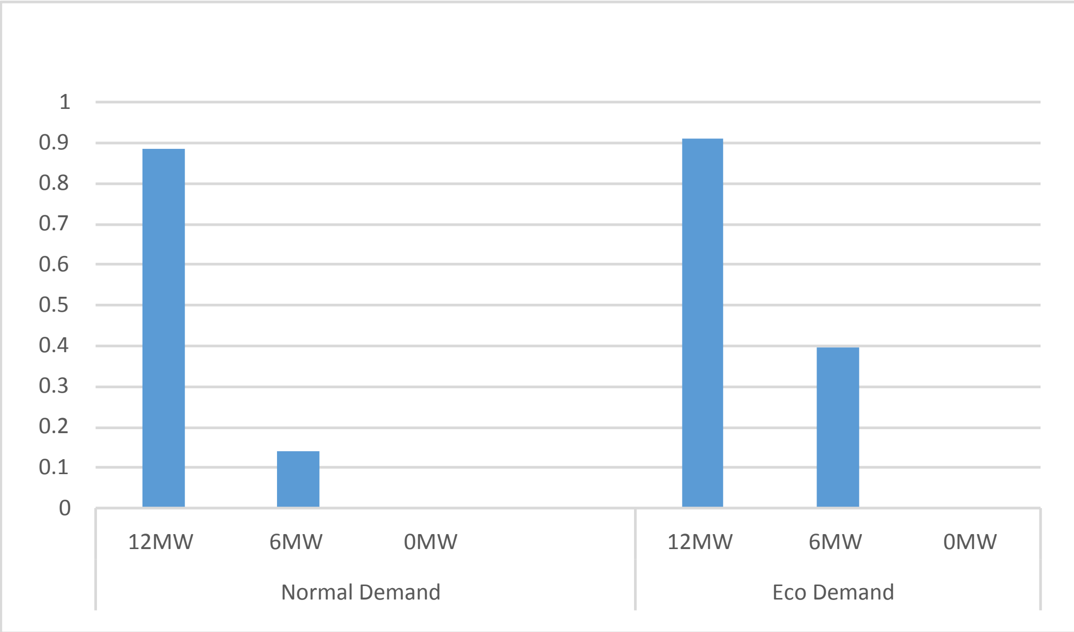
	Diesel Power Plant: 12MW	Diesel Power Plant: 6MW	No Diesel Power Plant
Solar PV (MW)	5	72	120
Storage (MWh)	48	180	450

MW = megawatt, MWh = megawatt hour, PV = photovoltaic.
Source: Authors.

3.3.3. Diesel Operation Rate at the Best Power Mix

Figure 3.8 shows the operation rate of the diesel generators at the best power mix corresponding to Table 3.14 and Table 3.15. These are calculated using simulation results shown in Table A3.1 to Table A3.5 of Annex 3. In case of 12MW, the operation rate is about 90% for both the normal and eco demands. On the other hand, in case of 6MW it is 40% for the eco demand and 14% for the normal demand. This may be caused by the difference of capacity of solar PV. In case of 6MW, to avoid blackout significant capacity of solar PV will be needed – 120MW for the normal demand and 72MW for the eco demand as shown in Table 3.14 and Table 3.15. Solar PV generates electricity during daytime and charges the surplus electricity in the storage. Therefore, diesel power generation is less needed during night-time because charged electricity in storage will be discharged at night-time.

Figure 3.8. Diesel Operation Rate at the Best Power Mix

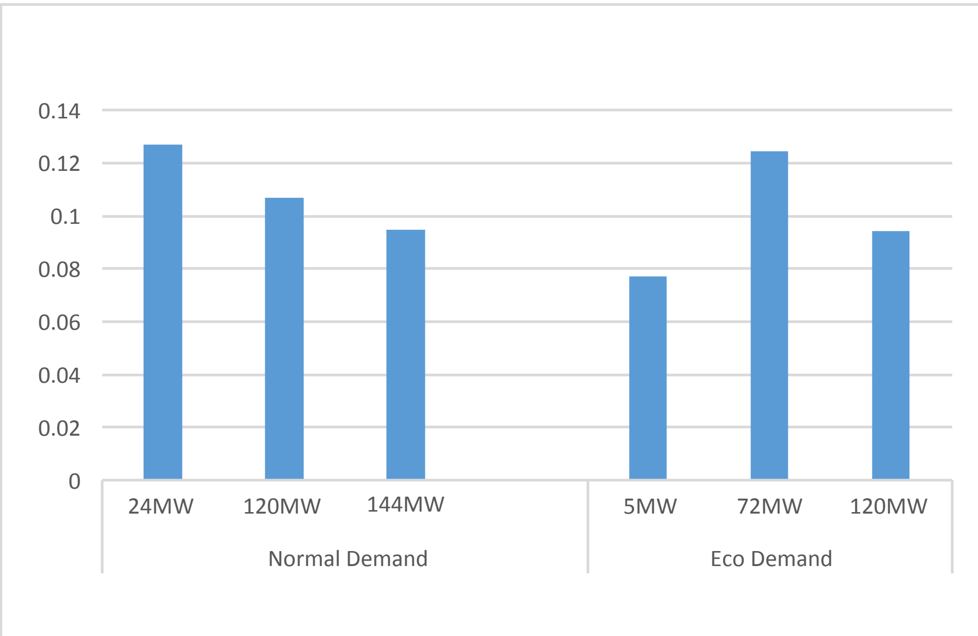


MW = megawatt.
Source: Authors.

3.3.4. Solar PV Load Factor at the Best Power Mix

Solar PV load factor at the best power mix corresponding to Table 3.14 and Table 3.15 is calculated using simulation results shown in Table A3.6 to Table A3.10 of Annex 3, and the calculated results are shown in Figure 3.9. Operation rates of solar PV are in the range of 8%–13% as shown in Figure 3.9. These rates are considered appropriate in the ASEAN region.

Figure 3.9. Solar PV Load Factor at the Best Power Mix

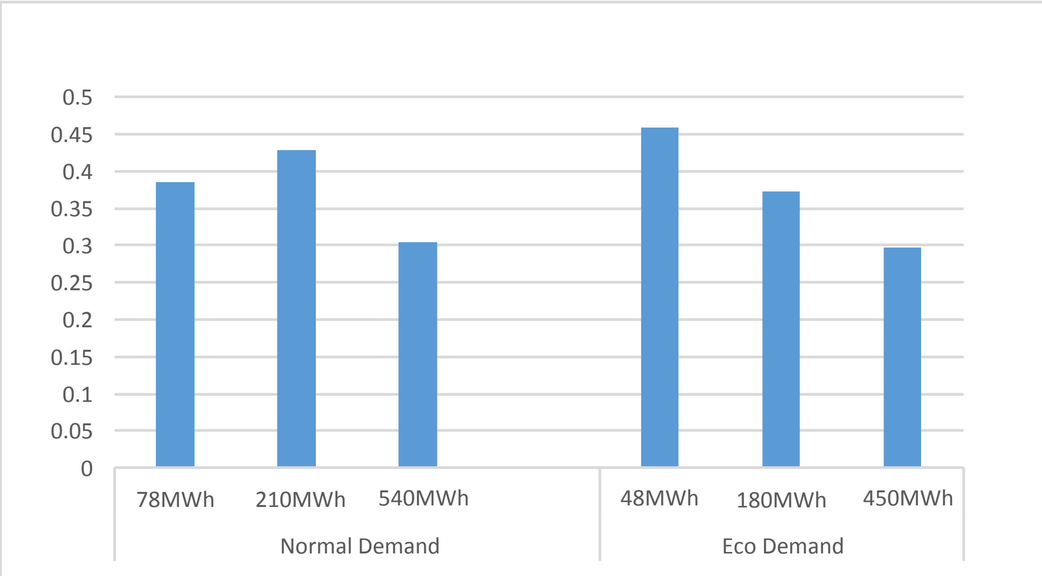


MW = megawatt.
Source: Authors.

3.3.5. Storage Operation Rate at the Best Power Mix

Average values of storage operation rate at the best power mix are calculated using simulation results shown in Table A3.11 to Table A3.16 of Annex 3, and the calculated results are shown in Figure 3.10. The average values of storage operation rate are in the range of 30%–45%. The minimum and maximum are close to 0% and 100%. This means that the storage is efficiently used to balance demand and supply under the fluctuation of solar PV-generated electricity.

Figure 3.10. Storage Operation Rate at the Best Power Mix

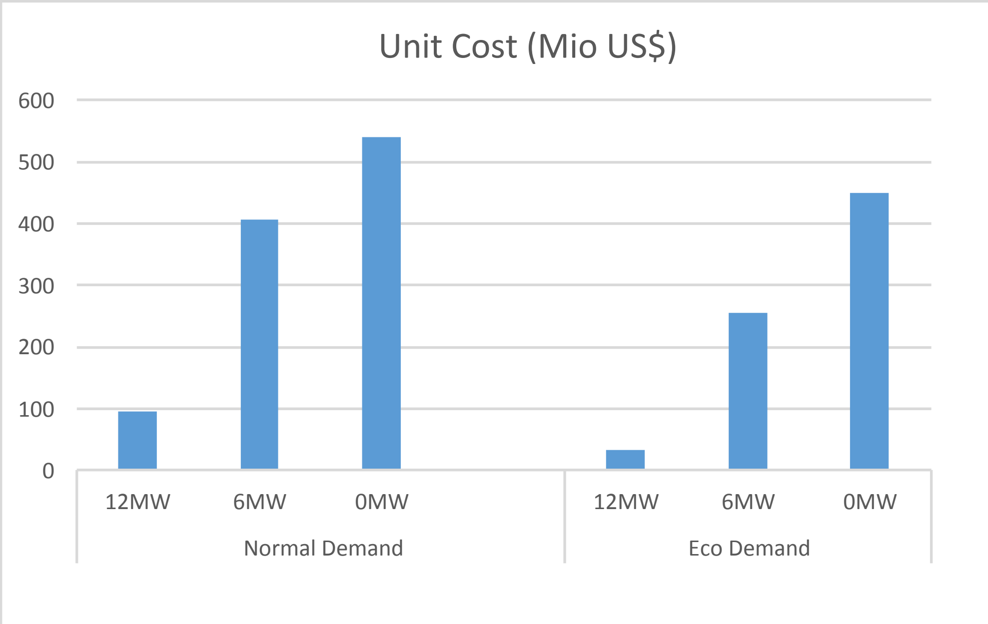


MWh = megawatt hour.
Source: Authors.

3.3.6. Initial Investment Cost at the Best Power Mix

Initial investment costs at the best power mix corresponding to Table 3.14 and Table 3.15 are calculated using simulation results shown in Table A3.17 to Table A3.22 of Annex 3, and the calculated results are shown in Figure 3.11. Without using the diesel generator, combination of solar PV and storage will be technically feasible to supply Temburong Eco Town with electricity although its initial cost is still very high. Cost of solar PV will be dominant, about 80%, followed by cost of electricity storage. If Temburong Eco Town seeks completely carbon-free power supply, more than US$400 million will be required under application of currently available technologies.

Figure 3.11. Initial Investment Cost at the Best Power Mix

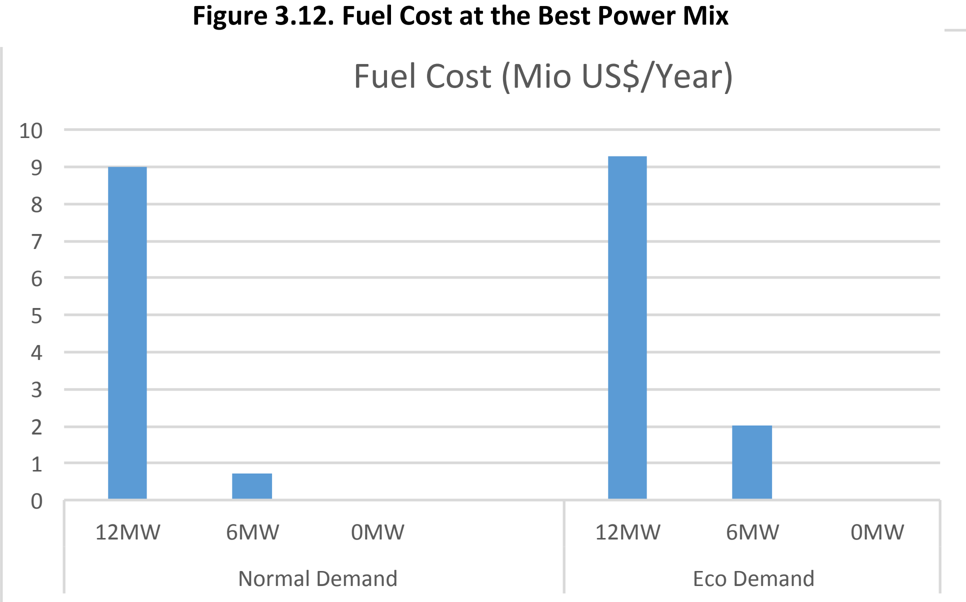


mio = million, MW = megawatt.
Source: Authors.

3.3.7. Fuel Cost at the Best Power Mix

Fuel costs of diesel generators at the best power mix corresponding to Table 3.14 and Table 3.15 are calculated using simulation results shown in Table A3.23 to Table A3.26 of Annex 3, and the calculated results are shown in Figure 3.12. The costs are equivalent for the normal demand and the eco demand. However, these are slightly different by reflecting the diesel operation rate shown in Figure 3.8.

Figure 3.12. Fuel Cost at the Best Power Mix

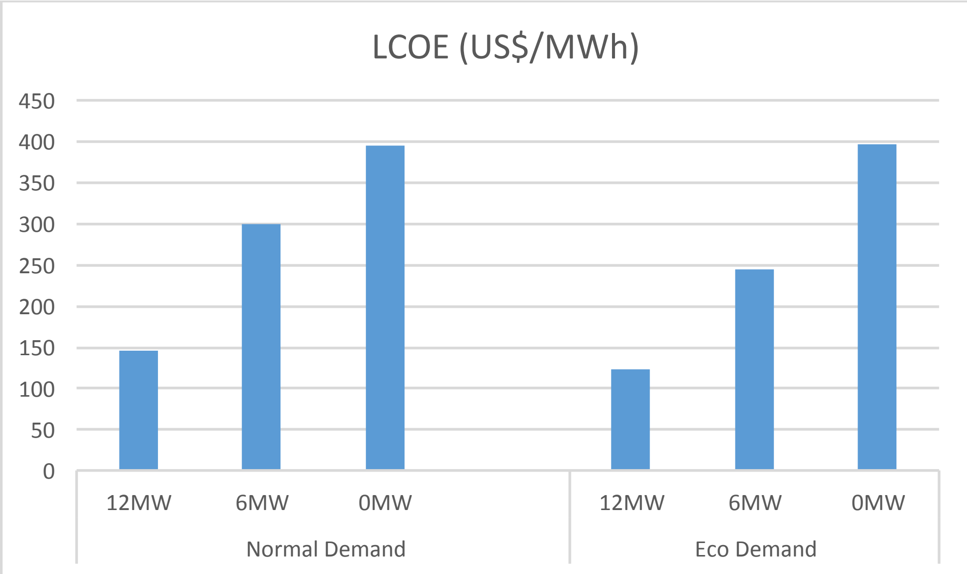


mio = million, MW = megawatt.
Source: Authors.

3.3.8. LCOE at the Best Power Mix

LCOE at the best power mix corresponding to Table 3.14 and Table 3.15 is shown in Fig. 3.13. Completely carbon-free power system with combination of solar PV and electricity storage will be very expensive although significant cost reduction of solar PV and storage is expected. Thus, gradual shifting to a carbon-free power system is a realistic energy policy in Temburong Eco Town development.

Figure 3.13. LCOE at the Best Power Mix



LCOE = levelised cost of energy, MW = megawatt, MWh = megawatt hour.
Source: Authors.

3.4. Conclusion

Operation schedule of diesel generators and electricity storage was simulated to balance demand and supply with the minimum operation cost. Considering fuel cost and investment and maintenance costs, LCOE was estimated for a given mix of power generation system. The best power mixes are identified in terms of the smallest LCOE. Diesel operation rate, solar PV load factor, storage operation rate, initial investment cost, and fuel cost are compared with the best power mixes. The analysis shows that a completely carbon-free power system with a combination of solar PV and electricity storage will be very expensive although cost reduction of solar PV and storage is expected. Therefore, a gradual shift to a carbon-free power system is recommended as a realistic energy policy in Temburong Eco Town development.