Danish Energy Agency

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EREA
Electricity & Renewable Energy Authority

EMBASSY OF DENMARK
Hanoi

Balmorel Data Report

Background to Vietnam Energy Outlook Report 2019

June 2019

20-06-2019

This report has been conducted for the **Electricity and Renewable Energy Authority in Vietnam (EREA)** and the **Danish Energy Agency (DEA**). The report should be cited as *EREA & DEA: Balmorel Data Report. Background to the Vietnam Energy Outlook Report 2019 (2019)*

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1 Introduction and background

This is a Data Report relating to the project 'Capacity building within Balmorel and scenarios'. The project is being carried out by Ea Energy Analyses in collaboration with the Institute of Energy (Viện Năng lượng) as part of the Development Engagement 1: "Capacity Development for long-range energy sector planning with Electricity and Renewable Energy Agency of Viet Nam", currently being conducted under the Energy Partnership Programme between Viet Nam and Denmark (DEPP).

This Data Report documents the data and assumptions used for representing the Vietnamese power sector in the Balmorel modelling framework. This Data Report is prepared as supporting documentation to the Energy Outlook Technical Report (EOR) 2019.

Approach

To identify and quantify benefits and disadvantages of different development scenarios within the Vietnamese power system, the country's generation and transmission system is modelled based on the concept of least-cost optimization. Several scenarios are set up in consultation with Institute of Energy and the Danish Energy Agency to illustrate the economic consequences of possible future strategies.

All cost data in this report are in USD 2016 real terms.

2 The Balmorel model

The Vietnamese power system analyses are carried out with the Balmorel model, which is a least-cost dispatch power system model. The model is based on a detailed technical representation of the existing power system; all power generation plants are represented on individual basis as well as the interconnected transmission grid.

The output is a least-cost optimisation of all the production and transmission units represented in the model. In addition to simulating least-cost dispatch of generation units, the model simultaneously allows for investments to be made in different new generation units (hydro, coal, gas, wind, solar, biomass etc.) as well as in new interconnectors.

2.1 Investment approach

The Balmorel model is myopic in its investment approach, in the sense that it does not explicitly consider revenues beyond the year of installation. This means that investments are undertaken in each year if the annual revenue requirement (ARR) in that year is satisfied by the market. Construction time is not explicitly considered in the model (although interests during construction are included in the investment costs for new technologies). Capacity appears in the beginning of the year of commissioning. This means that the decision for investment should be considered as taken in an earlier year (considering planning and construction).

A balanced risk and reward characteristic of the market is assumed, which means that the same ARR is applied to most technologies, specifically 0.1175, which is equivalent to 10% internal rate of return for 20 years. This rate should reflect an investor's perspective. For transmission capacity this ARR becomes 0.1023 (10% internal rate of return for 40 years).

It should be stressed that the recommended socio-economic discount rate in many countries is significantly lower than the 10% rate applied in the present study (Germany: 2.2%, Sweden and Norway: 4%, Denmark and Finland: 2-4 %, UK: 1.0-3.5%, EU: 3.5-5.5%[1]). Applying a lower discount rate would favour capital-intensive technologies like wind power, nuclear power and solar pow-

[1] European Commission (2008): Guide to Cost-Benefit Analysis of investment Projects; Concito (2011): Den samfundsøkonomiske kalkulationsrente – fakta og etik.

er as opposed to, e.g. gas power plants. The current 10% discount rate was agreed upon as an appropriate value.

2.2 Time resolution

The model is set up to analyse the year 2017 as reference year and the period 2020-2050 in 10-year intervals.

To limit the computation time, not all hours of the year are included in the simulation. The dispatch and investment optimisation, both in generation capacity and in transmission capacity, are performed with 14x26 (364) time steps. The 13 seasons represent two-week periods in the year, where the hours are aggregated into 14 intervals representing evening peak demand, afternoon solar peaks, nights, morning etc. A more accurate dispatch optimization can be analysed in 7x168 (1176) time steps, where all hours of 7 weeks are simulated. The 7 selected weeks of the year are: week 4, 10, 16, 34, 39, 47, 52. The chosen weeks are important in relation to the data profiles included in the model. These weeks were chosen to represent low and high demand, high and low wind and solar generation, dry and wet weeks. This relates to electricity demand, hydro inflow, wind and solar profiles.

2.3 Geographical scope

The model contains data of the electricity system of Vietnam. The map below (Figure 1) illustrates the interconnected power system in Vietnam in 2019.

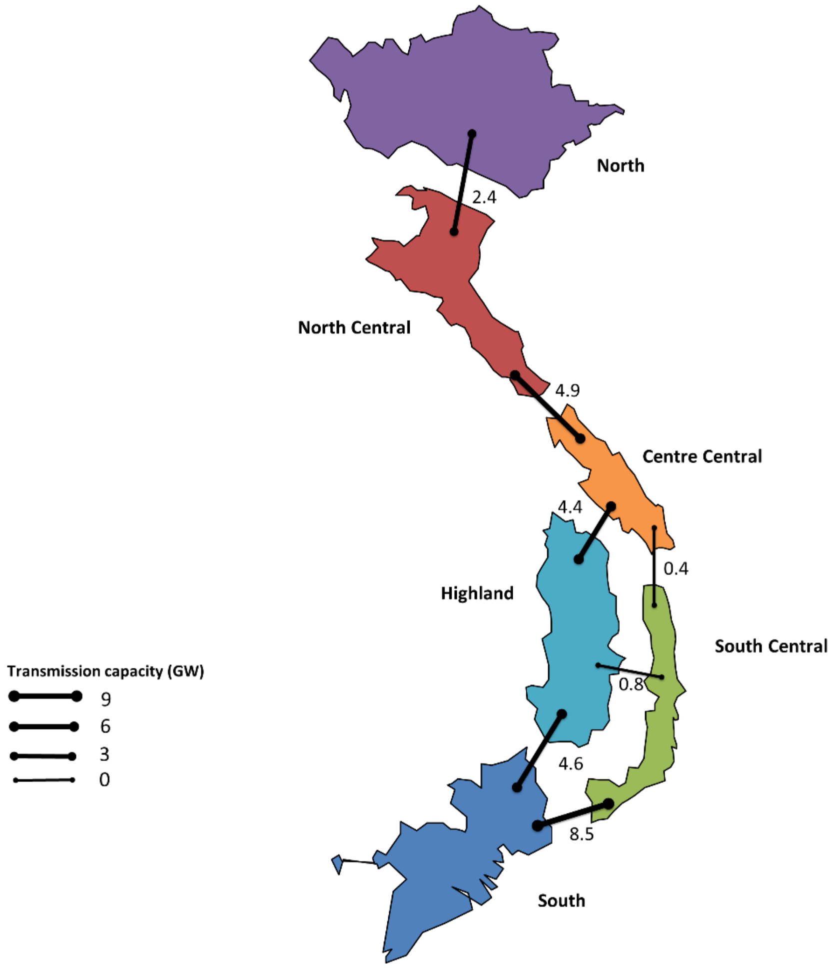


Figure 1. Current interconnectors in Vietnam (2019).

The country is represented in the Balmorel model as 6 transmission regions, each with its own electricity consumption. The transmission regions are connected by electricity transmission lines with fixed capacity. The six regions are selected to represent in more detail the central region of Vietnam, where a large part of the potential for wind and solar power is located. Moreover, the six regions were chosen in order to represent potential transmission bottlenecks in the system.

To allocate generation capacity to the transmission regions, areas are used. Areas are modelling entities in which generating units are placed. For each area, characteristics such as fuel prices, full load hours and hourly profiles for wind, solar and hydro, hydro-reservoir sizes etc. can be defined. Any area must be included in exactly one region. Each transmission region contains one or more areas. As such, it is possible to assign different technological properties to power plants within one transmission region by using several areas.

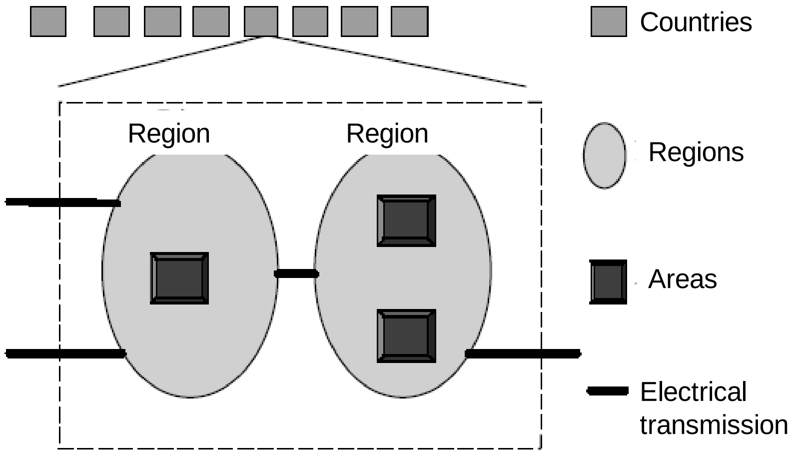


Figure 2: The geographical entity representation structure in the Balmorel model.

In the case of Vietnam, each transmission region has one corresponding area for existing generation and one area for new generation introduced after 2018 in which all generation capacity is allocated, and characteristics of solar and small hydro production are defined. Exceptions are made for all large hydro plants (reservoir plants), each one assigned to a specific area per individual plant to be able to describe their plant-specific inflow profiles, full load hours and reservoir sizes. Wind sites of Vietnam are also modelled in three separate areas per region, where wind speed profiles are assigned.

Electricity balances are given on a regional basis. Hence, for each region an electricity balance must be fulfilled but electricity may be exchanged between regions. Therefore, the transmission, and its constraints, losses and costs, are the motivation for the concept of regions.

3 Existing and committed system

Generation technologies in the Balmorel model can be divided into two groups: exogenous generation and endogenous generation. All exogenous capacity is fed into the model as input and is not the result of model optimization. On top of the exogenous capacity, the model can decide to invest in additional capacity, choosing from a list of options, namely the technology catalogue. This model-based additional capacity is called endogenous.

This chapter will look into exogenous generation and transmission capacity

3.1 Existing generation capacity

The generation capacity of existing and committed (i.e. planned with a high likelihood of being realized) power plants is entered in the model exogenously, meaning that it is put in "by hand" and not optimally "chosen" by the model. The exogenous generation fleet is taken from PDP 7 Revised [1]. A detailed list of all PDP 7 revised power plants implemented in the model is presented in the Appendix I. Existing technologies and planned facilities until 2025 as per PDP 7 revised are entered in the model as exogenous, except for coal-based technologies which are only committed until 2023, as investments are less certain due to public resistance and difficulties finding financing. RE capacities are committed until 2025 based on [2]. The exogenous implemented technologies are shown by fuel type in Figure 3.

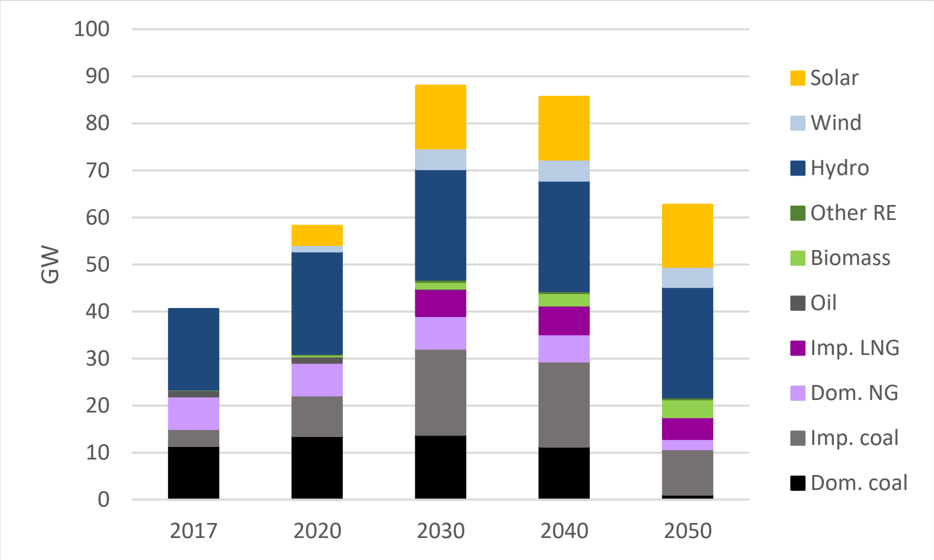


Figure 3: Exogenous generation capacity (existing and planned until 2025). The plants are exogenously decommissioned after their technical lifetime.

Existing and committed capacity (by 2025) is shown by region in Figure 4.

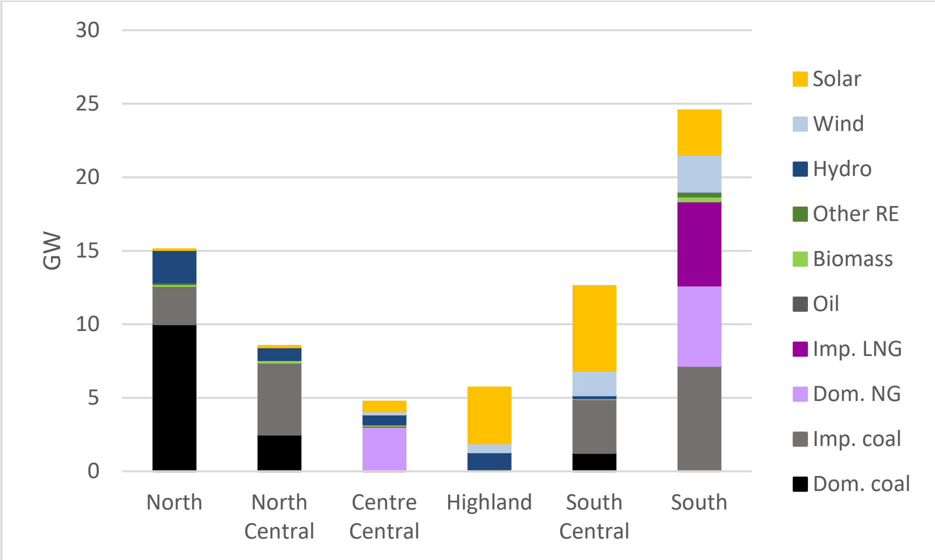


Figure 4: Existing and committed capacity per region (by 2025)

Exogenous decommissioning is applied to the existing and committed generation fleet, i.e. the technologies are removed from the model after their lifetime has ended.

The existing power plant capacity is based on 2018 statistics. However for solar PV and wind power the development has since then been remarkable due to profitable subsidy schemes. In end of June 2019 the capacity of connected solar PV and wind in Vietnam reached 4.5 GW and 0.45 GW solar PV and wind, respectively, however at this point the EOR19 modelling were already finalised. Comparing with the capacity in the model it shows that in the model year 2020 (the models are not run for 2019) a similar amount of capacity of 4.1GW and 1.4 GW solar PV and wind, respectively, in the model. Thus the solar PV capacity in 2020 in the model is only marginally lower than the realized June 2019 capacity in Vietnam, a correction of this would not in any significant way affect the EOR19 calculation results.

O&M for existing and committed units

Generic assumptions for fixed and variable operation and maintenance (O&M) costs are applied for existing and committed power plants and are uniform across the regions. The costs can be seen in the Table 1 below and are based on data from [3] and [1].

Generation type	Efficiency	Fixed O&M *($1000/MW el.)*	Variable O&M *($/MWh el.)*	Lifetime *(years)*
Coal	35-41%*	21.68	2.28	30
CCGT	59%	26.32	2.19	30
Oil thermal	24-44%**	8.00	6.4	25
Biomass	32%	56.56	3.0	25
Hydro	FLHs	45.00	0.6	40
Wind	FLHs	79.40	0.0	25
Solar	FLHs	15.00	0.0	25
Pumped hydro	70%	15.00	2.0	20
Coal	35-41%	21.68	2.28	30

Table 1: Generic fixed and variable O&M and lifetime for existing and committed power plants.
** Depending on coal grade*
*** Depending on individual plant*

Unit commitment

Unit commitment is implemented in Balmorel as a relaxed mixed integer problem. This means that variables which in the ideal case would be binary values (0 or 1) are represented as linear values (e.g. a unit can be 56% online). Variables in the unit commitment problem include:

- Whether the unit is online or not
- Whether the unit is starting-up or not
- Whether the unit is shutting-down or not

As the modelling includes many different units, the general impact of implementing unit commitment on a large scale in this form will be close to the realistic impact. For modelling dispatch of one specific unit, (non-relaxed) mixed integer programming is recommended.

Unit commitment is implemented with data on unit size, start-up costs and minimum generation, received from [1], for a large number of specific existing technologies, as can be found in Appendix II. For thermal technologies, where no specific data was available, as well as for investment options, the unit commitment parameters are implemented as shown in Table 2, based on [3].

		Unit size (MW)	Start-up cost (USD/MW)	Minimum gen. (% of MW)	Ramp up-down (%/hour)	Minimum up (hours)	Minimum down (hours)
2020	**Nuclear**	1000	260	50%	1.2	6	6
	Subcritical	600	180	67%	0.6	4	2
	Supercritical	600	180	75%	0.6	4	2
	Ultrasuper	600	180	30%	3.0	4	2
	CCGT	250	131	56%	4.2	4	2
	Biomass	25	180	30%	6.0	4	2
2030	**Nuclear**	1000	260	50%	1.2	6	6
	Subcritical	600	180	25%	2,1	4	2
	Supercritical	600	180	25%	2,4	4	2
	Ultrasuper	600	180	25%	3,0	4	2
	CCGT	250	131	30%	12,0	4	2
	Biomass	25	180	30%	6,0	4	2
2050	**Nuclear**	1000	260	50%	1.2	6	6
	Subcritical	600	180	20%	2,1	4	2
	Supercritical	600	180	20%	2,4	4	2
	Ultrasuper	600	180	20%	3,0	4	2
	CCGT	250	131	15%	12,0	4	2
	Biomass	25	180	30%	6,0	4	2

Table 2: Unit commitment parameters for thermal units.

Emission factors

The level of SO_2 and CO_2 emissions per fuel type is determined by the fuel used for power production in each time-period by the individual generation units and the corresponding emission factors. An overview regarding the emission factors employed in the current analysis is provided in Table 3. Coal technologies with CCS remove 90% of the CO_2 emissions in coal.

Fuel	CO_2 content (kg/GJ fuel)	SO_2 content (kg/GJ fuel)
Coal	95	0.714
Natural gas	56.8	0
Fuel oil	78	0.446
Light oil	74	0.023
Coke	106	1.428

Table 3: Assumptions regarding the CO_2 and SO_2 content in different fuels per GJ of fuel energy content. Only fuels emitting SO_2 and/or CO_2 have been listed.

Decommissioning

Decommissioning in Balmorel can take place both exogenously and endogenously. As explained above, existing and committed generation is decommissioned exogenously by calculating the decommissioning year from the start year. Endogenous decommissioning is not allowed in this study.

Outages

Forced and planned outages are assumed for both existing, committed and candidate power plants. All thermal units are characterized by an ‘availability factor’ of 90% to reflect the downtime for planned and unplanned outages. For coal power plants this outage rate is set at 80%. This factor is, however, applied as a constant over time, meaning that at any given time 10% (or 20%) of the rated generation capacity is not available. Wind, solar, and hydro are not set to be de-rated due to planned outages, since this is assumed to take place when there is no generation on the unit. Unplanned outages on these units are considered in their yearly energy output (full load hours).

3.2 Existing and committed transmission capacity

The starting point of the interconnected grid within Vietnam comprises all existing and committed interconnectors. The country is divided into 6 transmission regions. These regions are then connected by the transmission grid.

Committed interconnectors are projects that are under construction, projects that are decided and financed, or project planned with a very high likelihood of being realized. . These committed interconnection projects and their net transfer capacities are considered as exogenous capacity just as the existing interconnectors.

The figures below show maps of Vietnam with all existing and committed interconnectors for 2020 and 2030, as in PDP 7 [1].

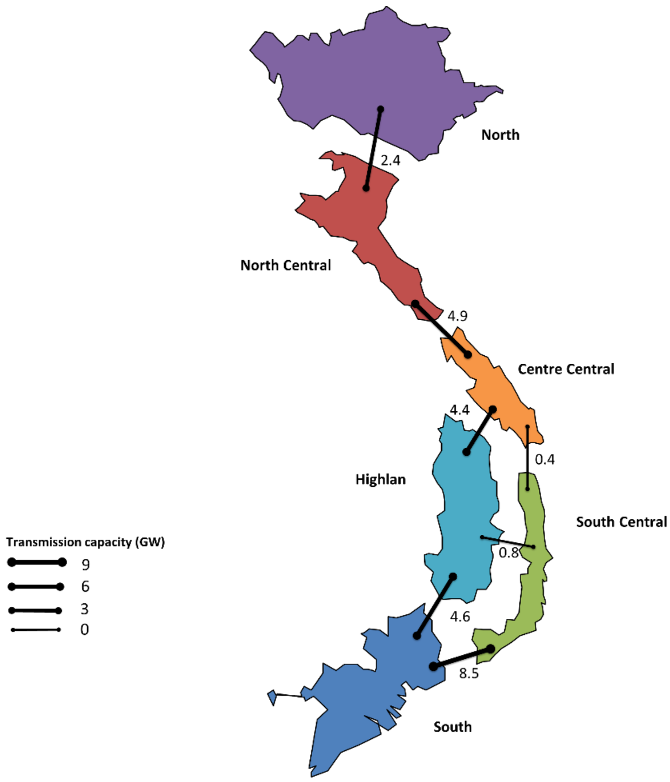


Figure 5: Existing and committed interconnectors in Vietnam, total capacity in 2020.

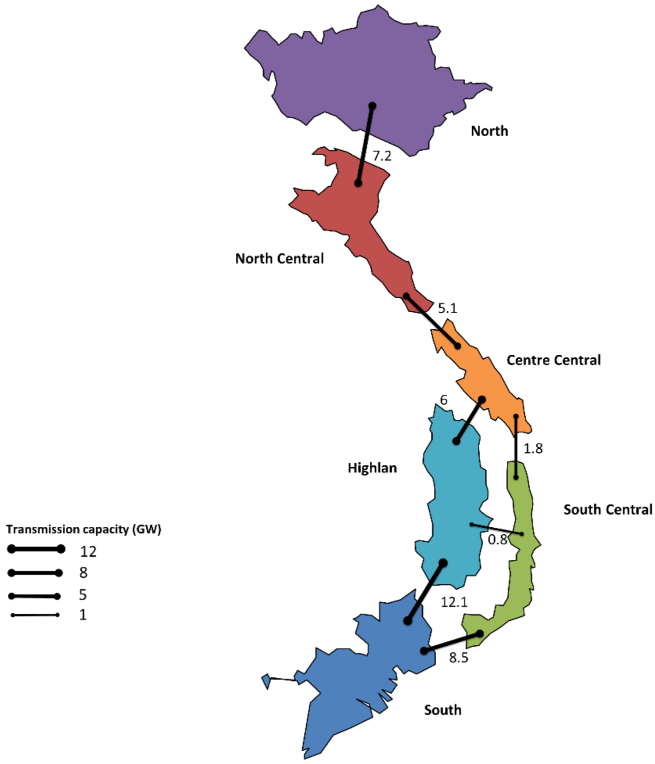


Figure 6. Existing and committed interconnectors in Vietnam, total capacity in 2030.

The net transfer capacity of all interconnectors in the model is de-rated by 10% to account for planned and unplanned outages of the lines based on own assumptions.

4 Future developments

4.1 Electricity demand

Annual electricity demand forecasts

The power demand projections used in this study, presented in Figure 7, are supplied by Institute of Energy, as result from the all-sector modelling of the Vietnamese energy system in the TIMES-Vietnam model. Power demand is an output of the latter and is used as input for the Balmorel model. More details can be found in the Technical background report for the EOR [4]. Disaggregation of the national demand over the six transmission regions is based on the regional division used in [5].

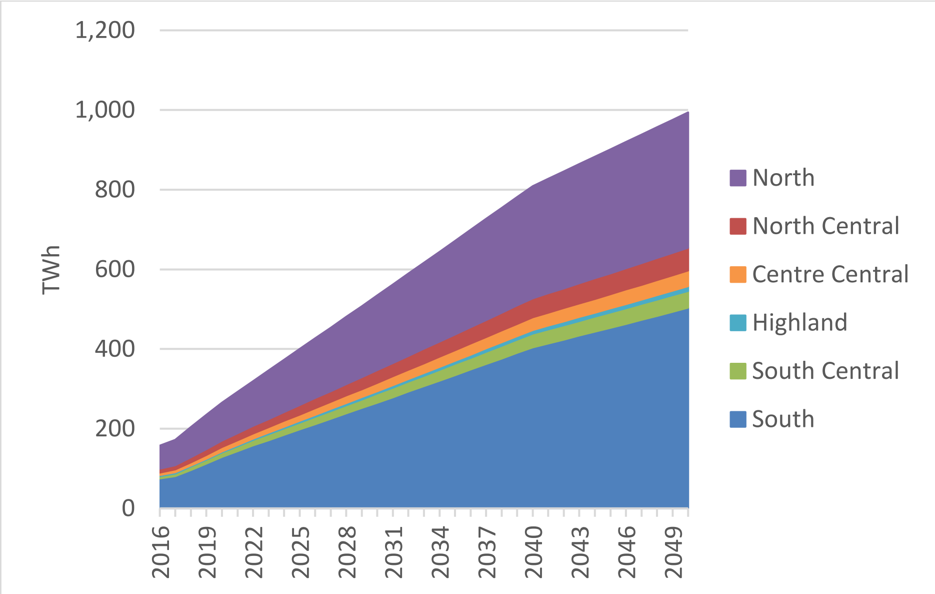


Figure 7: Annual electricity demands per transmission region

Demand profiles

Hourly demand profiles are used for all years based on statistics of 2017 [1].

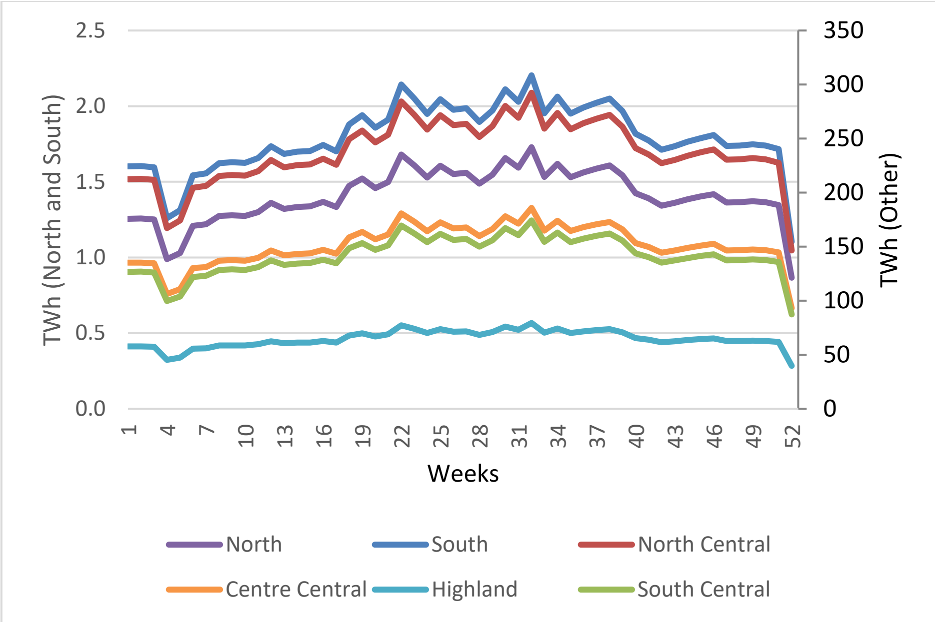


Figure 8: Weekly demands based on hourly demand profile (2017).

4.2 Import from third countries

The import of electricity to Vietnam from third countries is shown in Figure 9. North Vietnam imports electricity from China, while the regions North Central, Centre Central and Highland import from Laos. For the Laos connection, a hydro generation profile was used to represent the expected import from the designated hydro plants in Laos, whereas for China an hourly profile was obtained from [1].

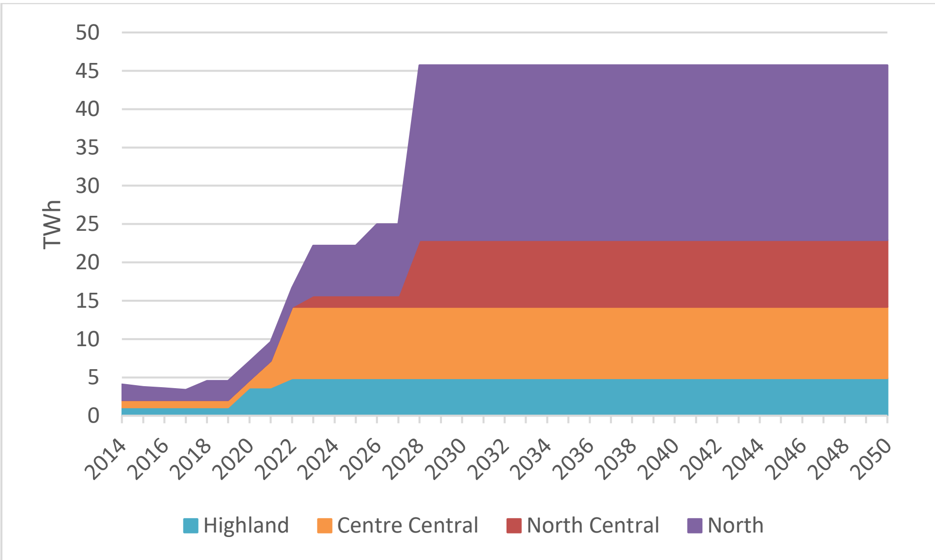


Figure 9: Annual import to Vietnam

The import of electricity from Cambodia does not have clear signals from the government and investors, so import from Cambodia is not considered in this report.

4.3 Fuels and fuel prices

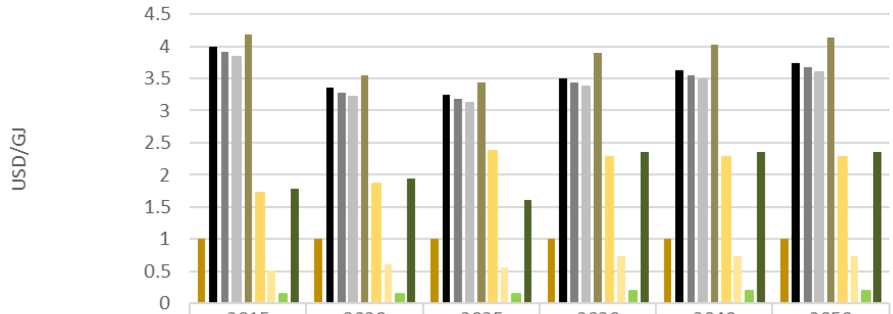
The fuels represented in the model are summarized in Table 4.

Fuel	Description	Origin	Available
Nuclear	Uranium	Imported	Everywhere
NG (South-East)	Natural gas	Domestic	South
NG (South-West)	Natural gas	Domestic	South
NG (Block B)	Natural gas	Domestic	South
NG (CVX)	Natural gas	Domestic	Centre Central
LNG	Liquidized natural gas	Imported	Everywhere
Dom. Coal (4b-5)	Coal (grade 4b or 5)	Domestic	North/North Central
Dom. Coal (6)	Coal (grade 6)	Domestic	North/North Central
Dom. Coal (7)	Coal (grade 7)	Domestic	North/North Central
Imp. Coal	Coal (grade 4)	Domestic	Everywhere
Fuel oil	Fuel oil	Imported	Everywhere
Light oil	Light oil	Imported	Everywhere
Rice husk	Biomass	Domestic	Regional*
Straw	Biomass	Domestic	Regional*
Bagasse	Biomass	Domestic	Regional*
Wood	Biomass	Domestic	Regional*

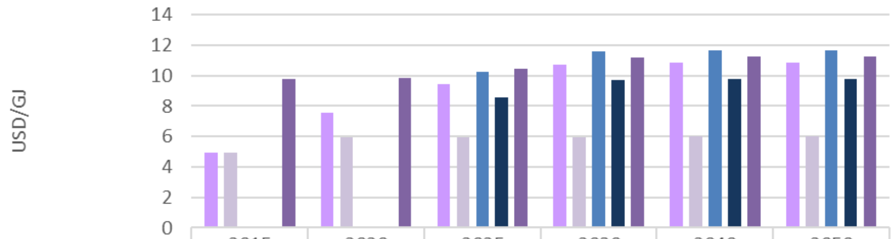
Table 4: Fuels used in the Balmorel model, including a description of whether the fuel is imported or domestic, and in which regions the fuel is available
**These fuels are restricted by generation capacity and by fuel potential, see Figure 20.*

The fuel prices used in the Balmorel model are shown in Figure 10. These are based on the prices projected in [6], which contains details on price formation, components and assumptions for the projections used. The prices considered are CIF (Cost, Insurance and Freight) prices, i.e. reflecting the cost associated with the fuel while still on board a ship in a Vietnamese harbour. For imported coal and LNG, Vietnam-specific cost add-ons[2] are added to obtain the fuel prices as seen by the plants.

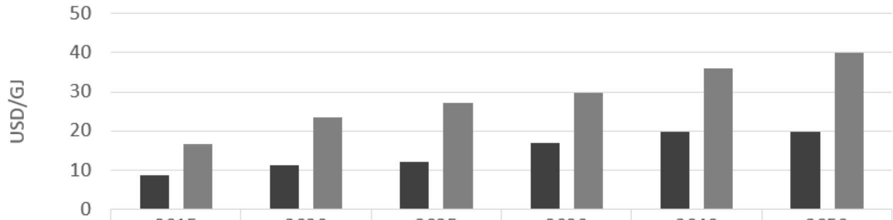
[2] Add-ons for coal: domestic shipping fee and transit port fee. Furthermore, differentiation in CIF price is made depending on whether the coal is shipped to the two Northern regions, the two Central regions or the two Southern regions. Add-ons for LNG: terminal and storage fee, transportation and distribution fee, management and profit fee.



	2015	2020	2025	2030	2040	2050
Nuclear	1.00	1.00	1.00	1.00	1.00	1.00
Dom. Coal (4b-5)	3.99	3.35	3.24	3.51	3.63	3.74
Dom. Coal (6)	3.91	3.28	3.18	3.44	3.55	3.67
Dom. Coal (7)	3.84	3.22	3.12	3.37	3.48	3.60
Imp. Coal	4.18	3.54	3.43	3.90	4.02	4.14
Rice husk	1.72	1.86	2.37	2.27	2.27	2.27
Straw	0.51	0.61	0.55	0.74	0.74	0.74
Bagasse	0.14	0.15	0.14	0.19	0.19	0.19
Wood	1.79	1.94	1.61	2.36	2.36	2.36



	2015	2020	2025	2030	2040	2050
NG (South-East)	4.92	7.53	9.45	10.73	10.82	10.82
NG (South-West)	4.92	5.97	5.97	5.97	6.01	6.01
NG (Block B)	-	-	10.26	11.56	11.65	11.65
NG (CVX)	-	-	8.57	9.69	9.77	9.77
LNG	9.75	9.84	10.41	11.17	11.26	11.26



	2015	2020	2025	2030	2040	2050
Fuel oil	8.71	11.22	12.20	17.06	19.91	19.91
Light oil	16.55	23.38	27.07	29.68	35.87	40.07

Figure 10: Fuel prices. The model also uses wind, sun, hydro and geothermal power, but for those technologies, the "fuel price" is assumed zero.

5 Investment options

In this chapter, investment options for generation and transmission capacity will be discussed together with their characteristics, learning curves, and locations in which they can be invested in. Based on this technology catalogue, the Balmorel model can optimize the additional generation capacity needed to fulfil demand increases and to compensate for exogenous decommissioning of existing or committed capacity. The model will find the least-cost solution by choosing the cost-optimal set of generation technologies and transmission lines.

5.1 Technology catalogue

The Balmorel model has a technology catalogue with a set of power generation technologies available for investment. The investment module allows the model to invest in a range of different technologies including (among others): coal power, gas power (combined cycle plants), small hydro, geothermal, biomass, solar PV and wind power.

Investment technology catalogue

Technical and economic data for the power generation technologies that the model may invest in can be viewed in Table 5. The data is based on [3] as well as some other Vietnamese and international sources. The technology assumptions develop from 2020 to 2050, which means that the costs and efficiencies are assumed to develop depending on the learning curves of the specific technologies. Generally, the technologies develop to have higher efficiencies and lower investments costs.

For the CCGT technologies, the model can invest in units that use domestic natural gas or in units that use imported LNG depending on the region.
Ultra-supercritical coal and advanced-ultra-supercritical coal technologies exist as investment options. A subcritical coal unit exists with carbon-capture storage (CCS) as well, where the unit is more expensive, but the CO_2 emissions are reduced by 90%.

Slow learning curves exist for CCGT technologies, while the learning curves of the investment costs for solar and wind are expected to be steeper.

Battery investments can occur independently for generation/charging capacity and storage size. The investment characteristics are shown in Table 6.

Technology type	Available (Year)	CAPEX incl. IDC (kUSD/MW)	Fixed O&M (kUSD/MW)	Variable O&M (USD/MWhel)	Efficiency (%)	Technical lifetime (Years)
Nuclear	**2030 - 2050**	6,042	20.33	0.15	33%	50
Coal subcritical	**2020 - 2029**	1,316	39.40	0.70	36%	30
	2030 - 2049	1,422	38.20	0.12	36%	30
	2050	1,387	37.00	0.12	36%	30
Coal supercritical	**2020 - 2029**	1,739	41.20	0.12	37%	30
	2030 - 2049	1,598	40.00	0.12	38%	30
	2050	1,551	38.70	0.11	39%	30
Coal ultra-supercritical	**2030 - 2049**	1,739	54.90	0.11	43%	30
	2050	1,681	53.20	0.10	44%	30
Coal AUSC	**2035 - 2050**	2,427	54.90	0.11	50%	30
Coal CCS subcritical	**2030 - 2049**	5,049	141.89	2.28	36%	30
	2050	4,923	137.43	2.28	36%	30
CCGT	**2020 - 2029**	881	29.35	0.45	52%	25
	2030 - 2049	812	28.50	0.13	59%	25
	2050	755	27.60	0.12	60%	25
Small hydro	**2020 - 2050**	2,057	38.00	0.46	*FLHs*	50
Wind (Low wind)	**2020 - 2024**	2,145	50.11	5.20	*FLHs*	27
	2025 - 2029	1,915	47.56	4.92	*FLHs*	28.5
	2030 - 2039	1,687	44.92	4.63	*FLHs*	30
	2040 - 2049	1,518	42.67	4.34	*FLHs*	30
	2050	1,349	40.26	4.04	*FLHs*	30
Wind (Medium wind)	**2020 - 2024**	2,049	47.88	4.96	*FLHs*	27
	2025 - 2029	1,830	45.44	4.70	*FLHs*	29
	2030 - 2039	1,611	42.91	4.43	*FLHs*	30
	2040 - 2049	1,450	40.77	4.15	*FLHs*	30
	2050	1,289	38.46	3.86	*FLHs*	30
Wind (High wind)	**2020 - 2024**	1,749	40.86	4.24	*FLHs*	27
	2025 - 2029	1,552	38.54	3.99	*FLHs*	29
	2030 - 2039	1,359	36.18	3.73	*FLHs*	30
	2040 - 2049	1,209	33.99	3.46	*FLHs*	30
	2050	1,064	31.76	3.18	*FLHs*	30
Solar PV (Low land-costs)	**2020 - 2024**	1,247	9.20	-	*FLHs*	25
	2025 - 2029	1,095	8.25	-	*FLHs*	25
	2030 - 2039	942	7.30	-	*FLHs*	25
	2040 - 2049	845	6.75	-	*FLHs*	25
	2050	747	6.20	-	*FLHs*	25
Solar PV (High land-costs)	**2020 - 2024**	1,333	9.20	-	*FLHs*	25
	2025 - 2029	1,177	8.25	-	*FLHs*	25

	2030 - 2039	1,021	7.30	-	*FLHs*	25
	2040 - 2049	924	6.75	-	*FLHs*	25
	2050	826	6.20	-	*FLHs*	25
Geothermal	**2020 - 2029**	4,675	20.00	0.37	10%	30
	2030 - 2049	4,229	18.50	0.34	11%	30
	2050	4,229	16.90	0.31	12%	30
Biomass	**2020 - 2029**	1,892	47.60	3.00	31%	25
	2030 - 2049	1,781	43.80	2.80	31%	25
	2050	1,558	38.10	2.40	31%	25
MSW	**2020 - 2029**	9,949	234.70	24.10	28%	25
	2030 - 2049	9,263	224.80	23.40	29%	25
	2050	8,234	193.50	22.60	29%	25
Tidal	**2020 - 2050**	2,961	21.75	4.00	*FLHs*	30

Table 5: Power generation technology catalogue. Investment costs for battery and pumped hydro (PH) technologies are shown per MWh storage capacity.
**Investment can either be made for using grade 4b/5 or 6 domestic coal or for using imported coal.*
***Investment can either be made for using grade 4b/5 domestic coal or for using imported coal.*
****Advanced ultra-supercritical; only imported coal.*
[IV] Investment can either be made for West, East or CVX domestic natural gas or imported natural gas. Domestic natural gas technologies can also use imported natural gas.
[V] Generation and charging capacity is one fourth of the storage capacity.

	Available (Year)	CAPEX incl. IDC (kUSD/MWh)	CAPEX incl. IDC (kUSD/MW)	Fixed O&M (kUSD/MW)	Variable O&M (USD/MWh)	Efficiency (%)	Technical life time (years)
Battery	2020 - 2029	270	500	0.62	2.28	91%	20
	2030 - 2049	160	300	0.62	2.06	92%	25
	2050	90	140	0.62	1.83	92%	30

Table 6: Battery investment options. The battery is a Li-ion battery. Battery investments can be optimized per MWh and per MW independently.

Interest paid during construction

Interest during construction (IDC) is of importance when evaluating the capital costs of one technology option compared to another. Units with a short construction phase pay less IDC than plants with longer construction time.
Most capital cost data on power generation are given in overnight costs, meaning that no IDC is considered. Therefore, the IDC costs are added to the investment costs taken from [3], to ensure that the true costs of technologies are represented in the model.

In this study an IDC calculation approach is used which assumes that all costs are distributed equally during the construction phase. The distribution of costs will be different from one project to another, therefore as a generic assumption this method is considered valid. The following formula is applied when calculating IDC.

$$IDC = a \times \frac{(1+i)^t - 1}{\mathrm{i} \times \mathrm{t}} \times \left(1 + \frac{i}{2}\right) - a$$

Figure 11: IDC formula. i = interest rate, t = construction time (years), a = invested capital

The IDC has already been included in the investment costs shown in Table 5 with an annuity factor of 10%. Construction times are used as documented in [3].

Years of construction	Added cost due to IDC
1	5.0%
1.5	7.6%
2	10.3%
3	15.9%
4	21.8%
5	28.2%
6	35.0%
7	42.3%
8	50.1%
9	58.4%
10	67.3%

Table 7: IDC cost depending on years of construction.

Wind technologies

Three turbine types are implemented as investment options in Balmorel. Their investment and fixed O&M costs have been based on the technology catalogue [3], but adapted to the turbine specifications used in the model. The technology catalogue details costs for a specific development in turbine technology. The turbine characteristics modelled in Balmorel differ from those in the technology catalogue (TC) because they are optimized for the wind resources in Vietnam. To adjust for the differences between the Balmorel turbines and the TC turbines, the investment costs and O&M costs are scaled according to the diameter size and the hub height. This method is described in [7]. The specific power (SP) and hub heights of the three modelled turbines are shown in Table 8. As the generator size is assumed to increase over the years, the rotor diameter is also expected to increase.

	SP	Hub height
Low wind class	200	100
Medium wind class	200	90
High wind class	285	85

Table 8: Specific power (SP) in W/m² and hub height in m for the 3 onshore wind turbines modelled as investment options.

The Low and the Medium wind class power turbines share the same power curve and differ only in height. The power curves of the wind turbines used in Balmorel are shown in Figure 12.

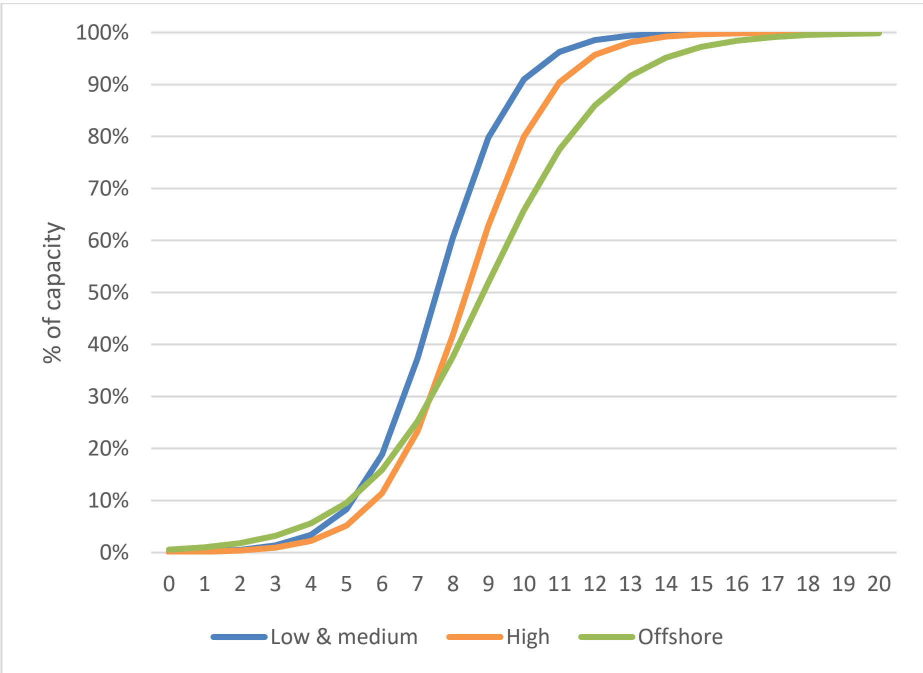


Figure 12: Power curves used in Balmorel

The power generation is modelled according to the following equation:

$$P = \frac{\gamma}{1 + e^{(-g*K_w*(u-M-\epsilon))}}$$

Where P is the generation share of capacity, *u* the wind speed, γ is the peak capacity (between 0 and 1), *g* the growth rate, K_w the smoothening factor, *M* the max growth and ϵ a reality factor.

The reality factor ϵ has been set to 0.7 as an average value.
The smoothening and peak factor are representing that the power curve should represent many turbines spread over a large region and therefore a smoother power curve should be applied. The smoothening and peak factor are based on region size and shown in Table 9.

	K_w	γ
North	0.80	0.95
North Central	0.90	0.98
Centre Central	0.95	0.99
Highland	0.95	0.99
South Central	0.90	0.98
South	0.90	0.98

Table 9: Smoothening and peak factor per region.

The offshore wind technology is based on [3], both for the specific power and the hub height (Table 10). Its power curve for 2050 can be seen in Figure 12.

	SP	Hub height
2020	309	90
2030	353	125
2050	332	140

Table 10: Specific power (SP) in W/m^2 and hub height in m for the offshore wind turbines modelled as investment options.

Solar technologies

For solar technologies, the generation profile and full load hours are based on irradiation data and temperature data. The technology assumptions made to determine these generation profiles are the following:

- South facing panels, with a tilt of 12˚
- 16% efficiency under test conditions
- 0.07%/˚C efficiency reduction under temperatures higher than 25˚C
- 1.1 W_p/W_{ac}
- 10% for other losses (not due to high temperatures)

A learning curve is applied to the FLHs. The relative increase in FLHs is shown in Figure 13, based on the development described in [3].

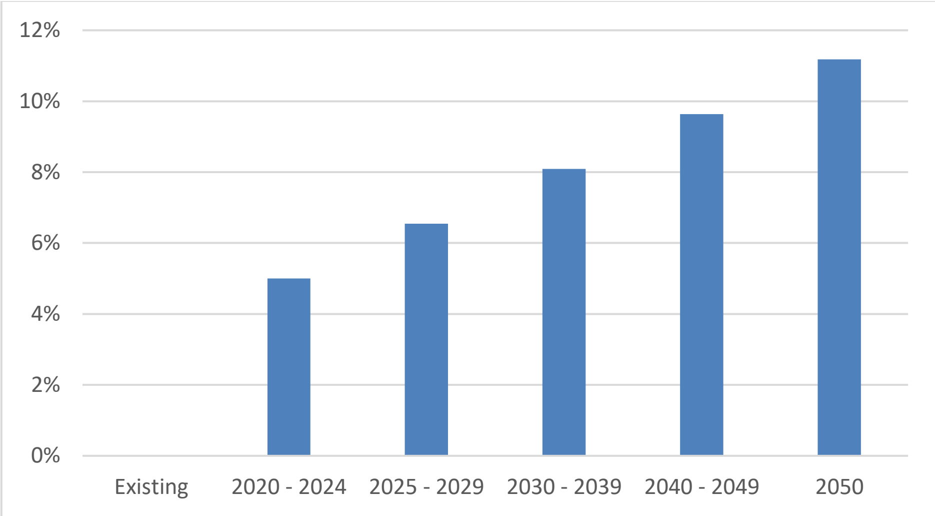


Figure 13: Relative increase in solar full load hours due to technology improvements.

The model can invest in solar technologies with two different capital costs:

- Low land cost: assumes a cost of 6 USD/m^2 for land use
- High land cost: assumes a cost of 12 USD/m^2 for land use

For the land cost calculation, a land use factor of 12 m^2/kW_p or 14.4m^2/kW_{ac} is assumed based on existing solar PV cases in Vietnam. The land cost is estimated from the feasibility study document of the solar PV projects [1] and decisions on land prices by land use purposes of some potential provinces (average land cost).

Pumped hydro projects

Apart from the generic technologies, the model can also invest in specific large pumped hydro projects with reservoir, which are planned in PDP7 after 2020. These projects are located in a specific region and have a maximum capacity (Table 11). Pumped hydro is assumed to have efficiencies of 80%.

Project (Area)	CAPEX incl. IDC (kUSD/MWh)	Maximum Turbine/Pump capacity (MW)	Maximum Reservoir capacity (MWh)	MWh/ MW
Moc Chau PSPP (North)	92	900	7,129	8
Phu Yen East PSPP (North)	62	1,200	17,518	15
Phu Yen West PSPP (North)	105	1,000	8,502	9
Chau Thon PSPP (North Central)	106	1,000	8,502	9
Don Duong PSPP (Highland)	107	1,200	10,479	9
Ninh Son PSPP (Highland)	98	1,200	10,390	9
Ham Thuan Bac PSPP (South Central)	101	1,200	10,390	9
Bac Ai PSPP (South Central)	97	1,200	10,104	8

Table 11: Specific large hydro projects [8].

Locations for investments

Most technologies can be invested in by the model in all 6 regions. However, some exceptions to this rule apply:

- Nuclear capacity: Only in Centre Central and South Central
- Domestic coal technologies: Only North and North Central
- Domestic NG (East and West) technologies: Only in South
- Domestic NG (CVX gas) technologies: Only in Centre Central

Investment restrictions

Nuclear power plants historically have been characterized by complex development process and lengthy construction timelines. In order to make sure that the modelling results are realistic with regard to the build-out of nuclear capacity, a maximum capacity addition cap is set for every 5-year period, as illustrated in Figure 14.

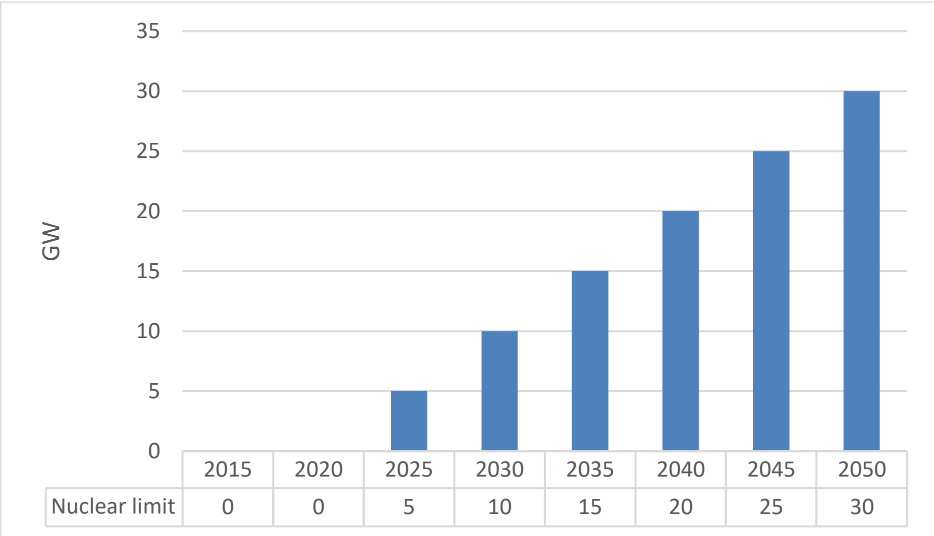


Figure 14: Nuclear capacity build-out limitations implemented in the Balmorel model.

5.2 Interconnector investment costs

The investment costs for new lines are shown in Figure 15. The investment rate of the transmission lines is taken from the PDP7 revised [5].
Investment costs for each transmission line ($/MW/km) are assumed as follows:

- 500kV line: 600 $/MW/km
- 220kV line: 850 $/MW/km

Based on the distance between regions, the investment cost is estimated in Table 12.

Connection	Connection Voltage (kV)	Length (km)	Investment cost ($/MW)
North - North Central (1-2)	500	300	180,000
North Central - Centre Central (2-3)	500	350	210,000
Centre Central - Highland (3-4)	500	250	150,000
Centre Central - South Central (4-5)	500	350	210,000
Highland - South (4-6)	500	300	180,000
South Central - South (5-6)	500	250	150,000
Highland - South Central (4-5)	220	150	127,500

Table 12: Voltage levels, lengths and investment costs for each transmission line.

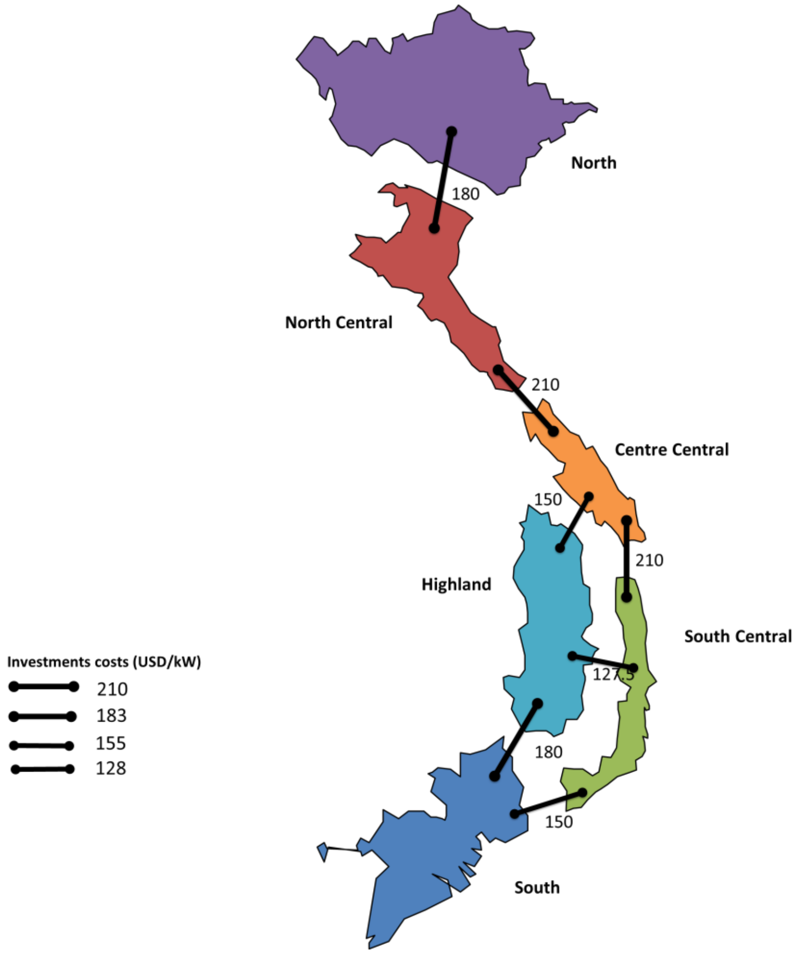


Figure 15: Investment costs in new transmission capacity between the 6 regions

When using higher voltage lines (1000kV AC or 800kV DC), the investment cost will be double compared to the 500kV AC line, but the transmission capacity of the line also will be double. In this way, we still can use the reported investment rate (USD/kW) for transmission investment (Table 12).

6 Fuel and RE resources and potentials

For domestic coal, domestic natural gas, hydro, biomass, MSW, solar PV and wind, investment restrictions are set to account for the limited resource availability. These restrictions are based on best available estimates of different resource potentials and act as upper limits not to be exceeded. These, however, might not necessarily be 'binding' in the model in the sense that the optimization might end up with results well below the potentials.

6.1 Domestic coal and natural gas

For domestic coal and domestic natural gas the restrictions are set on the fuel potential, expressed in energy terms, as presented in Figure 16, Figure 17 and 19. Domestic coal is only found in Northern Vietnam and is represented as two coal grades with different qualities:

- High: High quality and higher fuel price (coal grade 4b and 5)
- Low: Lower quality and lower fuel price (coal grade 6).
- Very Low: Lowest quality and lower fuel price (coal grade 7) - not restricted (only few existing plants use this fuel and there are no investment options)

The domestic coal resources are based on [9].

Two types of domestic natural gas are only used in the South and limited in fuel resource (East and West NG, Figure 17) [10]. The third type (CVX gas) of natural gas is used only in Centre Central and is limited in generation capacity (see Figure 18). A fourth type of domestic natural gas (Block B gas) is only found in the South region but no restrictions are implemented as there is no investment option available for this fuel type.

To represent the take-or-pay contracts in place for natural gas, 95% of the annual domestic natural gas resource available for the power sector must be used for electricity generation. For the domestic coal resource, the same restriction is applied to represent coal use contracts for domestic mines.

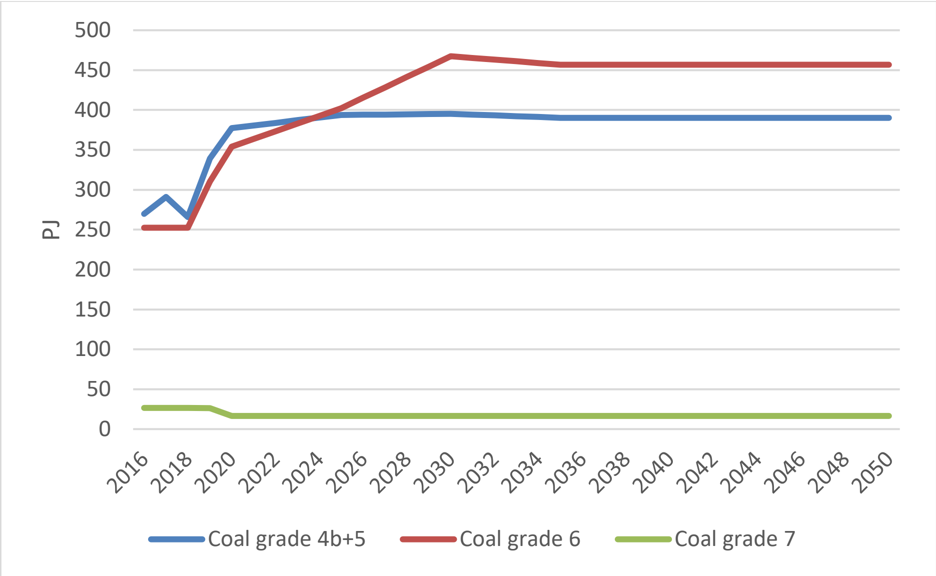


Figure 16: Maximum domestic coal use (PJ).

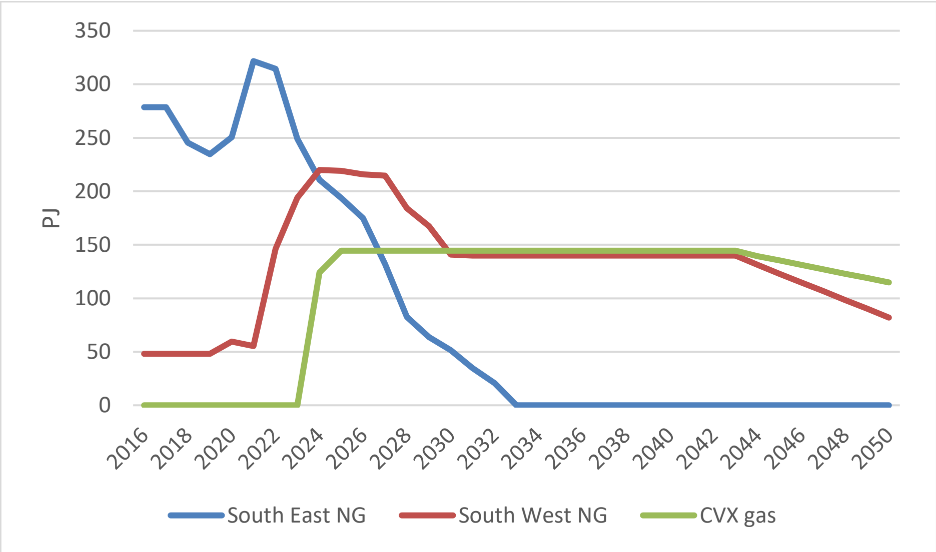


Figure 17: Maximum domestic natural gas use in South (East and West NG, PJ).

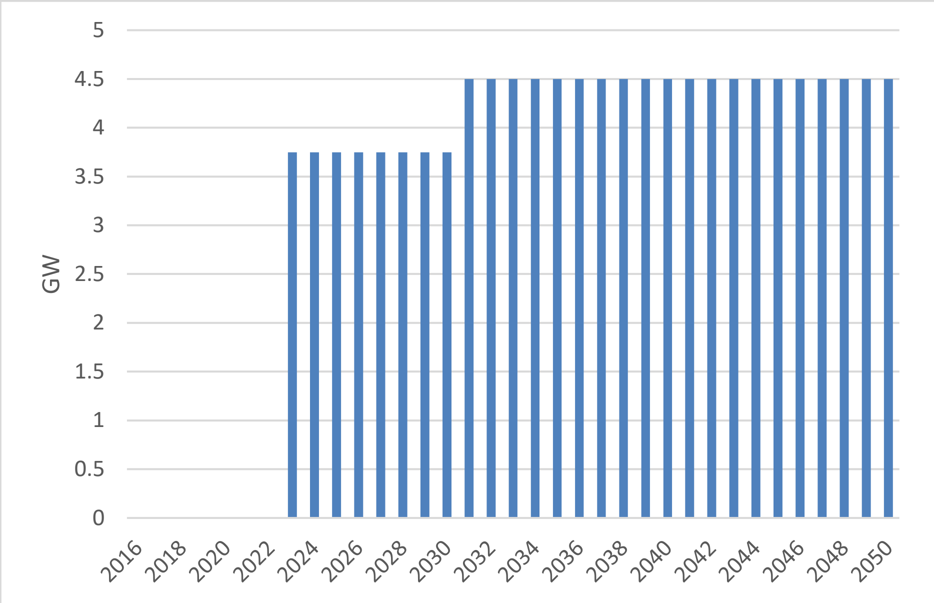


Figure 18: Maximum domestic natural gas use in Centre Central (CVX gas, GW).

6.2 Hydro

Hydro resource

There are two types of hydro power plants – hydro run-of-river plants and hydro reservoir plants. For both types the annual generation (ignoring spillages) is set by the full load hours of the area in which the plant is located and the capacity of the plant. Run-of-river plants do not have any reservoir capacity, and therefore must generate in accordance with the water inflow into the plant (though the option for water spillage is still available).

Reservoir plants can store the water and the model will use this functionality to maximise the value of the water. Both run-of-river and reservoir hydro plants are assigned a hydro inflow profile in the model. This profile in combination with the full load hours will correspond to the generation profile of a run-of-river plant, since the water must be used when available for this technology type. For a reservoir plant this profile will tell the model the level of water inflow to the reservoir throughout the year.
Run-of-river plants are modelled per region (one area per region). This means all run-over-river plants in the same region have the same inflow profile and full load hours. All regions see 2850 full load hours for small hydro.

Each existing and committed large hydro plant (modelled as reservoir plant) is modelled in its own area. This means that each plant has its own full load hours and reservoir size (acquired from [1]), as shown in Appendix III. When no FLHs were available, a regional average was used based on the hydro plants for which data was available.

The reservoir sizes are expressed in the model as percentages of total annual generation and are calculated for the hydro plants for which data was available. For the hydro generation, where no reservoir information was found (including all committed generation), the average for that region was used. Full load hours and reservoir averages are shown in Figure 19.

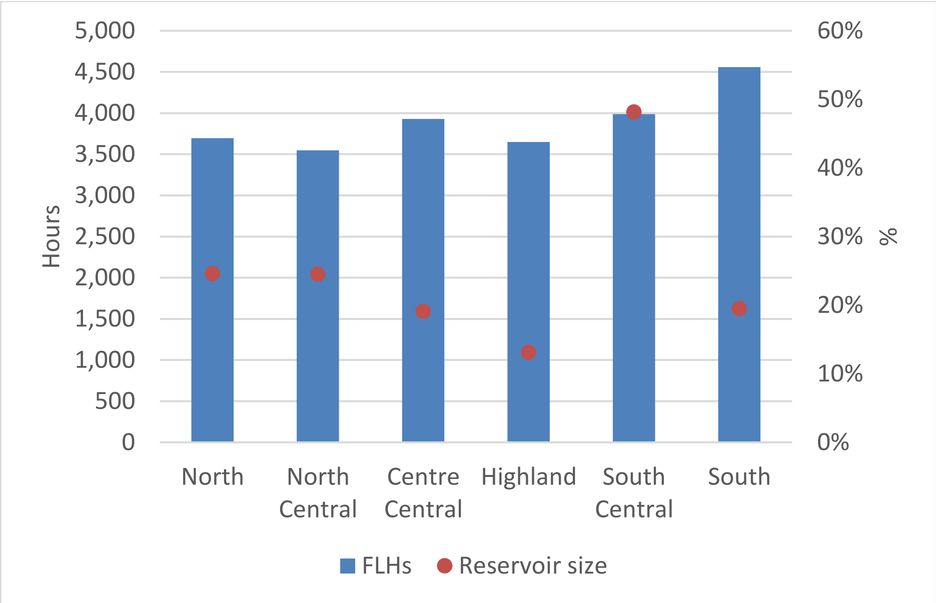


Figure 19: Full load hours and reservoir size for large hydro (average per region).

The hydro inflow profiles are based on the monthly inflow data received from IE [11] for 69 individual hydro plants and are averaged per region to approximate an inflow profile for the remaining plants (both reservoir and run-of-river).

6.3 Biomass and MSW

Restrictions on biomass-fired power generation capacity have been implemented based on an estimate of biomass resources that could be realistically used for power generation applications [12], as presented in Figure 20.

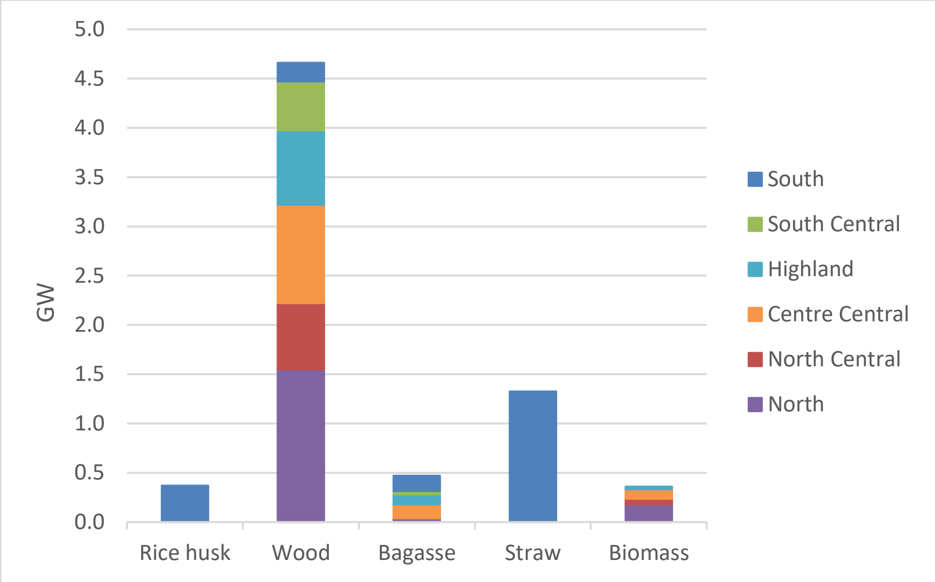


Figure 20: Resource limits on biomass-fired power generation capacity implemented in the Balmorel model (GW).

Similarly, limitations on the availability of Municipal Solid Waste (MSW), have been implemented [12], presented in Figure 21. The MSW potential has been based on the urban population in each of the 63 provinces and the proportion of solid waste assumed to be available for power production out of the total. A maximum annual capacity factor of 70% is implemented for power plants using MSW.

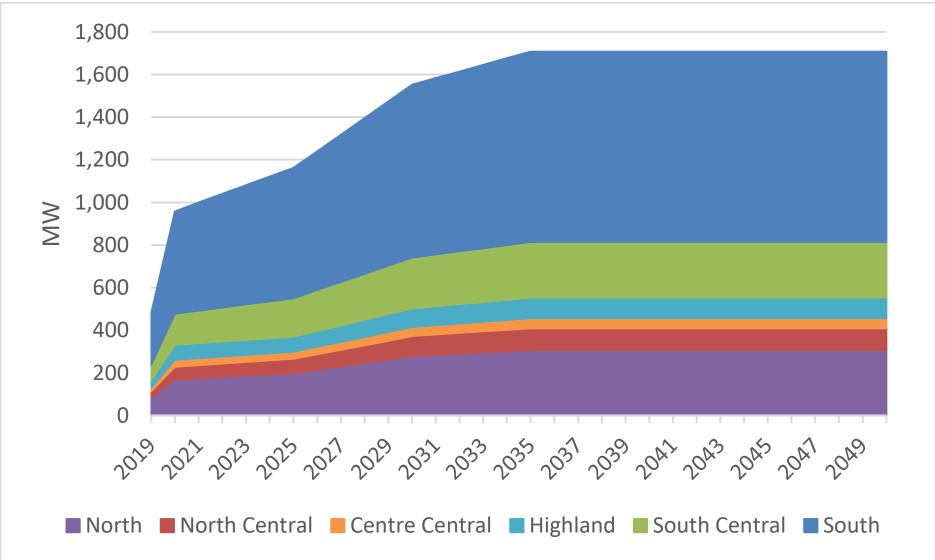


Figure 21: Resource limits on MSW-fired power plant generation capacity implemented in the Balmorel model (MW).

In addition to the capacity restraints, fuel constraints for bagasse, (all other) biomass and MSW are implemented based on the results from TIMES modelling by [4]

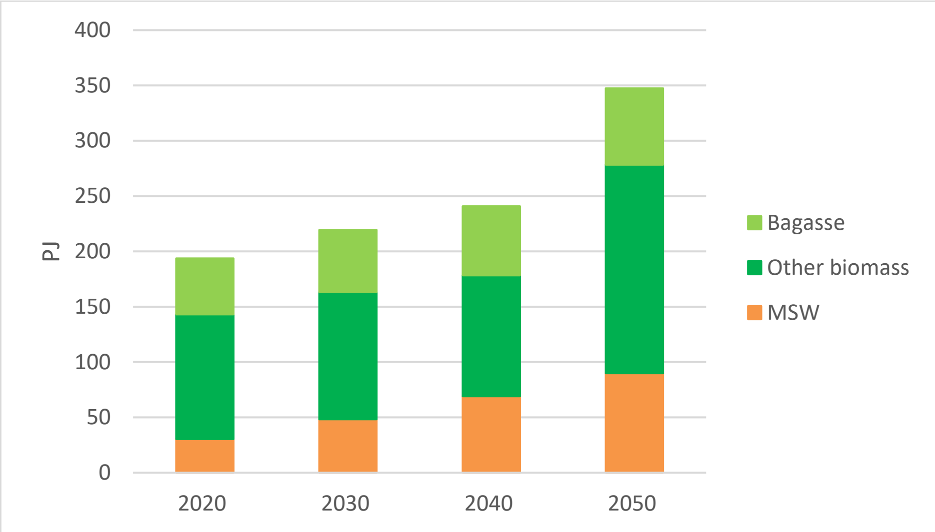


Figure 22: Resource limits on biomass and MSW fuel use implemented in the Balmorel model (PJ) – based on TIMES results.

6.4 Onshore wind

Wind resource

In order to represent the intermittent and variable nature of wind resources, hourly wind speed time series per regional wind class are used in the model. Within the framework of the current study, hourly wind speed time series have been kindly provided by Vestas, as well as DTU Wind (output from the wind resource mapping component of the activity "Resource Mapping and Geospatial Planning Vietnam" under contract to The World Bank, for which no publicly available results were available at the time of writing this report). Hourly wind speed time series of a 'normal' wind year (i.e. the year with the median annual average wind speed out of a sample of 9 modelled years) have been selected to be used in the model. The wind speed profiles provided by DTU Wind have been applied in the analysis due to the higher number of data points (63 locations nationally) in the data set obtained.

The wind speed profiles of 18 provinces were used to represent the 18 wind areas (6 regions with 3 wind speed classes each).
The 63 Vietnamese provinces were grouped per region and divided over the wind classed by average annual wind speed by the following classification which matches the wind speed groups 4.5 – 5.5 m/s, 5.5 - 6 m/s, above 6 m/s at a height of 100m instead of 80m (shear factor of 0.175 assumed).

- Low: 4.67 – 5.72 m/s
- Medium: 5.72 – 6.24 m/s

- High: 6.24 m/s and higher

The average annual wind speed per region and per wind class was used to scale the wind speed profile which was closer to this annual wind speed. The resulting provinces and average wind speeds are shown in Table 13.

Region	Wind Category	Wind speed Province	Average wind speed (at 100m)
North	**High**	Thai Binh	6.88
	Medium	Ha Giang	6.12
	Low	Hai Duong	4.92
North Central	**High**	Quang Binh	7.57
	Medium	Ha Tinh	6.01
	Low	Thanh Hoa	4.83
Centre Central	**High**	Quang Ngai	6.84
	Medium	Thua Thien - Hue	6.05
	Low	Da Nang City	4.86
Highland	**High**	Dak Lak|Dac Lac	7.74
	Medium	Kon Tum	6.08
	Low	Dac Nong	5.33
South Central	**High**	Binh Dinh	8.28
	Medium	Phu Yen	6.50
	Low	Binh Thuan	5.50
South	**High**	Ca Mau	7.39
	Medium	Dong Thap	5.99
	Low	Binh Phuoc	4.86

Table 13: The 18 wind areas in Balmorel, 3 per region and wind category.

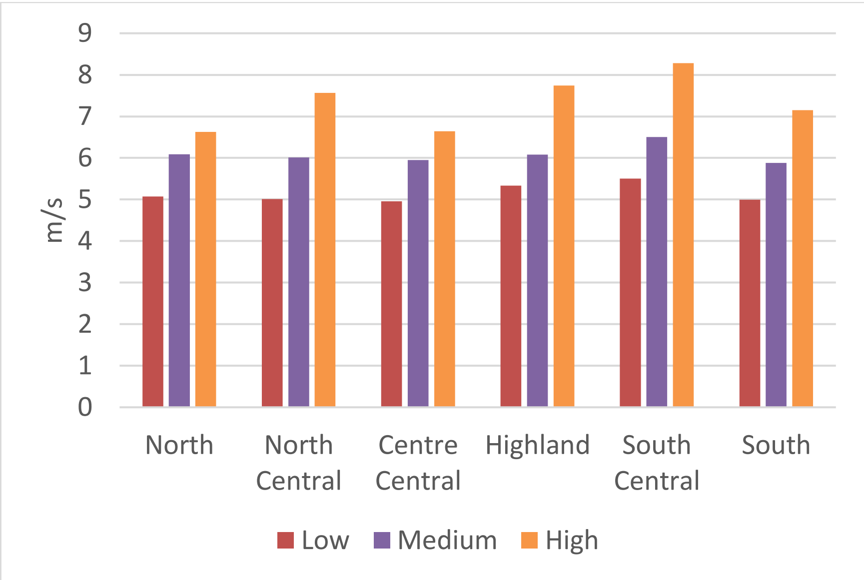


Figure 23: Average wind speed (at 100m) per region and wind speed class.

It is important to note that the wind speeds used in the power curves mentioned in section 5.1 on wind technologies, will be at hub height. The average wind speed at hub height can be calculated from the given number as:

$$u_{x\,meter} = u_{100\,meter} \times \left(\frac{x}{100}\right)^{\alpha}$$

Where x is the hub height and α is the shear factor. The shear factor of a region depends on the roughness and height of the location. For Vietnam they were assumed as shown in Table 14:

	α
North	0.18
North Central	0.18
Centre Central	0.18
Highland	0.17
South Central	0.17
South	0.17

Table 14: Shear factor per region.

Wind capacity potential

Land-based wind resource potential estimates have been based on [2], as shown in Table 15. The Low wind speed class has wind speeds between 4.5-5.5m/s, the Medium between 5.5-6 m/s and High wind speed classes 6 m/s and up at a height of 80m.

(m/s at 80m) →	4.5-5	5-5.5	5.5-6	6-6.5	6.5-7	7-7.5	> 7.5	Total
North	9,681	2,410	421	38	15	0	0	**12,565**
North Center	6,691	2,655	1,212	123	28	0	8	**10,717**
Mid Center	6,362	3,392	1,240	179	57	5	0	**11,235**
Highland	34,397	27,773	14,822	3,369	154	27	30	**80,572**
South Center	12,767	7,689	4,463	2,381	973	271	34	**28,578**
South	15,070	41,518	16,765	285	0	0	0	**73,638**
Total	**84,968**	**85,437**	**38,923**	**6,375**	**1,227**	**303**	**72**	**217,305**

Table 15: Wind potential in Vietnam (MW).

The resulting regional potentials divided over the different wind speed classes can be seen in Figure 24.

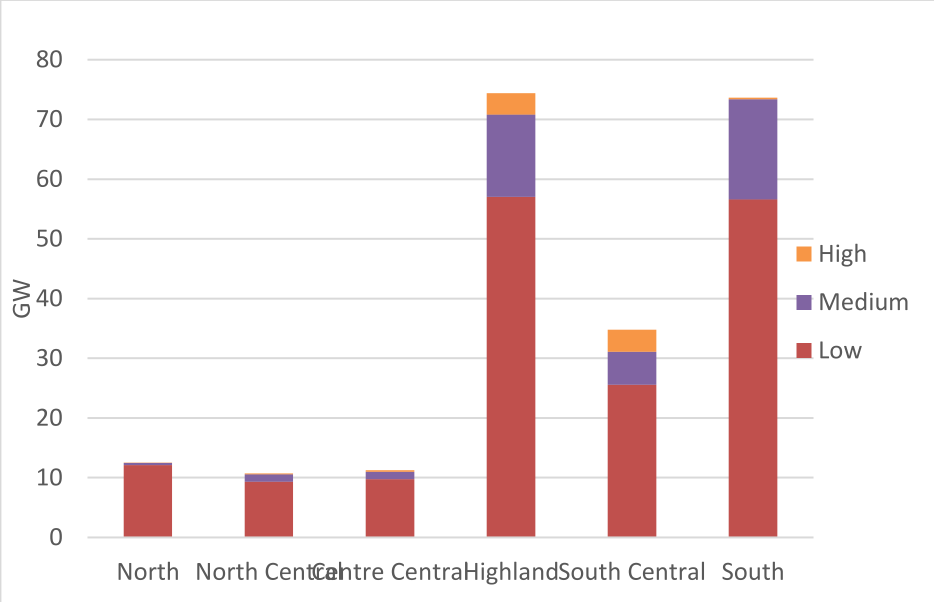


Figure 24: Resource potentials for onshore wind generation capacity per region and wind speed class implemented in the Balmorel model. Low: 4.5-5.5 m/s, Medium: 5.5-6 m/s, High: over 6 m/s (all at 80 m height).

6.5 Offshore wind

Vietnam displays potential for offshore wind power. In this study, the offshore wind areas close to Ninh Thuan (South Central region) have been considered in the modelling and included as 6 areas (Figure 25) each with a potential of 1000 MW (based on the size of the area). Each of the 6 areas is modelled with individual wind speed profiles based on [13]. Offshore wind shows much higher wind speeds compared to onshore wind (average of 9.73 m/s for the whole area, with area “E” having an average windspeed of 10.31 m/s). Other areas for offshore wind, in addition to the Ninh Thuan region, could be further investigated in future studies.

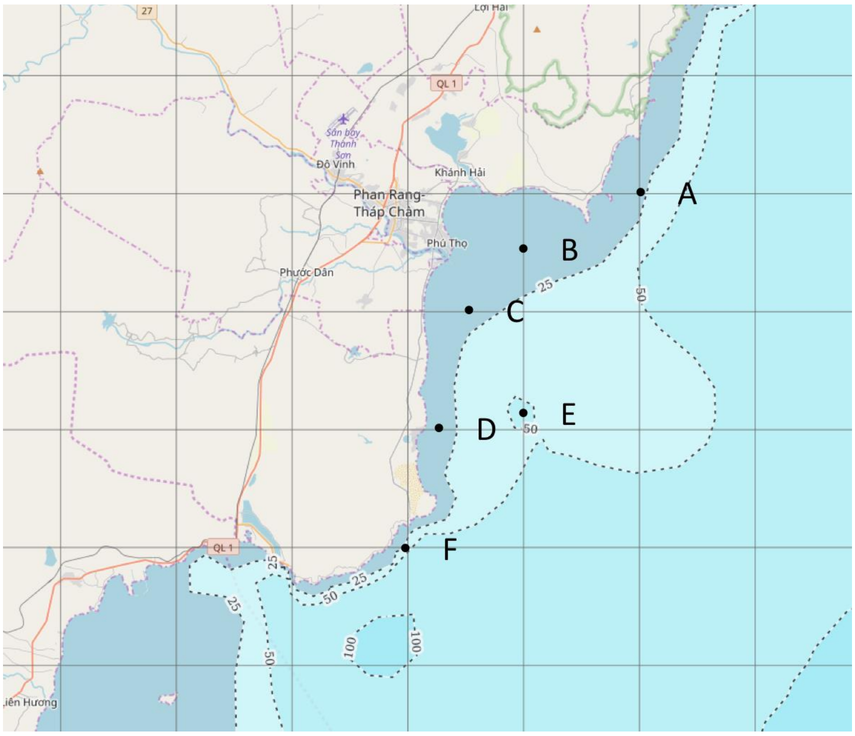


Figure 25: Offshore wind potential close to Ninh Thuan (South Central).

6.6 Solar

Solar resource

The solar generation profiles in Balmorel are calculated by assigning hourly profiles and full load hours to generate a production profile.
Solar irradiation and temperature profiles for 5 measurement locations are used from the project under the auspices of the ESMAP initiative of the World Bank [14]. These were used to calculate the generation profile assuming solar panels characteristics as described in section 5.1. The resulting solar full load hours of the 6 regions for existing technologies are shown in Figure 26. These full load hours increase in future years due to technology developments as shown in Figure 13.

Solar capacity potential

The solar potentials are based on the draft Vietnam Renewable Energy Development Plan [2], as shown in Table 16. The figures for the high potential case are used in the model, along with the full load hours (existing technologies), as shown in Figure 26. It is assumed that half of this potential can be used at low land costs, and the other half at high land costs. It should be noted that the methodology for the solar potential is roughly estimated and does not include potential increases in connection costs or construction costs (e.g. when moving to areas further away from the transmission grid or roads respectively).

	Base	High
North	40	6,689
North Central	100	736
Centre Central	664	8,938
High land	28,289	140,466
South Central	41,549	71,422
South	95,725	152,201
Total	**166,367**	**380,452**

Table 16: Solar potential for a base and high case (MW) [2].

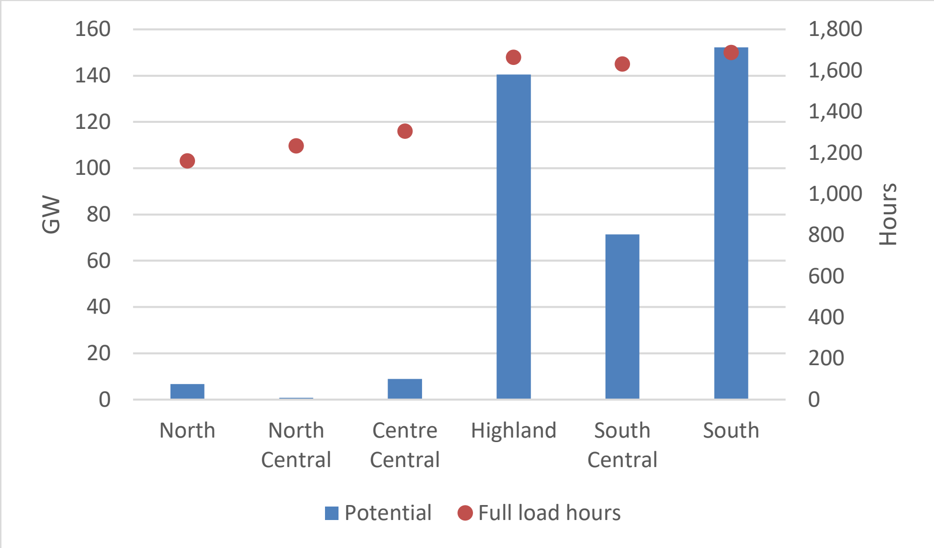
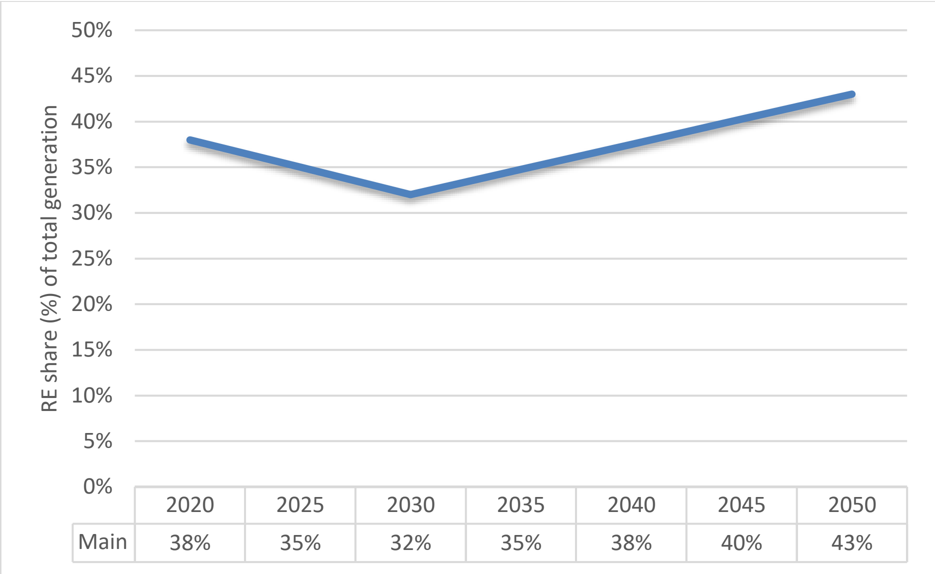


Figure 26: Solar potential and full load hours per region implemented in Balmorel.

6.7 Renewable energy requirements

In the model a renewable energy requirement is enforced. This requirement states that a certain percentage of the total generation in Vietnam needs to be supplied by renewable energy sources.

The shares of renewable energy that need to be achieved for each modelled year are shown in Figure 27 and based on The Renewable Energy Plan, Prime Minister's Decision No. 2068, 2015. The goal of the RE Plan is to increase the contribution of RE in power generation, including large hydro [15].



	2020	2025	2030	2035	2040	2045	2050
Main	38%	35%	32%	35%	38%	40%	43%

Figure 27: Renwable energy (RE) goals in Vietnam.

The following fuels are implemented as renewable in the model:

- Wind
- Solar
- Hydro (including large hydro)
- MSW
- Rice husk
- Straw
- Bagasse
- Wood
- Other biomass
- Geothermal
- Tidal

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Appendix

Appendix I: Exogenous capacity

Name	Region	Capacity (MW)	Fuel	Start year
Da Nhim	South - Center	160	Hydro	1964
Thu Duc #1 ST	South	33	East FO	1966
Thu Duc #5 GT	South	15	East FO	1968
Thu Duc #6 GT	South	15	East FO	1969
Thu Duc #2 ST	South	66	East FO	1972
Thu Duc #3 ST	South	66	East FO	1972
Thac Ba	North	120	Hydro	1973
ND Can Tho	South	33	FO	1975
Uong Bi	North	105	Domestic coal 4b&5	1977
Pha Lai 1	North	400	Domestic coal 4b&5	1986
Tri An	South	400	Hydro	1989
Thu Duc #4 GT	South	23	East FO	1989
DRAY HLING	Central Highlands	28	Hydro	1990
Ba Ria GT #1	South	23	East FO	1991
Ba Ria GT #2	South	23	East FO	1991
Thu Duc #7 GT	South	33	East FO	1992
Thu Duc #8 GT	South	33	East FO	1992
Hoa Binh	North	1920	Hydro	1994
Vinh Son	South - Center	66	Hydro	1994
SUOI VANG	Central Highlands	10	Hydro	1995
Thac Mo	South	150	Hydro	1995
Phu My 2-1extension	South	440	East Gas, East LNG after 2026	1999
TBK Can Tho	South	150	Diesel	1999
Hiep Phuoc (IPP) #1 ST	South	0	East FO, retired after 2025	1999
Hiep Phuoc (IPP) #2 ST	South	0	East FO, retired after 2025	1999
Hiep Phuoc (IPP) #3 ST	South	0	East FO, retired after 2025	1999
Song Hinh	South - Center	70	Hydro	2000
Buorbon	South	24	Biomass	2000
Ham Thuan	South - Center	300	Hydro	2001
Da Mi	South - Center	175	Hydro	2001
BaRiaC/C#1GT3x37.5ST56	South	168,5	East Gas, East LNG after 2023	2001
Pha Lai 2	North	600	Domestic coal 4b&5	2002
Ba Ria C/C#2 GT3x37.5MW, ST1x62M	South	174,5	East Gas, East LNG after 2023	2002
Can Don	South	78	Hydro	2003
Phu My 2-1	South	450	East Gas, East LNG after 2024	2003
Na Loi	North	9	Hydro	2004
Ryninh	Central Highlands	9	Hydro	2004
Amata+Vedan	South	92	East FO	2004
Formosa 1	South	150	Imported coal	2004
Phu My 1	South	1090	East Gas, East LNG after 2024	2004
Na Duong I #1	North	55	Domestic coal 6	2005
Na Duong I #2	North	55	Domestic coal 6	2005
Phu My 2.2	South	720	East Gas, East LNG	2005

			after 2027	
Phu My 4	South	450	East Gas, East LNG after 2026	2005
Phu My 3	South	720	East Gas, East LNG after 2025	2005
C.Ngan 1	North	50	Domestic coal 6	2006
North Diesel	North	40	Diesel	2006
SESAN 3 # 1	Central Highlands	260	Hydro	2006
HCHAN	Central Highlands	12	Hydro	2006
Srok Phu Mieng	South	51	Hydro	2006
Dam Phu My	South	20	East Gas	2006
Suoi Sap	North	16	Hydro	2007
C.Ngan 2	North	50	Domestic coal 6	2007
Quang Tri (Rao Quan)	Center-Center	64	Hydro	2007
Yaly	Central Highlands	720	Hydro	2007
SE SAN 3A	Central Highlands	108	Hydro	2007
EAK RONG ROU	Central Highlands	28	Hydro	2007
Ca Mau I CC	South	750	PM3-CAA Gas, Block B Gas after 2022	2007
Tuyen Quang	North	342	Hydro	2008
Binh Dien	Center-Center	44	Hydro	2008
Hmun	Central Highlands	15	Hydro	2008
Bac Binh	South	33	Hydro	2008
Dai Ninh	South - Center	300	Hydro	2008
Da Dang- Dachamo	Central Highlands	16	Hydro	2008
Bao Loc-Da Siat	Central Highlands	37	Hydro	2008
Nhon Trach I CC	South	450	East Gas, East LNG after 2031	2008
Ca Mau II CC	South	750	PM3-CAA Gas, Block B Gas after 2022	2008
Ban Coc	North-Center	18	Hydro	2009
Nam Dong	North	22	Hydro	2009
Uong Bi Extension 1	North	300	Domestic coal 4b&5	2009
A Vuong	Center-Center	210	Hydro	2009
Song Con 2	Center-Center	63	Hydro	2009
Loc dau Dung Quat	Center-Center	81	East FO	2009
PLEI KRONG	Central Highlands	100	Hydro	2009
SONG BA HA	South - Center	220	Hydro	2009
BUONKUOP #1	Central Highlands	280	Hydro	2009
EAK RONG HNANG	Central Highlands	64	Hydro	2009
SESAN 4 #1	Central Highlands	360	Hydro	2009
O Mon I #1-FO	South	330	West FO, Block B Gas after 2022	2009
Son La	North	2400	Hydro	2010
Huong Son 1	North-Center	34	Hydro	2010
Nam Chien 2	North	32	Hydro	2010
Thai An	North	82	Hydro	2010
Ho Ho	North-Center	18	Hydro	2010
Ho Bon	North	18	Hydro	2010

Hai Phong I#1	North	300	Domestic coal 4b&5	2010
NĐ Cam Pha I	North	300	Domestic coal 7	2010
Quang Ninh I #1	North	300	Domestic coal 6	2010
Quang Ninh I #2	North	300	Domestic coal 6	2010
Son Dong #1	North	110	Domestic coal 6	2010
Son Dong #2	North	110	Domestic coal 6	2010
Ban Ve (Ban La)	North-Center	320	Hydro	2010
Cöa §¹t	North-Center	97	Hydro	2010
Huong Dien #1,2	Center-Center	54	Hydro	2010
BUON TUA SRAH	Central Highlands	86	Hydro	2010
SEREPOK 3 #1	Central Highlands	220	Hydro	2010
Sre Pok 4 (80MW)	Central Highlands	80	Hydro	2010
An Khe-Ka Nak	Central Highlands	173	Hydro	2010
Dong Nai 3	Central Highlands	180	Hydro	2010
Muong Hum	North	32	Hydro	2011
Su Pan	North	35	Hydro	2011
Seo Chung Ho	North	22	Hydro	2011
Uong Bi Extension 2	North	300	Domestic coal 4b&5	2011
Hai Phong I#2	North	300	Domestic coal 4b&5	2011
NĐ Cam Pha II	North	300	Domestic coal 7	2011
Huong Dien #3	Center-Center	27	Hydro	2011
SE SAN 4A	Central Highlands	63	Hydro	2011
Sre Pok 4A (64MW)	Central Highlands	64	Hydro	2011
Dak Rtih	Central Highlands	144	Hydro	2011
Dong Nai 4	Central Highlands	340	Hydro	2011
Dong Nai 2	South - Center	73,5	Hydro	2011
Da Dang 2 (34MW)	Central Highlands	34	Hydro	2011
Nhon Trach II CC	South	750	East Gas	2011
Nho Que III	North	110	Hydro	2012
Van Chan	North	57	Hydro	2012
Nam Phang	North	36	Hydro	2012
Nam Phan 5	North	34	Hydro	2012
Nam Chim	North	16	Hydro	2012
Minh L-¬ng	North	22	Hydro	2012
Mao Khe I-220MW	North	220	Domestic coal 6	2012
Song Tranh 2	Center-Center	190	Hydro	2012
Dak Mi 4	Center-Center	195	Hydro	2012
A Luoi	Center-Center	170	Hydro	2012
Formosa 2	South	150	Imported coal	2012
Ban Chat	North	220	Hydro	2013
Nam Chien	North	200	Hydro	2013
Ta Thang	North	120	Hydro	2013
Khe Be	North-Center	100	Hydro	2013
Hua Na	North-Center	180	Hydro	2013
Chiem Hoa	North	48	Hydro	2013
Quang Ninh II #1	North	300	Domestic coal 6	2013
Quang Ninh II #2	North	300	Domestic coal 6	2013

Mao Khe II-220MW	North	220	Domestic coal 6	2013
B¸ Th-íc 2	North-Center	80	Hydro	2013
Song Boung 5	Center-Center	57	Hydro	2013
Song Boung 4A	Center-Center	49	Hydro	2013
New Small HPP-Center-South	Central Highlands	45	Hydro	2013
Dam Bri	Central Highlands	72	Hydro	2013
Ngoi Phat	North	72	Hydro	2014
Ngoi Hut 2	North	48	Hydro	2014
Nam Muc	North	44	Hydro	2014
Nam Na 2	North	66	Hydro	2014
Song Bac	North	42	Hydro	2014
Nam Mu	North	12	Hydro	2014
Hai Phong II #1	North	300	Domestic coal 4b&5	2014
Hai Phong II #2	North	300	Domestic coal 4b&5	2014
Mong Duong II #1	North	622	Domestic coal 6	2014
An Khanh #1	North	50	Domestic coal 6	2014
Nghi Son #1	North-Center	300	Domestic coal 4b&5	2014
Nghi Son #2	North-Center	300	Domestic coal 4b&5	2014
Vung Ang I #1	North-Center	622	Domestic coal 6	2014
Song Tranh 3	Center-Center	62	Hydro	2014
Song Tranh 4	Center-Center	48	Hydro	2014
Song Boung 4	Center-Center	156	Hydro	2014
Dak Mi 3	Center-Center	45	Hydro	2014
ND Than Nong Son	Center-Center	30	Domestic coal 4b&5	2014
DAK DRINH 1	Center-Center	125	Hydro	2014
Song Giang 2	South - Center	37	Hydro	2014
Vinh Tan II #1	South - Center	622	Domestic coal 4b&5	2014
Lai Chau	North	1200	Hydro	2015
Nam Toong	North	34	Hydro	2015
Nam Na 3	North	84	Hydro	2015
Mong Duong I #1	North	540	Domestic coal 6	2015
Mong Duong I #2	North	540	Domestic coal 6	2015
Mong Duong II #2	North	622	Domestic coal 6	2015
An Khanh #2	North	50	Domestic coal 6	2015
Vung Ang I #2	North-Center	622	Domestic coal 6	2015
Formusa HT1 (cogen)	North-Center	650	Imported coal	2015
Dong Nai 5	Central Highlands	150	Hydro	2015
O Mon I #2-FO	South	330	West FO, Block B Gas after 2022	2015
Vinh Tan II #2	South - Center	622	Domestic coal 4b&5	2015
Duyen Hai I #1	South	600	Imported coal	2015
Hue Quang	North	520	Hydro	2016
Bac Me	North	45	Hydro	2016
Trung Sơn	North	260	Hydro	2016
small hydrp center 1	Center-Center	45	Hydro	2016
Sekaman 1 - 80% (Lào)	Center-Center	0	Hydro	2016
ND than Vedan	South	60	Imported coal	2016

Formosa 3	South	150	Imported coal	2016
Duyen Hai I #2	South	600	Imported coal	2016
Duyen Hai III #1	South	600	Imported coal	2016
Nho Que	North	32	Hydro	2017
Nho Que II	North	48	Hydro	2017
Long Tao	North	42	Hydro	2017
Yen Son	North	70	Hydro	2017
Thai Binh I #1	North	300	Domestic coal 4b&5	2017
B¸ Th-íc 1	North-Center	60	Hydro	2017
Nh¹n H¹c	North-Center	59	Hydro	2017
Chi Khê	North-Center	41	Hydro	2017
Tra Khuc 1	Center-Center	36	Hydro	2017
Dak Mi 2	Center-Center	98	Hydro	2017
Song Boung 2	Center-Center	108	Hydro	2017
Biomass1	South	30	Biomass	2017
Duyen Hai III #2	South	600	Imported coal	2017
A Lin	Center-Center	62	Hydro	2018
La Ngau	South	36	Hydro	2018
Dak Mi 1	Center-Center	54	Hydro	2018
New Hydrp South	South - Center	100	Hydro	2018
Vinh Tan I #1	South - Center	600	Imported coal	2018
Duyen Hai III #3	South	660	Imported coal	2018
Vinh Tan IV#1	South - Center	600	Imported coal	2018
Vinh Tan IV#2	South - Center	600	Imported coal	2018
Small Hydro	North	1400	Hydro	2018
Small Hydro	North-Center	600	Hydro	2018
Small Hydro	Center-Center	329,1	Hydro	2018
Small Hydro	Central Highlands	827,9	Hydro	2018
PV solar	South - Center	100	PV solar	2018
Wind	South	100	Wind	2018
Wind	South - Center	80	Wind	2018
Song Lo 6	North	44	Hydro	2018
Song Mien 4	North	38	Hydro	2018
Thang Long I	North	600	Domestic coal 6	2018
Thai Binh I #2	North	300	Domestic coal 4b&5	2018
Hoi Xuan	North	102	Hydro	2018
Bao Lam 3	North	46	Hydro	2019
Pac Ma	North	140	Hydro	2019
UPPER KONTUM #1	Center-Center	220	Hydro	2019
Vinh Tan I #2	South - Center	600	Imported coal	2019
Vinh Tan IV ext	South - Center	600	Imported coal	2019
Thai Binh II #1	North	600	Domestic coal 4b&5	2020
Thai Binh II #2	North	600	Domestic coal 4b&5	2020
Hai Duong #2	North	600	Imported coal	2020
ND Hai Ha 1 (cogen)	North	150	Imported coal	2020
Nam Mo (Viet)	North-Center	95	Hydro	2020
Song Hieu (Ban Mong)	North-Center	60	Hydro	2020

Formusa HT2 (cogenaration)	North-Center	650	Imported coal	2020
My Ly	North	250	Hydro	2021
Na Duong II	North	110	Domestic coal 6	2021
Duyen Hai II #1	South	600	Imported coal	2021
Duyen Hai II #2	South	600	Imported coal	2021
Long Phu I #1	South	600	Imported coal	2021
Long Phu I #2	South	600	Imported coal	2021
Song Hau I #1	South	600	Imported coal	2021
Song Hau I #2	South	600	Imported coal	2021
Hai Duong #1	North	600	Imported coal	2022
Nam Ma (Lao)	North-Center	0	Hydro	2022
Nghi Son II #1	North-Center	600	Imported coal	2022
Quang Trach I #1	North-Center	600	Imported coal	2022
Dak Re	Central Highlands	60	Hydro	2022
Nhon Trach III CC	South	750	East LNG	2022
O Mon III - Lo B	South	1050	West Gas	2022
Nam Dinh I #1	North	600	Imported coal	2023
Nam Dinh I #2	North	600	Imported coal	2023
An Khanh II	North-Center	650	Domestic coal 6	2023
Nghi Son II #2	North-Center	600	Imported coal	2023
Vung Ang II #1	North-Center	600	Imported coal	2023
Quang Trach I #2	North-Center	600	Imported coal	2023
Cong Thanh	North-Center	600	Imported coal	2023
TBKHH Dung Quat #1	Center-Center	750	CVX Gas	2023
TBKHH Mien Trung 1	Center-Center	750	CVX Gas	2023
Nhon Trach IV CC	South	750	East LNG	2023
O Mon IV - Lo B	South	1050	West Gas	2023
Vinh Tan III #1	South - Center	660	Imported coal	2023
ND Hai Ha 2 (cogen)	North	750	Imported coal	2024
Vung Ang II #2	North-Center	600	Imported coal	2024
Quynh Lap I #1	North-Center	600	Imported coal	2024
ND Quang Tri I #1	Center-Center	600	Imported coal	2024
TBKHH Dung Quat #2	Center-Center	750	CVX Gas	2024
TBKHH Mien Trung 2	Center-Center	750	CVX Gas	2024

Appendix II: Unit commitment parameters for existing units

Suffix legend: CO: coal plant, NG: natural gas plant, FO: fuel oil plant, BIO: biomass plant.

Balmorel name	Unit size (MW)	Start-up cost (USD/MW)	Minimum generation (% of MW)
Pha_Lai_1_CO	100	91	60%
Pha_Lai_2_CO	300	119	83%
Uong_Bi_CO	53	185	75%
Hai_Phong_I1_CO	300	343	77%
Hai_Phong_I2_CO	300	343	77%
Hai_Phong_II_1_CO	300	343	77%
Hai_Phong_II_2_CO	300	343	77%
Quang_Ninh_I_1_CO	300	173	77%
Quang_Ninh_I_2_CO	300	173	77%
Quang_Ninh_II_1_CO	300	173	77%
Quang_Ninh_II_2_CO	300	173	77%
Nghi_Son_1_CO	300	194	75%
Nghi_Son_2_CO	300	194	75%
Vinh_Tan_II_1_CO	622	249	75%
Vinh_Tan_II_2_CO	622	249	75%
Duyen_Hai_I_1_CO	600	249	65%
Duyen_Hai_I_2_CO	600	249	65%
Mong_Duong_I_1_CO	540	896	63%
Mong_Duong_I_2_CO	540	896	63%
Thu_Duc_1_ST_FO	33	71	39%
Thu_Duc_2_ST_FO	66	71	39%
Thu_Duc_3_ST_FO	66	71	39%
O_Mon_I_1_FO_FO	330	64	20%
O_Mon_I_2_FO_FO	330	64	20%
Ba_Ria_CC2_GT3_37_NG	58	31	50%
Phu_My_2_1_NG	225	18	50%
Phu_My_1_NG	545	19	50%
Phu_My_4_NG	225	12	50%
Thu_Duc_4_GT_FO	23	4	49%
Thu_Duc_5_GT_FO	15	4	49%
Thu_Duc_6_GT_FO	15	4	49%
Thu_Duc_7_GT_FO	33	4	49%
Thu_Duc_8_GT_FO	33	4	49%
Coa_t_HRS	49	305	70%
Son_Dong_1_CO	110	129	65%
Son_Dong_2_CO	110	129	65%
Mao_Khe_I_CO	220	129	85%
Mao_Khe_II_CO	220	129	85%
Mong_Duong_II_1_CO	622	249	65%
Mong_Duong_II_2_CO	622	249	65%
Formusa_HT1_cogen_CO	130	179	65%
An_Khanh_1_CO	25	297	75%

Formosa_1_CO	150	360	65%
Formosa_2_CO	150	360	65%
Formosa_3_CO	150	360	65%
Phu_My_3_NG	240	20	46%
Phu_My_2_2_NG	240	20	50%
Nhon_Trach_I_CC_NG	150	13	50%
Nhon_Trach_II_CC_NG	250	44	40%
Ca_Mau_I_CC_NG	250	32	51%
Ca_Mau_II_CC_NG	250	32	51%
Buorbon_BIO	12	299	70%
Dam_Phu_My_NG	20	21	50%
Duyen_Hai_III_1_CO	600	249	70%
Duyen_Hai_I_2_CO	600	249	70%
Thai_Binh_I_1_CO	150	194	70%
Vinh_Tan_IV1_CO	600	251	75%
Vinh_Tan_IV2_CO	600	251	75%
An_Khanh_2_CO	50	244	75%

Appendix III: Large hydro characteristics

Note: reservoir is expressed in water capacity in energy terms (GWh) as a percentage of the annual generation of the hydro plant.

Name	Region	FLHs	Reservoir
Bac Me	North	4.378	25%
Ban Chat	North	3.549	53%
Chiem Hoa	North	4.104	25%
Ho Bon	North	3.889	25%
Hoa Binh	North	5.263	17%
Hue Quang	North	3.662	0%
Lai Chau	North	3.892	3%
Long Tao	North	3.429	25%
Minh L-¬ng	North	3.727	25%
Muong Hum	North	3.656	25%
Na Loi	North	3.556	25%
Nam Chien	North	3.635	26%
Nam Chien 2	North	4.125	25%
Nam Chim	North	3.625	25%
Nam Dong	North	3.864	25%
Nam Mu	North	3.250	25%
Nam Muc	North	3.614	25%
Nam Na 2	North	3.500	25%
Nam Na 3	North	3.452	25%
Nam Phan 5	North	4.176	25%
Nam Phang	North	3.500	25%
Nam Toong	North	3.882	25%
Ngoi Hut 2	North	3.479	25%
Ngoi Phat	North	3.500	25%
Nho Que	North	4.344	25%
Nho Que II	North	4.104	25%
Nho Que III	North	3.809	25%
Seo Chung Ho	North	3.000	25%
Son La	North	3.741	23%
Song Bac	North	3.833	25%
Su Pan	North	3.571	25%
Suoi Sap	North	3.813	25%
Ta Thang	North	2.333	25%
Thac Ba	North	3.250	53%
Thai An	North	3.841	25%
Trung Sơn	North	3.900	25%
Tuyen Quang	North	3.947	21%
Van Chan	North	3.842	25%
Yen Son	North	2.900	25%
B¸ Th-íc 1	North_Central	2.333	25%
B¸ Th-íc 2	North_Central	3.538	25%
Ban Coc	North_Central	3.611	25%

Ban Ve (Ban La)	North_Central	3.519	38%
Chi Khê	North_Central	3.585	25%
Cöa §¹t	North_Central	4.227	32%
Ho Ho	North_Central	3.833	25%
Hua Na	North_Central	4.017	17%
Huong Son 1	North_Central	3.176	25%
Khe Be	North_Central	3.970	11%
Nh¹n H¹c	North_Central	3.203	25%
A Lin	Center_Central	3.000	19%
A Luoi	Center_Central	3.359	19%
A Vuong	Center_Central	4.471	22%
Binh Dien	Center_Central	4.273	27%
DAK DRINH 1	Center_Central	3.600	37%
Dak Mi 1	Center_Central	4.426	19%
Dak Mi 2	Center_Central	4.235	19%
Dak Mi 3	Center_Central	5.089	19%
Dak Mi 4	Center_Central	3.938	19%
Huong Dien #1,2	Center_Central	3.333	7%
Huong Dien #3	Center_Central	3.333	7%
Quang Tri (Rao Quan)	Center_Central	3.813	19%
Sekaman 1 - 80% (Lào)	Center_Central	3.724	19%
Song Boung 2	Center_Central	3.861	19%
Song Boung 4	Center_Central	3.154	14%
Song Boung 4A	Center_Central	6.286	19%
Song Boung 5	Center_Central	3.596	19%
Song Con 2	Center_Central	4.286	19%
Song Tranh 2	Center_Central	3.158	19%
Song Tranh 3	Center_Central	3.774	19%
Song Tranh 4	Center_Central	3.750	19%
Tra Khuc 1	Center_Central	3.750	19%
An Khe-Ka Nak	Highland	3.237	13%
Bao Loc-Da Siat	Highland	3.054	13%
BUON TUA SRAH	Highland	3.000	30%
BUONKUOP #1	Highland	3.354	0%
Da Dang 2 (34MW)	Highland	3.794	13%
Da Dang- Dachamo	Highland	3.125	13%
Dak Rtih	Highland	2.854	13%
Dam Bri	Highland	4.194	13%
Dong Nai 3	Highland	3.222	40%
Dong Nai 3	Highland	3.222	40%
Dong Nai 4	Highland	3.441	1%
Dong Nai 5	Highland	3.753	1%
DRAY HLING	Highland	2.786	13%

EAK RONG HNANG	Highland	3.031	13%
EAK RONG ROU	Highland	3.536	13%
HCHAN	Highland	3.750	13%
Hmun	Highland	3.667	13%
PLEI KRONG	Highland	4.270	21%
Ryninh	Highland	3.444	13%
SE SAN 3A	Highland	3.861	13%
SE SAN 4A	Highland	3.873	13%
SEREPOK 3 #1	Highland	4.950	4%
SEREPOK 3 #1	Highland	4.950	4%
SESAN 3 # 1	Highland	4.458	1%
SESAN 4 #1	Highland	3.189	4%
Sre Pok 4 (80MW)	Highland	3.625	13%
Sre Pok 4A (64MW)	Highland	3.313	13%
SUOI VANG	Highland	3.500	13%
Yaly	Highland	4.806	12%
Da Mi	South_Central	3.331	48%
Da Nhim	South_Central	5.688	48%
Dai Ninh	South_Central	3.287	45%
Dong Nai 2	South_Central	4.762	48%
Ham Thuan	South_Central	3.240	40%
SONG BA HA	South_Central	4.186	3%
Song Giang 2	South_Central	2.919	48%
Song Hinh	South_Central	4.957	36%
Vinh Son	South_Central	4.652	117%
Bac Binh	South	7.030	20%
Can Don	South	4.000	20%
La Ngau	South	4.417	20%
Srok Phu Mieng	South	4.255	20%
Thac Mo	South	4.940	20%
Tri An	South	4.428	20%