On behalf of:

Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection

Of the Federal Republic of Germany

List of Annexes

Annex B
Methodology and assumption of LTES in LEAP

This document provides an overview of assumptions and methodology used to model energy demand in Thailand, using LEAP.

1 General configuration

1.1 Settings

Scope

LEAP is used to model only energy uses and related emissions in the following energy demand sectors: residential, commercial, industry, transport, and agricultural sectors.Energy supply and transformation, particularly electricity generation, will be modeled using a power system modelling tool (PyPSA). The results of LEAP are inputs to PyPSA.

Time resolution

The model is set up in two timeframes: historical, based on historical data, and projections based on assumptions of future developments in each sector.

- Historical period: 2010-2019
- Projections: 2020-2050

All data and assumptions in the model are provided with annual resolution. A finer time resolution (e.g., hourly) is captured in the modelling of the energy supply (PyPSA)

Geographical resolution

The model is structured in two possible geographical configurations: one single country-wide region or seven regions sub-national regions. The five regions in the model are:

- Northeastern
- Northern
- Southern
- Central
- Bangkok and vicinities

All data inputs in the model are provided for the country as a whole and for each region individually. Whenever possible, direct data inputs are region-specific based on statistics and information available for each region. In other cases, the data entries were derived based on a set of region-specific assumptions (e.g., distribute national energy consumption in each sub-sector based on regional population or GDP). See the assumptions of each sub-sector for more details.

In some occasions, when the regional data is not available at regional level with the same categorization used in the model (5 regions presented above), but there is data available at the province level, we aggregated the data in the corresponding five regions based on official province-region allocation (e.g. data from the National Statistics Office on GDP reports (link))

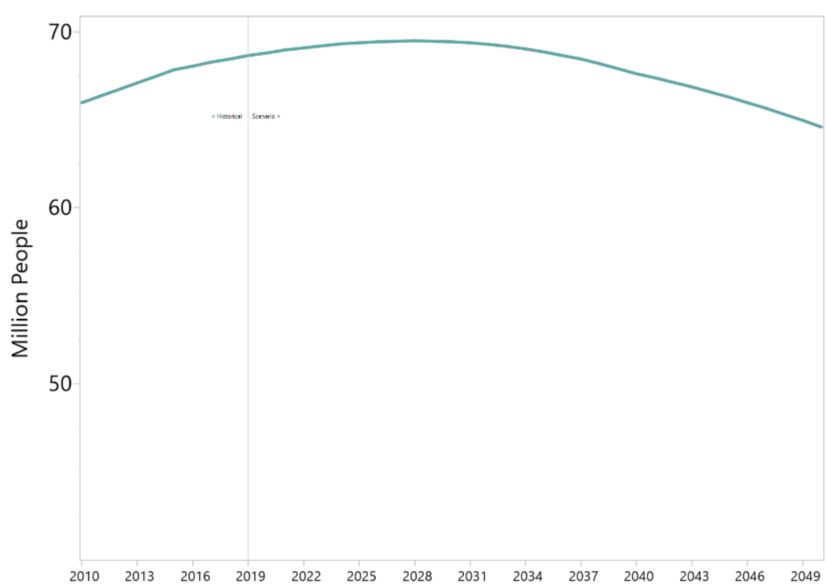
Note: Given that all data is provided either at national level or at the regional level, the model can be run either with regional granularity OR a simplified version with only national data and assumptions. The regional resolution chosen may lead to slightly different results.

2 Key assumptions

2.1 Demography

Population is one of the key parameters to derive activity level of energy demand in certain sectors and to project growth, distribution, and intensity of energy demand in the future. Population (total, growth and regional distribution) is used mainly to derive and project evolution of number of households in the residential sector.

Total population (million of people) – National



Base year (2010): Historical population is based on the 2010 census of Thailand (link). The 2010-census is the starting point in the base year for all data population in terms of absolute numbers.

Time series (2010-2040): The evolution of the population follows the trend reported in the data provided in the Report of the Population Projections for Thailand 2010-2040 by the Office of the National Economic and Social Development Board (NESDB). The trend of historical population (2010-2020) and projections (2020-2040) reported in NESDB is harmonized to the 2010 values of the census using annual growth rates. The values of population in 2010 in the Census differ from those ones reported in the NESDB, and consequently a harmonisation is needed.

Projection (2040-2050): starting from the latest available data reported in NESDB (2040), the evolution of the population follows the trend of population projections for Thailand, from the United Nations (World Population Prospects 2019, median variant). The trend of population projections (2040-2050) reported by the United Nations is harmonized to the 2040 values resulting from the NESDB using annual growth rates.

Regional distribution (%)

The regional distribution of population was done in several steps:

1. The historical population in each region was estimated using the same approach as for the national population explained above. This is, using 2010 values as base year from the Census and harmonization with NESDB, using annual growth rates.
2. The resulting population (million people) per region was translated to percentage values using the total population (as the sum of all regions). Note that the resulting values of total population across all regions slightly differ from the national population because the growth rates of each region are different than the growth rates at national level.
3. The 2020-2040 projection of regional distribution was estimated using the same projections from NESDB at the provincial level and aggregating at the regional level. For the period 2040-2050, the regional distribution is kept constant to 2040 values.
4. The regional distribution of population is used in LEAP as per cent values.

Urbanization (urban vs rural population) (%)

The urban distribution of population for each region was done in several steps:

1. The urban population during the period 2010-2020 at the country level was obtained from the NESDB.
2. The projection (2020-2040) of urban population is obtained from the Report of the Population Projections for Thailand 2010-2040 by the Office of the National Economic and Social Development Council (NESDB)
3. The urban population in each region (municipal area) was estimated using the same approach as for the national population explained above. This is, using 2010 values as base year from the Census and harmonisation with NESDB, using annual growth rates.
4. The resulting urbanization rate in each region is harmonized with national urbanization rates (steps 1-2)
5. The urbanization rates of population is used in LEAP as per cent values (urban population divided by total population)

People per household (urban vs rural population) (%)

The number of people per household, for each region was done in several steps:

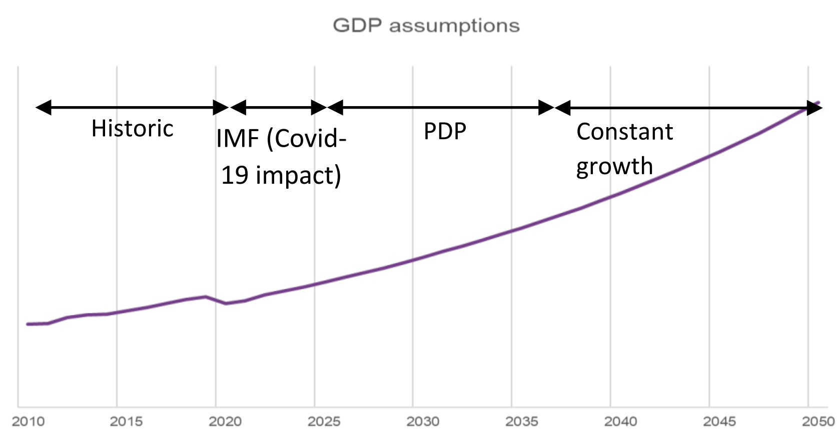
1. The number of households in each region (municipal area) was estimated using the same approach as for the national population explained above. This is, using 2010 values as base year from the Census and harmonisation with NSO, using annual growth rates.
2. The resulting number of households was used in conjunction with the corresponding population to estimate number of people per household.

3. Given the lack of data, the number of people per household is assumed constant after the last historical year. This can be modified based on better data or assumptions of demographic policies.
4. Same approach is used for rural population and households.

2.2 Economic

Gross domestic product (GDP) is one of the key parameters to derive activity level of energy demand in certain sectors and to project growth, distribution, and intensity of energy demand in the future. GDP (total, growth and regional and sectoral distribution) is used mainly to derive and project evolution of activity in the industry sectors.

National GDP



- 2010-2020: Historical GDP from the WorldBank data portal. The units used for GDP is USD from 2010 (constant values)

GDP projections based on growth rates (constant values):

- 2020-2021: historic growth (consistent across NESDC, WorldBank and IMF)
- 2021-2026: short-term projections from IMF to account for the impact of COVID-19 (decrease and rebound)
- 2027-2037: long-term projections from PDP. consistent with national planning and projections
- 2038-2050: constant, equal to latest available year.

The only values used in terms of monetary terms (e.g. absolute USD) is total constant GDP at the national level. The regional and sectoral distribution of GDP are calculated in percentage terms and multiplied with total GDP accordingly when needed.

Regional and sectoral breakdown of GDP (%)

The regional and sectoral distribution of GDP (e.g. Agriculture GDP in the southern region) is based on the data available in the Office of National Economic and Social Development Council (NESDC), which reports data until 2019. The distribution of GDP (in percentage terms) was calculated using the *GDP at current values.* This is necessary because GDP volumes in constant terms (e.g., 2002 Baht) are not additive: the sum of the sectoral and regional components is not equal to total or national GDP. Current values of GDP are additive hence they are used to estimate regional and sectoral breakdown of GDP.

The data available from NESDC includes the following economic sectors:

Sector		
Agriculture		
	Agriculture	
		Agriculture, forestry and fishing
Non-Agriculture		
	Industrial	
		Mining and quarrying
		Manufacturing
		Electricity, gas, steam and air conditioning supply
		Water supply; sewerage, waste management and remediation activities
	Services	
		Construction
		Wholesale and retail trade and repair of motor vehicles and motorcycle
		Transportation and storage
		Accommodation and food service activities
		Information and communication
		Financial and insurance activities
		Real estate activities
		Professional, scientific and technical activities
		Administrative and support service activities
		Public administration and defence; compulsory social security
		Education
		Human health and social work activities
		Arts, entertainment and recreation
		Other service activities

Although data form all economic sectors is processed and included in LEAP, not all sectors are considered in the modelling exercise. Data from all economic sectors is included for transparency purposes (e.g., check additivity of 100% across all sectors) and to have them readily available if needed.

Projection of regional and sectoral breakdown of GDP (%)

Due to the lack of data, the breakdown of regional and sectoral breakdown of GDP is assumed to remain constant after 2019. This assumption can be adjusted if better data is available or linked to assumptions based on discussion with stakeholders (e.g. linking a re-distribution of GDP breakdown as consequence of the implementation of an economic model such as BCG).

3 Demand

The modelling of all demand sectors starts with the calculation of reference values of each parameter (e.g., activity level, energy consumption, etc). The starting values are based on historical data of energy consumption, activity development, etc. (2010-2020). The approach and assumptions taken to derive the reference values of the parameters are explained in each section (energy use) below.

The projections of energy consumption in the residential sector are modelled in a bottom-up approach. Projections start from the reference values and assume a growth or change in key drivers. Each of these assumptions are also explained each section below.

3.1 Residential

Structure

Energy demand in residential sector is divided into urban and rural areas, using population data. The historic and projected number of households (per region and area) is the variable used as activity level in all activities in the residential sector.

For each region and each area, 8 activities were identified and modelled:

- Cooking
- Water heating
- Cooling
- Lighting
- Refrigeration
- Rice cooker
- Television
- Other appliances

Breakdown of energy across activities

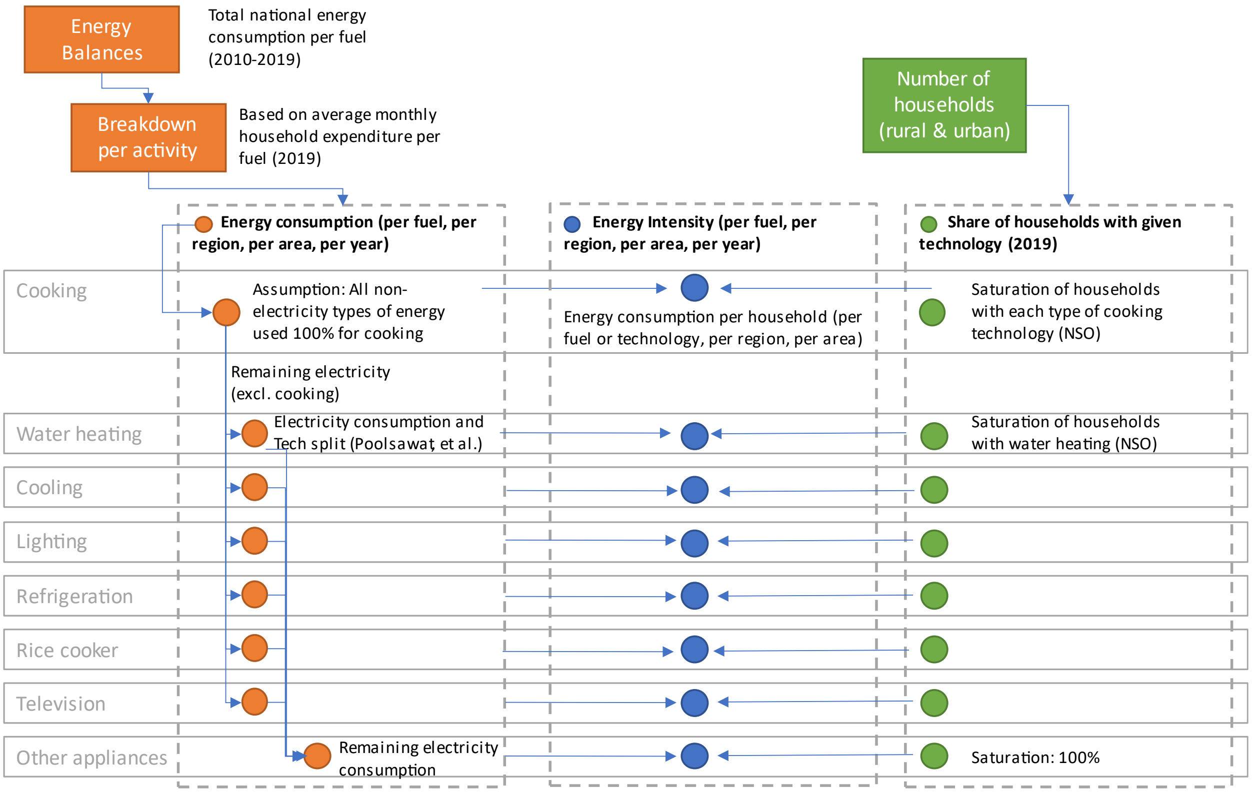
According to the energy balances (DEDE), the residential sector consumes mainly 6 fuels:

- Electricity
- LPG
- Fuelwood
- Charcoal
- Paddy husk
- Agricultural waste

Methodology

The raw data of energy consumption in the residential sector, taken from the energy balances, is provided at national level per fuel. The following steps and assumptions were taken to breakdown total demand into activities and region

The diagram below aims to illustrate the methodology (process) to breakdown total energy consumption in the residential sector across each of the activities in the historical years (i.e., 2010-2019). The methodology to calculate energy consumption in all residential activities follow a similar approach.



Step 1: breakdown total energy demand per region (5 regions), per area (urban and rural) and fuel

- The total fuel consumption is broken down into regions based on the average monthly household expenditure on energy – Baht/household (NSO). This data is provided per type of energy, per region, in 2019. The use of average expenditure on energy to breakdown energy consumption per region comes with the following underlying assumptions:
  - Whereas the total energy consumption varies year over year, the breakdown per region per fuel (%) is the same for all years, which uses the breakdown of expenditure in 2019.
  - It assumes that the cost of each fuel is the same in all regions per unit of energy (e.g. Baht/liter of LPG is the same in the south and the north)
- Average expenditure on energy is also provided by area (urban and rural). This was also considered for each region based on their share of urban and rural population
- The result of this breakdown is total energy consumption in the residential sector per region (5 regions), per area (urban and rural), per fuel (6 fuels), per year (2010-2019). This dataset constitutes the starting point to estimate the energy consumption in each activity.

Step 2: Calculate separately energy consumption for cooking

The total energy consumption in the residential sector already processed per region, area, and fuel (see above) is the starting point to calculate the consumption for cooking. The following steps and assumptions were used to calculate energy demand for cooking:

- It is assumed that all non-electricity fuel consumption in the residential sector (i.e., LPG, charcoal, wood, and biomass) is used entirely for cooking purposes. The main consequence of this assumption is that all residential activities, except cooking, consume only electricity as source of energy.
- The electricity consumption for cooking in each region and area is calculated using the same ratio between LPG consumption and the share of households using LPG. Thus, electricity consumption for cooking is calculated as: [% of households using electric cooking] * [ratio of LPG consumption per % of households using LPG for cooking]). This is a simplified approach that assumes that energy intensity in houses cooking with electricity is similar to the ones cooking with LPG. The impact of this assumption is relatively small given that currently less than 4% of households at national level cook with electricity.

Step 3: Calculate electricity consumption for other appliances in the residential sector

- Subtract electricity consumption for cooking (previous step) from total electricity consumption in the residential sector.
- The remaining electricity consumption is distributed among other appliances (share). Electricity consumption per appliance is also distinguished for both rural and urban areas. The distribution of electricity consumption per appliance and per area is based on a paper that investigated the characteristics of electricity consumption in the residential sector in Thailand (paper).
- Based on the characteristics of electricity consumption per appliance, and the rural/urban composition of each region, we derived the electricity consumption per region, area and year for the following appliances: water heating, cooling, lighting, refrigeration, and others.

The underlying assumption of this approach is that the share of electricity consumption of each appliance, excluding cooking, as a percentage of total electricity consumption in the residential sector, is constant over the historical years (2010-2019).

Step 4: Calculate energy intensity

Total energy consumption per technology is then used to calculate energy intensity per household. Energy intensity for historic years is calculated as the division between energy consumption (steps 1-3) and the number of households (per region, per area, per appliance in the residential sector).

3.1.1 Cooking

Energy consumption for cooking is divided in the following technologies/fuels:

- Electric stove
- Gas stove (LPG)
- Wood
- Charcoal
- Biomass (agrowaste)

Current accounts (2010-2019)

The share of households cooking at national and regional level is given in NSO and a UN report. The same reports also provide data of the share of households using each cooking technology with regional geographical detail. Additionally, the share of urban and rural population using each technology in each region is adjusted based on their urban/rural distribution.

Assumptions used for the projections (2020 – 2050)

Projections of energy consumption in residential cooking is based on the following assumptions:

Parameter	Description	Reference scenario	Carbon neutral scenario
Number of households	Measure of social activity for which energy is consumed	Result from the evolution of demographic parameters explained in section 2.1.	
% of households cooking	Saturation	Constant throughout the modelling horizon for each cooking technology. Current values are above 97% in all regions except in Bangkok that is 94%	
Energy intensity	Energy consumption per household (per technology)	Remains constant throughout the modelling horizon for each cooking technology	
Fuel split	Share of households cooking with each technology/fuel	**Gradual switch from LPG to electric cookstove**: Increase in the share of electric cookstoves by **5.5% per year until 2025 and thereafter by 3%**	**Higher rate of switch from LPG to electric cookstove**: Increase in the share of electric cookstoves by **8% per year**

3.1.2 *Water heating*

Energy consumption for water heating is assumed to come entirely from electricity.

Current accounts (2010-2019)

The share of households with water heating at national and regional level is provided in NSO. This report provides data of the share of households by ownership of electric boiler in 2019, per region. Due to the lack of data availability, the share of households with electric boiler is assumed to be the same in urban and rural areas within each region throughout the historical period.

Assumptions used for the projections (2020 – 2050)

Projections of energy consumption in water heating is based on the following assumptions:

Parameter	Description	Reference scenario	Carbon neutral scenario
Number of households	Measure of social activity for which energy is consumed	Result from the evolution of demographic parameters explained in section 2.1.	
% of households with water heating	Saturation	**Constant throughout the modelling horizon**. Current values are around 10-15% in all regions except in Northern that is 30%	
Energy intensity	Energy consumption per household (per technology)	**Constant throughout the modelling horizon** (same as last historical year). This is a conservative assumption since energy intensity has been on a slight upward trend over the last decade.	

3.1.3 *Cooling*

Energy consumption for cooling is assumed to come entirely from electricity. The technologies used for cooling are:

- Air Conditioner
- Fan

Current accounts (2010-2019)

The shares of households with each cooling technology at national and regional level are provided in NSO. This report provides data of the share of households by ownership of air conditioner and fan in 2019, per region. Due to the lack of data availability, the share of households with a given cooling technology is assumed to be the same in urban and rural areas within each region throughout the historical period.

Assumptions used for the projections (2020 – 2050)

Projections of energy consumption in cooling is based on the following assumptions:

Parameter	Description	Reference scenario	Carbon neutral scenario
Number of households	Measure of social activity for which energy is consumed	Result from the evolution of demographic parameters explained in section 2.1.	
% of households w/ cooling	Saturation	Fan: Constant throughout the modelling horizon Air conditioner: increase from current levels (26%) to 150% in 2050 (i.e., all households will have 1.5 ACs in average in 2050)	
Energy intensity	Energy consumption per household (per technology)	Fan: constant throughout the modelling horizon Air conditioner: Interpolation to achieve 30% reduction in energy intensity by 2037, compared to 2010 levels. Constant thereafter.	

3.1.4 *Lighting*

Energy consumption for lighting is assumed to come entirely from electricity. Based on the NSO statistics of ownership of energy devices, the technologies used for lighting in Thailand are:

- Incandescent lamps
- Fluorescent lamps
- LED

Current accounts (2010-2019)

The shares of households with each lighting technology at national and regional level are provided in NSO. This report provides data of the share of households by ownership of lighting technologies in 2019, per region. Due to the lack of data availability, the share of households with a given cooling technology is assumed to be the same in urban and rural areas within each region throughout the historical period (2010-2019).

Assumptions used for the projections (2020 – 2050)

Projections of energy consumption in residential lighting is based on the following assumptions:

Parameter	Description	Reference scenario	Carbon neutral scenario
Number of households	Measure of social activity for which energy is consumed	Result from the evolution of demographic parameters explained in section 2.1.	
Energy intensity	Energy consumption per household (per technology)	Remains constant throughout the modelling horizon for each lighting technology	
Technology split	Share of households with each technology	Lamp switch to **100% LED by 2030**	Lamp switch to **100% LED by 2025**

3.1.5 *Refrigeration*

Energy consumption for refrigeration is assumed to come entirely from electricity.

Current accounts (2010-2019)

The shares of households with refrigeration at national and regional level are provided in NSO. This report provides data of the share of households by ownership of refrigerator in 2019, per region. Based on the NSO statistics of ownership of energy devices, 92% of the households own a refrigerator. Due to the lack of data availability, the share of households with a refrigerator is assumed to be the same in urban and rural areas within each region throughout the historical period (2010-2019).

Assumptions used for the projections (2020 – 2050)

Projections of energy consumption in refrigeration is based on the following assumptions:

Parameter	Description	Reference scenario	Carbon neutral scenario
Number of households	Measure of social activity for which energy is consumed	Result from the evolution of demographic parameters explained in section 2.1.	
Energy intensity	Energy consumption per household (per technology)	Interpolation to achieve 30% reduction in energy intensity by 2037, compared to 2010 levels. Constant thereafter	

3.1.6 Others

Energy consumption for other residential energy uses is assumed to come entirely from electricity.

Current accounts (2010-2019)

Energy consumption of other electric appliances at national and regional level are provided in NSO. This report provides data of the share of households by ownership of electric appliances (e.g., television, rice cooker, etc.) in 2019, per region. Due to the lack of data availability, the saturation of households with electric appliances is assumed to be the same in urban and rural areas within each region throughout the historical period (2010-2019).

Assumptions used for the projections (2020 – 2050)

Projections of energy consumption in other residential appliances is based on the following assumptions:

Parameter	Description	Reference scenario	Carbon neutral scenario
Number of households	Measure of social activity for which energy is consumed	Result from the evolution of demographic parameters explained in section 2.1.	
Energy intensity	Energy consumption per household (per technology)	Constant for television and rice cooker. For other appliances: interpolation to achieve 30% reduction in energy intensity by 2037 compared to 2010 levels	

3.2 Commercial

Structure

Energy demand in commercial sector is modeled in a simplified top-down approach due to limited data availability. With this approach, total energy demand is a result of multiplying the activity level (GDP of service sectors) and energy intensity of GDP, calculated for historical years.

Current accounts (2010 – 2019)

Historical energy consumption in commercial sector is an input (either from DEDE or IEA) and it is the starting point of the calculations. Based on statistics of the sector, total energy consumption is distributed among the following fuels:

- Electricity
- LPG

The activity level of the sector (driver of growth) is GDP of service sectors. The GDP of service sectors is already broken down is the five geographical regions as described in section 2.2.

Sector		
	Services	
		Construction
		Wholesale and retail trade and repair of motor vehicles and motorcycle
		Transportation and storage
		Accommodation and food service activities
		Information and communication
		Financial and insurance activities
		Real estate activities
		Professional, scientific and technical activities
		Administrative and support service activities
		Public administration and defence; compulsory social security
		Education
		Human health and social work activities
		Arts, entertainment and recreation
		Other service activities

Total energy consumption (sum of all fuels) is used to derive energy intensity for the entire sector. Energy intensity is calculated as energy consumption per unit of GDP.

Assumptions used for the projections (2020 – 2050)

Energy consumption in commercial sector is calculated for the entire sector as Activity level * Energy intensity and distributed among fuels. Consequently, the projection of energy consumption in the commercial sector is based on the evolution of the following parameters:

Parameter	Description	Reference scenario	Carbon neutral scenario
GDP – service sectors	Measure of economic activity for which energy is consumed	Result from the evolution of macroeconomic parameters explained in section 2.2.	
Energy intensity	Energy consumption per unit of GDP	**2020-2037**: Interpolation to achieve the energy consumption target in the sector by 2037 as defined in EEDP2018 **2037-2050**: 1% annual improvement	
Fuel split	Split between LPG and electricity in the sector	Constant fuel mix until 2050 (same as last historical year)	Full electrification by 2050

3.3 Agriculture

Structure

Energy demand in agriculture sector is modeled in a simplified top-down approach due to limited data availability. With this approach, total energy demand is a result of multiplying the activity level (GDP of agriculture sectors) and energy intensity, calculated for historical years.

Current accounts (2010 – 2019)

Historical energy consumption in agriculture sector is an input (either from DEDE or IEA) and it is the starting point of the calculations. Based on statistics of the sector, total energy consumption is distributed among the following fuels:

- Electricity
- Diesel

The activity level of the sector (driver of growth) is GDP of agriculture sector. The GDP of agriculture is already broken down in the five geographical regions as described in section 2.2.

Sector		
Agriculture		
	Agriculture	
		Agriculture, forestry and fishing

Total energy consumption (sum of all fuels) is used to derive energy intensity for the entire sector. Energy intensity is calculated as energy consumption per unit of GDP.

Assumptions used for the projections (2020 – 2050)

Energy consumption in agriculture sector is calculated for the entire sector as Activity level * Energy intensity and distributed among fuels. Consequently, the projection of energy consumption in the agriculture sector is based on the evolution of the following parameters:

Parameter	Description	Reference scenario	Carbon neutral scenario
GDP – agriculture sectors	Measure of economic activity for which energy is consumed	Result from the evolution of macroeconomic parameters explained in section 2.2.	
Energy intensity	Energy consumption per unit of GDP	**2020-2037**: Interpolation to achieve 30% reduction in energy intensity by 2037, compared to 2010 levels **2037-2050**: 1% annual improvement	
Fuel split	Split between diesel and electricity in the sector	Constant fuel mix until 2050 (same as last historical year)	Full electrification by 2050

4 Industry

Structure

Energy demand in industry is divided into three: Light industry, Heavy industry, and others. The classification of specific industries into each category is as follows:

- **Light industry:**
  - Food and Tobacco
  - Textile and Leather
  - Wood and Wood products
  - Paper Pulp and Printing
  - Construction
- **Heavy industry:**
  - Iron and Steel
  - Chemical and Petrochemical
  - Mining and Quarrying
  - Machinery
  - Non-metallic Minerals
- **Other industry**

Due to limited data availability, the complexity and the heterogeneity within each industry, the representation of all sub-industries is modeled with a top-down approach where total energy demand is a result of energy intensity and a driver of the industry activity (e.g., production or added value).

Breakdown into secondary energy sources

To capture better the implications and pathways to decarbonize the industry sector and its synergies with electricity supply and other forms of clean energy supply (e.g., green hydrogen, syngas, etc.), the supply of primary energy for industry sectors is captured in more detail in PyPSA. This requires that LEAP models total energy demand in all industries in terms of secondary energy sources:

- Electricity
- Low temperature heat

- High temperature heat

A detailed calculation and modelling of energy consumption by secondary energy source requires a deeper understanding of the processes of each industry. However, the approach used in this study to determine the shares of secondary energy sources is simplified due to lack of data availability and complexity in the modelling.

The breakdown of total energy demand into each energy source for each industry is based in the following steps:

1) The historical energy consumption per industry per fuel (obtained DEDE and IEA) is the starting point of the calculations.
2) Total electricity consumption in each sub-industry is broken down into direct electricity use and electricity consumption for heat purposes.
   a) Electricity for heat purposes is calculated based on the share of electricity in total heat supply
   b) Electricity for direct use (e.g. mechanical purposes) is calculated as the difference between total electricity consumption and the electricity for heat (point above)
3) Total heat consumption is composed of the following points
   a) Electricity consumption for heat (as described in point 2.a.)
   b) Consumption of other fuels (it is assumed that all non-electricity fuels are used for heat purposes)
4) The breakdown of total heat consumption into high / low temperature per sub-industry is based on literature review. This means that it follows the average strucuture of each sub-industry.

Current accounts (2010-2019)

In all cases, energy intensity is calculated for base years (current accounts: 2010-2019) as the historical total energy consumption total energy consumption (electricity + low heat temperature + high heat temperature) divided by the activity driver (activity level) corresponding to each industry.

The activity level corresponds to the production of each industry. The production is estimated using the GDP-elasticity of production of each industry. The purpose of this approach is to estimate production levels as function of GDP (GDP corresponding to the specific industry or total GDP). The production levels of all industries are calculated as follows:

$$Production_{year} = prod_{2016}((Elasticity * GDP\ change) + 1)$$

Where:

- **Production** $_{year}$: is the production in a given year (monetary or physical values)
- **GDP change:** is the change in GDP (or industry specific GDP) from 2016 levels
- **Production** $_{2016}$**:** Is the production in the industry in 2016 (monetary or physical values)
- **Elasticity**: is the GDP elasticity of production in the corresponding industry (2016 as reference year).

  Elasticity is calculated for 2016-2019 years (where GDP and production values are available):

$$Elasticity = \frac{Production\ index}{GDP\ change} = \frac{\left(Production_{year} - Production_{2016}\right)/\ Production_{2016}}{(GDP_{year} - GDP_{2016})\ /\ GDP_{2016}}$$

The production indexes of each industry are reported in the industry statistics by the Office of Industrial Economics (as change in production from 2016 levels). The change in the corresponding industry GDP from 2016 levels is internally calculated based on the reported GDP statistics.

The table below provides an overview of the variables used to determine energy consumption in each industry, the variable used to break down the energy consumption into regions, and the production (activity level)

Industry category	Industry	Regional split of energy based on	Activity level (production)	Energy intensity	Refence industry for production index	Electricity	Low heat temperature	High heat temperature
Light Industry	Food and Tobacco	Regional GDP of *Accommodation and food service activities*	Monetary (Million Baht)	ktoe per million Baht	TSIC: 10 Manufacture of food products	x	x	
	Textile and Leather	Regional GDP *(total)*	Monetary (Million Baht)	ktoe per million Baht	TSIC: 13 Manufacture of textiles	x	x	
	Wood and Wood products	Regional GDP *(total)*	Thousand items	ktoe per item	TSIC: 31 Manufacture of furniture	x	x	
	Paper Pulp and Printing	Regional GDP *(total)*	Physical (Tonnes)	ktoe per tonne	TSIC: 17 Manufacture of paper and paper products	x	x	
	Construction	Regional GDP of *Construction*	Physical (Tonnes)	ktoe per tonne	TSIC: 23 Manufacture of other non-metallic mineral products (23941 manufacture of cement)	x	x	
Heavy Industry	Iron and Steel	Regional GDP of *Manufacturing*	Physical (Tonnes)	ktoe per tonne	TSIC: 24 Manufacture of basic metals	x	x	x
	Chemical and Petrochemical	Regional GDP of *Manufacturing*	Monetary (Million Baht)	ktoe per million Baht	TSIC: 20 Manufacture of chemicals and chemical products	x	x	x
	Mining and Quarrying	Regional GDP of *Mining and Quarrying*	Physical (Tonnes)	ktoe per tonne	Mineral Production of Thailand by Kind of Mineral Year: 2010 – 2019	x	x	x
	Machinery	Regional GDP of *Manufacturing*	Physical (Items)	ktoe per item	TSIC: 28 Manufacture of machinery and equipment n.e.c.	x	x	x
	Non-metallic Minerals	Regional GDP of *Manufacturing*	Monetary (Million Baht)	ktoe per million Baht	TSIC: 23 Manufacture of other non-metallic mineral products	x	x	x
Other	Others	Regional GDP *(total)*	Monetary (Million Baht)	ktoe per million Baht	TSIC: 29 Manufacture of motor vehicles, trailers and semi-trailers	x	x	x

Assumptions used for the projections (2020 – 2050)

Projections of energy consumption in industry sector is based on the following assumptions:

Parameter	Description	Reference scenario	Carbon neutral scenario
Energy efficiency	Energy consumption per unit of production	40% energy intensity reduction in 2050 compared to 2010 levels	30% energy intensity reduction compared to 2010 level in 2037, and further annual improvement of 1.3%
Low temp. heat	Fuels used to supply heat	All technologies	Heatpump as main heat supplier in 2050
High temp. heat	Fuels used to supply heat	All technologies	Biomass, synthetic fuel and electricity as main heat suppliers in 2050

5 Transport

Structure

Energy demand in transport sector is divided transportation mode: land-based, air, water. The modelling of energy demand is limited only to domestic transportation, excluding international transport. The classification of specific modes into each category is as follows:

- **Land-based transport:**
  - Passenger transport
    - Road
    - Rail
  - Freight transport
    - Road
    - Rail
- **Water transport**
  - Passenger transport
  - Freight transport
- **Air transport**

Road transportation modes (both passenger and freight) are modelled in a bottom-up approach with a detailed analysis of the stock turnover. This allows not only to analyze the implications of policies in the consumption of energy and the decarbonization of the sector but also to get a deeper insight of the evolution of the vehicles fleet.

Rail transport (both passenger and freight) are modelled in simplified top-down approach. Similarly, water transport and aviation are modelled in simplified top-down approach.

The table below show the types of vehicles and the fuels considered in the modelling of the transport sector:

Transp. Mode	Vehicle type	Gasoline	Diesel	LPG	CNG	Oil	Electricity	Jet Fuel
Land-based passenger	Private car	X	X	X	X		X	
	Pick-up	X	X	X	X		X	
	Motorcycle	X		X	X		X	
	3-wheeler	X		X	X		X	
	Bus	X	X	X	X		X	
	Taxi	X	X	X	X		X	
	Train	X	X					
Land-based Freight	Trucks		X		X		X	
	Train	X	X					
Water	Watercraft		X			X	X	
Air	Aircraft							X

5.1 Land-based passenger transport

Land-based passenger transport is modelled with two approaches combined:

1. Top-down approach to calculate total transport activity. This approach incorporates the following elements relevant for modelling energy consumption in transport.
    a. Links transport activity as funtion of other variables or parameters (e.g. as fuction of population growth)
    b. Modal shift among different modes of transportation
    c. Allows to incorporate behavioral changes in quantification of total transport activity (e.g. sharing to increase occupancy, reduced distance travelled, etc)

The main result of this approach is the evolution of transport activity (in terms of passenger-km, pkm) as a result of changes in population, intensity of pkm per capita, modal shift, sharing practices, etc.

2. Bottom-up approach with stock turnover analysis. This approach is used for the following purposes
    a. Changes in transport activity resulting from the top-down approach above (i.e. pkm per vehicle type) are translated in terms of additional vehicles requirement per type of vehicle
    b. The additional vehicle requirements correspond to vehicle sales used in the stock turnover analysis
    c. Stock turnover analysis quantifies evolution of the vehicles fleet, considering aging and replacement of vehicles, as well as calculating energy consumption and emissions in the sector

Methodology

Relevant calculations and methodology are detailed below:

1. Start from modal split to determine transport activity per type of vehicle (pkm)
    a. Pkm is first calculated for historical years, for each vehicle type, as function of size of the fleet, average distance travel per vehicle and occupancy rate (average number of passengers per vehicle)
    b. Pkm is projected to grow as function of population growth
    c. Modal split is calculated for historical years as the sum of historical pkm of all vehicle types
    d. Projections of future modal split is an external input defined as an assumption to support the narrative of each scenario

e. Projected pkm is distributed among types of vehicles based on the assumptions of future modal split shares. Total pkm per type of vehicle is the starting point to calculate sales requirement per vehicle type
f. Pkm for rail transport is used as activity level to model rail transportation with a simplified approach (Activity level * Energy intensity and distributed among fuels)

2. Total sales per vehicle type is calculated based on the estimated requirement of transport activity. This calculation is based on the following parameters:
    a. pkm of the respective vehicle type (point above)
    b. Total distance travelled with all fleet (vkm). This item incorporates a degradation factor, e.g. older vehicles travel shorter distances in average
    c. Occupancy (pkm/vkm): this parameter allows to incorporate car sharing behaviours
    d. Average distance travelled per vehicle
    e. Retirement of vehicles (survival and early retirements)
3. Sales is calculated as a function of changes in transport activity (e.g. modal shifting, sharing, distance travelled)
4. Total sales per type of vehicle is distributed per fuel type (e.g. gasoline, diesel, EV, etc) based on sales target shares (e.g. 100% EV sales by 2030)
5. Sales per vehicle type, per fuel type is an entry to the stock turnover calculation
6. Other relevant parameters for the stock turnover analysis are inputed directly in LEAP (e.g. vintage profile, distance travelled profile, fuel economy, etc)

Given the regional granularity of the data, the stock turnover analysis is also done with regional breakdown.

Assumptions used for the projections (2020 – 2050)

Energy consumption in land-based passenger transport is calculated for the entire sector as Activity level * Energy intensity and distributed among fuels. Consequently, the projection of energy consumption in the sector is based on the evolution of the following parameters:

Parameter	Description	Reference scenario	Carbon neutral scenario
Modal split	Percentage of transport activity using a particular mode of transport.	Switch to more public transport in Bangkok (15% train) following Mass Rapid Transit Master Plan	Switch to more public transport (25% train in BKK and 25% bus in other regions in 2050)
Mobility	Additional parameters that affect mobility (e.g., occupancy, distance)	Unchanged	Improved mobility (higher occupancy and less avg distance travelled)
Vehicle Sales	Distribution of annual sales among vehicle technologies (%)	69% of sales are electric in 2035 for cars, motorcycles, buses, and taxis (ZEV policy)	100% of sales are electric in 2035 for cars, motorcycles, buses, and taxis
Fuel economy standards	Improvement of fuel efficiency in vehicles	Unchanged	Fuel economy improvement 1% per year
Biofuel blending	Blending of biofuels to reduce consumption of fossil fuels	10% blending of ethanol in Gasoline, 7% biodiesel in Diesel	Increase to 20% blending of ethanol in Gasoline in 2025. Biodiesel same as reference
Rail electrification	Electrification of railways	Unchanged	Increased electrification in all regions, especially in BKK
Rail energy intensity	Energy consumption per pkm	Improvement of energy intensity 1% per year	

5.2 Land-based freight transport

Land-based freight transport is modelled with two approaches combined:

1. Top-down approach to calculate total transport activity. This approach incorporates the following elements relevant for modelling energy consumption in transport.
    a. Links transport activity as funtion of other variables or parameters (e.g. as fuction of economic growth)
    b. Modal shift among different modes of transportation
    c. Allows to incorporate behavioral changes in quantification of total transport activity (e.g. sharing to increase occupancy, reduced distance travelled, etc)
2. Bottom-up approach for a stock turnover analysis of trucks. This approach is used for the following purposes
    a. Changes in transport activity resulting from the top-down approach above (i.e. tkm per transportation mode: road vs rail) are translated in terms of additional trucks requirement or increased energy consumption in rail transportation
    b. The additional vehicle requirements correspond to vehicle sales used in the stock turnover analysis
    c. Stock turnover analysis quantifies evolution of the truck fleet, considering aging and replacement of vehicles, as well as calculating energy consumption and emissions in the sector

Methodology

Relevant calculations and methodology are detailed below:

1. Start from modal split to determine transport activity per type of vehicle (tkm)
    a. Tkm is first calculated for historical years, for each vehicle type, as function of size of the truck fleet, average distance travel per vehicle and occupancy rate (average tones travelled per vehicle)
    b. Tkm is projected to grow as function of economic growth (GDP adjusted with elasticity)
    c. Modal split is calculated for historical years as the sum of historical tkm of all transportation modes
    d. Projections of future modal split is an external input defined as an assumption to support the narrative of each scenario. Projected tkm is distributed among types of vehicles based on the assumptions of future modal split shares.
    e. Tkm for rail transport is used as activity level to model rail transportation with a simplified approach (Activity level * Energy intensity and distributed among fuels)
2. Total sales per vehicle type is calculated based on the estimated requirement of transport activity. This calculation is based on the following parameters:
    a. Tkm corresponding to trucks (point above)
    b. Total distance travelled with all fleet (vkm). This item incorporates a degradation factor, e.g. older vehicles travel shorter distances in average
    c. Occupancy (tkm/vkm): this parameter allows to incorporate improved occupancy rates in trucks
    d. Average distance travelled per vehicle
    e. Retirement of vehicles (survival and early retirements)
3. Sales is calculated as a function of changes in transport activity (e.g. modal shifting, occupancy, distance travelled)
4. Total sales per type of vehicle is distributed per fuel type (e.g. diesel, EV, etc) based on sales target shares (e.g. 100% EV sales by 2040)
5. Truck sales per fuel type is an entry to the stock turnover calculation

6. Other relevant parameters for the stock turnover analysis are inputed directly in LEAP (e.g. vintage profile, distance travelled profile, fuel economy, etc)

Given the regional granularity of the data, the stock turnover analysis is also done with regional breakdown.

Assumptions used for the projections (2020 – 2050)

Energy consumption in land-based freight transport is calculated for the entire sector as Activity level * Energy intensity and distributed among fuels. Consequently, the projection of energy consumption in the sector is based on the evolution of the following parameters:

Parameter	Description	Reference scenario	Carbon neutral scenario
Modal split	Percentage of transport activity using a particular mode of transport.	Increase of rail freight transport to 10% in 2050 (based on Thailand double-track Railway project)	Increase of rail freight transport to 20% in 2050
Mobility	Additional parameters that affect mobility (e.g., occupancy, distance)	Unchanged	Improved occupancy of trucks by 10% in 2050
Truck Sales	Distribution of annual sales among vehicle technologies (%)	69% of new sales are electric in 2040	100% of new sales are electric in 2040
Fuel economy standards	Improvement of fuel efficiency in trucks	Unchanged	Fuel economy improvement 1% per year
Rail electrification	Electrification of railways	Unchanged	Increased electrification to 80% by 2050

5.3 Water and Air transport

Structure

Energy demand of these two sub-sectors is modeled in a simplified top-down approach due to limited data availability and their lesser contribution to total energy consumption and national emissions. Total energy demand is a result of multiplying the activity level and energy intensity, calculated for historical years.

Historical energy consumption these sectors is an input (either from DEDE or IEA) and it is the starting point of the calculations. The following table provides a summary of the categorization of each transportation mode.

Transport mode	Fuels	Activity level
Air	- Jet fuel - Synthetic fuel - Biojet fuel	- Air passenger (domestic flights only)
Water	- Diesel - Fuel oil - Electricity	- Passenger transport: passengers transported domestically - Freight transport: tons of cargo transported domestically

Energy consumption water and air transport are calculated for each sector as Activity level * Energy intensity and distributed among fuels. Total energy consumption (sum of all fuels) is used to derive energy intensity for the entire sector. Energy intensity is calculated as total energy consumption divided by the activity level corresponding to the sector.

Assumptions used for the projections (2020 – 2050)

The projection of energy consumption is based on the evolution of the following parameters:

Sector	Parameter	Reference scenario	Carbon neutral scenario
Water	Electrification	Unchanged	Electrification of 30% in 2050
Air	Fuel split	Unchanged	Decrease the share of conventional Jet fuel by 2% annually from 2030. Substitute with biojet (2/3) and synthetic fuel (1/3)

Annex C
Power and Heat Sector Optimisation

1 Model Description - PyPSA

PyPSA (python for power system analysis)[1] is an open-source modelling framework for energy system analysis. The flexible and modular framework can be used to represent the energy system in a wide range of different temporal, geographic and sectoral representations. It is being used by academia, research institutes, private companies and utilities[2]. Fundamentally, PyPSA is a bottom-up cost optimization model. The model takes as input various techno-economic parameters such as fuel costs, CAPEX (capital expenditure), OPEX (operation expenditure), power plants capacities, interconnection capacities etc. The model carries out complete year cost optimization under given technical constraints such as energy balance (energy demand has to be met at all hours), ramp-up and ramp-down limits on technologies, maximum generation from power plants etc.

A brief description of the model implementation and some of the input data is provided here.

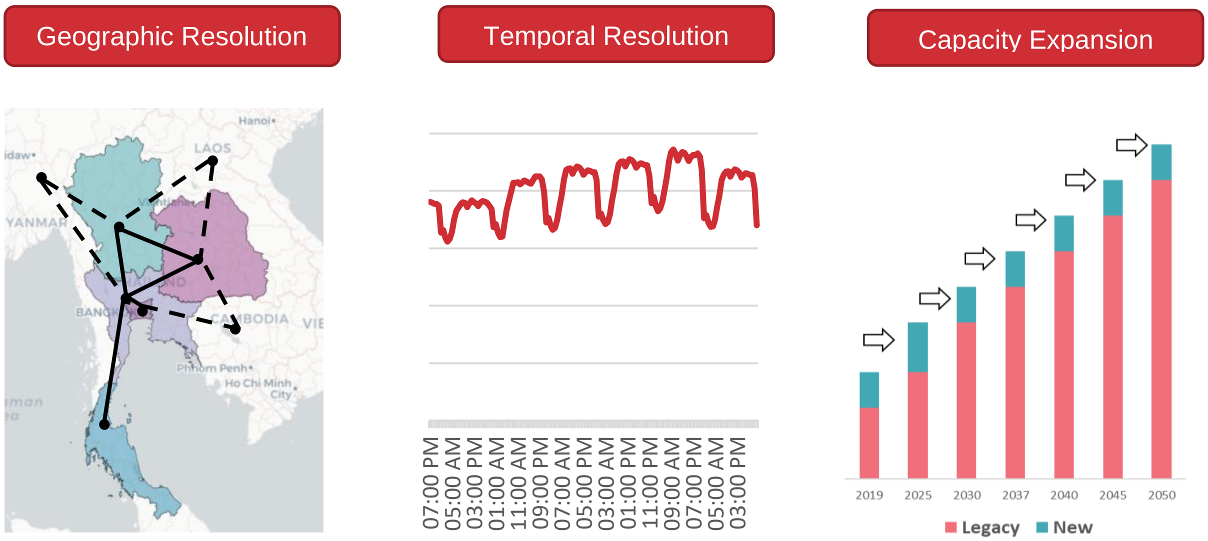
1.1 Model resolution

Thailand has been modelled with five geographic zones corresponding to the control regions. These are North (NR), North-East (NE), Central (CE), Bangkok and vicinities (BKK) and South (SO) (**Error! Reference source not found.**). The regions are connected through aggregated transmission capacity (in MW) between the regions allowing for a bi-directional flow of electricity. Detailed representation of load flows is beyond the scope of the work here. Thailand's connections with its neighboring countries have been included through generators in line with current PPAs, limiting the total amount of energy and power that can be imported. The power plants within each zone are represented at technology resolution.

Each year is represented with hourly resolution. The model optimizes a complete year (8760h) including operation and capacity expansion requirements to meet the energy demand at each hour under various system constraints. The capacity expansion planning is done through myopic approach. The model run of individual years gives as output the cost-optimal capacity mix for that year including the new investments required. This capacity mix is then updated for the next period of optimization. The base year of 2019 was chosen for model validation and testing. This is followed by 2025, 2030, 2037, 2040, 2045 and 2050. The year 2037 was taken instead of 2035 to align it with Thailand's PDP planning timeframe.

Exogeneous phase-out of technologies is carried out based on the commissioning year of the power plants and the technical lifetime of the power plants.

[1] Website: https://pypsa.org/
[2] A list of projects that have used PyPSA can be found at: https://pypsa.org/#projects.



1.2 Model scope and sectoral representation

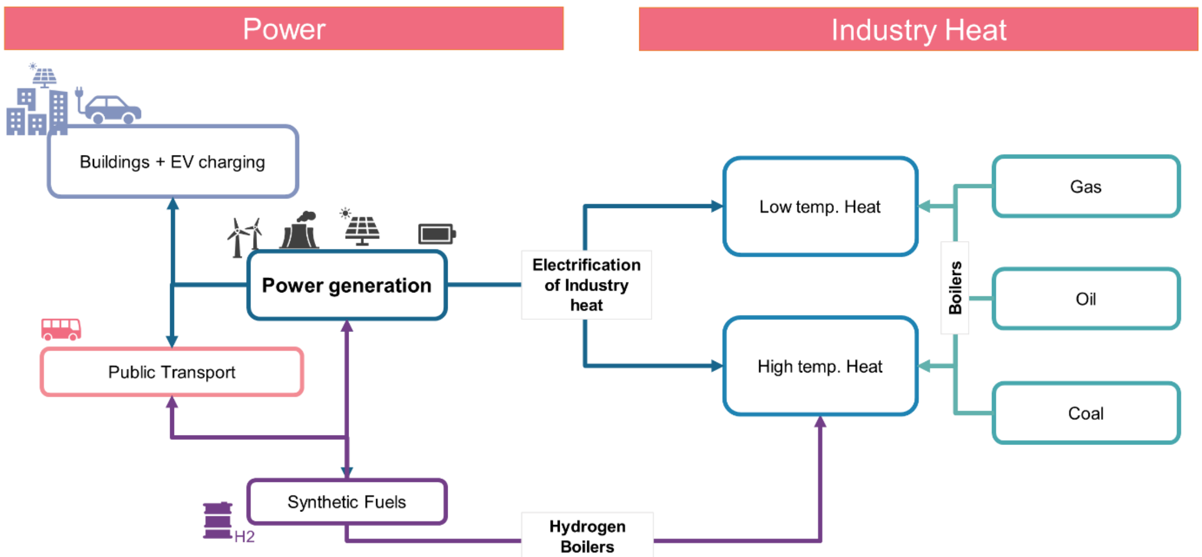
The focus of the model is the power system as it is going to be the backbone of the energy transition. Other sectors like transport and industry are also represented to capture the role of sector coupling in power system transformation. Broadly, the model has four main components: 1. Power Generation 2. Buildings and PEV (Personal Electric Vehicle) 3. Industry heat and 4. Synthetic fuels.

The central component of the model is power generation with technology aggregation level representation of power supply. Various current and future technologies for power generation are included like conventional thermal generators, renewables, utility-level storage, hydro etc. Capacity expansion for most technologies is allowed in the model. Reservoir capacity is treated as constant and further expansion of capacity is not allowed. Inter-regional electricity flow is also optimised by the model.

Since prosumers and optimal charging for PEV will play an important role in the future power system, this is included as a separate component in the model. The model optimises the capacity expansion of rooftop solar and optimal PEV charging. The model endogenously optimises the charging of PEV i.e., smart charging. Electricity demand for meeting the driving load is provided based on the driving profile. This load has to be met through the charging of PEV batteries. The maximum charging allowed is limited by the availability profile of the PEVs (Inverse of the driving profile). This setup allows investigating what should be the optimal charging of PEVs, at an aggregate level.

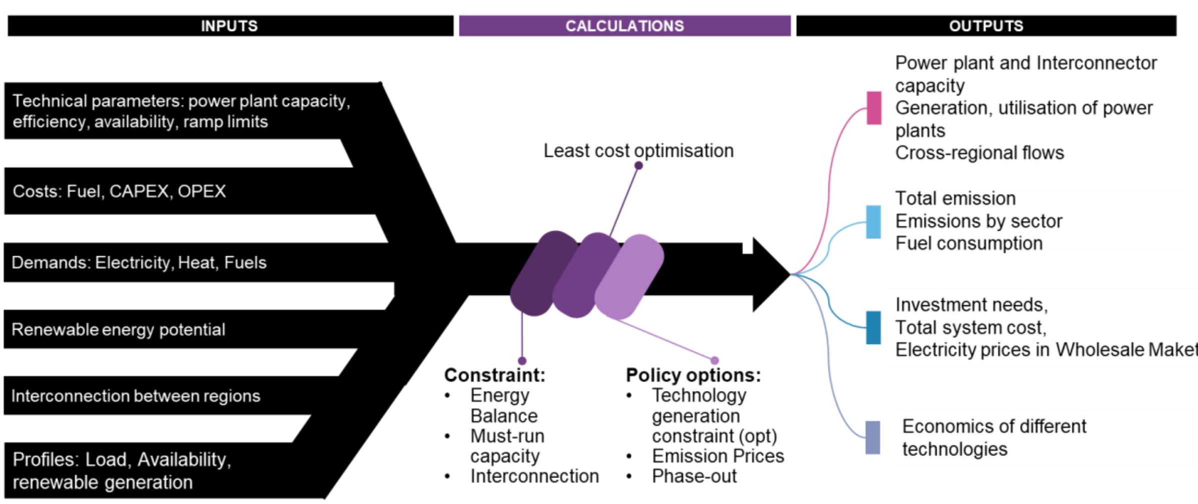
Industry representation in the model is through its electricity demand (non-heat related) and heat demand. The heat demand in the industry is modelled at two temperature levels: Low and medium-temperature heat (<400C) and high-temperature heat (>400C). Different technologies modelled can provide this heat demand based on temperature level. Certain technologies like boilers based on different fuels can provide heat at all temperature levels. Others are suited only to provide heat at certain temperature levels, for example, heat pumps can only provide heat at Low and Medium temperature levels. Several emerging technologies such as dielectric heating (EDHL), EERH (Electrical Resistance Heating) etc. are also included. Low-temperature heat storage is also included in the model.

Generation of synthetic fuels specifically hydrogen through electrolysis is also allowed in the model. The hydrogen can be fed back into the power sector and act as long-term storage or can be used to provide high-temperature heat for industry through hydrogen boilers.



2 Input Data and Assumption

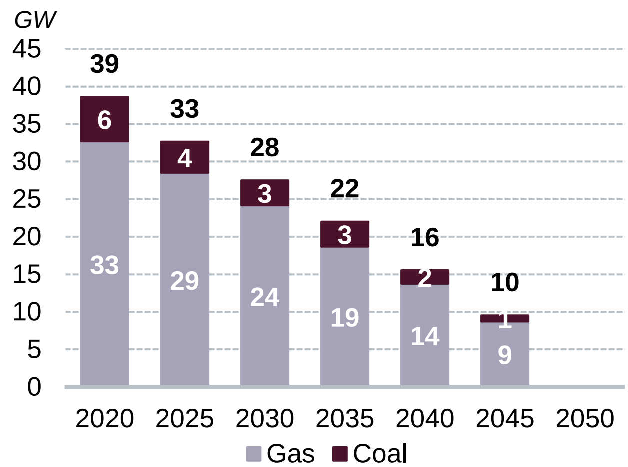
The model takes as input various techno-economic parameters used to represent the energy system. Some of the key input parameters and assumptions are presented here.



2.1 Current Generation Capacities

Power Plant Capacity [GW]	Biomass	Coal	Gas	Hydro	Oil	Solar	Waste	Wind Onshore
Bangkok and vicinities (BKK)	0	0.04	4.4	0	0	0.06	0.02	0
Central (CE)	0.95	3.44	24.36	1.08	0	1.69	0.22	0
North-East (NE)	0.94	0	0.97	1.24	0	0.45	0.01	0.97
North (NR)	0.61	2.46	0	1.29	0	0.63	0	0.06
South (SO)	0.64	0	2.96	1.61	0.32	0.06	0.02	0.06

The phase-out of current capacities of coal and gas power plants is calculated based on the age of the power plants and the lifetime of the technology. The Global Energy Monitor dataset is used to get power plants commissioning year. The assumption for the lifetime of power plants was taken as 25 years for gas-based power plants and 30 years for coal-based power plants.



2.2 Conventional generation technologies

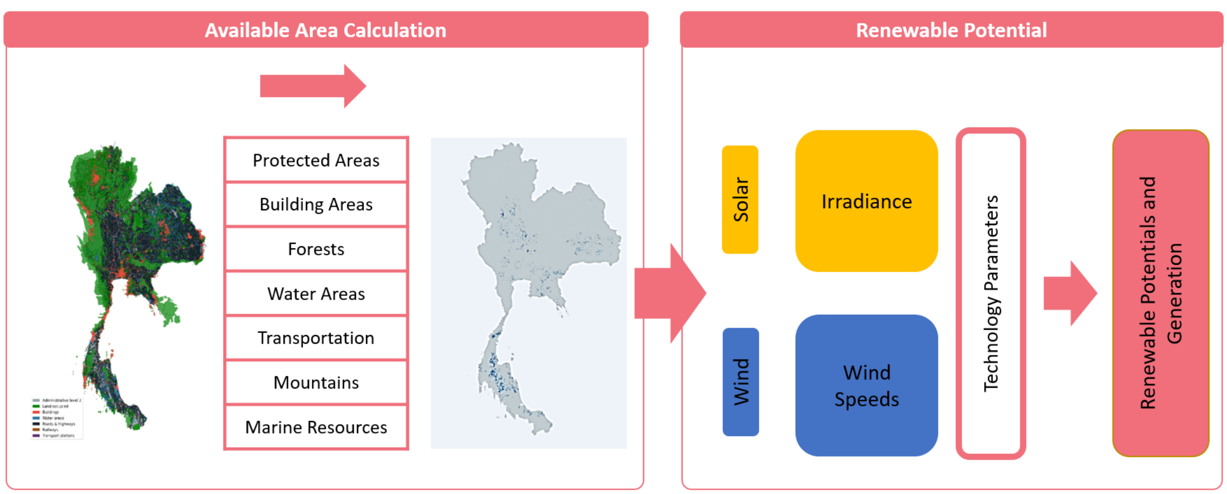
The power supply is represented through a technology-level representation of power plants for each of the regions – NR, NE, CE, SO and BKK. The techno-economic parameters used for conventional power plants are shown in Table 1. Efficiency refers to the electrical efficiency of converting thermal energy in the fuel to electrical energy. Maximum generation is taken as 90% of the capacity, to take into account the unavailability of power plants due to planned and unplanned outages. The Ramp-up and Ramp-down limit the increase and decrease respectively in the power plant output as a fraction of the capacity.

Table 1 Techno-Economic Parameters for the power plants

Power Plant Type	Efficiency	Maximum Generation	Ramp-up Limit	Ramp-down Limit
Brown coal sub-critical	0.35	0.90	0.58	0.76
Gas turbine	0.38	0.90	0.63	0.68
Gas turbine with carbon capture and storage	0.38	0.90	0.63	0.68
Battery Storage	0.97	0.90	1.00	1.00
Biomass Turbine	0.30	0.90	0.54	0.71
Hydro Dam	0.95	0.90	1.00	1.00
Hydro Pump Storage	0.80	0.90	1.00	1.00
Lignite sub-critical	0.31	0.90	0.58	0.77
Oil Turbine	0.33	0.90	0.65	0.77
Waste Turbine	0.32	0.90	0.53	0.69

2.3 Renewable technical Potential

Technical potential considers the availability of geospatial topography of a country or a region, different types of land use, wind speed distribution, and characteristics of a wind turbine, and thus it indicates the maximum capacity in that country or region that can be developed for certain renewable energy sources [NREL]. In this study, the methodology of estimation of technical potential is divided into two stages with a focus on wind (onshore and offshore) and solar energy (utility-scale and rooftop photovoltaic).



In the first stage, the available land area for renewable expansion is calculated by excluding land area which is under use, protected or not suitable for renewable expansion. The list and classification of land use data are provided in Table 1 and all data can be accessed via open-sourced license. The final available area after the exclusion represents the total area that can be further developed into solar or onshore wind power plants. The offshore wind energy is calculated based on the whole available marine area as shown in Table 1.

Table 2 List of land use data for available area calculation

Name of data	Data type	Description	Reference
Country boundary	Shapefile	National boundary[1] under NUTS 2 level	OpenStreetMap
Protected areas	Shapefile	Areas under protection e.g., national parks	OpenStreetMap
Vegetation areas	Shapefile	Areas with vegetation e.g., forests	OpenStreetMap
Build areas	Shapefile	Building outlines from bird's eye views e.g., residential areas	OpenStreetMap
Water areas	Shapefile	Hydrological areas e.g., rivers, lakes, reservoirs	OpenStreetMap
Transportation	Shapefile	Transportation networks e.g., roads, railways	OpenStreetMap
Mountainous areas	GeoTiff	Elevation data with slope rate larger than 30%	GlobalWindAtlas
Marine areas	Shapefile	Offshore area within EEZ[2]	GEBCO 2020

1 NUTS – Nomenclature of Territorial Units for Statistics
2 EEZ – Exclusive Economic Zones

In the second stage, the technical potential is calculated based on the irradiations, wind speed and performance of the wind turbine and solar panels. The irradiation and wind speed data are extracted from GlobalSolarAtlas and GlobalWindAtlas respectively. The power density of different energy potentials is listed in Table 3. The potential installed capacity can be calculated by multiplying the capacity of wind turbines/wind farms or PV panels with the available areas. The capacity factor by region is calculated by taking the average hourly values in a region throughout a year from RenewablesNinjas.

Table 3 The power density of wind and solar energy potentials

Regions	Onshore wind (MW/km^2)	Offshore wind (MW/km^2)	Solar PV (W/km^2)
North (NR)	3.80	0	200
North-East (NE)	6.25	0	
Bangkok and vicinities (BKK)	4.27	3.86	
Central (CE)	4.47	3.72	
South (SO)	4.63	2.96	

Table 4 Total onshore and offshore areas, and available area of wind and energy resources

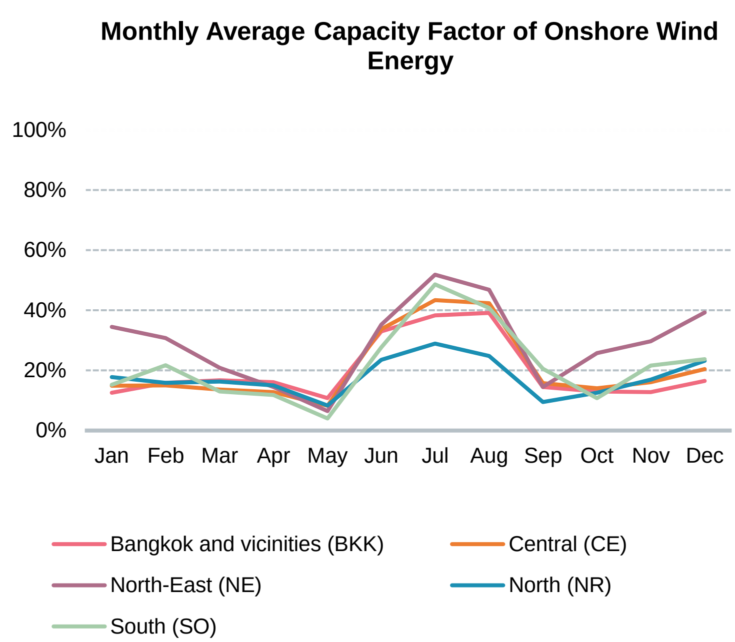
Regions	Total onshore area (km^2)	Onshore wind available area (km^2)	Solar PV available area (km^2)	Total offshore area (km^2	Offshore wind available area (km^2)
North (NR)	171942	495	742	0	0
North-East (NE)	167688	345	517	0	0
Bangkok and vicinities (BKK)	4654	10	16	32869	495
Central (CE)	99135	608	912	122212	1652
South (SO)	71335	1868	2802	143727	1982

2.2 Wind and solar generation

The generation from wind and solar is dictated by their capacity factor. Capacity factor is the ratio of maximum possible generation at a given hour to the installed capacity.

The wind capacity factors data has been taken from https://www.renewables.ninja/ . To calculate the average capacity factor within the region, 10 points have been taken randomly within each region and averaged.

Figure 1 Monthly Average Capacity Factor for Onshore Wind Energy



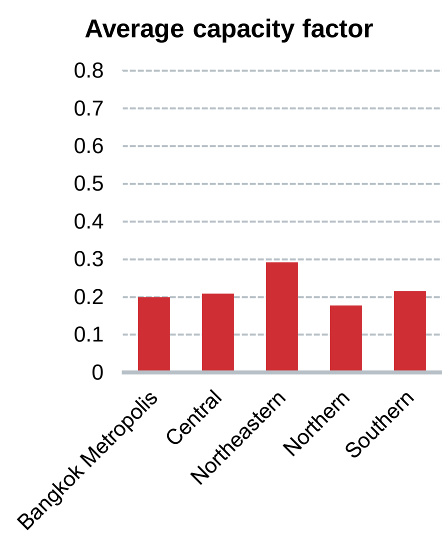


Figure 2 Monthly Average Capacity factor for Offshore Wind Energy

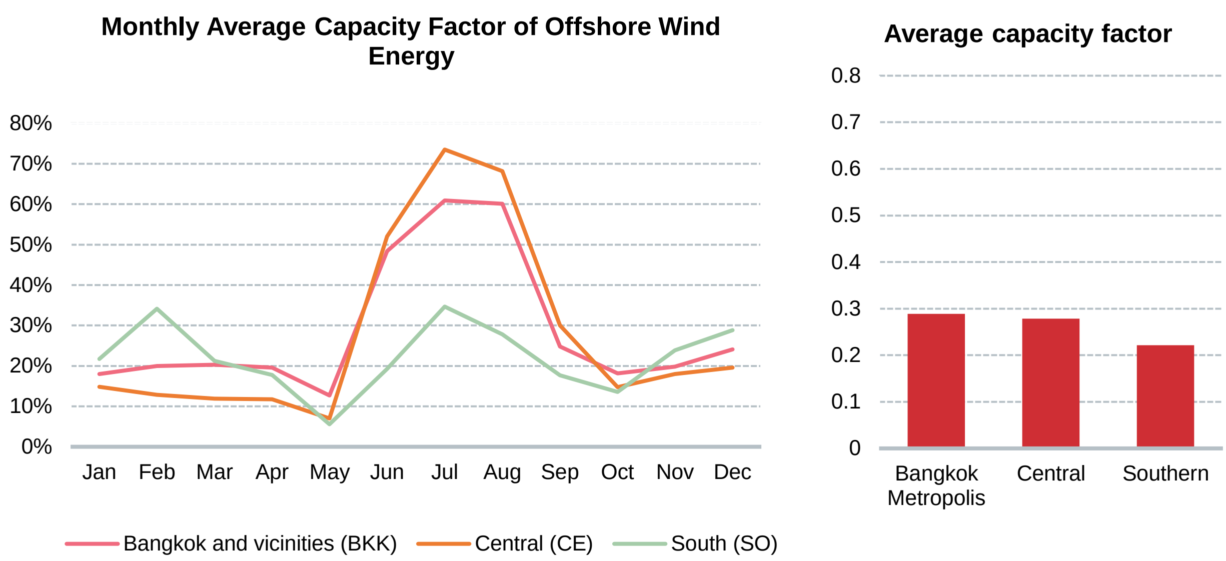
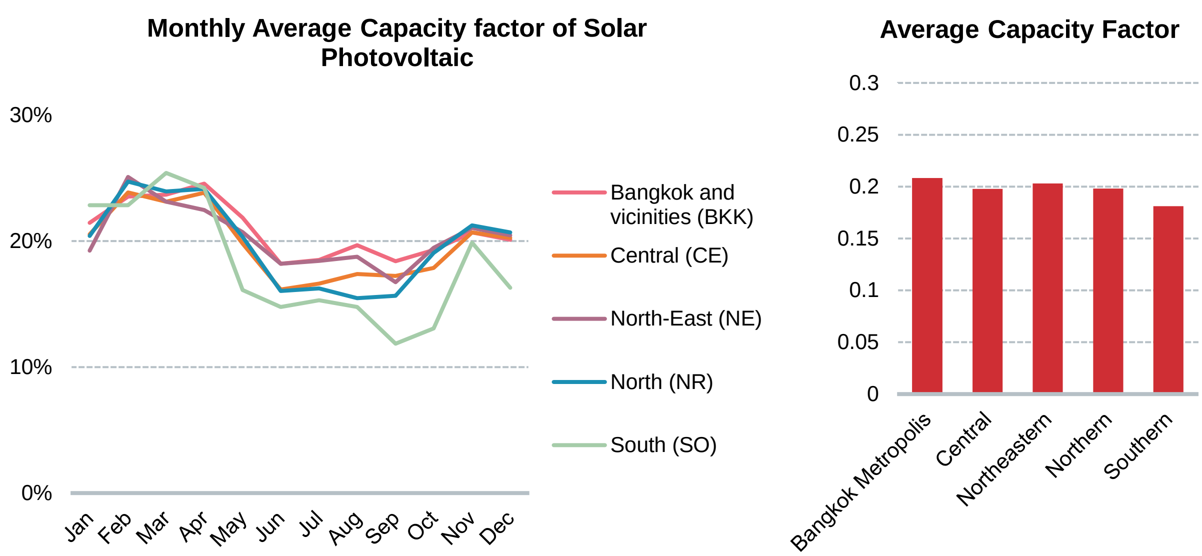


Figure 3 Monthly Average Capacity of Solar Photovoltaic



For generation from solar, the data on capacity factors has been sourced from EC-JRC PVGIS. Similar to the process of generating the average capacity factor for wind, 10 random points were taken, and an average of points was used to generate the average capacity factor per region for solar.

2.3 Technology Costs

In this report, the assumptions of the costs of each technology are based on several sources as listed in Table below. In discussion with country partners, the final cost assumption is agreed on.

	Source		Source
•	**DEA's study for Vietnam 2019 [link]**	•	**ERI Survey**
•	**DEA's study for Vietnam 2021 [link]**	•	**Fraunhofer ISE [link]**
•	**DIW [link]**	•	**LUT's study in Indonesia/Agora/IESR [link]**
•	**Tom Brown et al. [link]**	•	**EWG-LUT 2019 [link]**
•	**NREL [link]**		

Figure 7 Investment cost of solar and wind

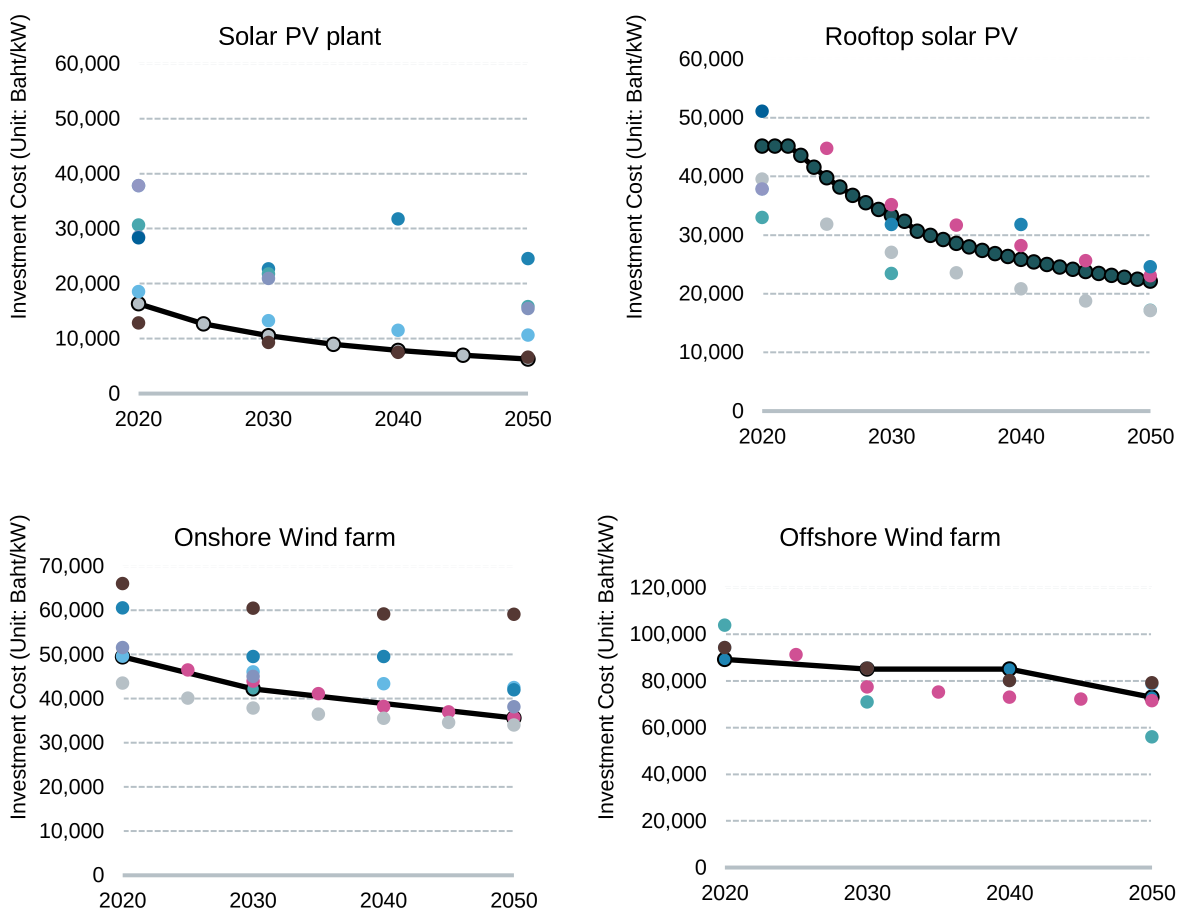
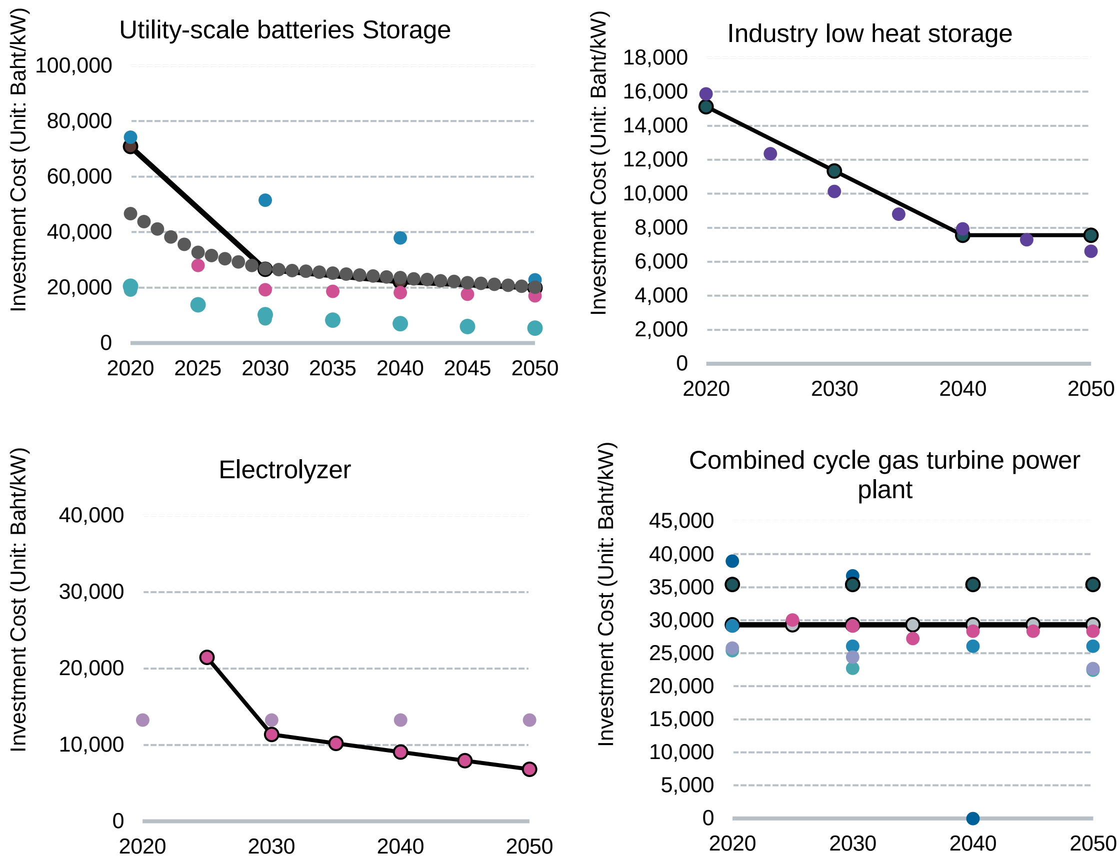


Figure 8 Investment cost of other generation technologies



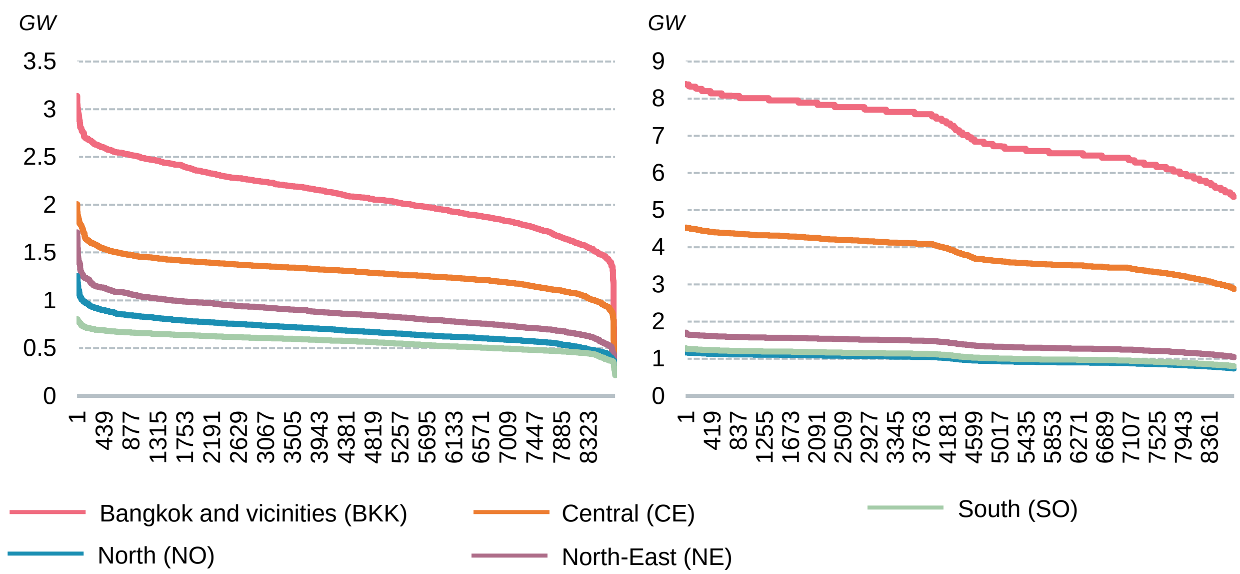
2.4 Load Profiles

Under energy transition, many new renewable energy systems, e.g., photovoltaic and wind will be installed and at the same time, electricity demands are expected to rise further due to direct electrification in transport and industry sectors. In this regards, demand-side activities' pattern (Load profiles) plays crucial role in dictating system's flexibility, meaning how feasible and fast-moving can non-dispatchable capacities be absorbed or how much additional flexibility measures, e.g., battery storages and demand-side management is required adopting. Indeed, the closer is the peak electricity load hour to daytime solar irradiance max, the cheaper photovoltaic (With possibility to couple with battery storage) capacities become, making it by far the most cost-optimal option for future power system supply.

For the PyPSA model, demands are separated into five groups of load profile according to their sectoral representation: Buildings, commercial, industry, agriculture, and transport. The former four were assembled based on monthly typical-day load patterns[3] collected from local statistics (PEA, 2021), while for latter typical driving profile was used.

The profiles for buildings, commercial and agriculture sectors are regional specific. Buildings demand is assembled by aggregating all electricity consuming activities from residential areas plus governmental buildings, while the commercial ones are added up from consumptions of small to large-size businesses (Figure 9). Water pumping pattern was used to represent agriculture activities due to the lack of sectoral breakdown.

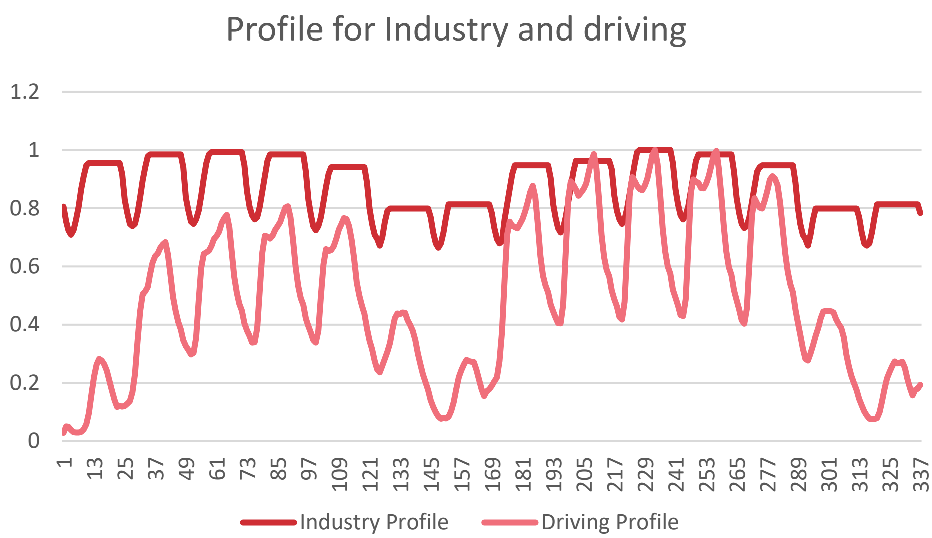
Figure 4 Load duration curves from Buildings sector (Left) and Commercial sector (Right) in 2019



Loads for industry and transport sectors, on the other hand, are constructed using similar pattern across all regions as their consumption behaviours can be assumed to be not geographically dependent. Both sectors consume more electricity during working days compared to weekend time.Figure 10 shows the normalized profile for the driving load and industry load used. This profile is scaled according to the total load for the sector.

[3] We used five types of load day for each month: Normal working day, holiday, peak load day, Saturday, and Sunday

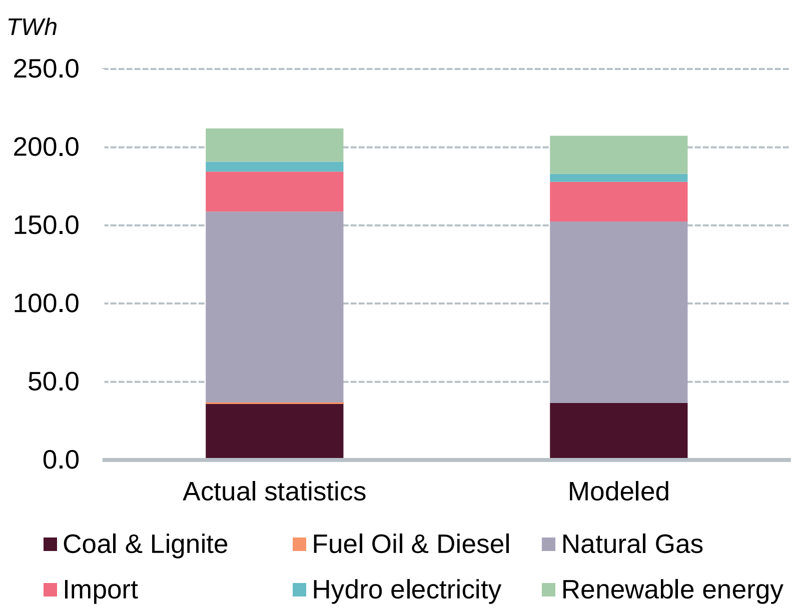
Figure 5 Two-week normalized demand profile from industry and EV sectors



2.5 Comparison of model output with real-world data for 2019

The model is validated for with real work generation data for the base year (2019). The model can be seen to perform rather well in representing the actual generation. The discrepancies are less than 5% for all the key generators. Overall, it can be concluded that the model is able to represent the power system satisfactorily.

Figure 11 Comparison between model output and realworld



2.6 Technical Implementation

The model run has been carried out on a server with 32 cores and 42GB of RAM. Each year model run with hourly resolution took around 10min to complete. Commercial solver Gurobi (Gurobi Optimizer - Gurobi) was used for solving the model.

Annex D
Co-benefits quantification: Air quality health impacts assessment

1 Air Pollution Impact Model for Electricity Supply (AIRPOLIM-ES)

NewClimate Institute's AIRPOLIM-ES (Air Pollution Impact Model for Electricity Supply) is developed under the Ambition to Action (A2A) project. It uses an accessible methodology for quantifying the health impacts of air pollution from different sources of electricity generation and other fuel combustion that can be applied in multiple countries in the form of an open-source Excel tool. The first version of this tool focuses on electricity generation from coal- and gas-fired power plants. It calculates the impacts on mortality from four adulthood diseases: lung cancer, chronic obstructive pulmonary disease, ischemic heart disease and stroke, all of whose prevalence is increased with the intake of pollution (WHO, 2016). The tool estimates health impacts for existing and planned electricity generation plants and can aggregate results at the country level.

1.1 Methodology

1.1.1 Estimating emissions

The health impact assessment is based on emissions of:

- particulate matter, or dust ($PM_{2.5}$);
- nitrogen oxides (NO_x); and
- sulphur dioxide (SO_2)

from coal- and gas-fired power plants. The model estimates the annual and lifetime electricity generation (GWh) for each plant as well as the corresponding emissions of air pollutants from fuel combustion using data on a plant's capacity (MW); annual capacity factor (%) and heat rate (Btu/KWh) informed by the LTES modelling exercise.

Depending on the type of emissions control equipment installed at the plant the model multiplies the estimated fuel consumption with the corresponding country-specific emissions factor from the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model developed by the International Institute for Applied Systems Analysis (IIASA). The GAINS model estimates emission factors for carbon and local air pollutant emissions for different fossil fuels and sectors at the country level. Where more detailed information is available plant-specific emission factors can be entered into the model to improve accuracy.

For the purpose of this study, we have used the "Average" emission factors for both coal- and gas-fired power plants. To increase the level of accuracy future studies should collect and incorporate plant-specific emission factors.

1.1.2 Population exposure

We estimate the exposed population living within four distance bands (0–100 km, 100–500 km, 500–1,000 km, and 1,000–3,300 km) from each power plant using an open-source geographical information system mapping software (QGIS) and the WorldPop gridded population data set which is compiled by the WorldPop project (2021). This calculation is carried out both for the population living within the analysis country and for the population beyond the analysis country borders, located within the distance bands. This approach allows us to assess both the health impacts within the country where the power plant is located as well as the inhalation of cross-border emissions. To estimate population exposure in the future we use country-specific population growth estimates from the UN World Population Prospects (2019).

For the purpose of this study, we estimated population exposure for each coal-fired power plant in Thailand which is included in the Global Coal Plant Tracker (2022) database. Based on these results we estimated the average population exposed in each of the four distance bands. We used this proxy for both coal- and gas capacity.

1.1.3 Concentration change and the intake fraction concept

We then use the intake fraction concept in order to estimate the change in $PM_{2.5}$ concentration in the ambient air dependent on the calculated pollutant emissions to avoid complex and resource intensive air dispersion modelling. Intake fractions indicate the grams of $PM_{2.5}$ inhaled per tonne of $PM_{2.5}$, NO_x and SO_2 emissions. These fractions allow us to infer (via a backwards calculation) the change in $PM_{2.5}$ concentration.

In order to estimate the intake fractions for the three pollutants included in the model we apply coefficients from a widely cited study from Zhou et al. (2006). The study uses a two-step statistical procedure to estimate the average fraction inhaled by an average person residing within the four distance bands from the emission source based on an analysis of 29 Chinese coal-fired power plants (Parry, Heine, Lis, & Li, 2014; Zhou, Levy, Evans, & Hammitt, 2006). Multiplying the population living in these distance bands by the corresponding Zhou et al. (2006) coefficient for the pollutant, and then summing the values for the four distance bands, gives the respective estimated intake fraction.

A limitation of this approach is that the coefficients do not account for location-specific characteristics such as the height at which the emissions are released into the atmosphere or meteorological conditions, although the authors show that population exposure by distance is by far the most significant factor that determines the dispersion of the pollutants.

1.1.4 Quantifying health impacts from air pollution

To calculate the increased mortality risk per additional tonne of pollutant emissions, we multiply the estimated change in $PM_{2.5}$ concentration with the respective concentration-response function. Concentration-response functions are estimated based on long-term medical cohort studies and indicate the increase in cause-specific mortalities per 10 μg/m³ increase in $PM_{2.5}$ (e.g. Burnett et al., 2014; Torfs, Hurley, Miller, & Rabl, 2007). For simplicity reasons we assume that the response functions are linear in the model, meaning that extra pollution has the same impact on mortality regardless of the initial pollution concentration.

The Global Burden of Disease project (2021) provides mortality rates by disease for 12 different age classifications (above 25 years) at the country level. We obtain age-weighted mortality rates by disease by using the share of the country's population in each age class based on data from the World Bank (2021). To calculate the number of years of life lost (YLL) we use life expectancy values at exact age from the UN World Population Prospects (2019).

The risk estimates, the age-weighted mortality rates and the exposed population are combined to calculate the number of premature deaths per tonne of pollutant for each cause of death. Finally, we multiply these numbers with the estimated pollutant emissions to obtain the total premature deaths per pollutant and cause for each power plant as well as the estimated number of YLL by multiplying with the respective life expectancy value.

1.2 ADDITIONAL MATERIALS

The Excel-based tool, the user guide and an overview presentation are available at ambitiontoaction.net/outputs.

1.3 REFERENCES

Burnett, R. T., Arden Pope, C., Ezzati, M., Olives, C., Lim, S. S., Mehta, S., … Cohen, A. (2014). An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. Environmental Health Perspectives, 122(4), 397–403. https://doi.org/10.1289/ehp.1307049

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Annex E
Co-benefits quantification: Economic impact assessment

1 Economic Impact Model for Electricity Supply (EIM-ES)

NewClimate Institute has developed a transparent tool which can be tailored to specific scenarios, country features and the level of data available, based on an analysis of investments across different electricity supply technologies over time. The model draws on Input Output tables which provide important context on the economic structure and sector inter-relationships of a country and allows an estimation of indirect and induced impacts which extend beyond the final products and services used to generate electricity. Users are provided with a wide range of economic and employment indicators which can be selected according to the context and need – including both gross and net effects, impacts over time, across sectors and technologies, and comparisons across technologies denominated in different units – all of which can provide critical insight to inform an assessment of different future pathways for the electricity sector.

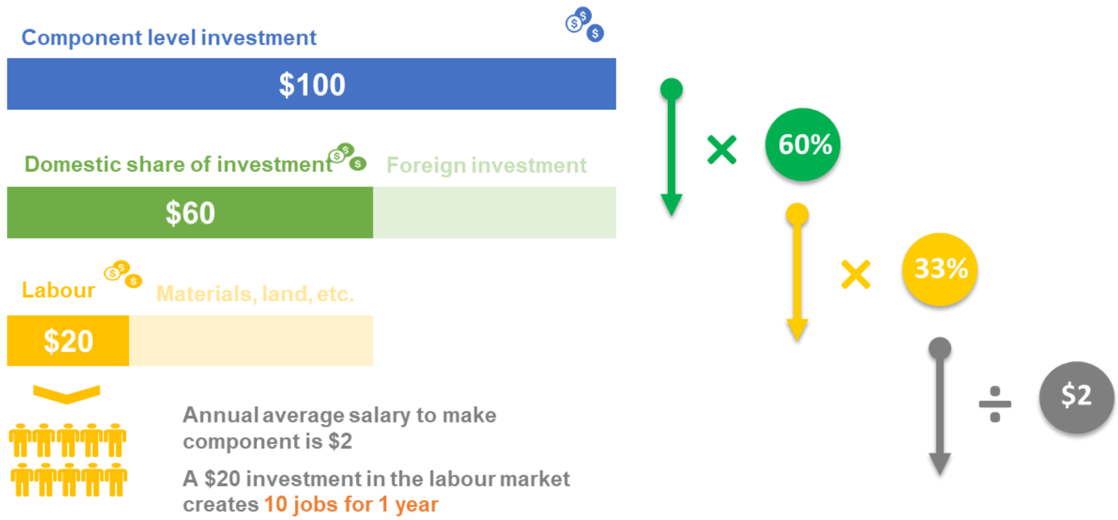
1.1 Overview of methodology

1.1.1 Investment based analysis

The analysis undertaken in the EIM-ES is based on investment cost data that is disaggregated, where possible, into its component parts (see Table 1 for an example of component parts for onshore wind) for new and existing electricity generation capacity. The model calculates the share of each investment that is spent domestically and the share of that domestic investment that is directed to the labor market based on input data and underlying assumptions.

Figure 1 shows an illustrative example of a $100 investment in a component part, such as the tower for a wind turbine. In this case $60 of the total is spent in the country and the remaining $40 is spent on imports. One third of the domestic investment ($20) is spent on the labor market, with the remaining amount spent on inputs such as land (where the wind turbine is sited) and materials, such as cement or steel and machinery used in the construction of the tower.

Figure 1: Overview of approach to estimating direct employment impacts



1.1.2 Direct jobs

The model calculates the direct employment impact of the investment in the labor market by dividing domestic investment in each year by an estimate of the annual average wage paid to workers employed in that sector[1], including taxes and any other costs faced by employers, such as social security payments. In this illustrative example the annual wage is $2. The $20 investment in the labor market therefore directly stimulates 10 jobs for 1 year, or alternatively 5 jobs for a period of 2 years.

The model apportions the direct jobs created over time based on assumptions related to the duration of the various tasks and services. For example, construction jobs typically may last for 2 to 5 years preceding the start of operations of new capacity, depending on the technology. Jobs created to provide operational and maintenance services typically cover a much longer period of time, linked to the expected lifetime of the asset.

1.1.3 Indirect and induced jobs

In addition to estimating annual direct jobs, the model calculates indirect and induced employment impacts by drawing on economic multipliers derived from Input Output tables for the economy. Input Output tables reflect the interdependencies of sectors across the economy, based on national statistics. Economic multipliers are calculated from the data in the Input Output tables to reflect the wider ripple effect of investments extending into the supply chains of the final goods and services and, in turn, the whole

[1]Bank of Thailand, EC_RL_014_S2 : Average wage classified by industry (ISIC Rev.4) 1/, https://www.bot.or.th/App/BTWS_STAT/statistics/ReportPage.aspx?reportID=636&language=eng

economy. Their use provides an approximation of the wider employment impacts of investment in electricity generation.

For the purpose of this study, we have used the OECD Input Output Database "Thailand 2018 Domestic Imports and Output Table" (2021 version).

1.1.4 Economic impacts

The main focus and application of the model is in estimating employment impacts. To help inform the assessment of different scenarios the model also reports additional economic indicators beyond jobs, such as the total investment in the country over time, split by economic sector; the overall scenario cost, including spending on imports; and the added value to the domestic economy from the investments.

1.2 Coverage of analysis

1.2.1 Technologies

The technology coverage is defined by the user to best reflect the range of different technologies that are currently operating in the country, and which are envisaged in long-term projections of new capacity. This allows an analysis of the full electricity supply system, aggregated according to the needs of the user and availability of data.

Required data inputs for each technology set up in the model include annual capacity and electricity generation projections as well as estimates of investment costs, split into capital expenditure as well as fixed and variable operational expenditure. These high-level cost estimates should then be broken down into their component parts (for example see Table 1 below). The model includes a set of default cost component breakdowns for a selection of common electricity generation technologies based on an analysis of publicly available sources. These default cost component breakdowns can be used where detailed country-specific data are unavailable.

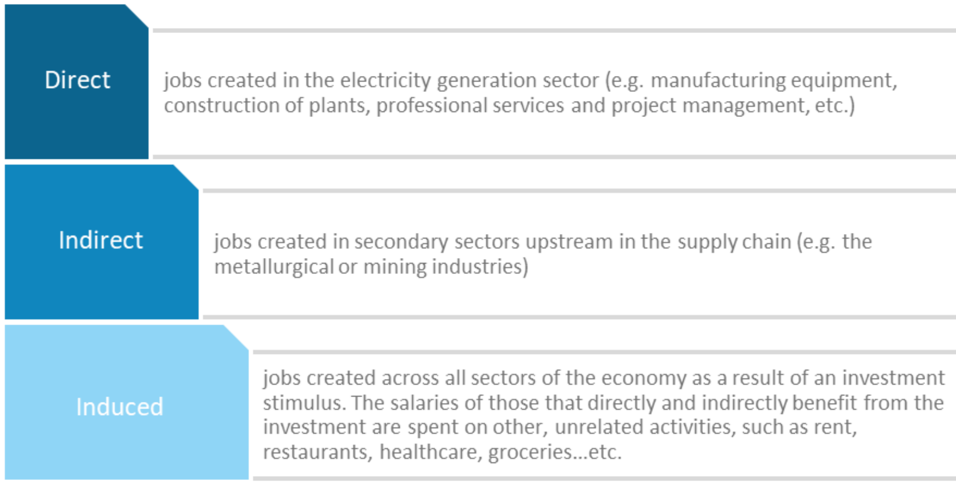
Learning curves can be included, where available, for each technology in the form of an index that captures projected annual change in costs at the level of capital expenditure and both operational and fixed operational expenditure.

For the purpose of this study, all of the above inputs have been derived from the LTES modelling exercise (see Table 2 for technology list).

1.2.2 Direct, indirect and induced impacts

The economic analysis in the EIM-ES considers different categories of employment and investment that extend beyond the electricity generation sector to all areas of the economy. The main focus of the analysis is on the direct impacts of the investments in the electricity generation sector, which are estimated over time. However, the model also derives economic multipliers from the country Input Output table and uses these to estimate indirect and induced impacts. Examples of direct, indirect and induced impacts are set out in Figure 2.

Figure 2: Direct, indirect and induced economic impacts



1.2.3 And what it does not cover

The EIM-ES is designed to provide an accessible tool to analyse employment and wider economic impacts in the electricity supply sector, balancing its level of sophistication against the objective to make the model relatively easy to use, to ensure transparency of the calculations and considering constraints in data availability in many countries. There are a number of limitations to the analysis – as discussed in section below – which are important to take into account when interpreting the results. In addition, it is important to note that the standard model does not cover the following areas:

- **Energy efficiency measures**: Scenarios with lower electricity demand (and corresponding supply) may include increased uptake of energy efficiency measures. These measures may stimulate jobs – for example workers employed in retrofitting household insulation – which are not considered within the EIM-ES. In comparing scenarios in the EIM-ES it is important to consider the overall electricity supply of the respective scenarios and analyse results expressed per unit of electricity generation or per unit of investment.

- **Grid infrastructure**: Electricity systems may require significant investment in either new electricity grids or upgrades to existing grids over time, particularly where transitioning from centralised systems, built around large fossil-fuel based power plants, to more decentralised systems. In the standard version of the EIM-ES the impact of required grid investments is not included even though these may have significant implications for the total investments required for a given scenario.

- **Sub-national or foreign impacts**: The EIM-ES is set up to calculate impacts at the national level, particularly given that Input Output tables are often not available at sub-national level. Any sub-national scenario analysis would have to incorporate assumptions about the local share of production within that particular region as well as the inter-relationship between economic sectors in the region. Additionally, it is important to note that the model is focused on assessing the impacts of investments within the country of interest. It does not consider the wider economic impacts accruing to other countries, for example, which export materials that are used in the electricity supply sector of the analysis country.

- **Quality of jobs**: The model estimates the number of full-time job years for a given scenario, broken down by technology and economic sector. It does not, however, provide any assessment of the potential quality of these jobs. Such an assessment could draw on the quantitative outputs of the model, complemented with further information on the potential quality of jobs according to economic sectors and the electricity generation technologies, where available.

1.3 Data inputs

The level of accuracy of the analysis depends on the quality of data inputs and the extent to which they reflect the country context. Where country-specific data points are either missing or unreliable users may need to draw on regional and international information, adjusted as necessary to the target country. The model is set up to enable sensitivity analysis (via different scenarios) on key data inputs to offer information on the extent to which their level influences the final results. Figure 3 sets out the main inputs that are required for the model. Users of the model can adjust input data according to their needs and knowledge.

Figure 3: Data inputs required to set up EIM-ES

New capacity	New capacity added to the system by technology and year; where only total capacity projections are available then assumptions related to capacity retirements are required
Generation	Electricity generation by technology and year; where output data is unavailable default load factor assumptions can be used to derive estimates of output from the total capacity data
Investment	Investment costs by technology broken down into component parts; where detailed disaggregated data is unavailable capex, fixed opex and variable opex can be allocated using default assumptions
Local share	Estimate of the share of the total investment in a component part spent in the domestic market
Sector	Sector of the economy corresponding to the component part activity based on sector granularity of the Input Output table
Input Output	Input Output tables that reflect the interrelations between economic sectors of the country and include estimates of the share of investments in a sector directed to the labour market
Salaries	Average annual salaries, including employee and employer taxes (if available), by economic sector as a proxy for the labour cost

Table 1: Example of cost component parts for onshore wind

Onshore wind cost components (example)	Cost category
Nacelle	Capex (USD/MW)
Blades	Capex (USD/MW)
Tower	Capex (USD/MW)
Transport	Capex (USD/MW)
Electrical balance of plant	Capex (USD/MW)
Installation	Capex (USD/MW)
Project planning and management	Capex (USD/MW)
Civil works	Capex (USD/MW)
Contingency and finance	Capex (USD/MW)
Operation	Fixed opex (USD/MW/yr)
Maintenance	Fixed opex (USD/MW/yr)
Land lease costs	Fixed opex (USD/MW/yr)

For each cost component an estimate of the share of the investment that is made in the country is included. For example, if all wind turbine blades are imported, the local share of the investment in the cost component for blades will be zero (percent). Identifying accurate data to inform the estimates of the local share of investments is challenging and to be the most resource intensive part of preparing input data for the EIM-ES, particularly as the estimates depend to a large extent on the supply chains in the country. These data inputs should be informed by experts familiar with developing electricity generation projects in the analysis country, ideally drawing from knowledge across different technologies.

Table 2 gives an overview of the data used in this report. The inputs are informed by a review of existing literature and combined with default data where no further data is available. Future studies should conduct on additional data collection and draw on local expert knowledge to improve the accuracy of the results.

Table 2: Average local and labour shares for Capex and Opex by technology

Technology	Capex average local share	Opex average local share	Capex average labour share	Opex average labour share
Solar PV plant	49%	52%	12%	10%
Rooftop solar PV	49%	52%	12%	10%
Concentrated solar power plant	58%	91%	12%	11%
Onshore Wind farm	28%	53%	12%	10%
Offshore Wind farm	41%	49%	13%	10%
Geothermal power plant	59%	51%	13%	10%
Hydro with dam power plant	55%	49%	10%	10%
Hydro pumped storage	55%	49%	10%	10%
Biomass power plant	34%	60%	13%	10%
Waste Generator	34%	63%	13%	10%
Combined cycle gas turbine power plant	32%	50%	14%	11%
Simple cycle gas turbine power plant	26%	50%	14%	10%
Simple cycle gas turbine with CCS	26%	50%	14%	10%
Open cycle hydrogen turbine power plant	55%	49%	10%	10%
Hard coal subcritical power plant	46%	50%	13%	10%
Lignite Sub-critical	46%	50%	13%	10%
Bitumenous coal generator	46%	50%	13%	10%
Oil power plant	46%	50%	14%	10%

1.4 Limitations and challenges

As with any modelling exercise, it is important to be aware of key limitations in the analysis that should be considered when interpreting results. The level of accuracy of the analysis using the EIM-ES depends on the quality and granularity of data inputs and the extent to which they are reflective of the country context. Where country-specific data points are either missing or unreliable the user can draw on regional and international information, adjusted where relevant to the target country. The model is set up to enable sensitivity analysis on key data inputs to offer information on the extent to which their level influences the final results.

The model draws on information included in Input Output tables to inform the estimation of impacts. These include economic multipliers as well as the share of spending that flows to the labor market for a given sector. The Input Output tables used in the EIM-ES provide a static representation of the structure of the economy and are based on historic data points that are, for some countries, somewhat outdated. The model does not include any mechanism or assumptions to dynamically update the economic structure over time (as is done in more sophisticated modelling tools). The sector inter-relationships are therefore an approximation of – but will not necessarily reflect - the future structure of the economy over the modelling period.

A further limitation is that the sector disaggregation in the model (based on the Input Output table and which is also applied to salary information) is typically at a relatively high-level, e.g., the sector for 'fabricated metal products', or 'electrical machinery'. The model therefore does not provide a detailed representation of the specific goods and services relevant to the electricity supply sector, but assigns each cost component to one of 45 economic sectors (in the case of tables from the OECD database). Where a cost component is not representative of the sector it is allocated to, the results may be less accurate, particularly in the estimation of the indirect and induced impacts of investments.

Finally, an additional simplification within the model is to include cost estimates that are expressed in units of capacity (e.g., per MW) or, for variable costs, in units of electricity generation (e.g., per GWh). The model scales these estimates in a linear manner based on the total capacity added or electricity generated for a given technology without factoring in any potential economies of scale. For example, the relative impact of a 10MW wind farm is the same as that of a 100MW wind farm, even though in practice the costs per MW might be lower in the case of the larger project.

1.5 Further resources

The Economic Impact Model for Electricity Supply, an overview presentation and a user guide are available at https://ambitiontoaction.net/methodologies-and-tools-eim/.

CASE for Southeast Asia

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