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Technical Report

Background to Vietnam Energy Outlook Report 2019

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Contents

Foreword

The activity described in this report is part of 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). The objective of Development Engagement 1 is to make Vietnam's energy system more sustainable through implementation of cost-optimised policy and planning.

This objective is to be achieved by assisting the Electricity and Renewable Energy Authority of Viet Nam (EREA) and the Vietnamese Ministry of Industry and Trade (MOIT) to commission, develop, and analyse comprehensive long-term energy scenarios.

This report documents the model-based analyses that are expected to be a cornerstone in the Vietnam Energy Outlook Report (EOR) 2019, which builds on the work carried out in the first edition, EOR 2017 (MOIT and DEA, 2017).

The core activities comprising the current study include:

- Installation and use of the energy system modelling server at EREA
- Training of analysts and operators in the electricity system model Balmorel
- Econometric analyses of historical electricity demand and future prognoses
- Development of a Vietnamese technology catalogue, including investment costs for power generation technologies such as coal, gas, wind, solar and several other relevant technologies for the years 2020, 2030 and 2050.
- Fuel price prognoses for imported and domestic fuels (2020-2050).

The econometric analyses, the technology catalogue and the fuel prices prognoses are published as separate background reports to the EOR 2019.

The energy scenarios presented in this report are based on a modelling framework comprising two energy optimisation models, TIMES (encompassing supply, conversion and end-use sectors) and Balmorel (representing the power sector in high technical, temporal and geographical detail). The two models have been calibrated in order to represent the Vietnamese energy system.

Furthermore, the power grid model PSS/E has been applied to strengthen the conclusions regarding the power grid.

This report is based on close cooperation with EREA, the Danish Energy Agency (DEA), the Vietnam Institute of Energy (IE) and many national stakeholders.

Executive summary

Affordable and secure energy is key while environmental concerns growing

Energy is a crucial component of all sectors in a modern well-functioning society. Access to affordable energy with a high degree of security of supply is therefore essential, while providing this energy in an environmentally low-impact fashion is also becoming increasingly important. This report presents findings from a study that investigates the long-term development of the Vietnamese energy system (2020-2050). Different scenarios describe varying future potential pathways for the whole energy system and the results in terms of electricity generation mix, fuel use, import dependency, total system costs, local pollution, and CO_2 emissions.

High growth accompanied with challenges for the energy system

Vietnam has experienced high rates of economic growth in recent years, a trend that is expected to continue. While positive, this growth is also accompanied with challenges for the Vietnamese energy sector. The country for example became a net importer of energy in 2015. Domestic energy sources, such as coal, gas and hydro will not be able to meet the growth in energy demand, and this import dependency will increase in the future.

Suite of modelling tools utilised in analysis

The models TIMES, Balmorel and PSS/E are used to analyse different aspects of the energy system. TIMES includes all energy sectors on a general level, Balmorel allows for more detailed analysis of the power (and heat) sector, while PSS/E is an even more detailed model of the power system that is used to check the assumptions regarding power flow and transmission capacities used in Balmorel. TIMES and Balmorel meet the given requirements while optimising for a least-cost energy system solution.

Energy efficiency particularly for air conditioning

With improved economic development comes both increases and changes to electricity demand. For example, only a minor share of energy consumption today is used for air conditioning. In 2050 however, air conditioning in households and the commercial sector is expected to reach 20% of the total electricity consumption. There exist numerous options for high efficiency air conditioning, which also highlights the importance of energy efficiency in general, which should be a focus point in order to guide end-users to improve comfort at the lowest possible costs.

Energy efficiency key element

In the current study the TIMES model provides a bottom-up approach including 5 demand sectors and 12 industrial subsectors to analyse energy demand development. Energy efficiency measures in transport, industry and households prove to be very attractive in both reducing fuel and power demand in the end-use sectors and reducing the total system costs. Increased implementation of energy efficiency in certain sectors should therefore be a key element in the development of the future energy system.

CHP in industry increases system efficiency

In industry the analyses highlight the potential to use combined heat and power (CHP) to produce both process heat and electricity. Combined generation is much more efficient than generating heat and electricity separately.

Cost reductions in solar, wind and batteries provide new opportunities and challenges

Within the power sector new technologies may soon play a much more prominent role in the generation mix. The cost of wind and solar power, as well as batteries, has fallen dramatically during the last few years. These cost reductions provide new possibilities (and challenges) for the future development of the power sector. Wind and solar are variable in their generation and require new procedures for system balancing. In the current study, solar power in combination with battery storage results as the main future RE technology given the good solar resources in Vietnam.

Series of wide-ranging scenarios provide insights into effects of potential pathways

The analysis found that it is possible to reduce the annual costs of imported fuel from 7.5 billion USD to 4 billion USD in 2030 with 32% and 52% shares of RE in the power sector respectively. In 2050, the reduction would go from 16 billion USD with 43% RE share to below 4 billion USD with 80% RE). However, due to higher upfront installation costs, the higher the share of RE (and corresponding lower CO_2 emissions and reduced cost for imported fuels), the higher the overall system cost.

Starting at 40% RE, for each percentage of CO_2 emissions reduction from the Vietnamese power sector, the total system costs increase with 0.3%. The costs increase slightly more when strong emissions reductions (more than 50% RE) are realised. Across the analysed scenarios, the CO_2 emissions range between 200-280 Mt in 2030, and 160-550 Mt in 2050.

LNG is expensive, but can play a role in a low CO_2 future

Liquified natural gas (LNG) is an imported energy source that may be used in Vietnam in the future. CO_2 emissions from LNG are considerably lower than those from coal, and there is essentially no sulphur or particulate matter emitted when combusting LNG. However, LNG is an expensive fuel, nearly three times the cost of imported coal. In this study, LNG becomes an attractive solution if strong CO_2 reductions are pursued.

Future studies - Inter-connectors, demand response and CSP should be studied

Across the studied scenarios, batteries are used extensively to balance the power system. Pumped storage has also been tested, yet the system requires a relative high capacity (MW) compared to storage volume (MWh), and in this respect Li-ion batteries are more attractive than pumped storage. However, a number of alternatives should be investigated in relation to power storage and balancing options. Alternatives could include more interconnectors to neighbouring countries, activation of demand response (where a portion of electricity demand reacts to the price of electricity and thereby acts as a form of storage), or concentrated solar power (CSP), where energy can be stored as heat.

1 Introduction

1.1 Vietnamese energy landscape

During the last decades, Vietnam has experienced increased economic activity, industrial development, urbanisation, increased transport demand, improved energy access and rising living standards, all of which are major drivers for growing energy consumption.

2007-2017: Annual primary energy supply grows by 5.5%

In the period 2007-2017, the Vietnamese total primary energy supply (TPES) grew at 5.5% per annum, thereby increasing from 45.9 Mtoe (1,922 PJ) in 2007 to 78.4 Mtoe (3,282 PJ) in 2017. Hydropower experienced the highest growth at 15% p.a., followed by coal at 11% p.a.. Coal's share of energy supply therefore increased significantly during this period, as it went from the 3rd largest fuel source in 2007, to being the largest source 10 years later. Meanwhile, the opposite is true for biomass, which, due to a gradual decline in energy supply, saw its share go from being the largest contributor in 2007, to the 3rd largest in 2017. Non-hydro renewables (i.e. solar and wind, etc.) have historically only contributed to a very small share in TPES. An overview of the historical Vietnamese TPES according to fuel type for 2007-2017 is presented in Figure 1.

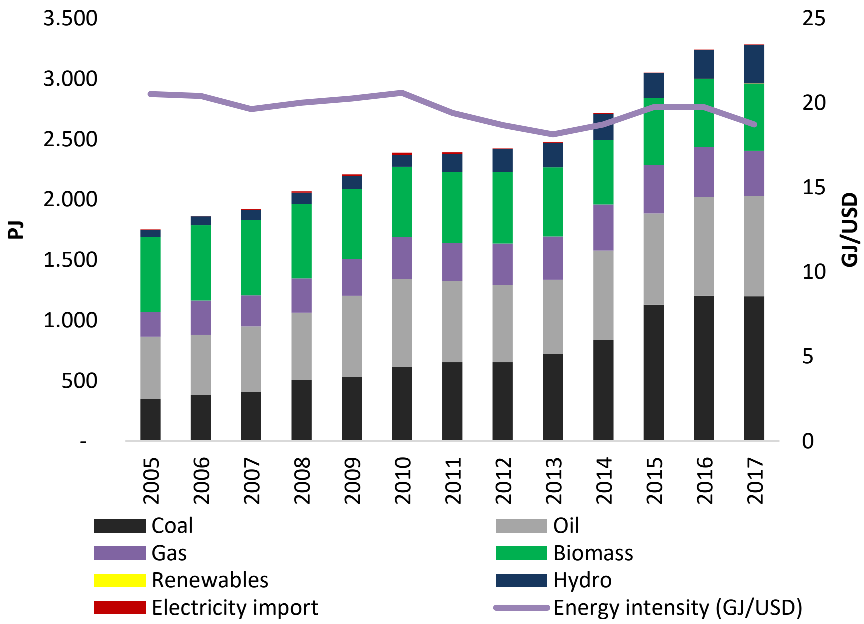

*Figure 1: Historical TPES according to fuel type and energy intensity. *Note that the jump from 2014 to 2015 is partially due to a change in data collection methods that resulted in more detailed data being collected from Industry. (IE, 2017), GSO.*

GDP slightly outpacing energy supplied

Annual GDP grew at a rate of 6.0% during the period 2007-2017, thus increasing slightly faster than the annual growth rate in energy supply, i.e. 5.5%. This resulted in an average primary energy vs. GDP elasticity of 0.92. Energy intensity, expressed as the ratio of primary energy to GDP, exhibited a slightly decreasing trend.

From net exporter to net importer of energy

After being a net energy exporter for a long time, recent increases in domestic activities and a policy limiting coal exports, Vietnam became a net energy importer in 2015 with an import dependency rate of 6%. This rate continues to grow quickly, as it was already 16% in 2016 and 19% in 2017, primarily driven by increased coal imports. Due to foreseen continued economic growth, and limited domestic resources, it is anticipated that this import dependency rate will continue to rise in the future. The 2007-2017 historical development in the energy import/export balance and the related import dependency is displayed in Figure 2.

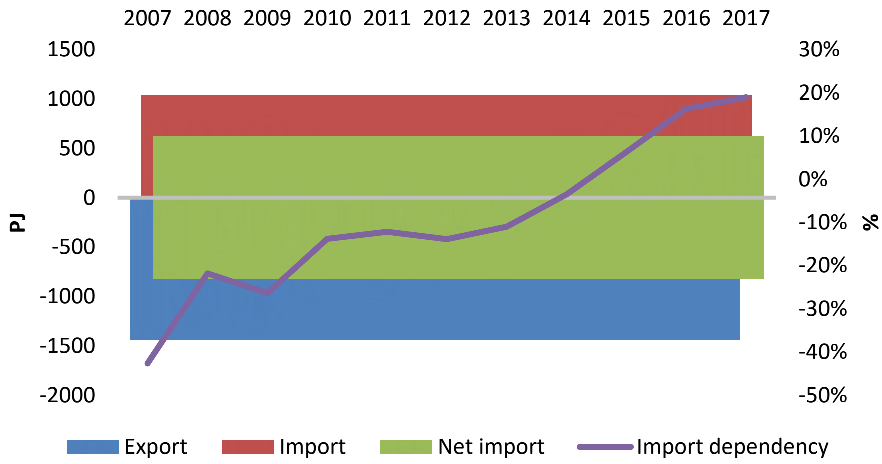

Figure 2: Historical development in energy import/export balance and the related import dependency 2007-2017 (IE, 2017), GSO.

During the period 2007-2017, the total final energy consumption (TFEC) increased from 40.4 Mtoe (1,691 PJ) in 2007 to 65.2 Mtoe (2,730 PJ) in 2017, with a growth rate of 4.9% per annum. The industrial sector underwent the largest annual average growth during the period at 10.6%[1], followed by the commercial and transport sectors with 6.4% and 5.2% per annum respectively. Residential final energy consumption decreased during the period due to a trend involving displacing traditional biomass use with electricity and other fossil fuels. By 2017, industry represented 55% of TFEC, followed by transport and residential with 21% and 17% respectively. Development in TFEC for 2007-2017 is displayed in Figure 3.

[1] Note however that this large growth figure for industry includes a large jump from 2014 to 2015, which is partially due to a change in data collection methods that resulted in more detailed data being collected from Industry.

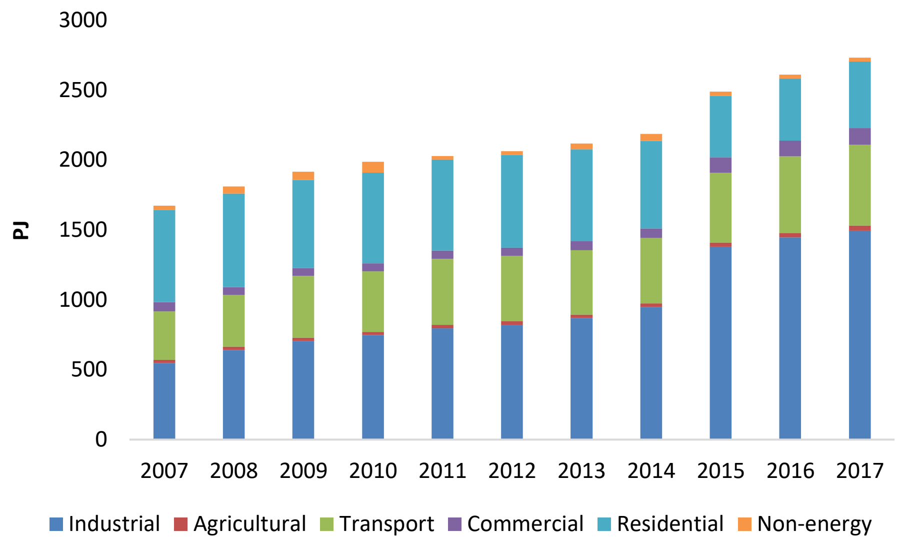

*Figure 3: Trends for TFEC in 20017-2017. *Note that the large jump from 2014 to 2015 is partially due to a change in data collection methods that resulted in more detailed data being collected from Industry. (IE, 2017), GSO.*

Following the socio-economic development, energy consumption in recent years has increased quickly, and consequently greenhouse gas emissions (GHG) from energy uses, processes and extractions have increased from 134 Mt CO_2e in 2010, to 179 Mt CO_2e in 2014 (MONRE, 2014), with one third related to electricity generation in 2014.

Based on the past development, challenges for sustainable energy development include:

- Decoupling the high economic growth rates from increases in energy demand;
- Limiting the environmental and climate change impacts of energy development;
- Limited domestic fossil resources, especially coal and natural gas;
- Uncertainty related to the establishment of the necessary infrastructure for coal and LNG import;
- Promoting effective funding schemes for financing RE and EE development;
- Resolving possible challenges for the integration of variable renewable energy (VRE) into power system.

1.2 Vietnamese power sector

In 2018, the total power generation capacity of the Vietnam electricity system was roughly 49 GW, of which large hydro power accounted for nearly 35%, coal roughly 39%, natural gas about 15%, and small hydro and other renewables accounting for nearly 8%. Peak electricity demand was over 35 GW in 2018, while total annual generation from all of Vietnam's power plants reached over 220 TWh. In terms of ownership structure, Vietnam Electricity, EVN, and its joint stock companies (GENCO 1,2,3) account for about 58%, Petro of Vietnam accounts for roughly 9%, the Vina Comin owns nearly 4%, BOT power sources account for slightly over 8%, and private investors' power sources own nearly 21%.

As Vietnam is still a developing country, the demand for energy consumption in general, and the demand for electricity consumption in particular, continue to grow quickly. During the years from 2008 to 2018, the demand for electricity in Vietnam increased by an average of over 11% per year. To meet this growing electricity demand, Vietnam needs to put into operation an additional 3-4 GW of generation capacity each year. Total investment in the electricity sector is roughly 11 billion USD per year.

Electricity sector challenges

The rapid speed of development, the large annual required investment capital, the impact of scientific and technical developments, and the environmental effects associated with the electricity sector pose a number of challenges going forward. Seven main issues have been identified and are described briefly below.

- *The Vietnamese electricity demand is anticipated to continue to grow rapidly in the period from now through to 2025 and 2035*. According to the most recent Power Development Plan (PDP VII revised), the electricity generation sector will have to ensure the production and import of 400 TWh in 2025, and 572 TWh by 2030. Annual electricity growth rates during the period from 2021-2025 are estimated to become roughly 8.5%, and only falling slightly to 7.5% per year during the 2026-2030 period. According to the PDP, the estimated installed generation capacity in 2030 may grow to nearly 130 GW. Growth of this magnitude poses major challenges covering many aspects, including: securing adequate investment capital, construction of electricity generation sources, transmission and distribution grids and other related infrastructure, modernising operation of the electricity system, ensuring cost-effective and efficient use of electricity, and ensuring human resource development.
- *Shift to a net importer of energy required for electricity production as domestic sources become exhausted*. In 2018, the total installed capacity of hydro power plants in Vietnam was 17 GW, and by 2020 this is planned to grow to 18 GW. At that point Vietnam will have exploit-

ed most its economic and technical potential of large and medium-sized hydro plants. With respect to coal, domestic production output is estimated to be able to support only 13 GW of coal-fired capacity. As a result, in 2017, Vietnam had imported coal with large amount for electricity production (about 3 million tons). Import volumes are estimated to be over 55 million tonnes in 2025 with this growing to 85 million tonnes in 2030. Domestic gas production capacity is anticipated to be able to supply gas to nearly 10 GW of thermal gas-fired capacity in 2020, and up to roughly 15 GW after the Blue Whale gas field comes into operation. With an estimated 22.8 GW of gas-fired generation capacity in 2030 (according to PDP VII revised) Vietnam will need to import LNG after 2020 for electricity generation. Limited primary energy resource, or their depletion thereof, e.g. hydropower, domestic coal and gas, represents a huge challenge for the electricity sector, as it raises issues related to energy security, ensuring a safe and reliable power supply, as well as financing the large sums required for imported fuels and related infrastructure.

- The Vietnamese electricity system is the third largest in Southeast Asia (after Thailand and Indonesia), and is in a rapid development stage. Vietnam's electricity system has however some weaknesses. The electricity infrastructure requires reinforcement, as a number of aspects within the system are outdated.
    - There are some thermal power plants with long remaining lifetimes that have outdated equipment and low efficiencies, including Ninh Binh, Uong Bi and Pha Lai 1.
    - The transmission grid can still become overloaded and power quality is not high (e.g. overload occurs in the transmission grid of Ha Noi and Ho Chi Minh city areas, over voltage still occurs in the 500kV inter-regional transmission line).
    - The systems for protection, automation, and communication are not synchronised, and the automatic control functions do not work smoothly. Smart grid implementation is still at a testing level.
- *Strong growth in renewable energy deployment can pose challenges*. According to the PDP VII revised, the share of electricity demand from renewable sources (primarily wind and solar) will be roughly 12% in 2025 and grow to 21% in 2030. Wind and solar power production are non-dispatchable and operating a power system that incorporates a large proportion of solar and wind power sources requires research and investment in sources of electricity storage, improved weather

and meteorological forecasting, and improved grid connection. According to information from EREA, by the time of January 2019, the total size of registered investment projects of solar and wind has reached about 22GW and 10GW respectively. These capacities are larger than those for 2030 published in the PDP VII revised.

- *Environmental and climate change issues increasingly put pressure on the electricity sector*. It is estimated that PDP VII revised expects up to 120 million tonnes of CO_2 emissions from electricity production in 2020 and nearly 260 million tonnes in 2030. In 2030 these emissions account for 70% of total emissions from the energy sector and 60% of total national CO_2 emissions. As a result, the impact of electricity production on the environment, biodiversity, our lifestyle, cultural practices and traditions of the people has become an increasingly important issue for power development.
- Vietnamese national economy and overall infrastructure is still under development, and it may therefore be difficult to allocate the required resources for the development of the power sector. In 2017, Vietnam's GDP was estimated to be roughly 220 billion USD, and this is anticipated to more than triple, reaching nearly 810 billion USD by 2030. According to the revised PDP7, the required investment in the electricity sector in 2030 is forecasted to be more than 10 billion USD (not including investment capital under BOT form), thus accounting for more 1% of GDP and about 3.3% of total national investment. Vietnamese transport infrastructure, infrastructure that supports industry, and construction capacity are also all in the development stage. The above issues all pose challenges to the development of the electricity sector.
- *Development of a competitive electricity market and the liberalisation of the electricity sector are being promoted*. Accordingly, the state will only retain power plants for strategic purposes (for example, large hydroelectric power plants, multi-purpose services such as Hoa Binh HPP, Son La HPP), while other power plants will be gradually sold. The government encourages both foreign and domestic actors to invest in building electricity generation sources. The state only holds monopolies regarding the transmission grid. The policy of expanding ownership in the electricity sector development has created investment opportunities for many sectors. This leads to positive changes in how the power development structure will be in the future, but also requires adequate market design and transitional arrangements.

2 The models used

The current project utilises three energy models to be able to (i) encompass the entire energy system, (ii) represent the necessary level of technical, geographical and temporal detail, and (iii) maintain an operational and flexible model setup. The modelling framework includes:

- TIMES-Vietnam model, covering all sectors in the energy system, including total energy use in industry, residential and service sectors as well as transport. See section 3.1.
- Balmorel model, representing investment and operation of the power system in great detail. See section 3.2.
- PSS/E model, encompassing the power transmission system with detailed information about transmission lines (220 kV and greater), transformers and other grid components. See section 3.3.

2.1 The TIMES model

TIMES model generator: principles and coverage

The TIMES (The Integrated MARKAL-EFOM System) model generator was developed as part of the IEA-ETSAP's methodology for energy scenarios to conduct in-depth energy and environmental analyses. The TIMES model generator combines two different, and complementary, approaches to modelling energy: a technical engineering approach and an economic approach (Loulou, Goldstein, Kanudia, Lettila, & Remme, 2016). Currently 19 countries, the EU and two private sector sponsors are participating to ensure the continual advancement of the methodology.

Moreover, TIMES is an economic model for analyses of national energy systems, which provides a technology-rich basis for estimating energy dynamics over a long-term horizon. It is usually applied to the analysis of the entire energy sector. The reference case estimates of end-use energy service demands (e.g., car road travel; residential lighting; steam heat requirements in the paper industry; etc.) are provided by the user for each region. In addition, the user provides estimates of the existing stock of energy equipment in all sectors, and the characteristics of available future technologies, as well as present and future sources of primary energy supply and their potentials.
Using these as inputs, the TIMES model aims to supply energy services at minimum global cost by simultaneously optimizing technology investment and operation.

On the other hand, TIMES presents some modelling limitations, including assumptions on perfect foresight, perfect market conditions and modelling from the point of view of a central planner with perfect information on all events on the time horizon.

TIMES-Vietnam

The TIMES-Vietnam has been developed under the World Bank funded project "Getting Vietnam on a Low-Carbon Energy Path to Achieve NDC Target" (DWG, 2018) which supports MOIT in developing cost-effective low-carbon energy mitigation options and pathways both on the demand and supply sides to achieve the NDC target. The TIMES-Vietnam model has been developed along with building local expertise to effectively steward and apply the methodology on a long-term basis. The TIMES-Vietnam model has been further adapted to support the scenario analysis of the EOR (this report).

The TIMES-Vietnam model covers all parts of the energy system, from primary energy resources to power plants and other fuel processing plants, ultimately to various demand devices in all five demand sectors[2].

Primary energy, in the form of domestic and imported fossil fuels, and a variety of domestic renewable energy sources are available to meet the energy demands of the country. Power plants and fuel processing plants convert the primary energy sources into final energy carriers, such as electricity, oil products and natural gas, which are used in the demand sectors. There are both existing and potential future plants grouped by fuel and type, which are characterized by their existing capacity or investment cost, operating costs, efficiency and other performance parameters. The final energy carriers are consumed in demand-specific end-use devices (e.g. electricity is used in residential lamps for providing lighting), that are used to satisfy the demands for energy services in that sector.

The model contains five demand sectors: Agriculture, Commercial, Industry, Residential and Transportation. Each demand sector is characterized by a specific set of end-use devices that deliver end-use services (such as lighting, cooling, cooking, industrial process heat, motor drive, passenger and freight travel). These existing and potential new end-use devices are characterized by their existing capacity or investment cost, operating costs, efficiency and other performance parameters. Transport demands include road passenger, road freight, railway passenger, railway freight, airway passenger, airway freight and waterway freight. Transport demands are provided by different transport devices, which capacities and activities are exogenous in the current

[2] For further information about the TIMES – Vietnam model see separate "TIMES Data Report".

Vietnam-TIMES model and based on scenarios provided by the Ministry of Transport. These devices are characterized with investment and operating costs, which allow the model to calculate the costs for transport sector. The demands for energy services are determined by projecting the base year energy demands, which are derived from the energy balance 2014 (IE, 2017) as part of the calibration process, in accordance with sector-specific drivers, such as GDP growth, GDP per capita growth, industrial production projections, space cooling growth expectations, etc. The base year 2014 is chosen due to solid data availability and consistency with other NDC assignments, which are being implemented in line ministries (MOIT, MONRE, MOT etc.).

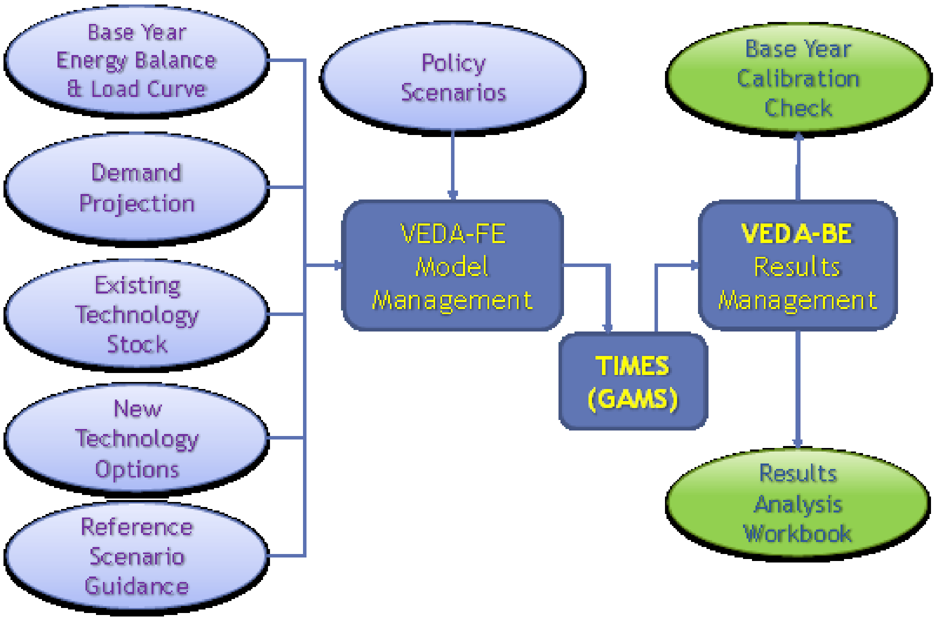

Figure 4: Modelling framework for TIMES-Vietnam

Base year energy service demands are extrapolated up to 2050 with following assumptions and expert judgements:

- Energy balance 2014 reflects business-as-usual energy use intensities and existing technology stock;
- GDP increases at 7% per annum to 2030; afterwards it has a decreasing rate to 2050 (IE, 2015);
- Population and urbanization as in GSO's projections to 2049 (GSO, 2016);
- Industrial demands grow as in approved development plans for several industrial subsectors[3];
- Residential demands grow in line with the increases in population and urbanization;

[3] Collected from various official documents for approval of sectoral development plans.

- Agricultural, commercial and transport demands grow in line with the GDP growth rate

TIMES-Vietnam is structured with twelve (12) time slices: three seasons (Wet, Intermediate and Dry) and four divisions of the day (day, morning peak, evening peak and night).

Owing to the nature of the availability of resource supplies and the long-distance transmission lines in Vietnam, three transmission regions are identified in TIMES-Vietnam: North, Central and South for domestic resources (including renewables), refineries, and power plants. The existing capacity of the transmission lines between the regions are reflected in the model, along with the cost for expanding the infrastructure in the future. A fourth consumption region (Vietnam) is used to depict the national demand for the five (5) end-use sectors. The three transmission regions each deliver their outputs (power and fuels) to the national consumption region. In order to reflect the limitation of e.g. power plants in the North delivering power to the South, consumption centre constraints have been set on the transmission lines connecting each transmission region to the consumption region. The capacity of these transmission lines are limited to reflect that a maximum electricity generation can be supplied within the regions. Setting the capacity bounds is mainly based on expected regional electricity demands and partly regional generation potential.

2.2 Balmorel

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

The model finds an energy balance for the system in each time step. The output is a least-cost optimisation of the dispatch of the generation units represented in the model. In addition, the model simultaneously allows for investments to be made in different new generation units (e.g. coal (incl. CCS option), gas, wind, solar, biomass, small hydro, biomass and nuclear as well as in new interconnector capacity. The model can be run on hourly time steps to allow for adequate analysis of the integration of the variable renewable energy (RE) in the power system.

Balmorel - Vietnam

The model contains data of the Vietnamese electricity system: the map in Figure 5 illustrates the existing (2018) interconnected power system in Vietnam. The country is represented as six transmission regions, with their individual hourly electricity consumption.[4] The transmission regions are connected by electricity transmission lines with fixed capacity. In total, seven lines connect the transmission regions, and electricity balances are given on a regional basis. Hence, for each region an electricity balance must be fulfilled, while electricity may be exchanged between regions.

In addition, four transmission lines connect China, Laos and Cambodia to the Vietnamese grid. Import from the neighbouring countries takes place with fixed profiles. For more details on the setup of the Vietnamese model please see: (Ea Energy Analyses, 2019a).

The model can be run with full hourly resolution or with aggregated time steps to save computational time. The current analysis represents each year by 364 time-slices, utilizing 26 aggregated seasons, representing two-week periods each. Each of these seasons is modelled with 14 time-steps, which are aggregated in a logical way, grouping all hours of the week with a similar character (e.g peak load, solar peak, low demand in weekends and nights etc.).[5] In order to represent the dynamic properties of the different generation technologies, unit commitment is activated in the model. This is done in the simplified form referred to as *relaxed mixed integer modelling of unit commitment*. The unit commitment procedure applies start-up costs for various generation technologies, which result in additional costs for less dynamic technologies. Additionally, unit commitment restrictions, such as minimum generation, ramping times and minimum up/down time are included. For example, gas turbines are more dynamic than steam turbines (i.e. typical coal plants), but hydro power is even more dynamic than gas turbines. The relaxed form of mixed integer modelling indicates that binary (0/1) variables related to unit commitment can take any real value between 0 and 1. This results in a representation of the dynamics of unit commitment, in which individual constraints might be broken.

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[4] As part of the current project, the Balmorel-Vietnam model has been developed from three to six transmission regions. The six regions are selected to represent the central region of Vietnam in more detail. This is where a large part of the potential for wind and solar power is located. The six regions were chosen in order to represent potential transmission bottle-necks in the system.

[5] For this setup (364 time-steps and relaxed unit commitment), computation time for one scenario for 4 years is typically 20 minutes.

Lastly, it is worth noting that Balmorel is a free of charge[6] open source model and has been adapted for Vietnam during a series of activities in the last three years. For more information about the model and examples for published studies, see: (Ea Energy Analyses, 2018). For a simplified online demonstration model, see: (Danish Energy Agency, 2018).

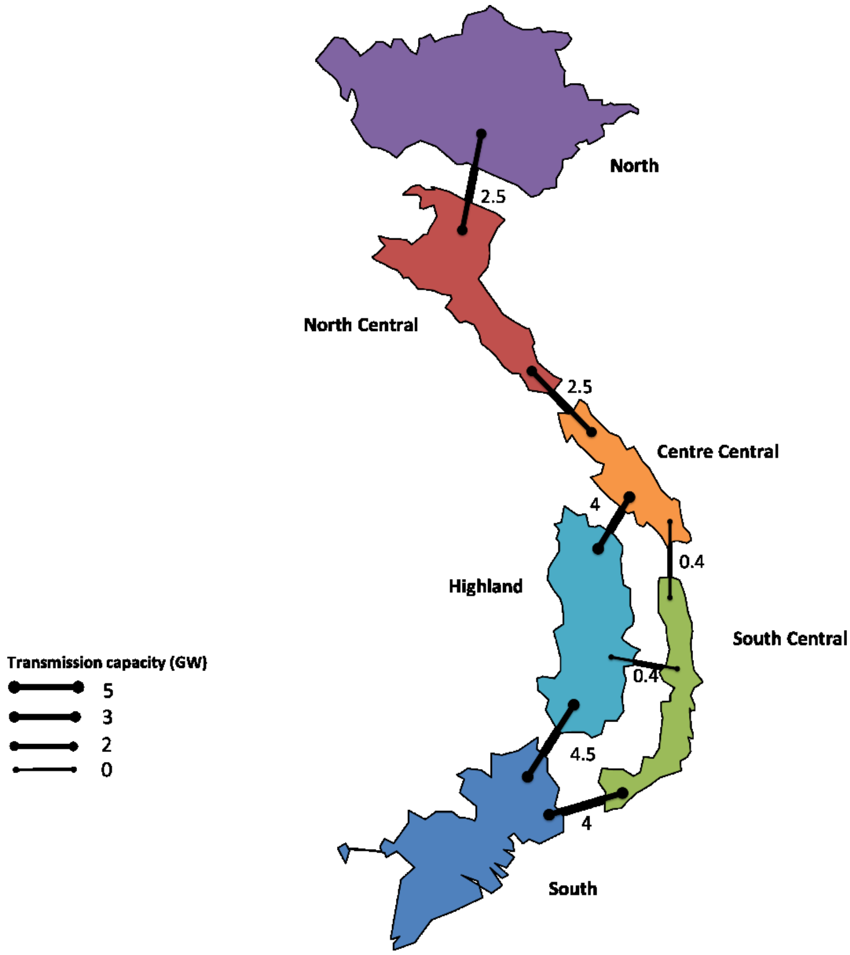


Figure 5: Transmission region and the current interconnectors in Vietnam (2018).

2.3 PSS/E

The model PSS/E[7] (Power System Simulator for Engineering) belongs to Power Technology Inc Company of Siemens Group. It is a program to simulate, analyse and optimize operational features of the power system, as well as power system planning.

[6] License for GAMS is needed in order to run the model
[7] See: https://new.siemens.com/global/en/products/energy/services/transmission-distribution-smart-grid/consulting-and-planning/pss-software/pss-e.html

The PSS/e model is widely used in Vietnam for making short-term and long-term grid planning. Its main functions in Grid Planning are Load flow, short circuit calculation, P-V curve and Q-V curve analysis, dynamic stability simulation. Additionally, N-1, N-2 criteria of the Grid can be checked by using PSS/e simulation to analyse where these criteria are violated.
The PSS/E model was first used in National Load Dispatching Center (NLDC-A0) in early 1990s. Then, Institute of Energy (under EVN at that time) used PSS/e for grid design of National Power Development Plan (PDP) 4 (1995), PDP5 (2000), PDP6 (2005), PDP7 (2010) and PDP7 Revised (2015).

Now, NLDC (A0) and its subsidiary (Regional Load Dispatching Center – A1,2,3) are using PSS/E V33-34 for making their operation planning: Weekly, Monthly and Yearly Planning. The version of PSS/E used in this study is expected to be used for Long-term Grid Planning in PDP8.

PSS/E Vietnam

A detailed model of the Vietnamese power grid has been used to test grid related assumptions in the Balmorel power system analyses. The 500kV and 220kV national power grids for the years 2020 and 2030 are represented in the model. The model has around 600 nodes and 1200 branches of lines for the system in 2030, including all plants (detailed by machines), loads, transformers, shunts, facts, branches of lines. The example of 500kV, 220kV power grid of a province can be seen in Figure 6.

In this study, the PSS/E model is harmonized with Balmorel results such as generation capacity and demand projections. For selected critical hours (snapshots) from the in the years 2020 and 2030, the Balmorel generation dispatch mix was modelled in PSS/E to compute the load flow of the power system. Over and under voltage on nodes and transmission lines was determined, in both normal operation mode (N-0) and in contingency mode (N-1) to assess breach of safe operation of the grid.

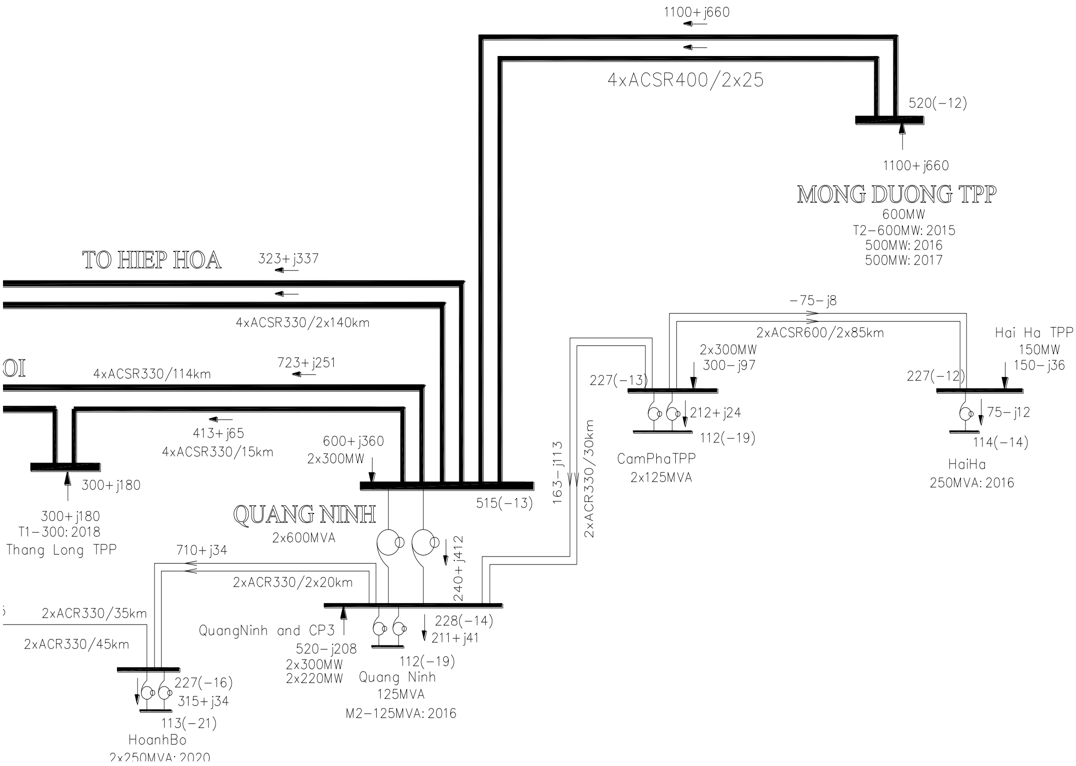


Figure 6: The 500kV and 220kV power grid of Quang Ninh province in year 2020.

2.4 Combined model setup

TIMES – Balmorel

One of the main strengths of TIMES is the broad coverage of the energy system, especially the end-use economic sectors. The power sector is simplified with three transmission regions and one demand region. Also, TIMES uses only 12 aggregated time steps per year.

Balmorel – on the other hand – only covers the electricity sector, yet at a more detailed geographical level (e.g. six regions) and temporal resolution with more time steps (364 time-steps). This higher level of detail may be important for an accurate representation of wind and solar power.

The models are combined by soft-linking. The following section describes how the linking is performed.

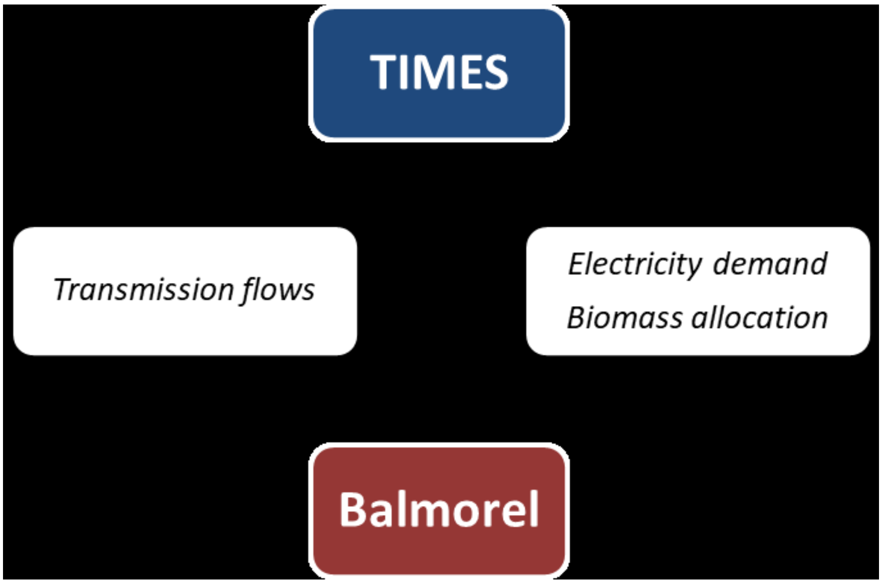


Figure 7: The interaction between TIMES and Balmorel.

In order to realise consistent and interpretable results from both the TIMES model and the Balmorel model, careful harmonization of both model's input data took place. Consistency was ensured on data assumptions such as: existing and committed power system, transmission grid, costs and characteristics of future investment options, fuel prices, wind and solar resources etc.

Linking the two models involved several iterations of model runs for calibrating results from the two models (Figure 7). These iterations are designed for best use of the two powerful tools. In general, the soft-linking from TIMES to Balmorel is performed to answer two major questions:

- How will the electricity demand develop? This includes the impact of energy efficiency, the expansion of air-conditioning, electric vehicles and the type on technology used in industry, etc.
- Which is the best use of domestic resources? E.g. biomass, domestic coal and natural gas can be used in industry, residential or in the power sector.

The TIMES model is used for optimizing across the whole energy system. Therefore, TIMES has advantages in allocating resources among sections of the system. Important results from TIMES for linking the two models are: electricity demands and allocations of resources in the power sector. In this analysis restrictions on different types of bioenergy feedstocks have been implemented in Balmorel based on the model output from TIMES.

In turn, Balmorel features *a more* detailed power sector representation, thereby providing more accurate and creditable results for power sector in terms of feasible capacity and generation.
Information on the transmission flow from generation centres to demand centres is fed back by soft-linking to the TIMES model to improve the TIMES modelling of the power sector.

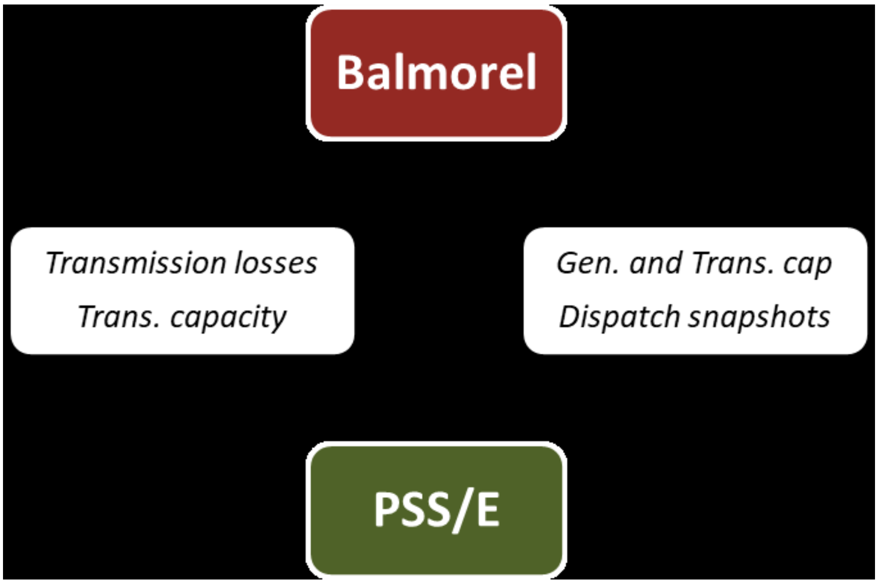


Figure 8: Data flow between Balmorel and PSS/E.

Balmorel – PSS/E

The analyses represent a static solution to a number of snapshots extracted from Balmorel. For each snapshot, the generation per plant has been exported from Balmorel to PSS/E, within which the detailed system balance was found (Figure 8).
The data supplied from Balmorel to PSS/E include the generation capacity of all power plants and transmission lines for each analysed year, i.e. 2020 and 2030, as well as the generation dispatch and transmission flow in selected snap shots, representing hours which could be critical for the grid.
Snapshots exported from Balmorel to PSS/E are as following for the year 2020:

- Maximum load
- Minimum load
- Maximum residual load
- Minimum residual load
- Maximum total transmission flow (all 7 lines summed)
- Minimum total transmission flow (all 7 lines summed)
- Maximum wind and solar generation in South Central
- Minimum wind and solar generation in South Central

Subsequently, the PSS/E model calculates the load flow of the power grid system, check the voltage and load of lines. In addition, N-1 situations are tested, thus answering the question of whether the system will sustain the most critical fault (e.g. tripping of a major line or plant).

The simulations performed with PSS/E can provide important information for the calibration of the power system in Balmorel:

- If PSS/E accepts all situations, the transmission capacities may have been too restrictive, and may be increased.
- If PSS/E indicates that the operation is not safe, as voltage cannot be secured in all parts of the transmission grid, then there are two options:
    - To add additional grid components (lines, transformers, compensators) to ensure safe operation (this is an option for future years, not for the start year)
    - To reduce the transmission capacity used in Balmorel

These new transmission capacities from PSS/E results are fed back to Balmorel to determine a new optimal dispatch. Iteration can continue until a safe operation is confirmed.

3 Data input to the TIMES and Balmorel models

This chapter briefly describes the input data for the modelling of the different scenarios. More information can be found in the two data reports for TIMES and Balmorel models, respectively (Institute of Energy, 2019) and (Ea Energy Analyses, 2019a).

The model results are heavily dependent on input data, not the least on the technology cost of the different generation technologies, fuel prices and renewable energy potentials. All these inputs are openly described in this report and the corresponding data reports. Uncertainty is associated to many of the values, e.g. the investment costs in 2030 and 2050.

3.1 Demand drivers

The primary demand drivers include GDP growth from (IE, 2015) (Figure 9), population growth from (GSO, 2016) (Figure 10), GDP per capita growth, and the number of persons per household. There are secondary drivers for each demand sector, such as the elasticity of energy use to GDP growth, industrial production projections, and market penetration rates for space cooling, refrigeration and electric appliances.

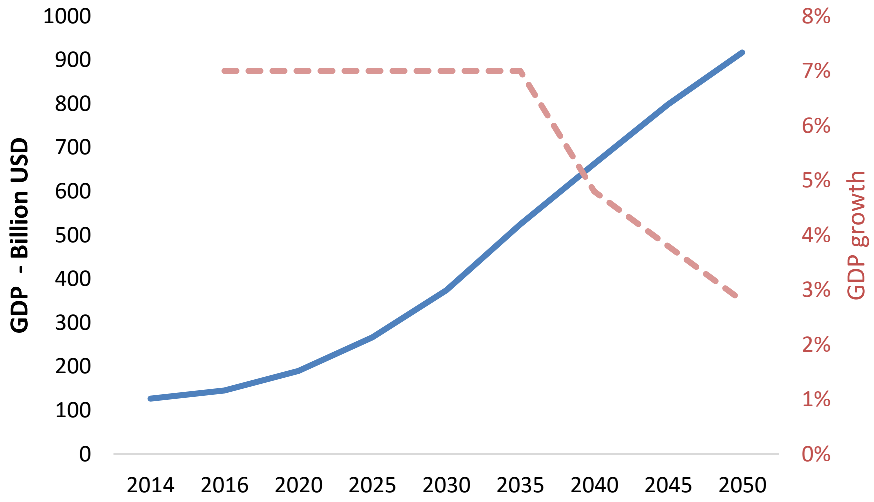


Figure 9: GDP projection for Vietnam.

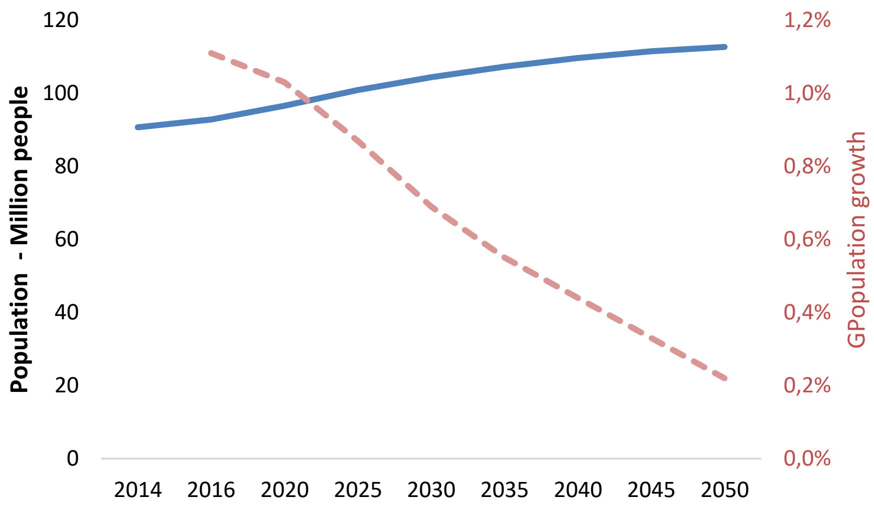


Figure 10: Population projection for Vietnam.

3.2 Electricity demand

Electricity demand is one of the outputs from the TIMES model and will be discussed in the results section. The power demand from TIMES is used as an input to the Balmorel model by means of soft-linking. The demand found in the TIMES modelling includes transmission losses (assumed 2.5%), which are subtracted when fed to Balmorel, as the latter models transmission losses per flow on the transmission lines. The division of the national demand over the 6 transmission regions is based on projections from PDP7 revised.

3.3 Future fuel prices

Fuel and electricity demand are growing quickly and a few years ago Vietnam went from being a net exporter of fuel to a net importer. The country is therefore directly exposed to international fuel prices and projections of future prices are an important input to the least-cost analyses development of the Vietnamese energy system.

Fuel prices have shown large variations in the last three decades. Figure 11 for example displays historical prices, as well as a number of International Energy Agency (IEA) price prognoses, for European steam coal. The prognoses, e.g. in 2030, vary from nearly 2.5 to 5.0 USD/GJ. The individual prognoses appear to be highly dependent on the cost of the fuel at the time the prognosis is undertaken.

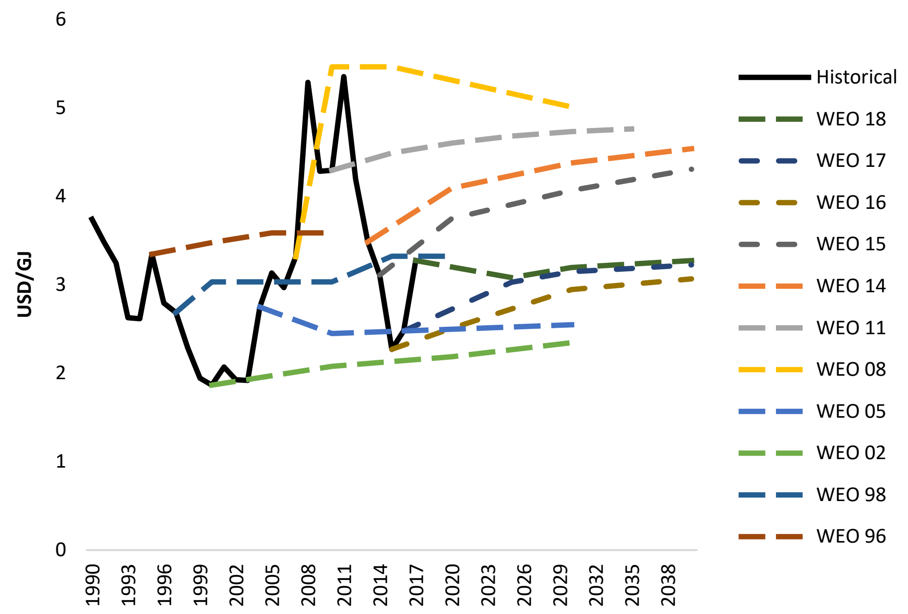


Figure 11: Historical coal prices and IEA prognoses from various years. USD₂₀₁₅ (European steam coal).

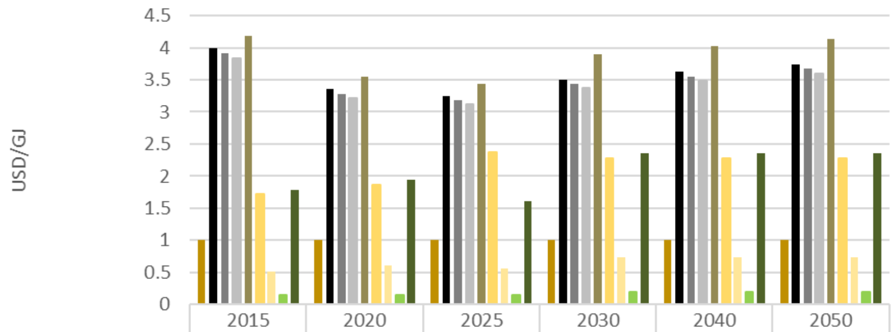
A study of fuel prices and the methodology for projection has also been undertaken, the results of which are detailed in a separate report (Ea Energy Analyses and Institute of Energy, 2019). The recommendation in the report for the Vietnamese case suggests using forward prices, e.g. (KPMG, 2018) for the short term and IEA price prognoses (IEA, 2018) for the long term. The *New policies* scenario is recommended to be the central price prognosis, while the two other scenarios can be seen as high and low-price prognoses.[8]

The prices considered in the (Ea Energy Analyses and Institute of Energy, 2019) 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[9] are added to find the fuel prices as seen by the plants.

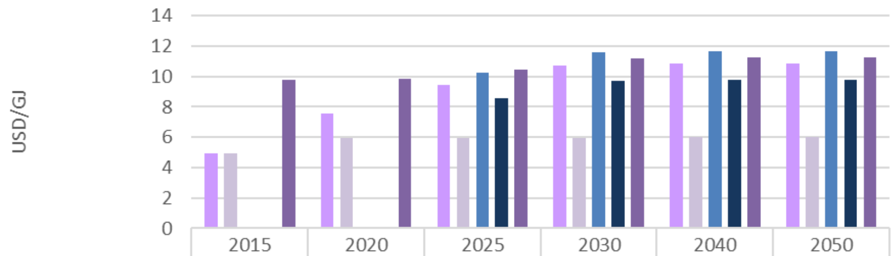
[8] In the IEA World Energy Outlook report, there are three scenarios:
- Current policy is a frozen policy scenario with no new decisions
- New policies represent a central scenario with the expected policies implemented
- Sustainable development is a more aggressive policy scenario where the global goals for CO_2 reduction (Paris scenario) will be met.

As the fuel demand is reduced in the more aggressive scenarios, the fuel price is expected to be lower.
[9] 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 Northern two regions, the Central two regions or the Southern two regions.
Add-ons for LNG: Terminal and storage fee, transportation and distribution fee, management and profit fee

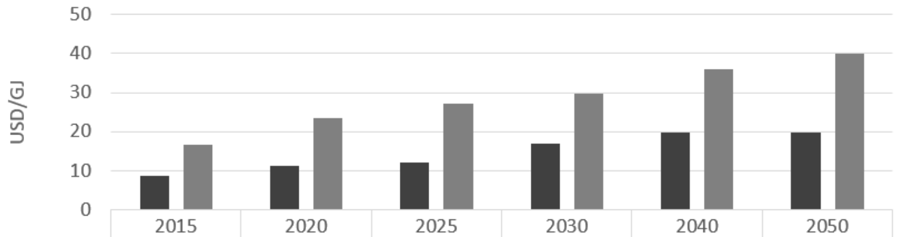
The fuel prices of all fuels, including add-ons, used in the Balmorel model are shown in Figure 12. In addition to the fuels modelled in Balmorel, other fuels included in TIMES are oil products (i.e. gasoline, kerosene, jet fuel, LPG). The prices for these fuels are indexed to the projected crude oil prices based on the existing correlation between crude oil and oil products in 2016.



	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 12: Fuel prices used in Balmorel

3.4 Investment options for power, storage and transmission capacity

Power and storage capacity

In the Vietnamese Technology Catalogue, international and Vietnamese investment costs for coal and natural gas-based generation plants, as well as wind and solar power have been compared, along with the development of expected investment costs for 2020, 2030 and 2050. For more information please see: (EREA, DEA, Institute of Energy and Ea Energy Analyses, 2019). The catalogue also contains information about hydro, biomass, biogas, waste, geothermal, diesel, pumped hydro and batteries. In addition to investment costs, operation and maintenance costs (variable and fixed O&M), technology efficiencies, as well as many other technical parameters are described.

The Technology Catalogue work has been based on Danish and Indonesian Technology catalogues and key references such as: (IRENA, 2018, b), (IEA, 2017), (IEA, 2018), (IEA, 2015), and (ASEAN, 2016).

The techno-economic information from the Vietnamese Technology Catalogue has been implemented in the modelling framework (both for Balmorel and TIMES). Additional technologies have been introduced as investment options in the model, e.g. Advanced Ultra Supercritical (AUSC) coal plants, low-power wind turbines and nuclear plants. Lastly, concrete investment options for pumped hydro have also been introduced. See: (Ea Energy Analyses, 2019a). Small differences exist between the Technology Catalogue and the Balmorel modelling investment costs, as e.g. in the model input interest during construction is added based on 10% investment cost and the lifetime of the power plant. With respect to solar PV power, land costs are also included in the investment costs (6 USD/m^2 and 12 USD/m^2 for the low and the high land costs respectively).

Table 1: Power generation technology investment options.

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 landcosts)	**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 landcosts)	**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 2: Battery investment options. The battery is a Li-ion battery. Battery investments can be optimized per MWh and per MW independently.

	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 3: Specific pumped hydro projects. Pumped hydro project can only be invested in with a fixed ratio between MWh and MW. Ratio indicated in the table per project. Efficiency is assumed 80%.

Project (Area)	CAPEX incl. IDC (kUSD/MWh)	CAPEX incl. IDC (kUSD/MW)	Maximum Turbine/Pump capacity (MW)	Maximum Reservoir capacity (MWh)	MWh/ MW
Moc Chau PSPP (North)	92	736	900	7,129	8
Phu Yen East PSPP (North)	62	930	1,200	17,518	15
Phu Yen West PSPP (North)	105	945	1,000	8,502	9
Chau Thon PSPP (North Central)	106	954	1,000	8,502	9
Don Duong PSPP (Highland)	107	963	1,200	10,479	9
Ninh Son PSPP (Highland)	98	882	1,200	10,390	9
Ham Thuan Bac PSPP (South Central)	101	909	1,200	10,390	9
Bac Ai PSPP (South Central)	97	776	1,200	10,104	8

Transmission capacity

The model is also able to optimize the transmission capacity between the different regions. The investment costs for new lines are shown in **Fejl! Henvisningskilde ikke fundet.**. The investment rate of the transmission lines is taken from the PDP7 revised [6].

Investment costs for each of the transmission line ($/MW/km) are as follows:

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

Based on the distance between regions, the investment cost is estimated in **Fejl! Henvisningskilde ikke fundet.**.

Table 4: Voltage levels, lengths and investment costs for each transmission line.

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

3.5 Investment options for end-use technologies

Investment costs for end-use devices modelled in TIMES-Vietnam are collected from various studies and energy audit reports for local factories and buildings. Data for advanced technologies, which are not available yet in Vietnam, are referred from DEA and USEPA databases.

Industrial subsectors include different end-use demands such as machine drive, process heat, facility and feedstock. These demand devices can be provided by standard and improved devices (based on their energy efficiency performance), which consume alternative fuels. Standard and improve devices feature different investment costs and efficiencies. For demonstration purpose, data for different end-use devices in iron and steel sector are presented in Table 5.

Table 5: Data for iron and steel subsector, as modelled in TIMES-Vietnam.

Process / Technology	Input Fuel	Start Year	Lifetime	Investment (US$2015M)	Fixed O&M (US$2015M)	Utilization Factor
Feedstock - Anthracite (Hard Coal - Domestic) - Standard	Coal - Domestic	2016	30	19.9	3.2	1
Machine Drive - Electricity - Standard	Electricity	2016	30	2.2	0.2	1
Facilities/Other - Electricity - Standard	Electricity	2016	30			1
Process heat - Anthracite (Hard Coal - Domestic) - Standard	Coal - Domestic	2016	30	25.7	3.3	1
Process heat - LPG - Standard	LPG	2016	30	22.0	2.9	1
Process heat - Kerosene - Standard	Kerosene	2016	30	23.3	3.0	1
Process heat - Diesel - Standard	Diesel	2016	30	23.3	3.0	1
Process heat - Fuel Oil - Standard	Fuel Oil	2016	30	24.5	3.2	1
Process heat - Natural Gas - Standard	Natural Gas	2016	30	22.0	2.9	1
Process heat - Electricity - Standard	Electricity	2016	30	23.3	3.0	1
Process heat - Cogen Heat - Standard	Cogen Heat	2016	30	22.0	2.9	1
Feedstock - Anthracite (Hard Coal - Domestic) - Improved	Coal - Domestic	2018	30	23.9	3.8	1
Machine Drive - Electricity - Improved	Electricity	2018	30	2.7	0.3	1
Facilities/Other - Electricity - Improved	Electricity	2018	30			1
Process heat - Anthracite (Hard Coal - Domestic) - Improved	Coal - Domestic	2018	30	30.8	4.0	1
Process heat - LPG - Improved	LPG	2018	30	26.4	3.4	1
Process heat - Kerosene - Improved	Kerosene	2018	30	28.0	3.6	1
Process heat - Diesel - Improved	Diesel	2018	30	28.0	3.6	1
Process heat - Fuel Oil - Improved	Fuel Oil	2018	30	29.4	3.8	1
Process heat - Natural Gas - Improved	Natural Gas	2018	30	26.4	3.4	1
Process heat - Electricity - Improved	Electricity	2018	30	27.9	3.6	1
Process heat - Cogen Heat - Improved	Cogen Heat	2018	30	26.4	3.4	1

Commercial and residential devices are classified into standard, improved and better types, according to their energy efficiency performance. These devices feature different investment costs and efficiencies. For demonstration purpose, data for household space cooling are presented in Table 6. In addition, costs for transport technologies have been now estimated in the TIMES model. These cost assumptions are used to perform a post calculation to extract the total cost of the transport sector. All technical details on demand devices modelled in TIMES-Vietnam are available in the TIMES Data Report (Institute of Energy, 2019).

Table 6: Data for household space cooling devices, as modelled in TIMES-Vietnam.

Demand Device	Activity / Capacity Units	Fuel	Start Year	Lifetime	Efficiency	Investment (US$2015M)	Fixed O&M (US$2015M)	Availability Factor
Central-Standard	PJ / PJa	Electricity	2016	15	3.81	40.61	0.85	0.15
Central-Improved	PJ / PJa	Electricity	2016	15	5.00	42.75	0.85	0.15
Central-Better	PJ / PJa	Electricity	2016	15	7.57	103.66	2.07	0.15
Room-Standard	PJ / PJa	Electricity	2016	10	3.21	50.06	0.89	0.15
Room-Improved	PJ / PJa	Electricity	2016	10	4.00	55.62	1.11	0.15
Room-Better	PJ / PJa	Electricity	2016	10	5.65	85.11	1.70	0.15

3.6 RE and domestic fuel potentials

Coal and natural gas

Vietnam has large coal resources. The utilisation is controlled by law and cannot exceed the values shown in Figure 13. Even with maximum utilisation the resource can last for the entire modelling period until 2050. Also, significant onshore natural gas resources exist (see Figure 14), however these are expected to decease after 2025. 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 has to be used for electricity generation. For the domestic coal resource the same restriction is applied to represent coal use contracts for domestic mines.

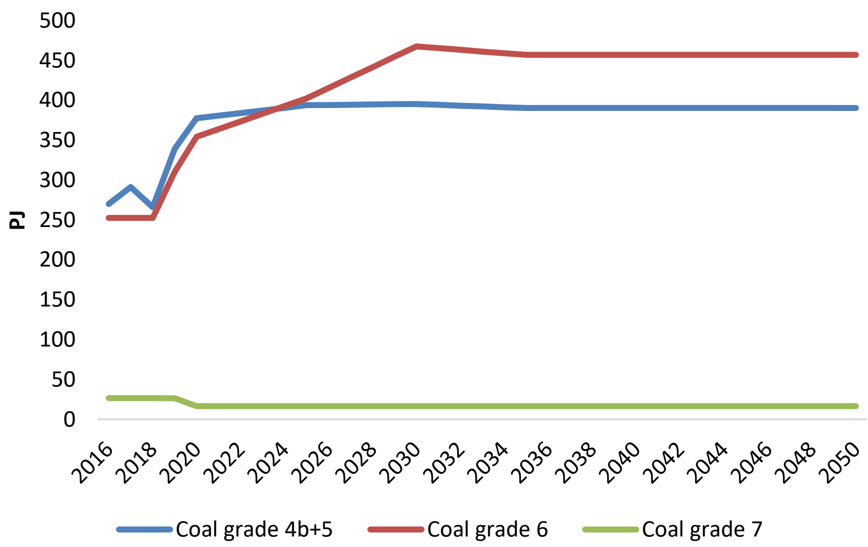


Figure 13: Maximum domestic coal use (PJ).

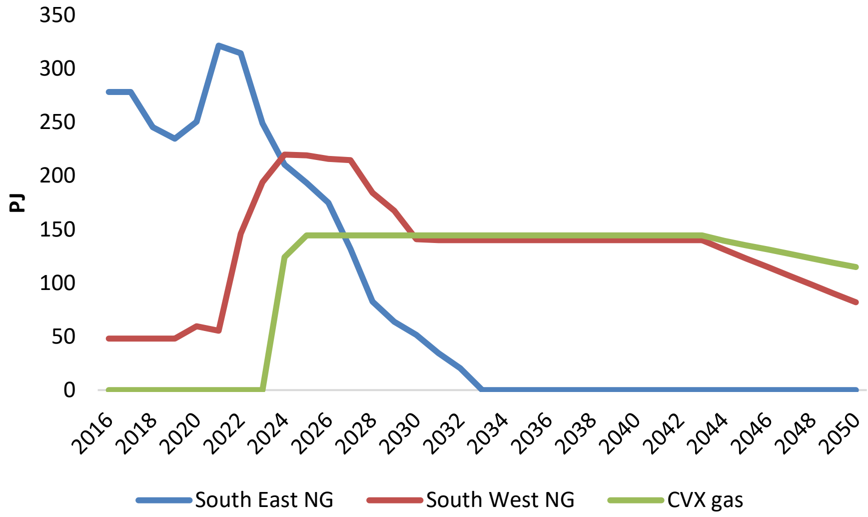


Figure 14: Maximum domestic natural gas use in South (East and West NG, PJ).

Biomass and waste

Biomass potentials for the whole energy system are estimated for the different biomass types and the different regions. Domestic biomass potentials are presented in Table 7.

Table 7: Total biomass potentials (PJ), as modelled in TIMES-Vietnam.

	2020	2030	2050
Rice Husk	99.5	111.9	120.9
Municipal Waste	64.3	69.2	90.0
Landfill Gas	0.1	7.0	11.8
Primary Solid Biofuels	366.9	458.1	526.2
Bagasse	51.5	61.4	69.2
Straw	327.8	368.7	398.4
Biogas	0.0	32.8	70.3
Other biomass	248.7	290.8	331.2

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 (Viet Nam's Renewable Energy Development Strategy up to 2020 with an Outlook to 2050, 2015), as presented in Figure 15.

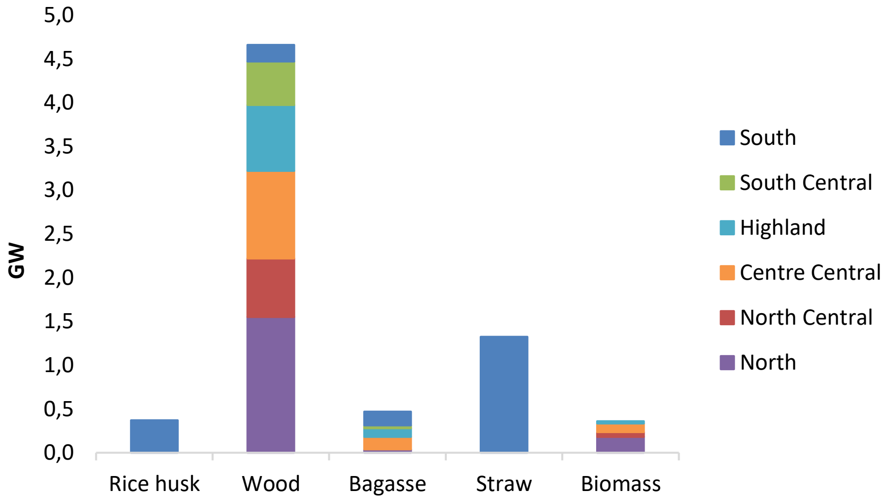


Figure 15: Resource limits on biomass-fired power generation capacity implemented in the Balmorel model.

Limitations on the availability of Municipal Solid Waste (MSW), have been implemented (Viet Nam's Renewable Energy Development Strategy up to 2020 with an Outlook to 2050, 2015), presented in Figure 16. 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.

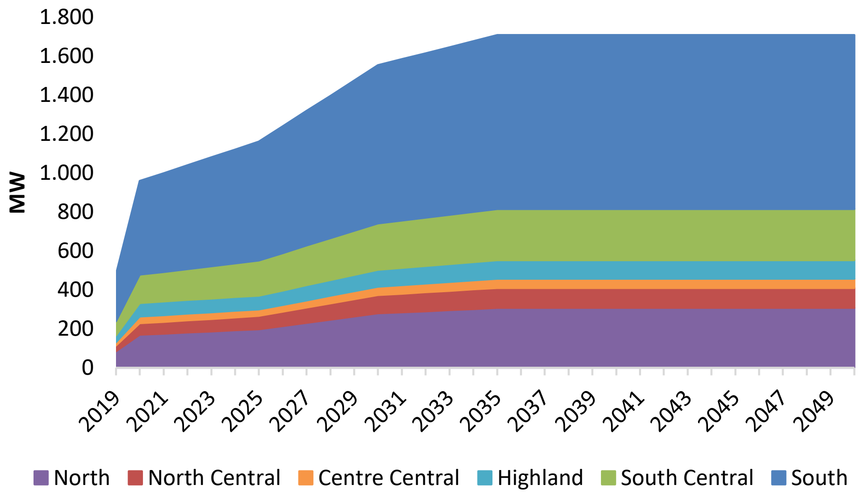


Figure 16: Resource limits on MSW-fired power plant generation capacity implemented in the Balmorel model.

Apart from capacity constraints based on official sources, annual fuel constraints for bagasse, other biomass types and MSW are inputs to the Balmorel model found from the optimization of all energy sectors in TIMES.

Onshore wind

Based on hourly wind speed data provided by Danish Technical University Department for Wind power, an hourly wind profile for a normal year has been computed for three zones for each of the six transmission regions. The three zones represent areas with low, medium and high wind speed. Also, a maximum potential per zones has been computed (MOIT, 2019) - see Figure 17.

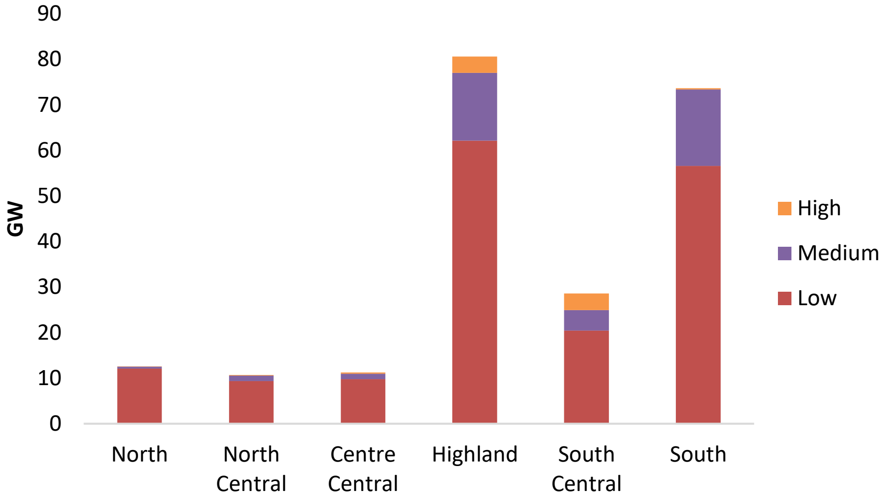


Figure 17: Resource limits on wind generation capacity per region and wind speed class implemented in the Balmorel model. Low: 4.5-5.5 m/s, Medium: 5.5-6 m/s, High: over 6 m/s (all at 80 m height).

Offshore wind

Vietnam has offshore areas relevant for offshore wind power. In this study, the offshore wind areas close to Ninh Thuan (South Central - Figure 18) have been included as 6 areas, 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 (Van Quang Doan et al., 2018). 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 and average wind speed of 10.31 m/s).

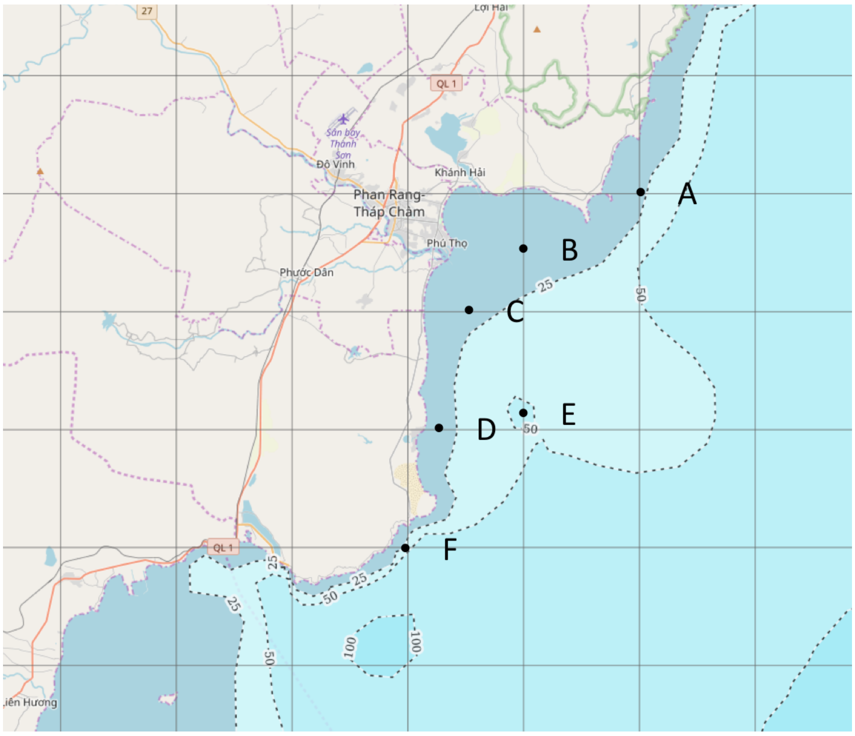


Figure 18: Offshore wind potential close to Ninh Thuan (South Central)

Solar

The southern parts of Vietnam are endowed with attractive solar resources, e.g. with full-load hours above 1,600 hours.

Solar irradiation and temperature profiles for five measurement locations are used from the World Bank solar resource mapping study (World Bank, 2018). An hourly profile for PV power production has been developed for each of the six transmission regions. For the North-Central region (only region with no measuring point for solar irradiation and temperature) the average between the North region and Centre Central region was used.

The solar potentials are based on the draft Vietnam Renewable Energy Development Plan in the period to 2035 (MOIT, 2019). A total potential of 380 GW divided on the six transmission regions is used (Figure 19). This potential is based on land use planning (national and provincial), thus considering exclusion of land use for protected areas, forestry land, agriculture, industrial zones, infrastructure, cultural sites and residential areas. Using the full potential would occupy 1.6% of the total land area. For the Southern regions, this number is higher (3.4% for South and 3.7% for Highlands and South Central). In the Northern regions less than 0.5% of land has potential for solar generation.

For half of the potential a land cost of 6 USD/m^2 is assumed. For the other half the double land cost is assumed. While the 6 USD/m^2 is a concrete evaluation of land costs for the first solar farms, more information is needed to describe land costs (and land availability) in a scenario with aggressive solar power expansion. It should be noted that land costs represent a modest fraction of the total costs, e.g. 13% and 21% with the high land costs in 2020 and 2050 respectively.

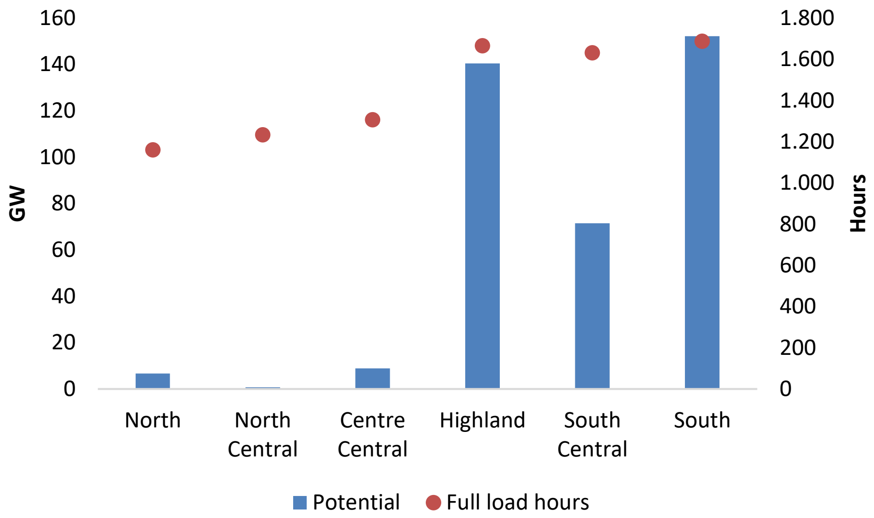


Figure 19: Solar potential and full load hours per region implemented in Balmorel.

Roof-top solar PV is currently not included as an investment option. Roof-top PV will typically have specific investment costs that are 50-100% higher than the larger plants and will therefore not be a relevant least-cost solution as long as utility scale PVs are possible. Roof-top PVs are widely used in many countries, where investments may be motivated by high feed-in tariffs or high avoided taxes for off-grid solutions.

3.7 Transmission system – Input from PSS/E modelling

For the transmission grid, input from the grid model PSS/E was used to find the current net transfer capacity (NTC) of the seven transmission lines between the 6 transmission regions (**Fejl! Henvisningskilde ikke fundet.**). These capacities are based on a detailed representation of the Vietnamese transmission grid and include N-1 considerations.

The losses on the transmission lines between regions were also calculated for the seven lines (Table 9). They are shown as percentage and were calculated at a transmission line load of 80% for each line.

PSS/E modelling of the Balmorel scenarios also resulted in feedback on the location of power plants seen from a transmission grid perspective rather than a geographical perspective. Several power plants were re-allocated to the six transmission regions based on this feedback.

Table 8: Transmission capacity between regions in 2019

		MW
North	**North Central**	2.400
North Central	**Centre Central**	4.900
Centre Central	**Highland**	4.400
	South Central	400
Highland	**South Central**	800
	South	4.600
South Central	**South**	8.500

Table 9: Losses on transmission flow between regions.

		Losses on flow
North_Central	**North**	2.3%
Center_Central	**North_Central**	3.2%
Highland	**Center_Central**	1.9%
South_Central	**Center_Central**	0.9%
South	**Highland**	1.4%
South	**South_Central**	3.0%
South_Central	**Highland**	2.1%

4 Energy scenarios

The analyses are built around three sets of scenarios for the Vietnamese energy system:

- Five core scenarios (covering all sectors)
- Green power scenarios (RE-share and CO_2 emission limit)
- Sensitivity analyses

4.1 Core scenarios

The Energy Outlook Report 2019 is planned to have a focus on five core scenarios (Figure 20):

- **C0 Unrestricted:** This scenario simulates a future without any RE targets, coal restrictions or energy efficiency measures implemented.
- **C1 RE Target:** This scenario includes an RE target on the power sector, which corresponds to the current Renewable Energy Development Strategy[10] (REDS) (Figure 21).
- **C2 No New Coal:** This scenario implements the REDS target and an additional restriction on investments in new coal-fired power plants from 2030, after which investments in coal capacity are only allowed to maintain the domestic coal capacities constant.
- **C3 Energy Efficiency:** This scenario implements the REDS target and includes high introduction of energy efficiency measures.
- **C4 Combination:** This scenario implements the REDS target, the coal restrictions from 2030 and the energy efficiency measures.

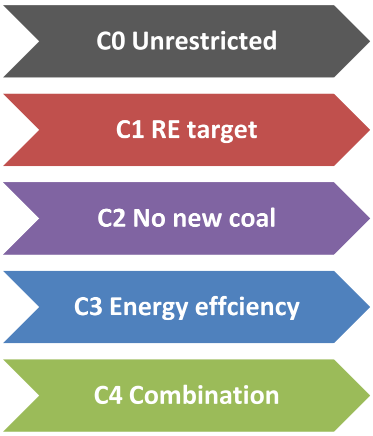


Figure 20: The five core scenarios.

[10] Prime Minister's Decision No 2068/QD-TTg dated on 25 November 2015 on approval of renewable energy development strategy to 2030, with outlook to 2050

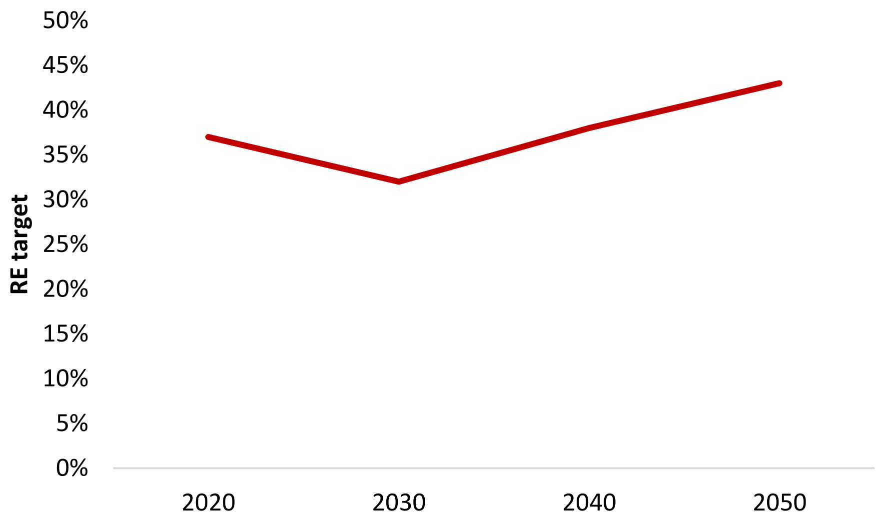


Figure 21: REDS RE target implemented in the C1 RE target, C2 No new coal, C3 Energy efficiency and C4 Combination scenarios.

All core scenarios are computed in the combined TIMES-Balmorel setup and are based on least-cost energy system development under the above mentioned constraints.

In TIMES, the scenarios are built based on the base year demands and technology stocks. All scenarios are to meet the RE targets in REDS but with different penetrations of efficient technologies and combined heat and power (CHP) applications in industries. A more detailed definition of the five core scenarios as implemented in the TIMES energy system model follows in Table 10, with focus on EE measures.

Table 10: Definition of the five core scenarios in TIMES-Vietnam.

Scenario	Service demand	Policy	Efficient technologies and CHP
C0 Unrestricted	Business as usual	No policy	Efficient demand technologies (improved and better) are not allowed in this scenario. Industrial CHP technologies are only allowed at penetration rates of 10-20% of the heat demand.
C1 RE Target	Business as usual	REDS	Efficient demand technologies (improved and better) are not included in this scenario. Industrial CHP technologies are only allowed at penetration rates of 10-20% of the heat demand.
C2 No New Coal	Business as usual	No new investments in coal after 2030 (power sector)	Efficient demand technologies (improved and better) are not included in this scenario. Industrial CHP technologies are only allowed at penetration rates of 10-20% of the heat demand.
C3 Energy Efficiency	Energy efficiency	REDS	Efficient demand technologies (improved and better) can penetrate up to 50% by 2030 and fully by 2050. Industrial CHP technologies are allowed at penetration rates of 80% of the heat demand.
C4 Combination		REDS + No new investments in coal after 2030 (power sector)	Efficient demand technologies (improved and better) can penetrate up to 50% by 2030 and fully by 2050. Industrial CHP technologies are allowed at penetration rates of 80% of the heat demand.

On the one hand, results from TIMES on annual electricity demand and domestic resource allocations to the power sector are important inputs for Balmorel in further investigations of power generation options in power sector. On the other hand, Balmorel results (i.e. power plant capacities and generation profiles) are fed back to TIMES to match the regional generation and transmission constraints.

4.2 Green power scenarios

Additional scenario analyses look into the consequences of different RE shares or CO_2 emission limits in the power sector (Figure 22). Moreover, they assess how a RE target and CO_2 limit will affect the energy system differently. For this analysis, the Balmorel model is used to compute least-cost expansion for the Vietnamese generator mix:

- **RE shares (RE)**: a set of five alternatives with varying renewable energy targets. The scenarios are set by introducing a requirement fora certain share of RE in the power system by 2050 (the scenarios range from 40% to 80% RE share in steps of 10 percentage points). For all scenarios, the target increases linearly between 2020 and 2050 to reach the required RE share in 2050 (See Figure 23).
    - The goal is defined as the share of renewable generation (incl. hydro) on the national power generation (demand minus import).
    - Because of the strong growth in electricity demand, all these goals are very demanding. The 80% goal is included as an extreme case to illustrate the challenges of the high share of (variable) renewable energy.
- **Emission limit (EL)**: a set of five alternatives where a CO_2 emission limit is introduced. The limit is equal to the CO_2 emission level resulting in the above RE share scenarios. Year by year the emission levels are observed in the renewable energy scenarios and transferred as an emission limit in the CO_2 cap scenarios, as exemplified in Figure 24.

Figure 22: Power system RE share and CO_2 cap scenarios.

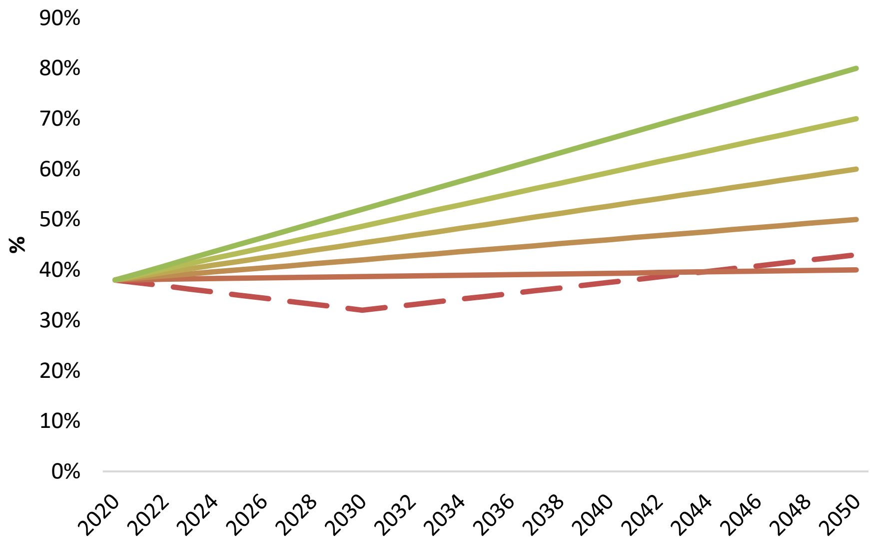


Figure 23: The current REDS goal for the share of renewable (dashed line) and the five alternative goals.

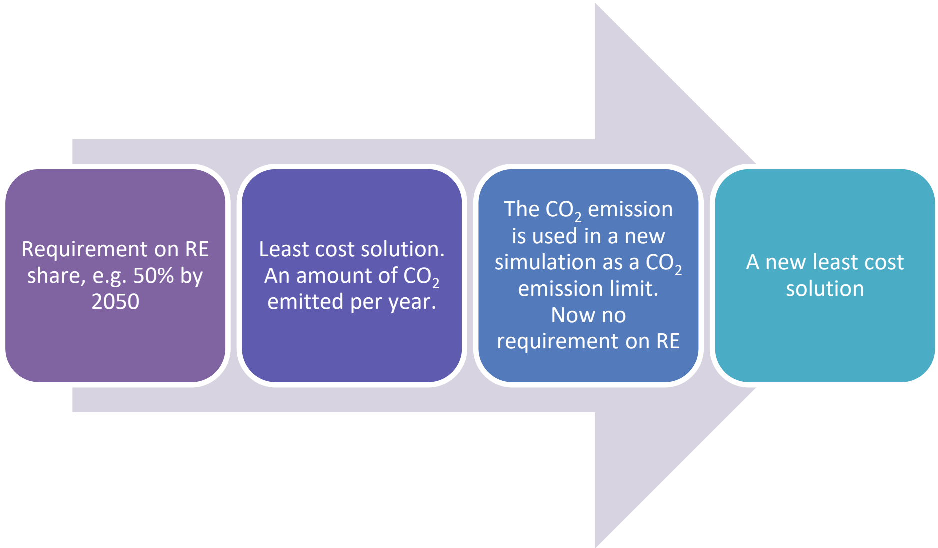


Figure 24: Result from the RE scenarios is used as input to the CO_2 cap scenarios.

5.3. Sensitivity analyses

Sensitivity analyses on some of the most uncertain input parameters are performed (Figure 25):

- Alternatives with high and low fuel prices for imported coal and natural gas. Two alternative scenarios of imported coal and LNG prices are calculated referring to the IEA scenarios. The high and low fuel price scenarios are equivalent with the Current policy scenario and the Sustainable policy scenario.
- Alternative without improvement in UC. The unit commitment of new power plants in the future will be the same with parameters in 2020.
- Alternative with more expensive investment of battery (High cost Battery): the investment cost of battery is not reduced in the future and assumed equal to that in 2020.
- Alternative with lower solar PV resources. Potential parameters of the base case in the national renewable energy development plan will be used for sensitivity analysis. In the less PV scenario, the potential of solar power is expected to fall by more than a half compared to the *C1 RE target* scenario.
- Alternative with lower output from hydro. For the *C1 RE target* scenario, hydropower parameters are calculated for normal weather years. During the dry years, it is necessary to consider the impact of reduced hydro power output on the national power generation to ensure energy supply. In Vietnam, hydropower sources are built on

many different rivers with different hydrological frequencies. According to hydrological studies of the past years, the driest years still have a hydropower production corresponding to 75% of the total output potential at national level. Therefore, hydrological parameters at 75% water frequency of hydropower plants are herein calculated to check the results of the source capacity structure.

All these scenarios are compared with the *C1 RE target* scenario.

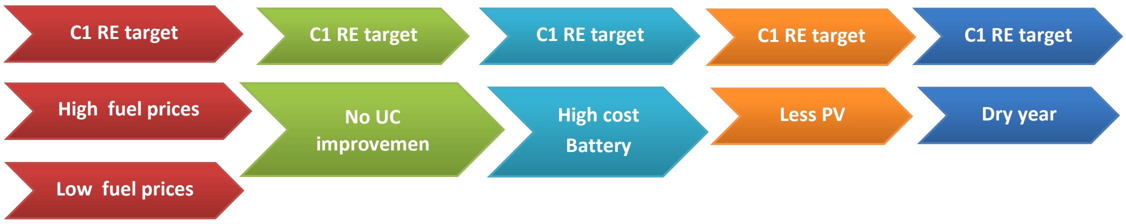


Figure 25: Sensitivity scenarios.

5 Modelling results - Core scenarios

This chapter presents the modelling results for the five core scenarios analysed in the linked modelling framework using TIMES and Balmorel. The results cover the whole energy system, from primary resource use to final energy demand in the end-use sectors, as well as illustrating disaggregated results for the power sector. The chapter will conclude by comparing the total system cost and CO_2 emissions across the core scenarios.

5.1 Resources

The total primary energy supply (TPES) increase more five times in the period 2014-2050 in the *C1 RE target* scenario, following from the assumed growth across all sectors of the economy in Vietnam, thereby increasing from 2713 PJ in 2014 to around 7600 PJ in 2030, and 14200 PJ in 2050. Energy efficiency measures implemented in the *C3 Energy efficiency* scenario help reduce the primary energy supply by 770 PJ in 2030 (10.2%) and by 3000 PJ in 2050 (21.1%) with respect to *C1-RE target* scenario. Fossil fuels still account for the largest share in both scenarios while the renewable energy (RE) share reaches about 20% of the TPES across scenarios and years. Renewable energy sources like solar and wind display increasing shares in TPES in future years. TPES in the five scenarios is shown in Figure 26.

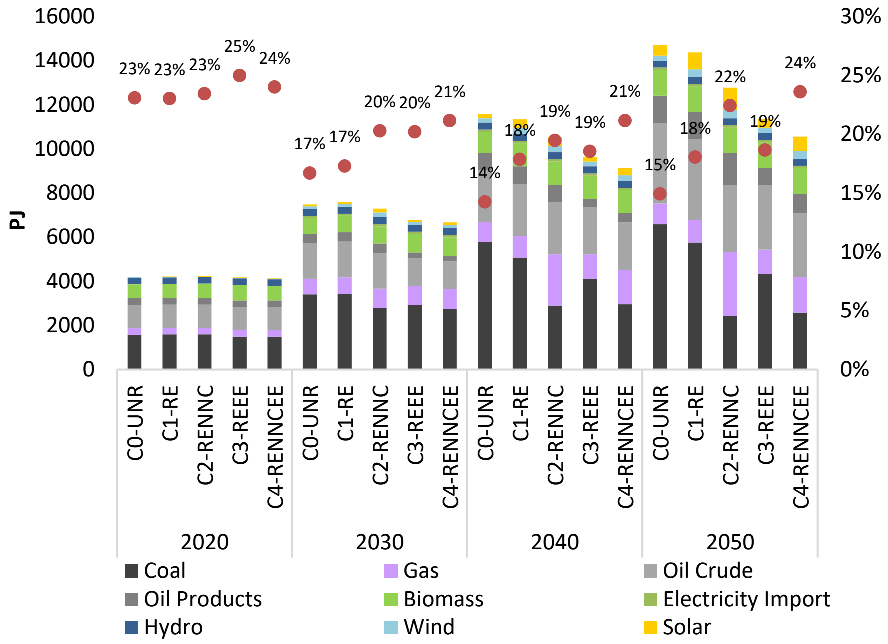


Figure 26: TPES by fuel type and RE share for the five scenarios (PJ).

With the increased trends for TPES, coal will be the main fuel followed by oil. Therefore, fossil fuels still account for the largest shares in all scenarios, while the renewable energy (RE) share accounts for about 20% of the TPES. RE share may increase over 25% in scenarios with no new coal after 2030 (i.e. *C2 No new coal* and *C4 Combination*).

Most domestic fuels are fully utilized in all scenarios (i.e. coal, natural gas, crude oil and biomass), therefore solar and wind energy, as well as imported fuels (i.e. oil, coal and LNG), will be central for supplying the demand (Figure 27). Biomass resources are allocated among power generation, industries and residential uses. The main differences across scenarios are the levels of solar, wind and imported fuels.

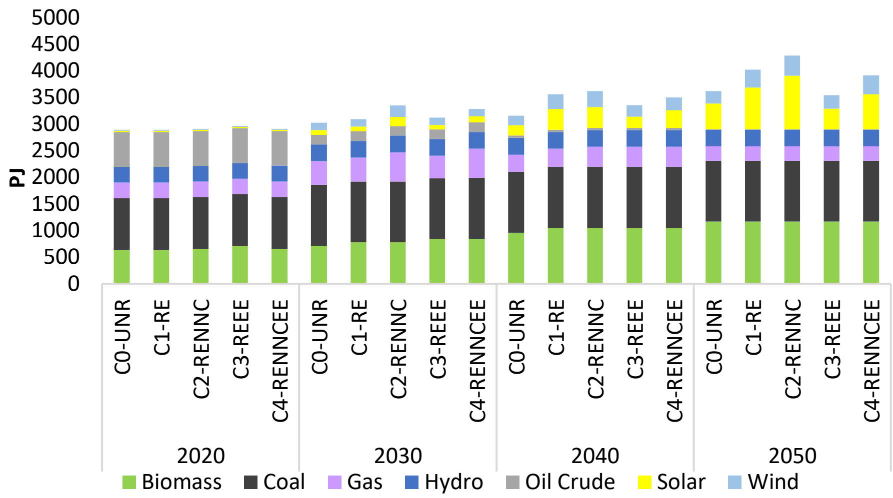


Figure 27: Domestic energy supply in the five core scenarios (PJ).

The effects of energy efficiency activities on the demand side will mainly reduce the consumption of fossil fuels like coal and oil, while the development of solar PV is also affected by the lower electricity demand in the *C3 Energy efficiency*. The differences in the primary energy supply by fuel for the two scenarios *C1-RE target* and *C3 Energy efficiency* are shown in Figure 28.

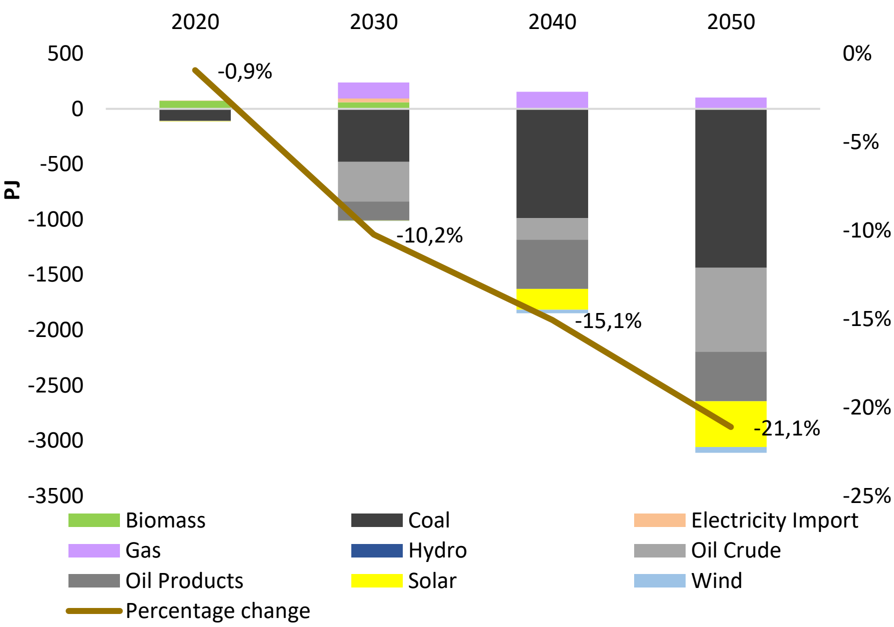


Figure 28: Differences in TPES by fuel in the scenarios C1 RE target and C3 Energy efficiency (PJ).

If no new coal-fired plants are developed after 2030, imported natural gas will be the major alternative up to 2030. After that, in the period 2030-2050, a combination of solar PV, natural gas and wind will substitute the coal use. The changes between the *C1 RE target* and *C2 No new coal* scenarios, as an effect of the restriction on coal, are shown in Figure 29.

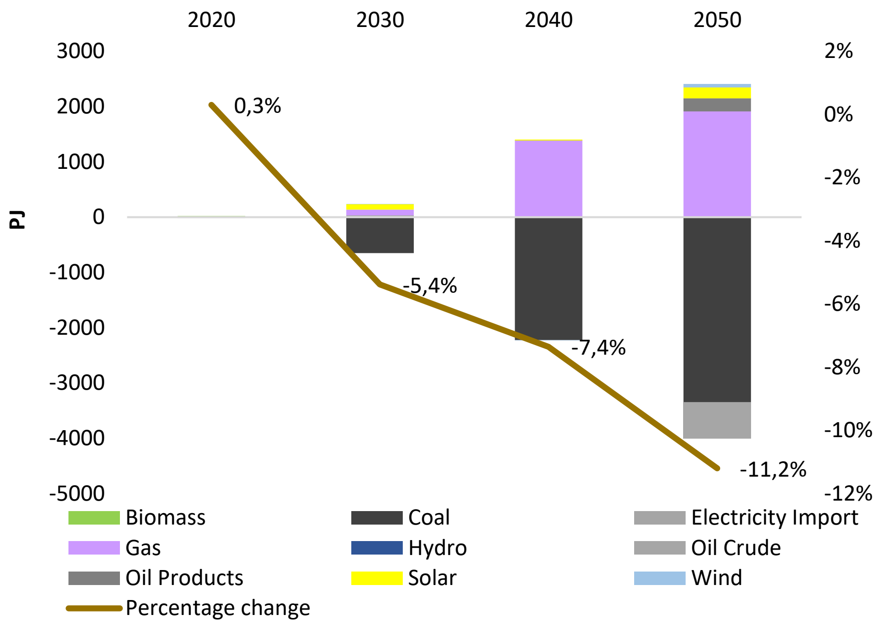


Figure 29: Difference in TPES between the C1 RE target and C2 No new coal scenarios (PJ).

Imported coal, oil and gas are needed for supplying the energy system in the coming decades. Imported coal is mainly used for power generation. Crude oil and oil products are mainly required for transport activities. Imported LNG will be valuable for industries as well as power sector especially in the no-new coal scenarios. Electricity imports are also utilized at their maximum potential. By 2020, imported fuel dependency will reach around 30% of TPES, and it will increase quickly to 51% to 61% by 2030, then to 58 to 79% in 2050 across scenarios. In the *C0 Unrestricted* scenario, imported fuels will contribute to almost 80% of TPES by 2050 with very large amount of coal. A combination of EE efforts and a no new coal policy may reduce reliance on imported fuels to 58% by 2050 with some increases in total system cost (about 3.1% by 2040 and 5.7% by 2050 when comparing *C1 RE target* with *C2 No new coal*). Trends for fuel imports are presented below in Figure 30.

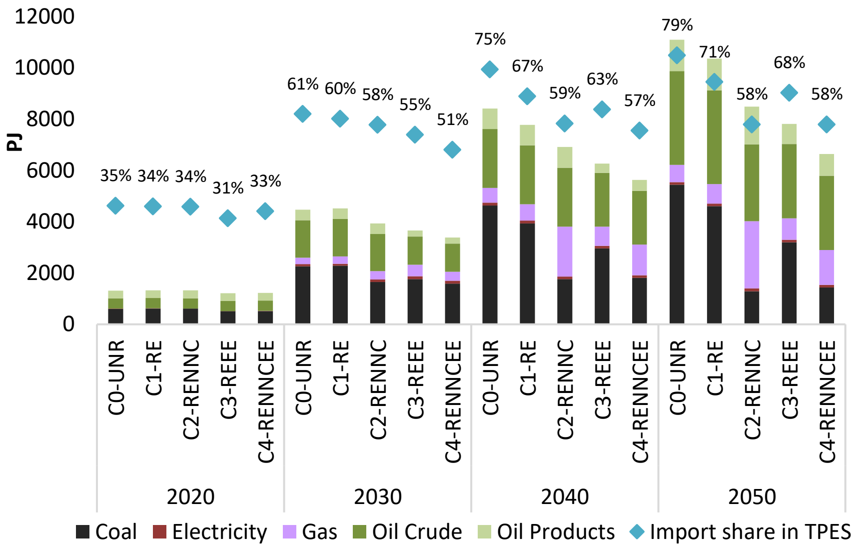


Figure 30: Fuel imports across the core scenarios (PJ).

5.2 Demand sectors

Total final energy demand

Following the trend observed for the TPES, the total final energy consumption (TFEC) will increase by 443% in the period 2014-2050, from 2261 PJ in 2014 to about 5100 PJ in 2030 and 10000 PJ in 2050 in the C1 RE target scenario. In this scenario, TFEC will increase by 6.6% p.a. in 2020-2030 and 4.4% p.a. in 2020-2050. In 2020-2030, commercial and industrial sectors have the highest growth rates of 7.4% p.a. and 7.0% p.a. respectively. For the whole period 2020-2050, the transport sector features the highest growth rate of 5.1% p.a.. In C1 RE target scenario, the industrial sector accounts for about half of TFEC, increasing to 53.7% of TFEC by 2030 and then reducing to 47.9% of TFEC by 2050. In 2030, the transport sector accounts for 20.4% of TFEC, while the residential for 17.8%, the commercial for 5.9% and agricultural for 2.2% of TFEC. The evolution of TFEC in the five analysed scenarios is presented in

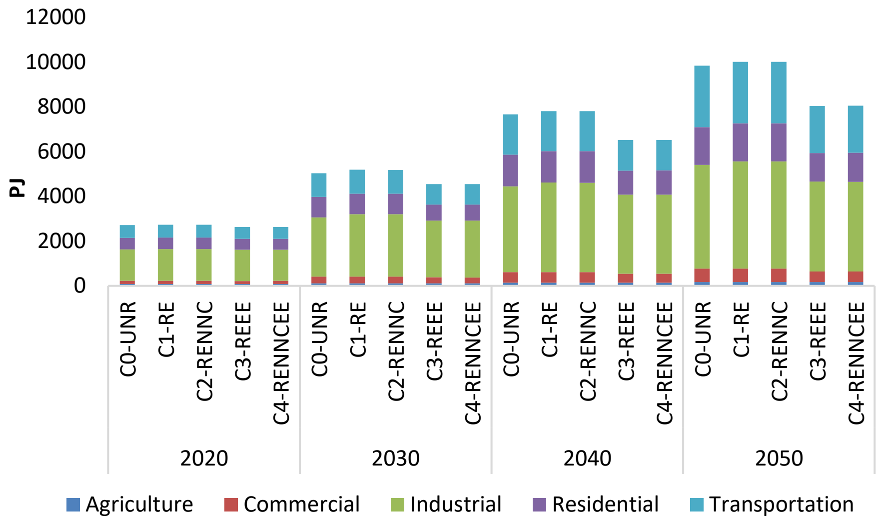


Figure 31.

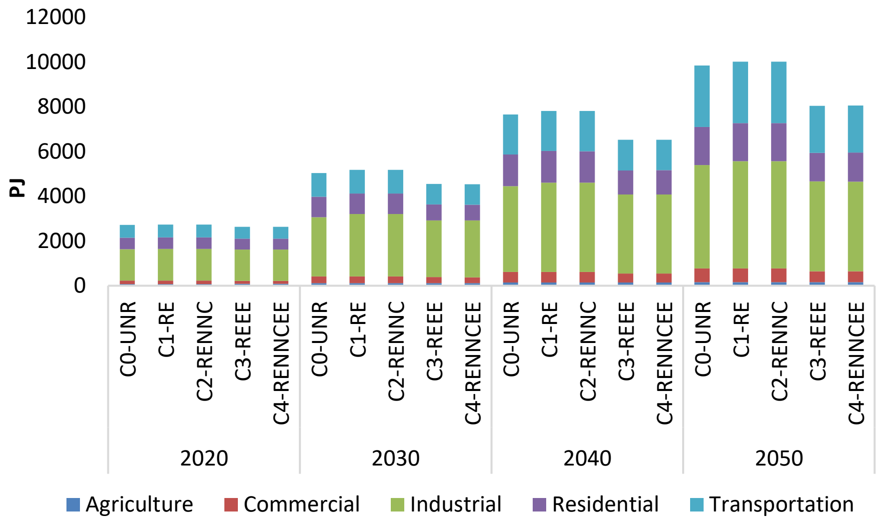


Figure 31: Final energy consumption by sector in five core scenarios (PJ).

Sectoral energy saving potential

Different sectors feature different levels of energy savings, when compared to the baseline demand. By 2030, EE measures in the *C3 Energy efficiency* scenario will reduce the final energy demand by 8.9%, 11.0%, 22.7% and 13.4% for industrial, commercial, residential and transport sectors with respect to *C1 RE target*. For comparison, Vietnam Energy Efficiency Program (VNEEP) reported saving achievements of 3.40% during 2006-2010 and 5.65% during 2011-2015. Figure 32 illustrates the energy savings by sector along the analysed time horizon.

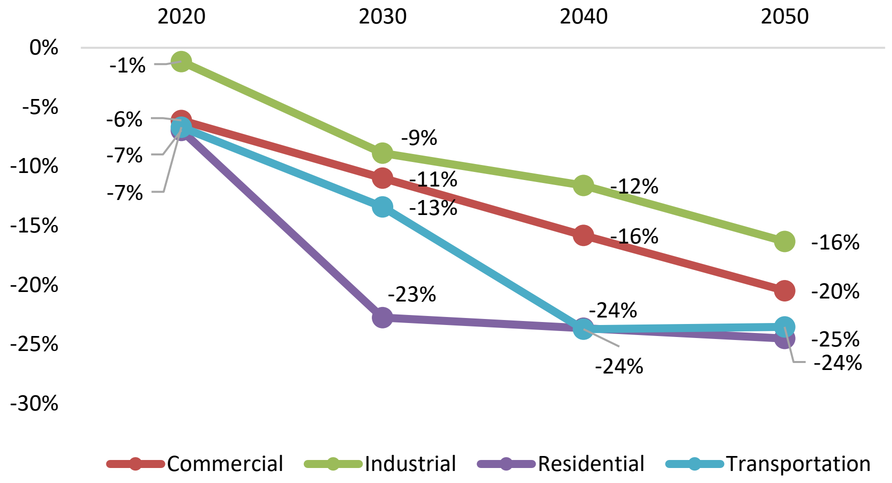


Figure 32: Energy saving by sector as a comparison of C1 RE target and C3 Energy Efficiency scenarios.

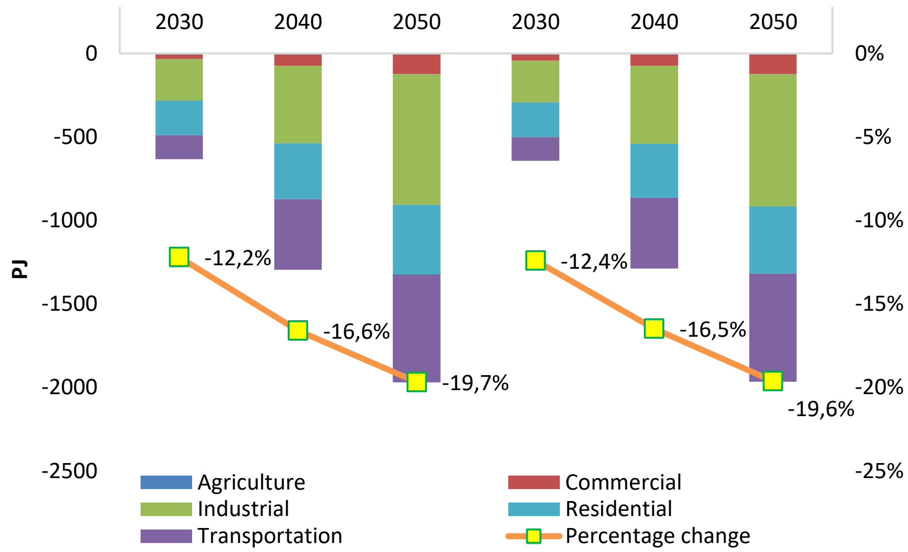


Figure 33: Differences in TFEC by sector in C3 Energy efficiency scenario (left) and C4 Combination scenario (right) with respect to C1-RE target scenario (PJ).

Figure 34 shows the economic energy saving potential in *C3 Energy efficiency* as compared to *C1 RE target* by end-use and by sector in 2030 and 2050.

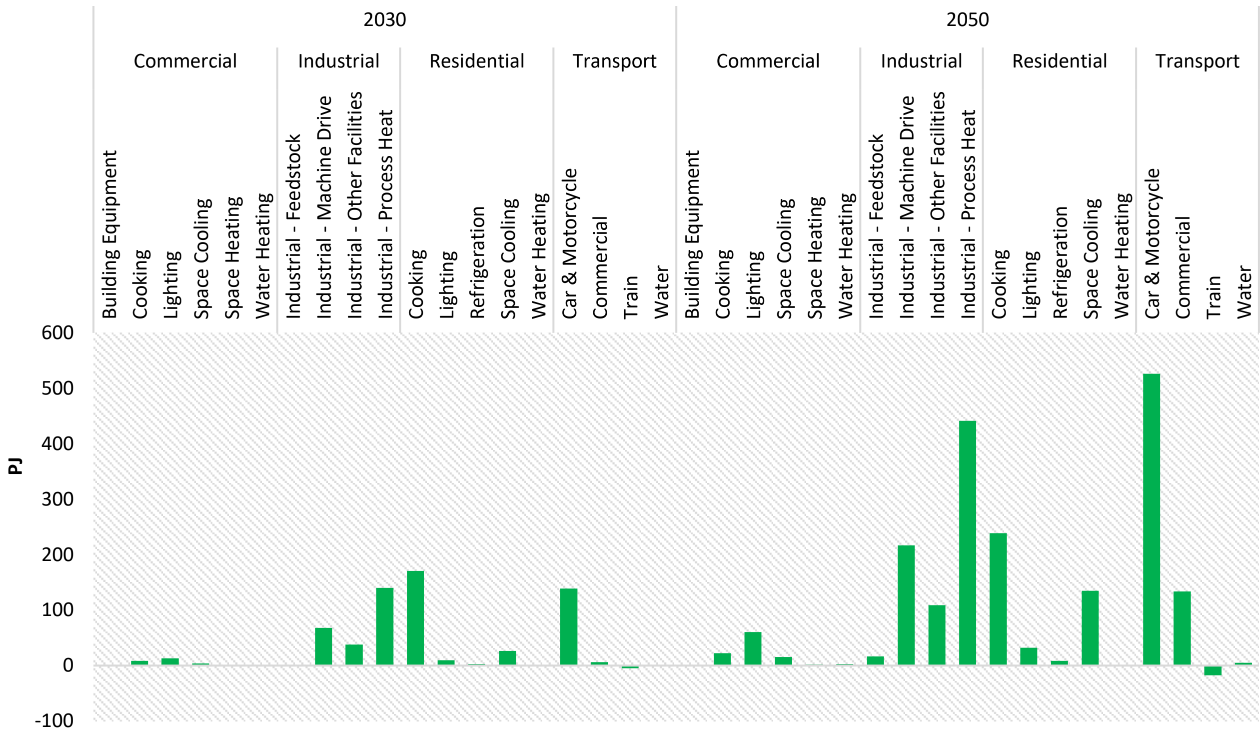


Figure 34: Economic energy saving potential by end-use and by sector.

In industrial sector, cement, iron & steel, textile and food are main subsectors for EE improvement. EE measures in heat processes contribute for 61% of the total energy saved followed by machine drive (20.5%) and facilities (18.3%). in the period to 2030, EE improvements in process heat in cement, iron & steel, pulp and paper, food and textile subsectors is the most important area for realizing energy saving potential. Efficient motors and variable speed drive (VSD) applications are also important in all subsectors, especially in iron & steel and textile, for reducing energy consumption. Additionally, efficient lighting is needed in all subsectors and should be prioritized by industrial factories. The energy saving potential by industrial subsector is presented in Figure 35.

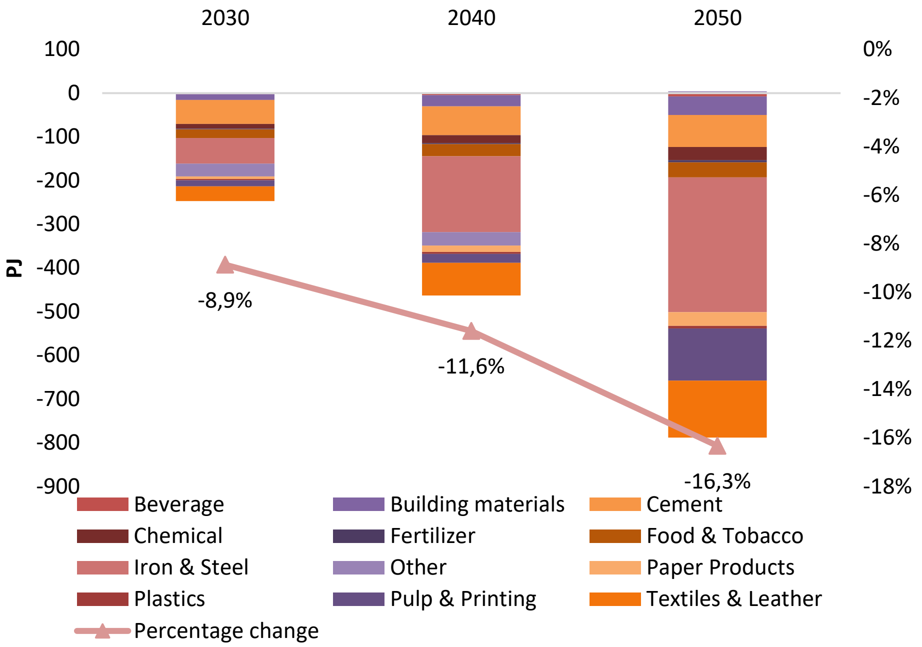


Figure 35: Energy saving potential by industrial subsector in C3 Energy efficiency scenario with respect to C1 RE target scenario.

In the residential sector, efficient cooking, space cooling and lighting are three main areas for energy improvements. Employment of efficient cook stoves and fuel switching in rural households are very important for conserving bio-mass resource uses for cooking. In addition, with the projected cooling de-mand, penetrations of efficient air conditioners play central role in reducing energy consumption in residential sector. The energy saving potential by resi-dential end-use is presented in Figure 36.

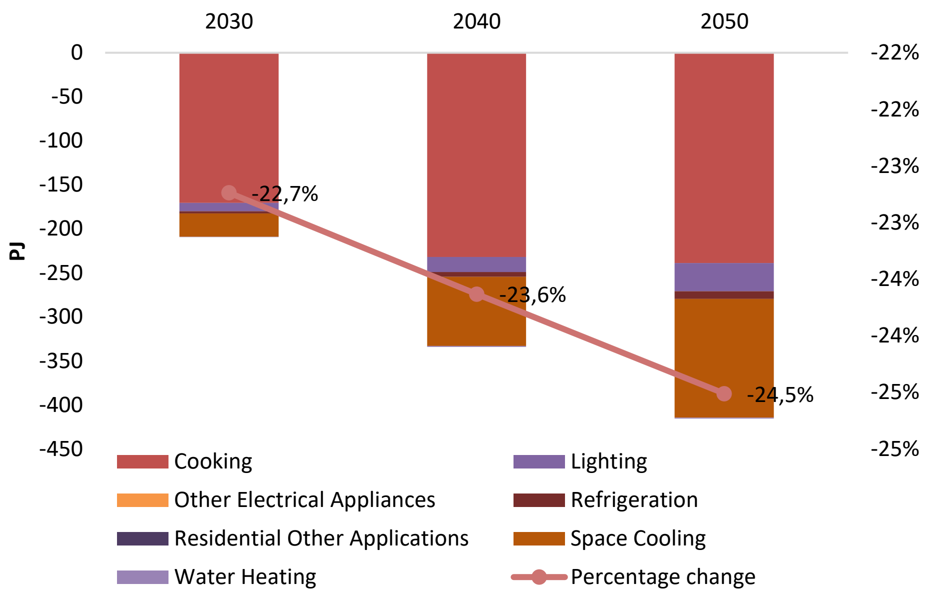


Figure 36: Energy saving potential by residential end-use in C3 Energy efficiency scenario with respect to C1 RE target scenario.

In the commercial sector, lighting is the main area for energy efficiency improvements with employment of efficient lighting devices. Space cooling is also main area for energy saving in commercial sector with installation of efficient air conditioners (Figure 37).

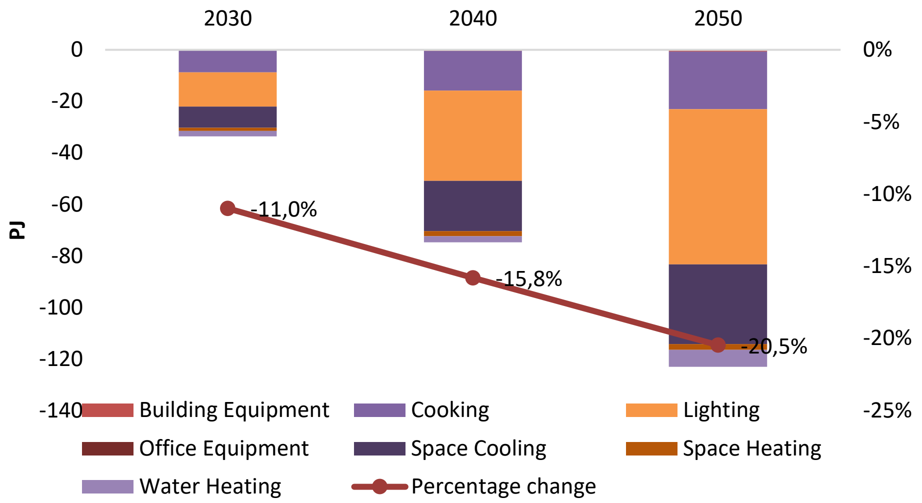


Figure 37: Energy saving potential by commercial end-use in C3 Energy efficiency scenario with respect to C1 RE target scenario.

In the transport sector road transport is the main area for energy efficiency improvement with significant contributions from car, motorbike and other commercial vehicles (bus and truck) mainly due to introductions of higher fuel economy standards. Detailed measures for transport sector are as below (GIZ, 2018):

- Higher fuel economy standards;
- Modal shift from private to public transport (bus, bus rapid transit, metro);
- Modal shift from road to waterway and railway;
- Gasoline E10 is used in 2025;
- Electric vehicle: electric two-wheeler accounts for 30% of 2W fleet in 2030, electric car for 33% in 2030, electric bus introduced from 2025 in Hanoi and Ho Chi Minh City;
- 10% new electric bus sales in period 2020-2030;
- Load factor improves from 56% to 65%.

EE activities reduce electricity generation requirements for centralized power plants by reducing electricity demand and increasing electricity generation from decentralized power sources (decentralized PV solar and industrial CHPs). EE activities in the C3 scenario may save total centralized electricity generation by 9.8% in 2030 and 28.6% in 2050 with respect to C1 scenario.

Decentralized sources may generate up to 2.9% in 2030 and 8.6% in 2050 of the total electricity demand in the C3 scenario. Biomass and natural gas CHP applications become economically attractive in industries by providing both electricity and low-temperature heat (LTH) for industrial uses. Figure 38 depicts the effects of EE activities and CHP applications on electricity demand and electricity generation requirements.

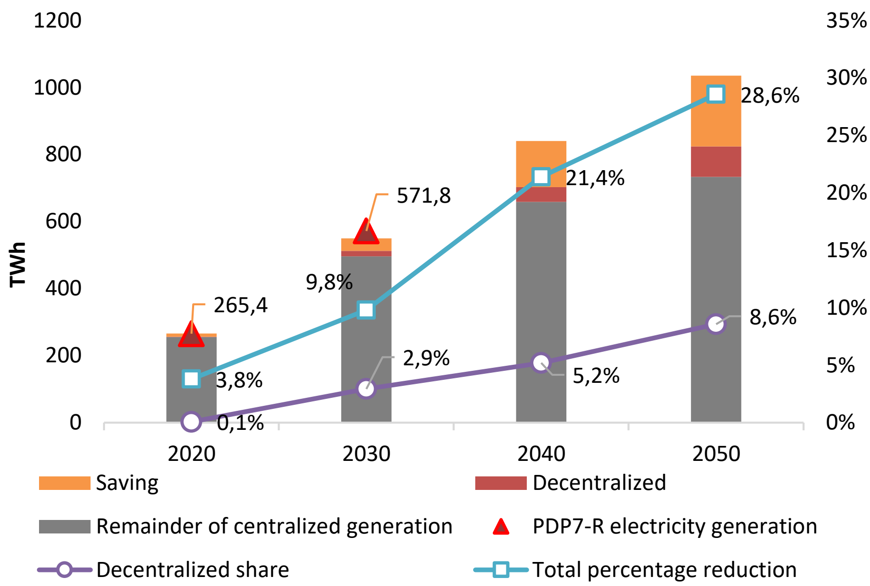


Figure 38: Effects of EE measures and industrial CHPs in C3-REEE scenario with respect to C1-RE scenario. "Decentralized" consists of approximately 80% industrial CHPs and 20% decentralised solar PVs.

5.3 System costs and emissions

The total system cost can be broken down into investment cost, fixed operation and maintenance (O&M) cost, variable O&M cost and fuel cost. Differences in annual discounted costs for the whole system (supply and demand) by cost type for the five core scenarios are presented below in Figure 39.

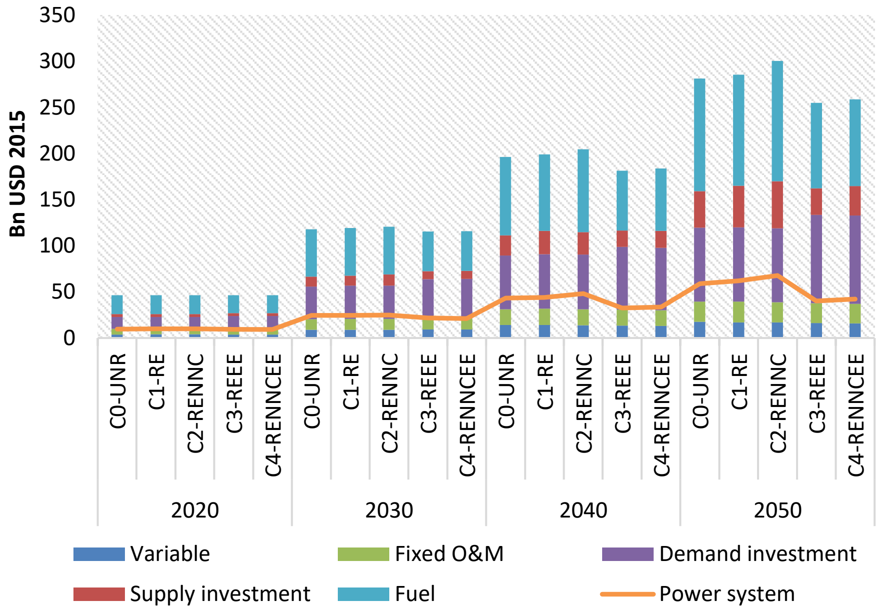


Figure 39: Annual discounted system costs by cost type in five scenarios.

The *C3 Energy efficiency* scenario assumes high penetration levels of EE technologies, which allow for all economic energy saving potential to be realized (penetration rates about 50% by 2030 and 100% by 2050). This scenario is also featured with an increased application of industrial biomass and gas CHPs. The EE measures introduced in the *C3 Energy efficiency* scenario can save system costs annually from 3% to 10.6% in the period 2030-2050 with respect to *C1 RE target* scenario. Even though additional investment occurs for EE technologies, a large amount of fuel costs can be saved, thus resulting in an overall reduction of the total system cost. Figure 40 presents the effects of EE measures on system cost by cost type in the *C3 Energy efficiency* scenario, as compared to the *C1 RE target* scenario.

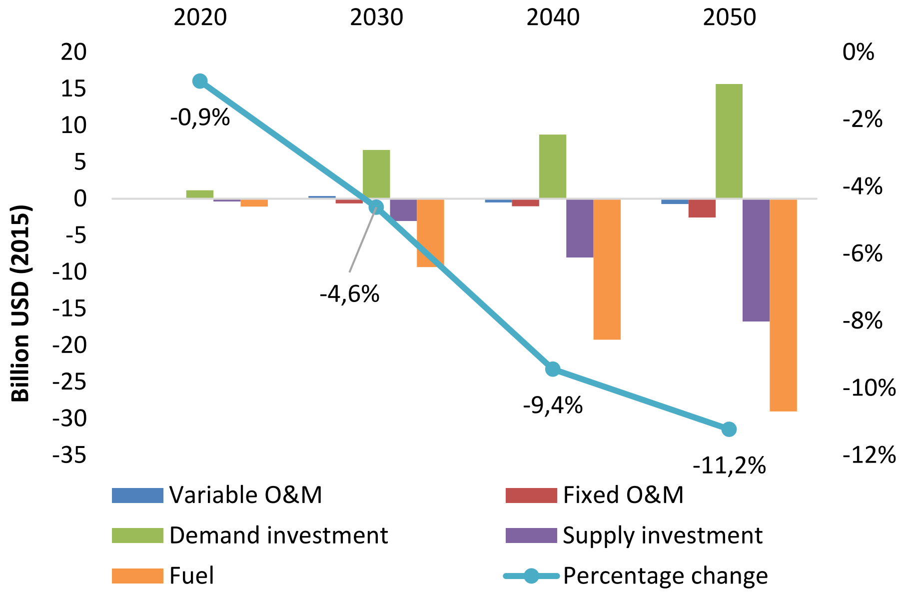


Figure 40: Changes in annual discounted system cost in C3 Energy efficiency compared to C1 RE target.

In the *C1 RE target* scenario, CO_2 emissions from the energy sector are increasing quickly at 7.4% p.a. in 2020-2030 and 4.4% p.a. in the whole period of 2020-2050. Power generation is the main contributor for the increased CO_2 emissions followed by industrial and transport sectors. Figure 41 reports the trends for CO_2 emissions from the energy sector across the analysed scenarios.

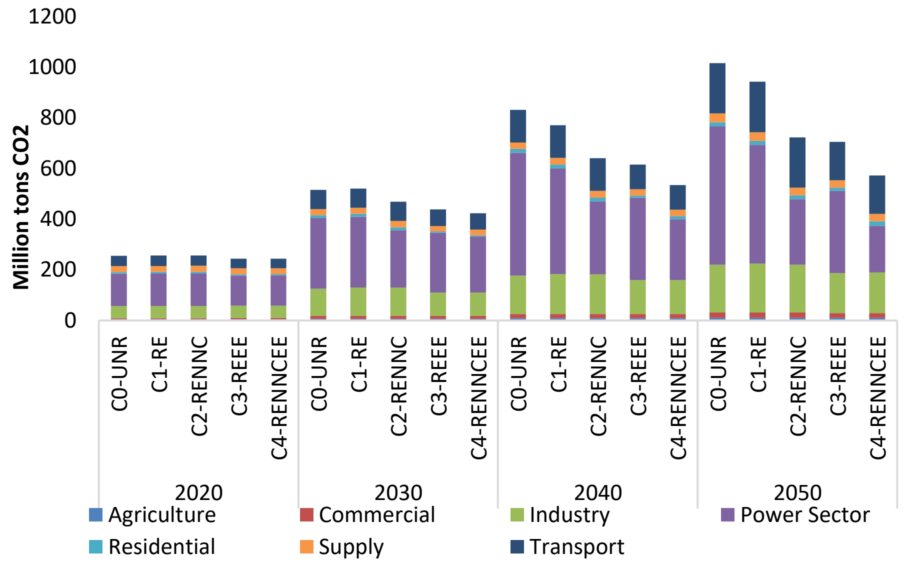


Figure 41: Trends for CO_2 emissions by sector in all five scenarios.

Coal use contributes from 65% to 75% of total CO_2 emissions from the whole energy system in different scenarios. Annual CO_2 emissions in the *C0 Unrestricted* scenario are 5% to 10% higher in 2020-2030, and 20% to 30% higher in 2040-2050, as compared to the *C1 RE target* scenario. This implies the necessity for fulfilling the RE targets as set out in REDS for reducing GHG emissions in the energy system.

In the *C3 Energy efficiency* scenario, EE measures can reduce the CO_2 emission growth rate in 2020-2050 from 4.4% p.a. in *C1 RE target* scenario to 3.6% p.a.. CO_2 emission reductions are mainly obtained in the power and transport sector. Figure 42 shows the CO_2 emission reduction by sector achieved in the *C3 Energy efficiency* scenario with respect to the *C1 RE target* scenario.

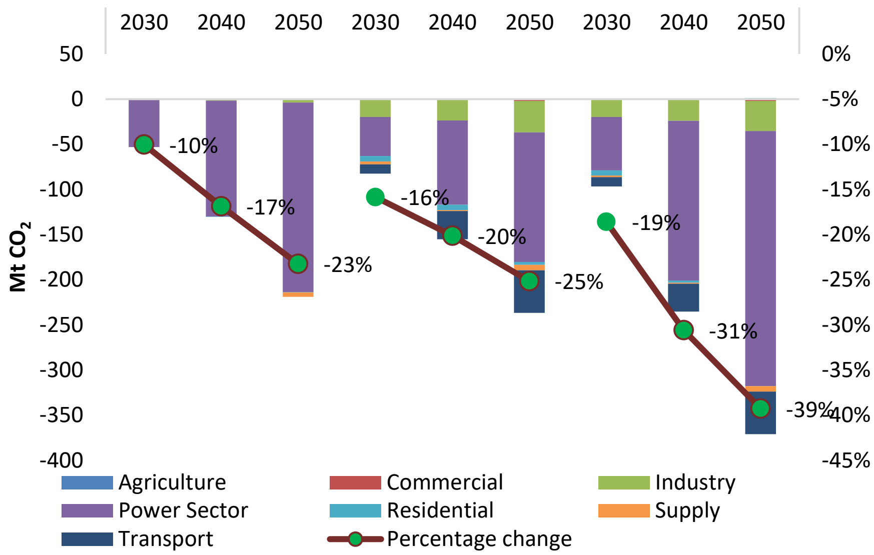


Figure 42: CO_2 emission reduction by sector in C3 Energy efficiency scenario (left) and C4 Combination scenario (right) with respect to C1 RE target scenario.

In the draft updated BAU by MONRE (GIZ, 2018), the total GHG emissions from the energy sector equal 643 $MtCO_2eq$. By 2030, CO_2 emissions in *C1 RE target* and *C3 Energy efficiency* scenarios are 521 and 443 $MtCO_2$. As compared to the MONRE's BAU emissions, CO_2 emission reductions with REDS's RE targets can fulfill the unconditional target of 8%. Moreover, the RE target and the additional EE efforts in *C3 Energy efficiency* can fulfill the conditional target of 25%. Table 11 compares the emissions across scenarios with the NDC targets.

Table 11: CO_2 emissions in the scenarios in comparison with NDC-BAU and mitigation scenarios.

Scenario	Emissions in 2030 (Mt)	Reduction compared to NDC-BAU (Mt)	Percentage reduction compared to NDC-BAU (%)
C1 RE target	520	123	19%
C2 No new coal	468	175	27%
C3 Energy efficiency	438	205	32%
C4 Combination	424	219	34%
NDC-BAU	643	0	0%
NDC-Unconditional 8%	592	51	8%
NDC-Conditional 25%	482	161	25%

5.4 Detailed results for the power sector

Based on the electricity demand and the biomass allocation to the power sector from TIMES, detailed analyses have been performed with Balmorel for the power sector. This is done with more details (i.e. 6 regions, 6 demand profiles, 18 wind speed profiles, 6 solar profiles, and 364 time-steps) and the results reflect to a higher degree the challenges with the variable generation, e.g. from wind and solar power.

Figure 43 shows the generation capacity for the five core scenarios. In all scenarios (also the *C0 Unrestricted* scenario), large investments in solar, wind and batteries take place, indicating that these technologies represent the socio-economic least-cost solution for the expansion of the generation capacity.

The annual generation is shown in Figure 44. In 2050, 43% of the generation comes from renewable sources in the *C1 RE target* scenario, hereof 23% solar, 9% hydro, 7% onshore and 3% offshore wind. The remaining generation is mostly domestic and imported coal-based. In the *C0 Unrestricted* scenario, only 37% of the generation is renewable. The *C2 No new coal* scenario has a higher RE share of 50% and high shares of LNG generation coming in after 2030 (up to 32% by 2050). In the *C4 Combination* scenario the RE share is even higher (59%) due to the lower power demand by energy efficiency.

The regional generation shown in Figure 45 (*C1 RE target*) shows that most of the generation takes place in the North and the South regions, which are the largest demand centres. Northern generation is mainly coal-based, complemented with hydro and small shares of biomass generation. Southern generation sees more wind, solar and natural gas generation.

From 2030, investments in batteries appear in the power system. Although pumped hydro is also an investment option, batteries are a more attractive investment option when considering balancing investment costs and efficiency results. In the *C1 RE target* scenario, 68 GW of batteries are installed in 2050 (Table 12). The batteries have a relatively small storage capacity (MWh) compared to the charging/generating capacity (MW): 1.5-3.5 MWh/MW. This factor is optimised by the model.

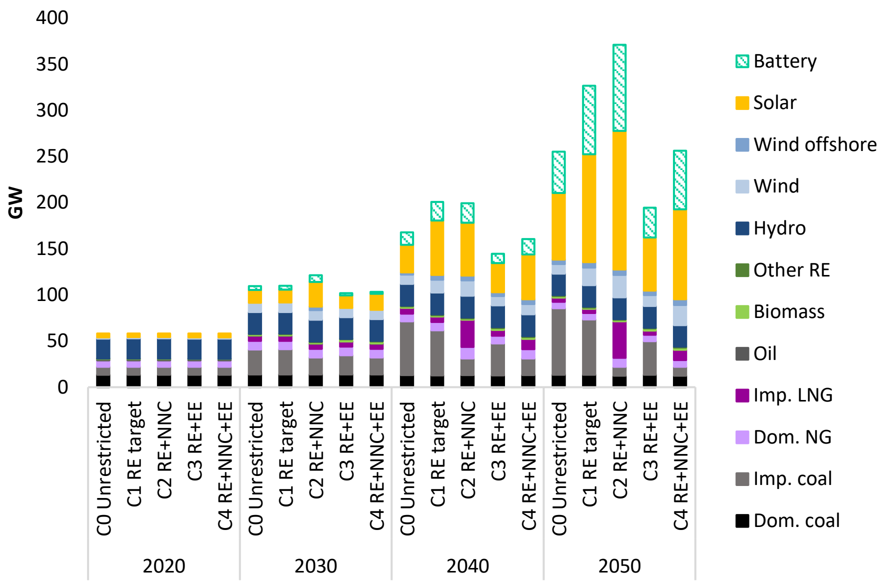


Figure 43: Generation capacity power sector in the five core scenarios.

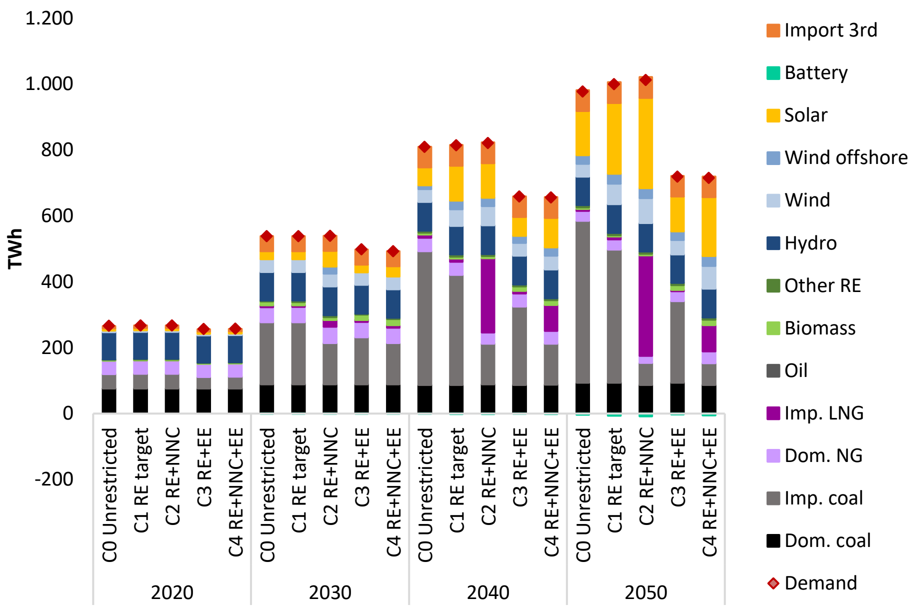


Figure 44: Annual electricity generation, import from 3rd countries and power demand (including transmission and distribution losses) in the five core scenarios. Negative values for batteries represent the loss in the batteries.

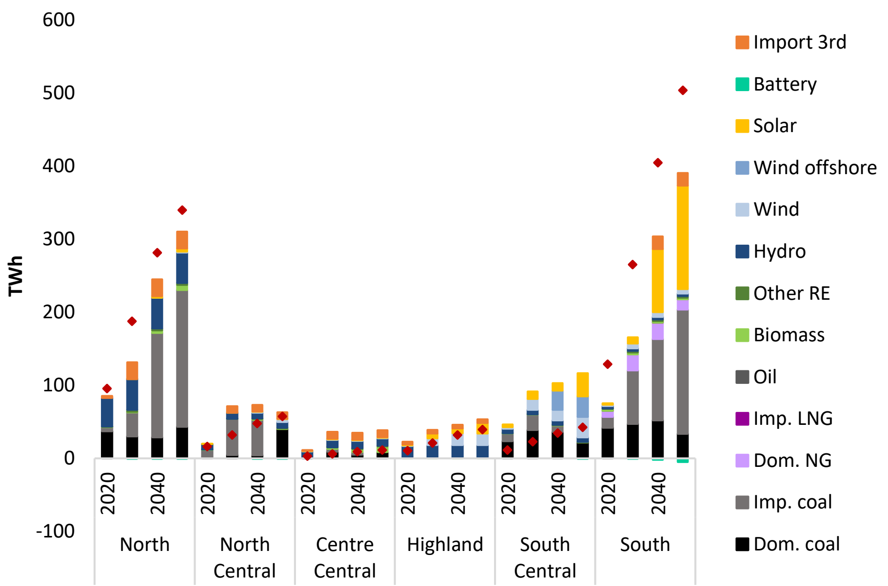


Figure 45: Annual electricity generation, import from 3rd countries and power demand (including transmission and distribution losses) per region for the C1 RE Target scenario. Negative values for batteries represent the loss in the batteries.

Table 12: Battery capacities in the five core scenarios.

Year	CaseName	Charging and generation capacity (GW)	Storage capacity (GWh)	GWh/GW
2030	**C0 Unrestricted**	4	7	1.68
	C1 RE target	4	7	1.68
	C2 No new coal	7	12	1.68
	C3 Energy efficiency	3	4	1.68
	C4 Combination	2	3	1.68
2040	**C0 Unrestricted**	13	22	1.68
	C1 RE target	20	44	2.20
	C2 No new coal	21	46	2.17
	C3 Energy efficiency	10	17	1.68
	C4 Combination	16	32	1.97
2050	**C0 Unrestricted**	45	116	2.59
	C1 RE target	74	205	2.77
	C2 No new coal	93	270	2.90
	C3 Energy efficiency	32	73	2.27
	C4 Combination	63	170	2.68

Figure 46 shows the CO_2 emissions in the five core scenarios. The *C1 RE target* scenario has an emission level that is 14% lower in compared to the *C0 Unrestricted* scenario in 2050. In the *C2 No new coal* and the *C4 Combination* scenarios the emissions are 47% and 34% of the *C0 Unrestricted* scenario respectively. However, the system costs are also the highest in the *C2 No new coal* scenario with about 15% increase compared to the *C0 Unrestricted* scenario in 2050 (Figure 47). The *C1 RE target* has a cost increase of 6% compared to *C0 Unrestricted.* The energy efficiency scenarios have lower total costs for the power sector as the demand which needs to be supplied is lower.

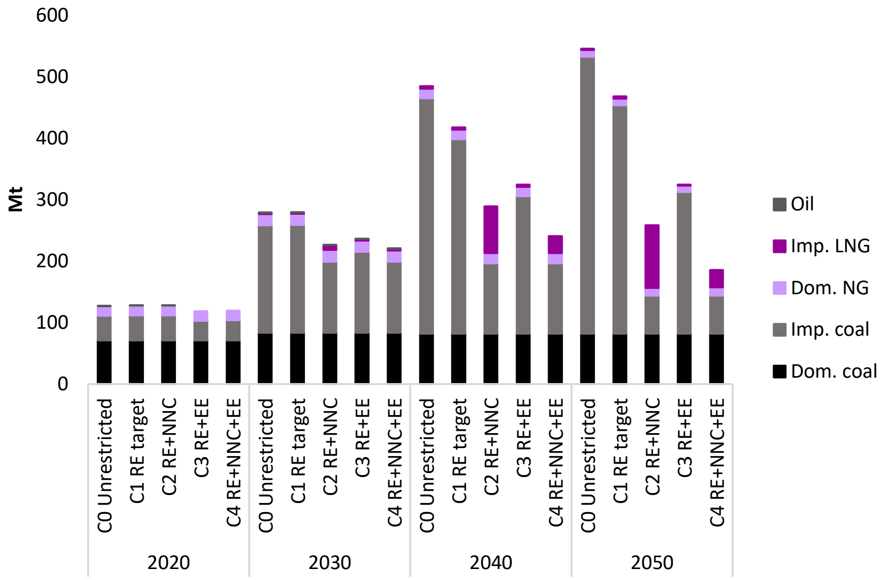


Figure 46: CO_2 emissions from the power sector in the five core scenarios.

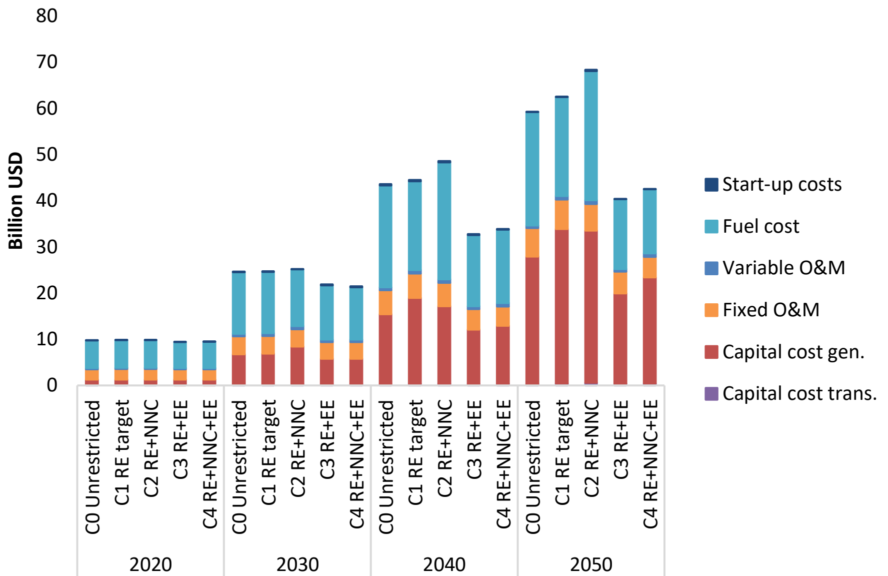
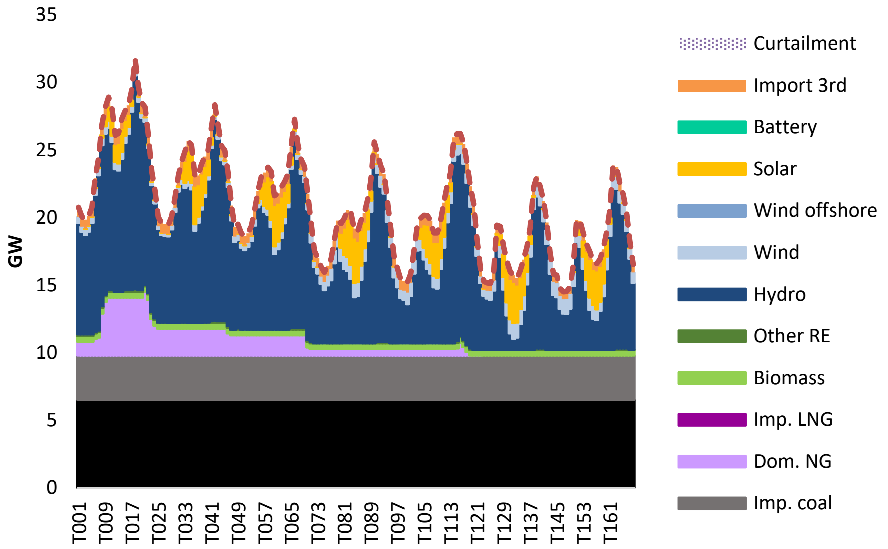


Figure 47: System costs for the power sector in the five core scenarios.

Figure 48 and Figure 49 show examples of the hourly dispatch of the power system in 2020 and 2050 for a low and a high demand week respectively. It can be seen how batteries and solar power interact.

The scale of the generation increases strongly between 2020 and 2050 due to much larger power demand. In the low demand week in 2050, some curtailment takes place during peak solar hours, where the capacity of the batteries is maxed out.



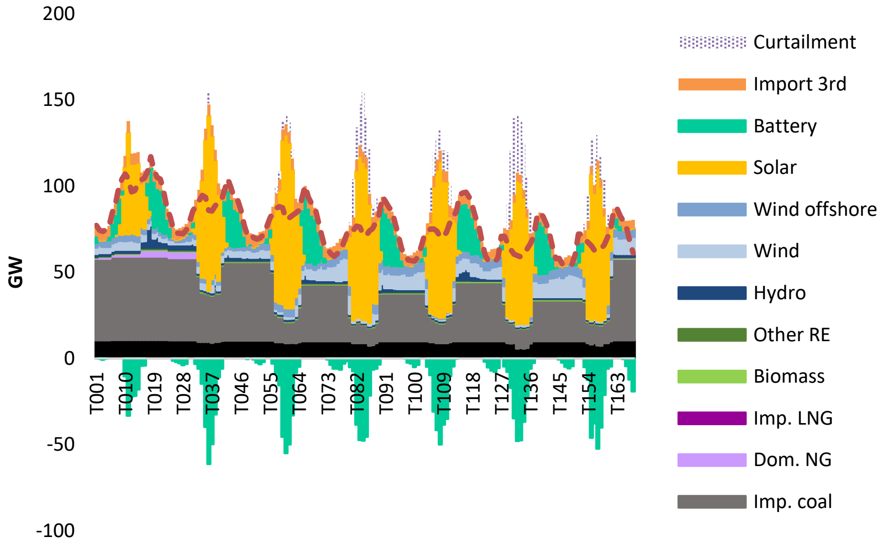


Figure 48: Hourly dispatch in the C1 RE target scenario. Week 4 (low demand). Above 2020 and below 2050.

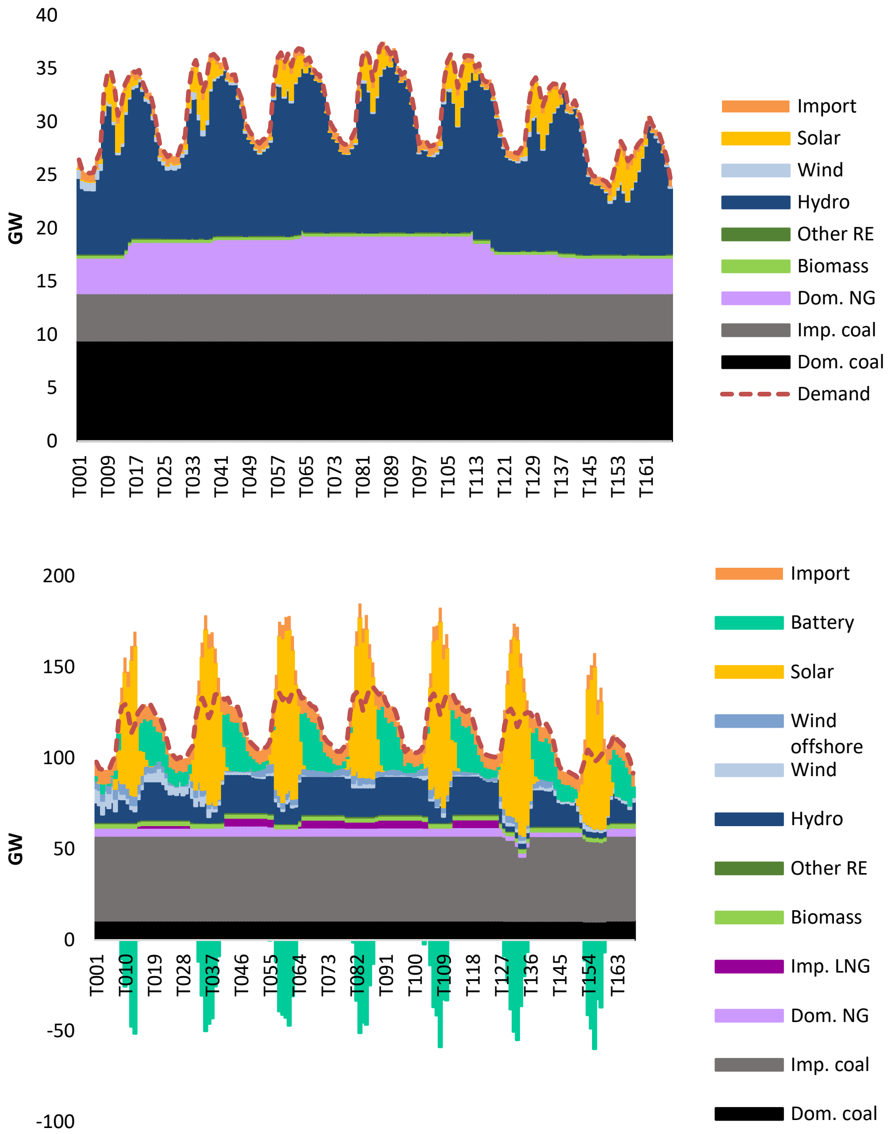


Figure 49: Hourly dispatch in the C1 RE target scenario. Week 39 (high demand). Above 2020 and below 2050.

6 Modelling results – Green power scenarios

Wind and solar power represent a new type of generation. Dramatic cost reductions make investments in these power technologies realistic, allowing a significant contribution from these sources in the power mix. The varying generation from wind and solar is different from traditional generation used in Vietnam. This chapter will analyse the interaction between wind and solar and the other generation technologies, by presenting the modelling results of the designed scenarios.

6.1 Renewable energy scenarios

Five additional scenarios are analysed and compared to the *C1 RE Target* scenario. The scenarios have requirements from 40% to 80% (steps of 10%) between 2030 and 2050. Figure 50 shows that the least-cost solution to fulfil the requirements comprises an extensive investment in solar power and batteries while wind power plays a lesser role and LNG is not utilised.

For wind power, mainly sites with high and medium wind speeds are used. No investment takes place in low wind speed area in any of the scenarios despite the model having the opportunity to invest wind turbines designed for low wind speeds. In all RE scenarios all six available offshore wind farms are built by 2050. From the RE3 50pct scenario and higher RE shares, the assumed offshore potential is already all used by 2040.

The reason for LNG not being utilised is that after having fulfilled the RE target it is cheaper to invest in coal power plants based on imported coal. Therefore, LNG is not relevant in a least-cost solution for these scenarios.

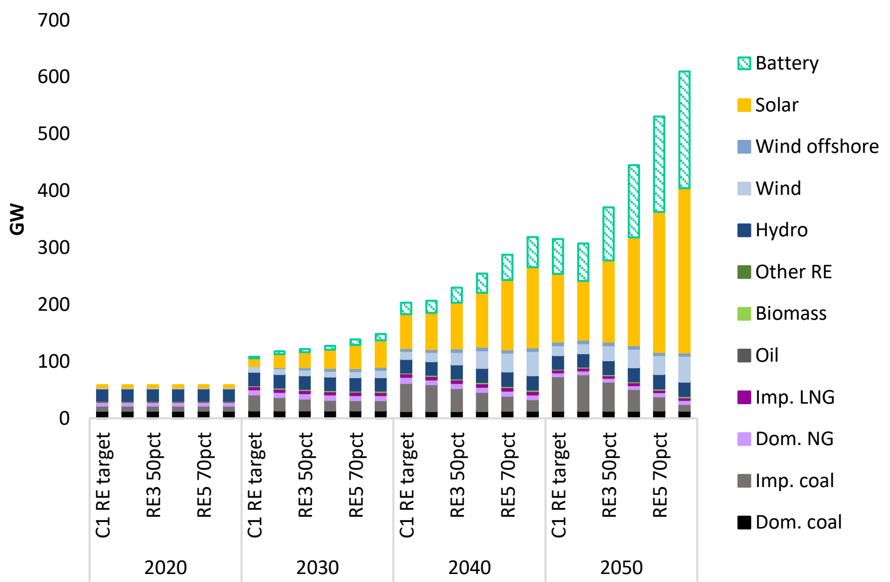


Figure 50: Generation capacity for C1 RE target and the five RE share scenarios.

Figure 51 shows the electricity generation per type. The potential hydro and other renewable sources (biomass, geothermal, tidal) are quickly fully exhausted, and only wind and solar power is left to fulfil the renewable energy requirements.

As more renewable energy enters the system, the use of imported coal is reduced. The fuel costs related to imported coal decrease as a higher share of renewable power is incorporated in the system (Figure 52).

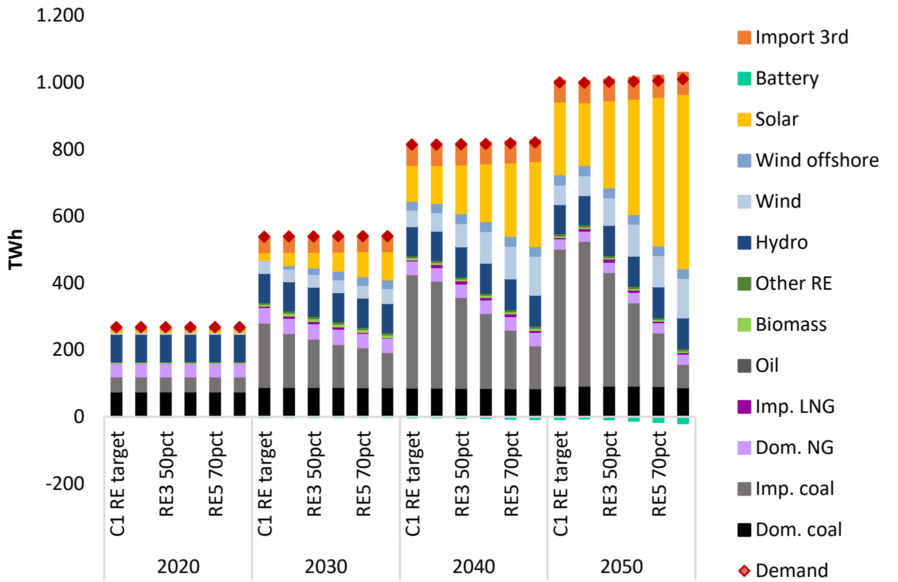


Figure 51: Annual electricity generation, import from 3rd countries and power demand (including transmission and distribution losses) in C1 RE target and the five RE share scenarios. Negative values for batteries represent the loss in the batteries.

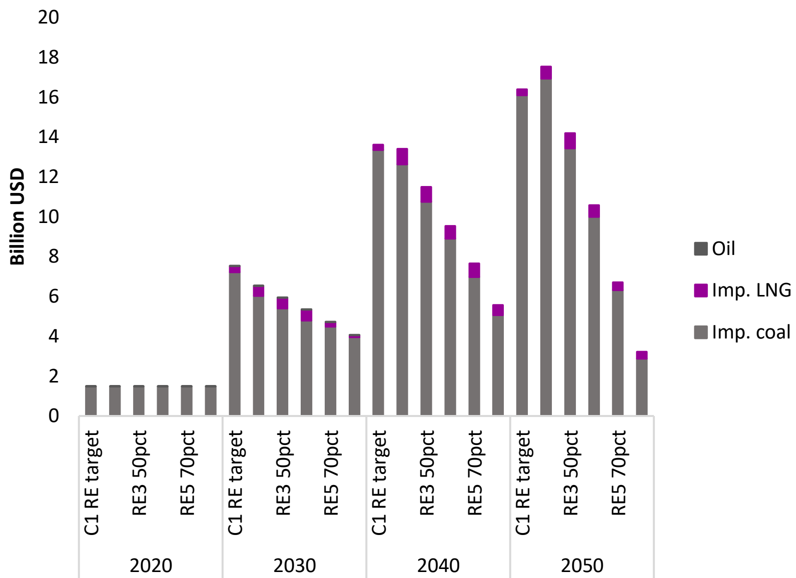


Figure 52: Costs for fuel import C1 RE target and the five RE share scenarios.

Figure 53 shows the CO_2 emissions in the six scenarios. While the *C1 RE target* scenario ends at 469 Mt in 2050, the renewable energy scenarios significantly reduce the emissions, i.e. to 161 Mt (66% reduction) in the most ambitious scenario. Note that these results on CO_2 emissions are used to define the CO_2 emission limits in the Emission limit scenarios (Section 7.2).

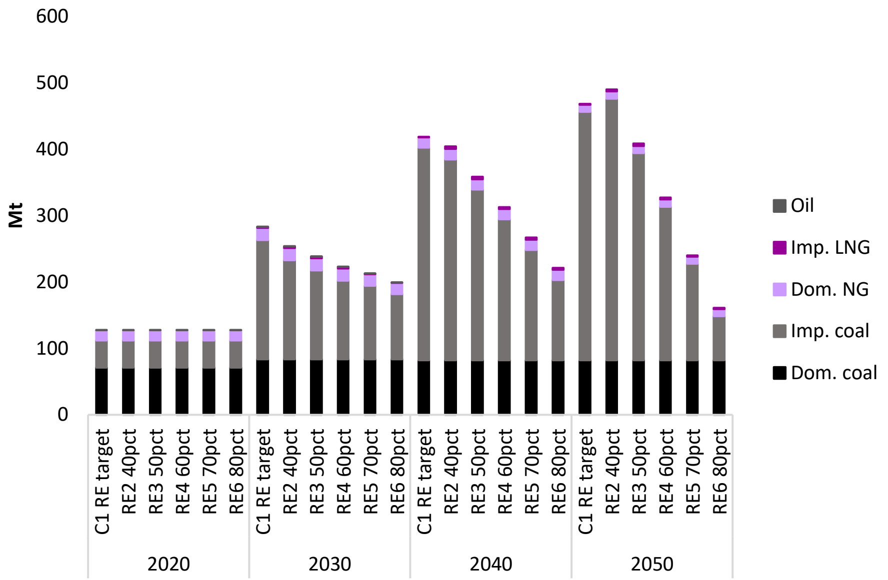


Figure 53: CO_2 emissions in C1 RE target and the five RE share scenarios.

Figure 54 shows the total system costs in the different scenarios[11]. The costs are heavily influenced by the growth in electricity demand. This result is a consequence of the investment in wind and solar, where capital costs dominate and where there are no fuel costs. The specific system costs (USD/MWh) are increasing over time in all scenarios (also in RE target). The increase in fuel costs and the shift to renewable energy are the main drivers behind this development.

[11] Total system costs include the six elements: Capital cost for new generation and transmission (computed as annualized costs), Fixed and variable O&M costs, fuel costs and start-up costs. Note that cost of existing and committed generation and transmission is not included (same amount for all scenarios). The capital costs are annualised based on the discount factor of 10% and 20 year economic lifetime (annuity factor of 0.1175).

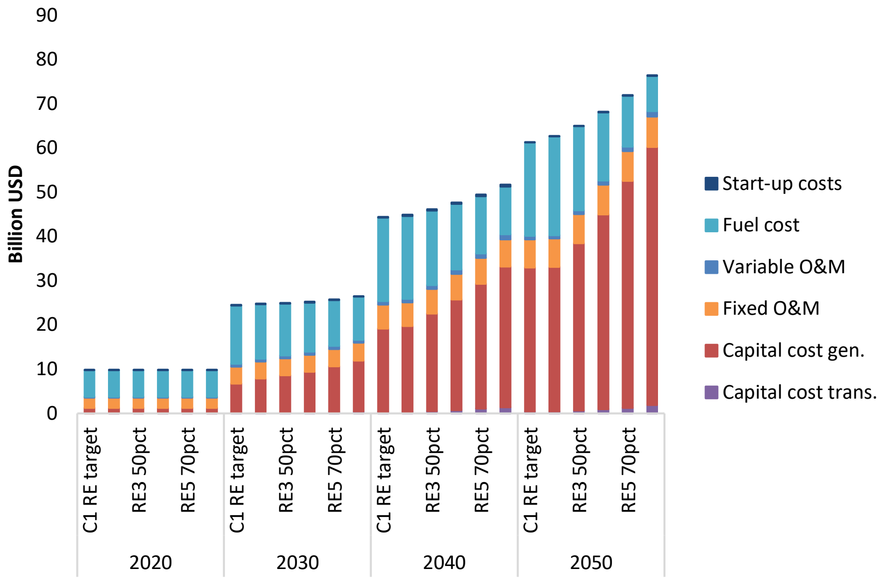


Figure 54: Total system costs in C1 RE target and the five RE share scenarios.

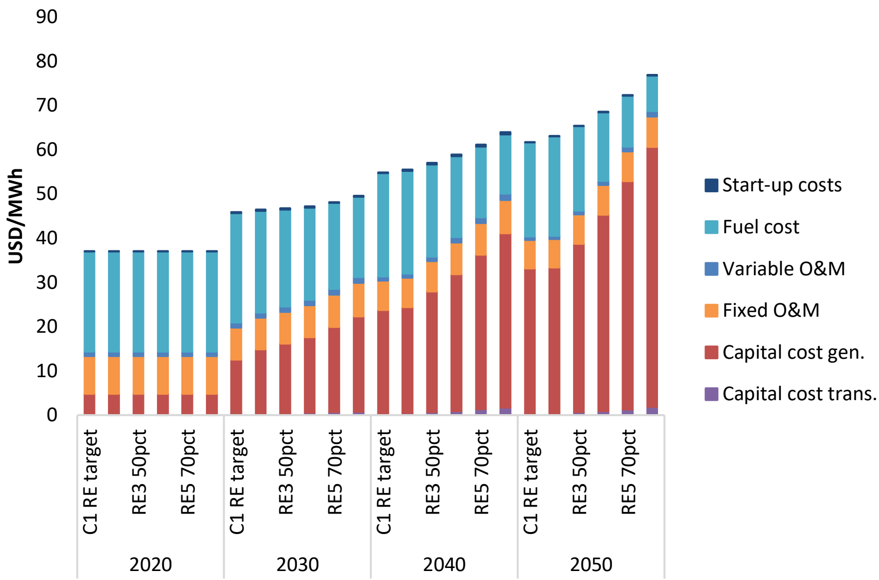


Figure 55: Total system cost per MWh in C1 RE target and the five RE share scenarios.

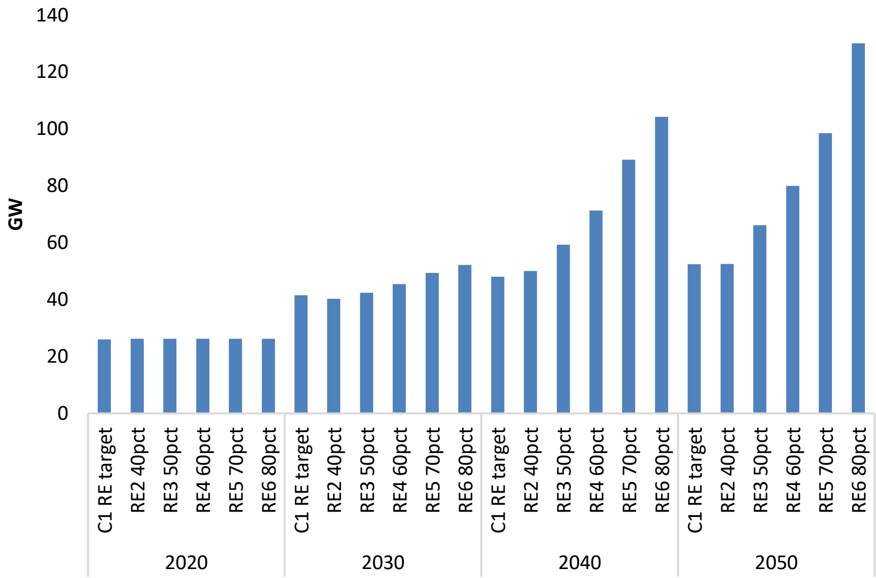


Figure 56: Transmission capacity in C1 RE target and the five RE share scenarios. The figure shows the sum of the capacity of the seven transmission lines.

Table 13 shows the transmission capacity for selected years and scenarios as well as an estimated maximum capacity (limit) for each of the seven lines. It can be seen that the 40% scenario is within these limits. For the more ambitious scenarios (60 and 80%) the result for transmission capacities is seriously over the estimated maximum capacity for four lines (a factor 3-4 for the 80% scenario). It must be investigated if it is possible to increase the transmission capacity beyond what is now considered at a realistic maximum – or what measures can be taken to solve the conflict.

Table 13: Transmission capacities for selected years and scenarios. The last column indicates the realistic maximum capacity. Numbers in red exceed the maximum value.

MW		RE2 40 pct		RE4 60 pct		RE6 80 pct		Estimated
Region From	**Region To**	**2040**	**2050**	**2040**	**2050**	**2040**	**2050**	**Max capacity**
North	**North Central**	8,438	8,438	12,709	12,709	24,227	30,341	10,000
North Central	**Centre Central**	8,394	9,513	13,343	17,079	25,424	35,509	10,000
Centre Central	**Highland**	6,000	7,277	9,557	14,229	23,940	30,422	16,000
	South Central	3,349	3,349	5,244	5,244	3,714	6,952	-
Highland	**South Central**	1,018	1,018	1,018	1,018	1,018	1,018	18,000
	South	10,798	10,798	13,733	13,916	11,089	11,089	10,000
South Central	**South**	12,132	12,132	15,751	15,751	14,843	14,843	18,000

6.2 CO_2 emission limit

Based on the level of CO_2 emissions in the RE share scenarios, a new set of scenarios are analysed. The CO_2 emissions from the RE share scenarios (see

Figure 53) are used as an emission limit on CO_2. Since there are other ways of reducing CO_2 than renewable energy (e.g. fuel shift from coal to natural gas), the new set of scenarios will illustrate the same CO_2 reduction, but potentially with a different energy mix.

Figure 57 and Figure 58 show the generation capacity (GW) and the generation (TWh) in the new set of scenarios. The main difference with the previous set of scenarios is that significant investments take place in 2040 and 2050 to utilise LNG. There is lower solar power and battery capacity, as well as less imported and domestic coal. On an overall level the results show that to achieve CO_2 reduction, replacing coal with LNG can be cost-effective compared to PV and batteries in some places of Vietnam. The LNG capacity is located near the demand centres in the North and the South regions.

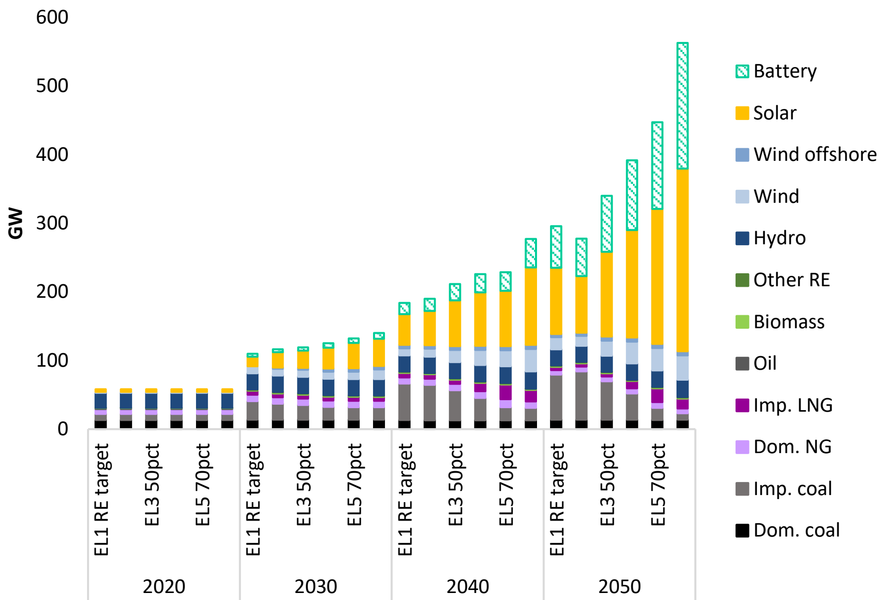


Figure 57: Generation capacity for the six CO_2 emission limit (EL) scenarios.

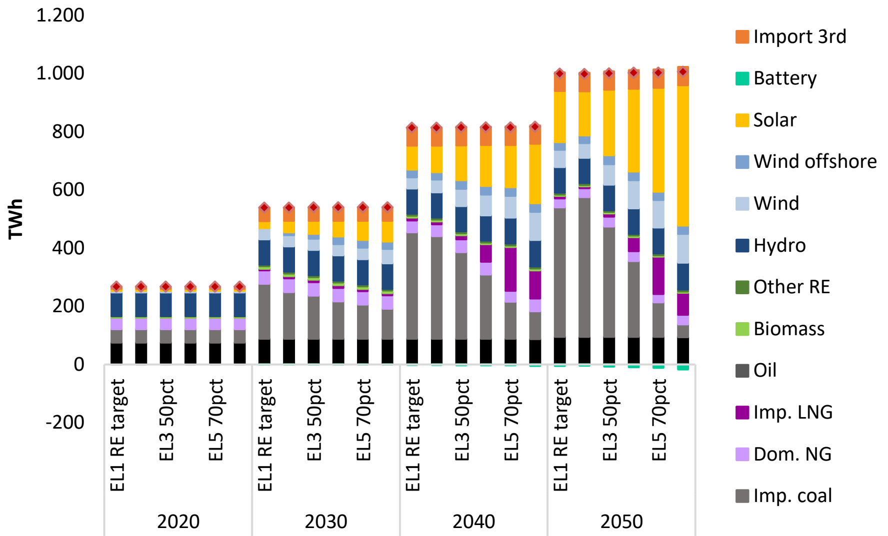


Figure 58: Annual electricity generation, import from 3rd countries and power demand (including transmission and distribution losses) in the six CO_2 emission limit scenarios. Note: The negative generation from batteries is the net loss.

Figure 59 shows that the share of renewable energy is, as expected, lower than in the first set of scenarios. For example, in the most ambitious scenario (i.e. 80% RE-share scenario) the fulfilled RE target corresponds to an 80% share of renewables in the total generation, but an RE share of only 74% RE is achieved in the corresponding CO_2 scenario (for the year 2050).

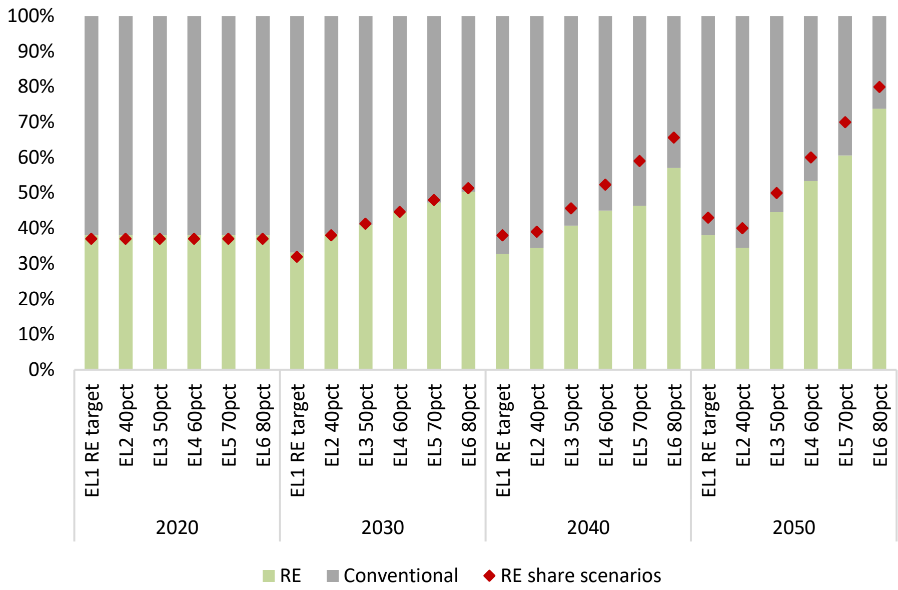


Figure 59: Share of renewable energy in C1 RE target and the five CO_2 emission limit scenarios. The red marks represent the RE-share goals in the corresponding renewable energy scenarios (see section 7.1). This goal is not active in the CO_2 scenarios.

Figure 60 shows the annual CO_2 emissions. The total emission level is the same as in Figure 53. However, the emissions from coal have been reduced, while more emissions come from LNG in the most ambitious scenarios. The CO_2 shadow values for the emission limit scenarios are shown in Figure 61. The shadow values range between 2.5 and 60.5 USD/t for all emission limit scenarios. Despite growing power demand and increasing RE target, by 2050, reasonable CO_2 shadow values are still seen (between 2.5 and 55.5 USD/t).

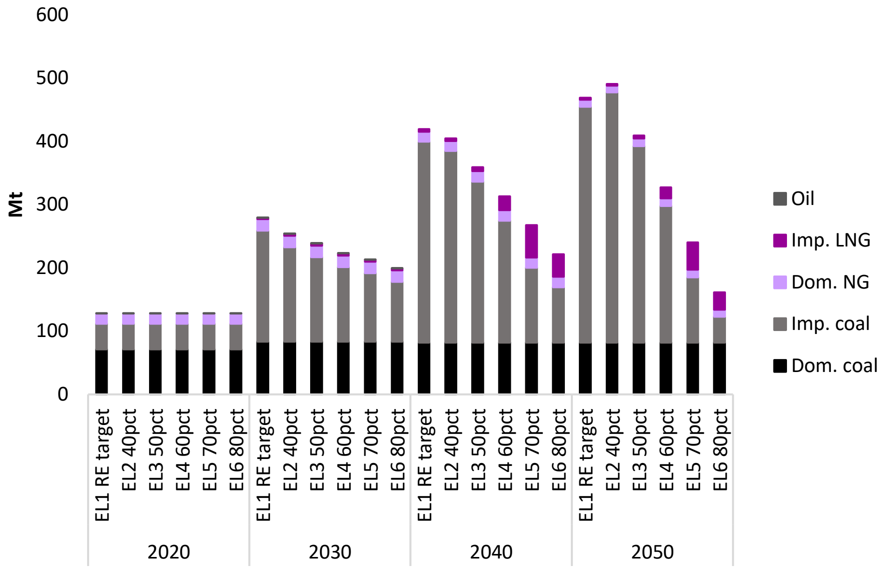


Figure 60: CO_2 emissions in the six CO_2 emission limit scenarios.

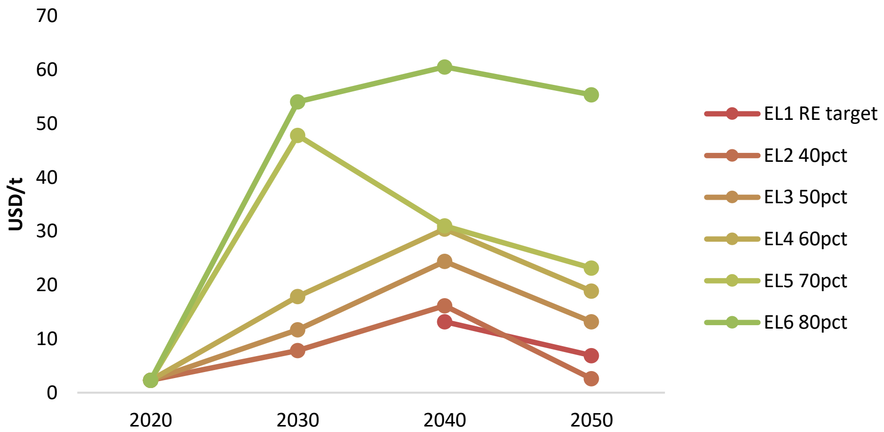


Figure 61: CO_2 shadow values for the six CO_2 emission limit scenarios.

As shown in Figure 63, increasingly ambitious limits on CO_2 emissions results in larger total system costs. To a large extent, the increase in cost comes from investments in more wind and solar capacity. Unlike the RE share scenarios, there is no large decrease in fuel costs in the CO_2 emission limit scenarios, as more expensive LNG is imported (Figure 63).

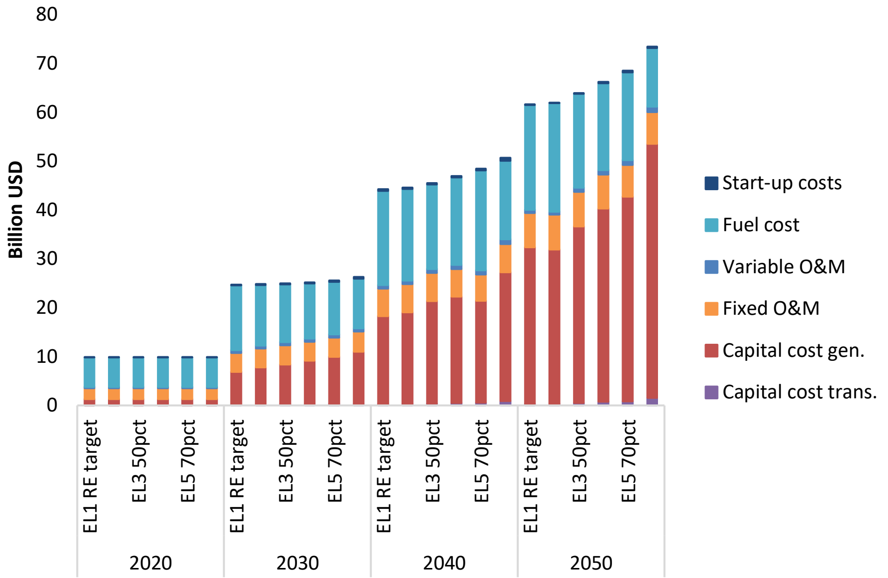


Figure 62: Total system costs in the six CO_2 emission limit scenarios.

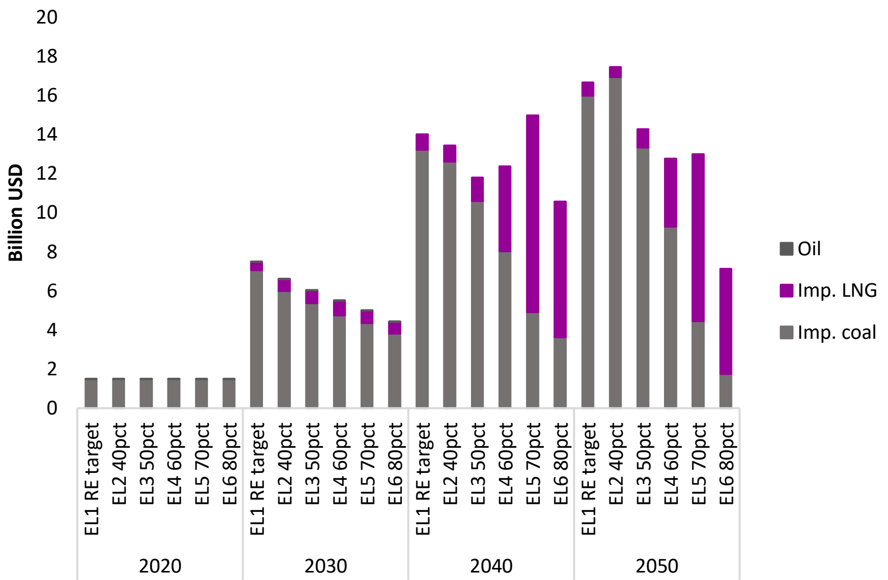


Figure 63: The costs of imported fuels in the six CO_2 emission limit scenarios.

While CO_2 emissions decrease to the same extent as in the RE share scenarios, Figure 63 shows that the drawback of the emission limit scenarios is a large dependence on imported fuels, with high LNG costs as a result.

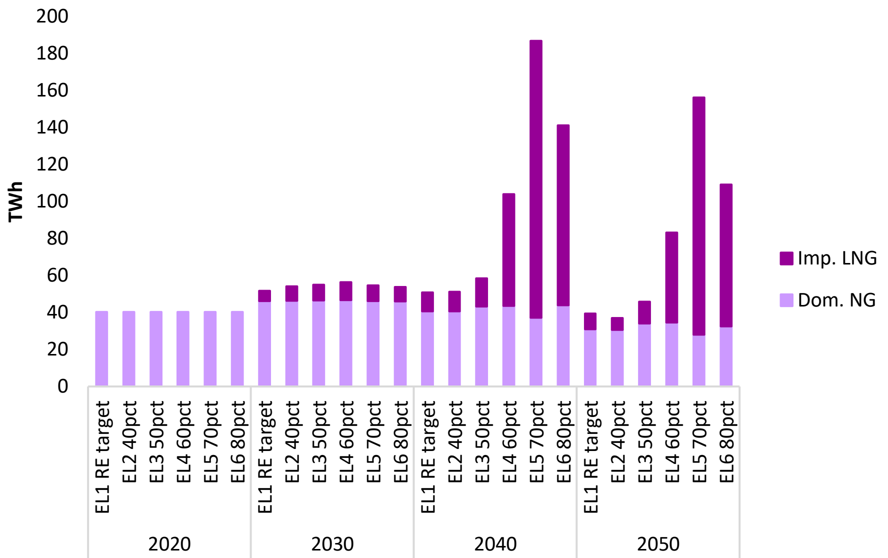


Figure 64: Electricity generated by natural gas and LNG in the six CO_2 emission limit scenarios.

6.3 Comparison of the two sets of scenarios

Figure 65 shows the total power system cost versus the CO_2 emissions in the two sets of scenarios for 2050. The total cost is increasing, when the CO_2 emission is decreased. In the most ambitious renewable energy scenario (80%) the CO_2 emission is reduced with 66% compared to the *C1 RE target scenario* - and this comes at a cost of 25% increase in total yearly costs in 2050. The same CO_2 reduction can be achieved in the CO_2 cap scenario, but at a reduced increase in cost: 20%.

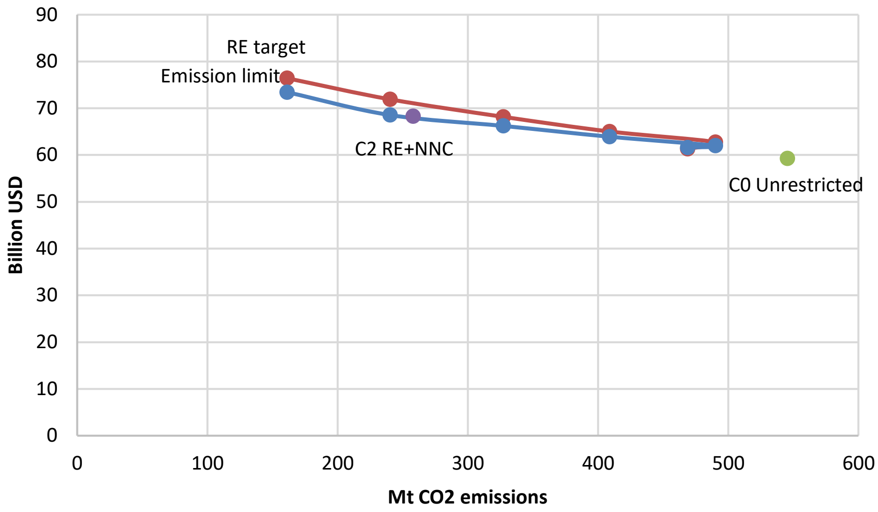


Figure 65: Comparison of total yearly costs and CO_2 emission in the two sets of Green power scenarios , the C0 Unrestricted scenario and the C2 No new coal in year 2050.

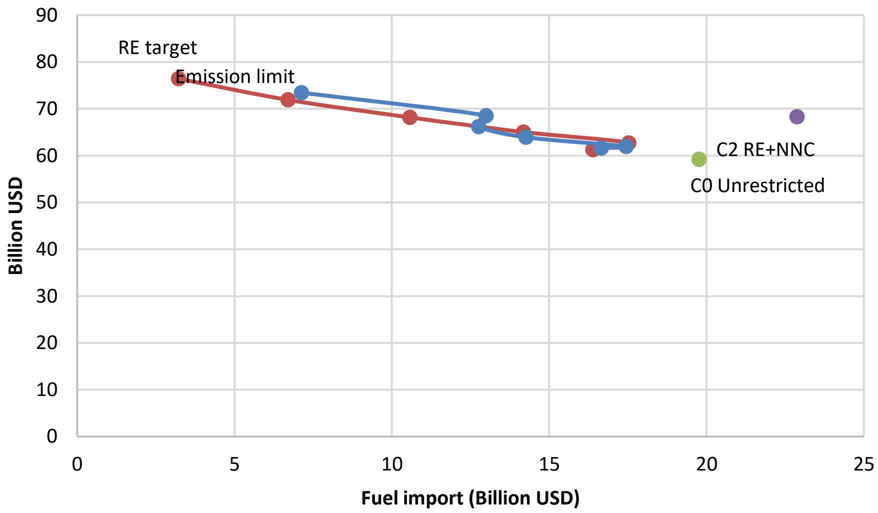


Figure 66: Comparison of total yearly costs and fuel imports in the two sets of Green power scenarios, the C0 Unrestricted scenario and the C2 No new coal in year 2050.

7 Model results - Sensitivity analyses

In this chapter, some parameters will be varied to analyse sensitivity. The results will show how the least-cost solution will change when these inputs are changed, i.e. generation capacity per fuel and the scale of the transmission capacity.

7.1 Sensitivity analysis on fuel prices

In the near future, the potential of domestic fuels (coal, gas and biomass) and hydropower will be fully utilised, and the ability to import electricity from neighbouring countries is limited. Therefore, with increased electricity demand, the power system will to an increasing extent be based on imported fuels like coal or LNG. Fuel prices of imported coal and LNG is difficult to forecast (see Figure 11 for historical coal price prognoses). In this section, it is investigated how an alternative forecasted fuel price of imported coal and LNG may influence investment decisions.

Two alternative scenarios of imported coal and LNG prices are calculated (Figure 67). The other fuel prices, including the domestic prices are assumed the same as in the *C1 RE target* scenario.

- **High fuel scenario:** Fuel price of imported coal and LNG in period to 2030-2050 will be higher than in the *C1 RE target* scenario. The high price scenario is equivalent with the forecasted fuel prices in the Current policy scenario of fuel price projection report (referring to the IEA scenario with the highest price) (Ea Energy Analyses and Institute of Energy, 2019).
- **Low fuel scenario:** Fuel price of imported coal and LNG in period to 2030, 2050 will be lower than in the *C1 RE target* scenario. The prices of imported coal and LNG are equivalent with the forecasted fuel prices in the Sustainable policy scenario of fuel price projection report (referring to the IEA scenario with the lowest price).

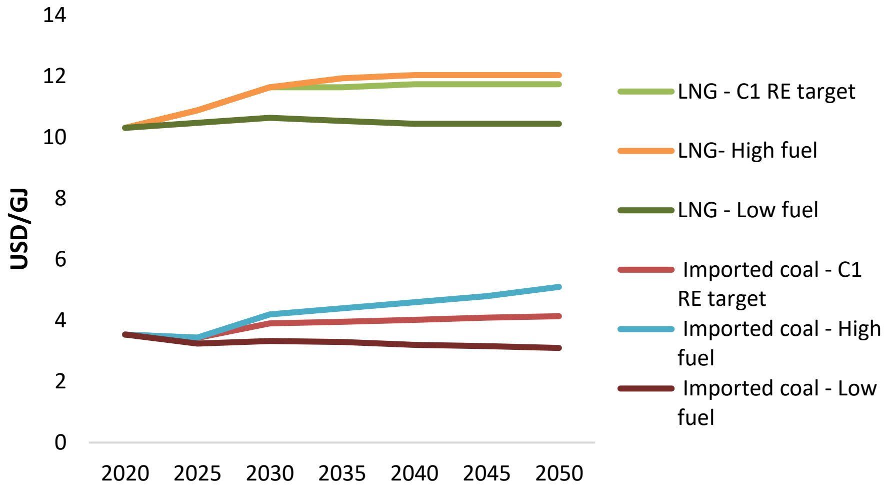


Figure 67: Forecasted imported coal and LNG prices to power plant in 3 scenarios (Source: Long-term fuel price projections for Vietnam, EaEA, 2019).

Results

The renewable energy requirement exists for all years: 32% in 2030, 37.6% in 2040, 43% in 2050, and is the same in *C1 RE target* scenario, the *High fuel* scenario and *Low fuel* scenario. The energy mix is to a high degree guided by the renewable energy requirement – and only to a lesser extent by the fuel price. In 2030, it follows what would generally be expected: higher fuel price, higher RE share**.** With low fuel price, the installed capacity of imported coal increases compared to the *C1 RE target* and *High fuel* scenarios, whereas the installed capacity of renewable energy (solar, wind…) decreases with lower fuel price. This is consistent with least-cost optimal solution. However, in year 2040, 2050 the change is not very large because of RE requirement.

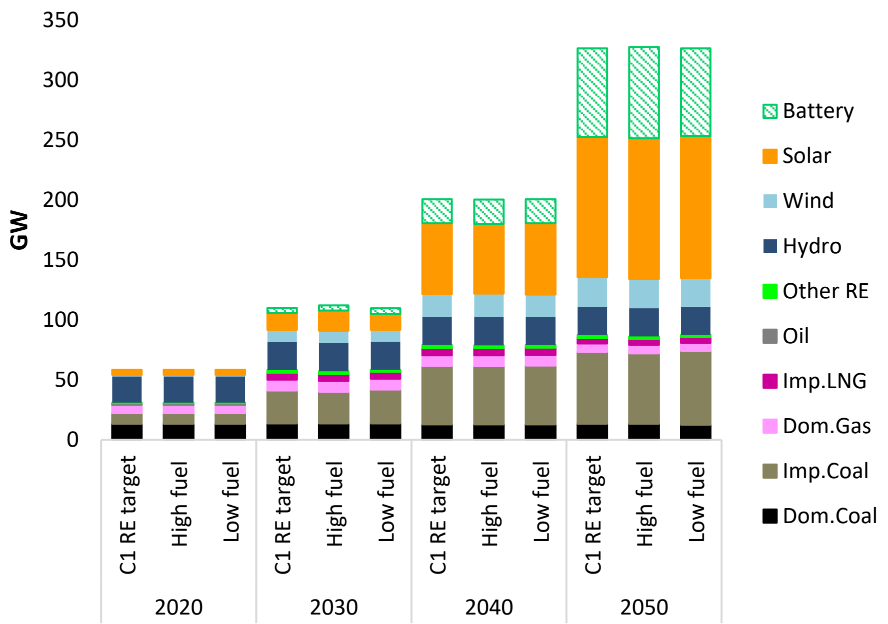


Figure 68: Installed capacity by power source type in the alternative fuel price scenarios.

In 2030, imported coal reaches 27.3 GW in *C1 RE target* scenario, increasing to 28.2 GW in low fuel scenario, and decreasing to 26.3 GW in high fuel scenario. Comparing with the *C1 RE target* and *Low fuel* scenario, the capacity of solar in the *High fuel* scenario increases about 3 GW in 2030.
In 2050, capacity of renewable energy is changed little between scenarios because of RE requirement. However, comparing with *C1 RE target* scenario, the capacity of coal reduces about 2 GW and capacity of battery increase about 3 GW in the *High fuel* scenario, the capacity of imported coal increases 1.5 GW and capacity of battery reduce 1 GW in the *Low fuel* scenario.

The renewable energy requirement exists for all years: 32% in 2030, 37.5% in 2040, 43% in 2050. In 2030, the *C1 RE target* and *High fuel* price scenarios are over fulfilling the RE requirement (33% for *C1 RE target* and 35% for *High fuel*), and the renewable energy requirement is not binding. For the *Low fuel* price scenario, however, the requirement is binding and renewable energy capacity is added to fulfil the requirement.

The results for 2040 and 2050 all have the renewable energy share equal to the requirement, independent of the fuel price. For these years, the energy mix is to a high degree guided by the renewable energy requirement – and only to a lesser extent by the fuel price.

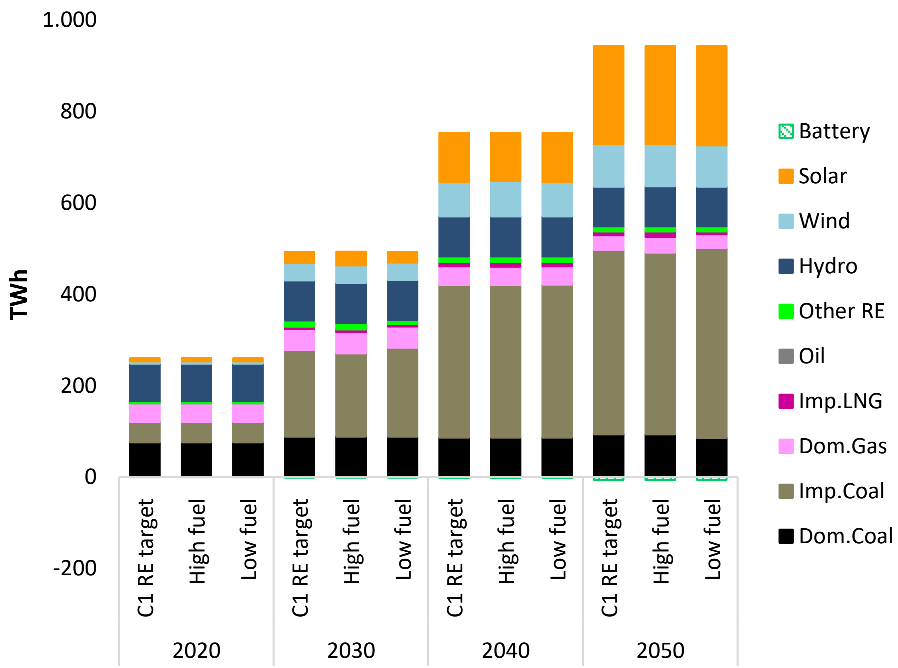


Figure 69: Electricity generation by power source type in the alternative fuel price scenarios.

In 2050, the significant change in energy generation mix is lower generation of coal and higher generation of gas in the *High fuel* scenario. About 7 TWh of coal in *C1 RE target* scenario will be replaced by domestic gas and LNG of *High fuel* scenario.

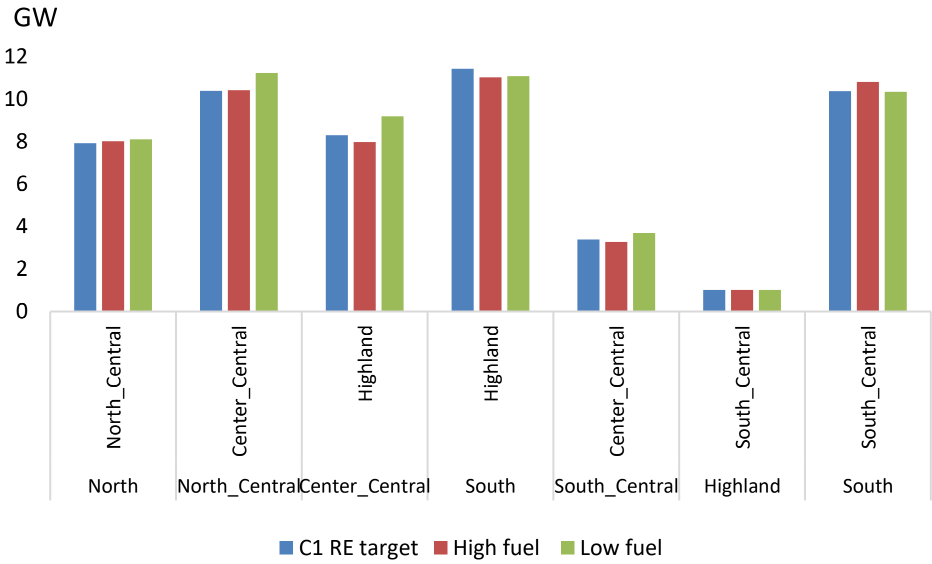


Figure 70: Transmission capacity between regions in the alternative fuel price scenarios in 2050.

The transmission capacity change between scenarios is not major. That is because the solution is controlled by the renewable energy requirement. The largest change occurs in the interface between Centre Central and North Central in the *Low fuel* scenario with 0.8 GW transmission capacity higher *than C1 RE target* and *High fuel* scenarios, due to higher imported coal in the South in the *Low fuel* scenario.

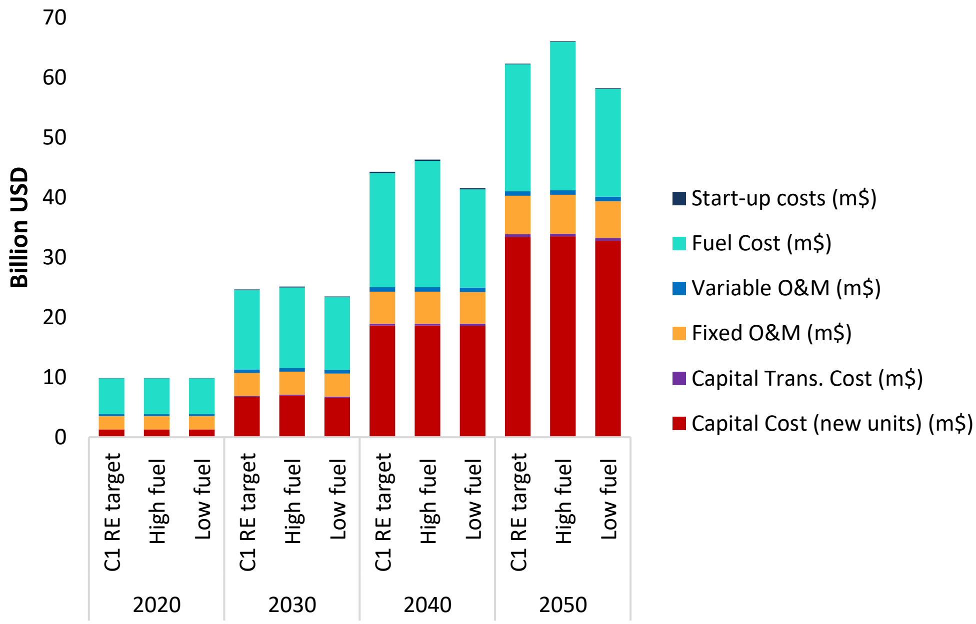


Figure 71: Total system cost in the alternative fuel price scenarios.

The result of total system cost shows that the fuel price mainly affects fuel cost. However, capital cost is lowered slightly in the *Low Fuel* price scenario. The capital cost will be higher with higher fuel price scenario.

In conclusion, the fuel price variation on imported coal and LNG will affect the decisions to a small degree about development capacity of imported coal, domestic coal, domestic gas, renewable energy and batteries. Because the renewable energy requirement is set in all scenarios, the solution is controlled by the RE requirement, so the generation capacity change between scenarios is not very large.

7.2 Sensitivity analysis on UC

When carrying out the modelling of capacity expansion, the operational restrictions of the generating unit (coal thermal, CCGT and biomass) are included, known as unit commitment (UC). These following UC parameters present the flexibility of technology generation unit: Start-up cost, minimum generation, fixed fuel use, minimum up/down time and ramp rate (up and down).

As shown in the Vietnamese Technology Catalogue (EREA, DEA, Institute of Energy and Ea Energy Analyses, 2019), currently the flexibility of technologies in Vietnam is quite low, e.g. subcritical pulverised coal thermal plants have a minimum load of 67% in average, while international design could reach lower than 25%. In the future, Vietnamese data are expected to converge to better values around the international level (e.g: for coal subcritical technology, the minimum load is expected to be 25% in 2030 and 20% in 2050).

Table 14: Parameters of Unit Commitment used in Balmorel modelling.

No.	Technology	Unit size (MW)	Pmin (%)	Start-up cost (USD/MW)	Fixed fuel use (%)	Ramp up/down (%/min)	Min up time (h)	Min down time (h)
	2020							
1	Subcritical	600	67%	180	45%	1%	4	2
2	Supercritical	600	75%	180	45%	1%	4	2
3	CCGT	250	56%	131	42%	7%	4	2
4	Biomass	55	38%	180	45%	4%	4	2
	2030							
1	Subcritical	600	25%	180	45%	4%	4	2
2	Supercritical	600	25%	180	45%	4%	4	2
3	Ultra super-critical	600	25%	180	45%	5%	4	2
4	CCGT	250	30%	131	42%	20%	4	2
5	Biomass	25	30%	180	45%	10%	4	2
	2050							
1	Subcritical	600	20%	180	45%	4%	4	2
2	Supercritical	600	20%	180	45%	4%	4	2
3	Ultra super-critical	600	20%	180	45%	5%	4	2
4	CCGT	250	15%	131	42%	20%	4	2
5	Biomass	25	30%	180	45%	10%	4	2

For the sensitivity analyses, to check the influence of flexibility characteristics to power generation expansion, a scenario with no improvements in UC parameters is calculated. In this case, ***all UC parameters in the next period up to 2050 will be the same as in 2020***.

Results

The result shows that the impact of no improvement of unit commitment to the generation expansion is small, with only minor differences in installed capacity and power generation compared to *C1 RE target* scenario. The transmission capacity in 2020 and 2030 remains the same, while in 2040 and 2050 the limit of transmission increase with 1000 MW and 600 MW respectively, to maintain the flexibility of power system.

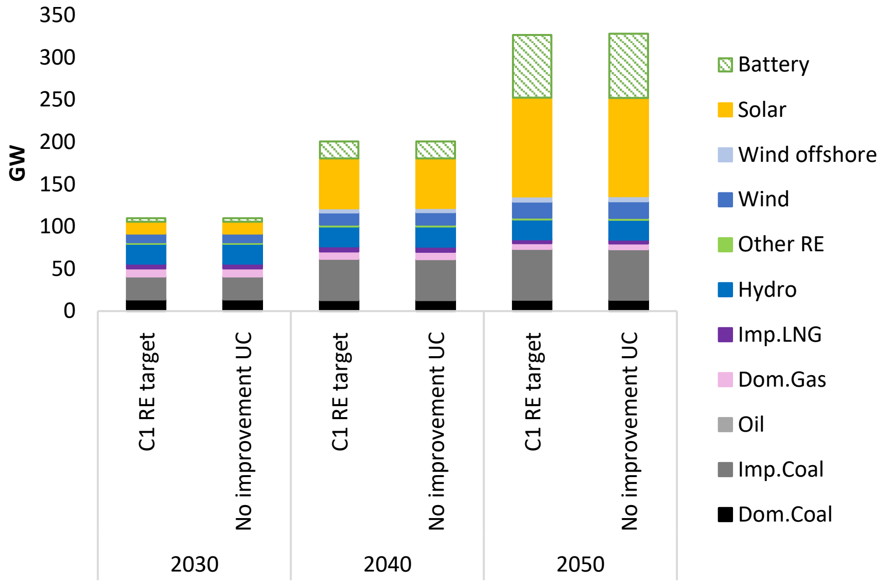


Figure 72: Comparing Installed capacity by power source type of the No improvement UC and C1 RE target scenarios.

The difference of installed capacity in the two scenarios is small; in 2050 the *No UC improvement* scenario has nearly 2 GW more total capacity than the *C1 RE target* scenario, corresponding to a 0.6% increase, mostly coming from the increase of the battery capacity.
Similarly, there is no significant change of power generation between the two scenarios. Only wind power generation increases nearly 2 TWh while solar and imported coal have a reduction of 1.4 TWh and 0.6 TWh respectively.

The total transmission capacity of transmission line in No UC improvement scenario is a little higher than *C1 RE target* of 0.8 GW in 2040 and 0.6 GW in 2050, mainly at the interface of South Central to the South and Highland to Mid Central relate to power releasing of solar generation.

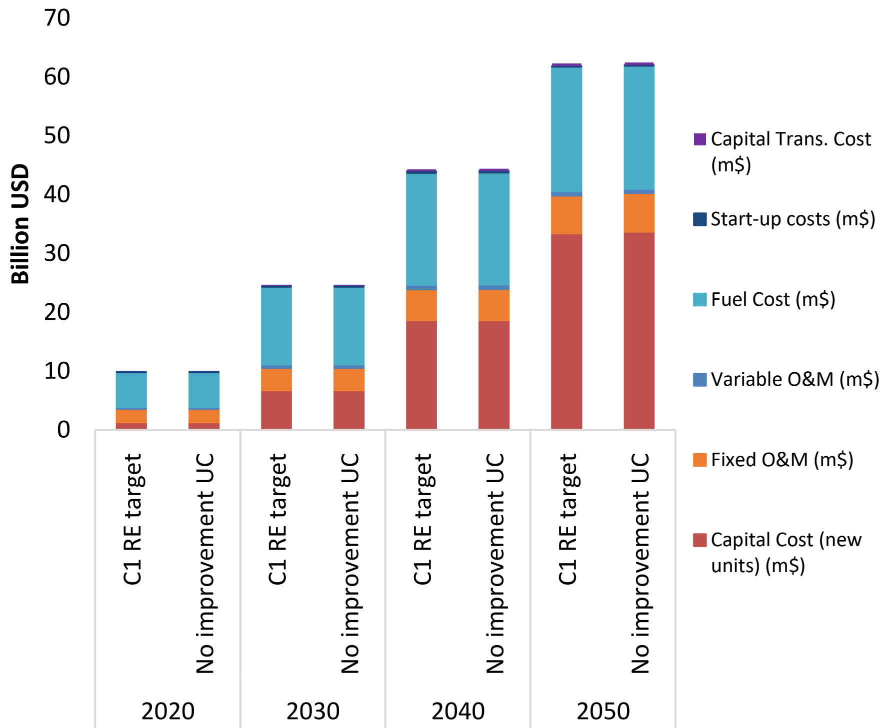


Figure 73: Comparing total system cost of the No improvement UC and C1 RE target scenarios.

The *No UC improvement* have the same total cost as compared to the *C1 RE target* scenario, where the capital, O&M cost and start-up cost increase but the fuel cost reduces, which is related to lower generation of imported coal. In particular, the start-up cost increase 38% in *No UC improvement* due to lower flexibility of coal, gas and biomass technology. However, the start-up costs still only constitutes a small fraction (0.15%) of the total costs

In conclusion, the impact of *No UC improvement* to the generation expansion is small. In case of lower flexibility of the fossil fuel technology (coal, gas and biomass), the system has to add slightly more battery and transmission capacity. In addition, the small increase of wind generation will replace some generation from solar and imported coal.

7.3 Sensitivity analysis on battery costs

In this sensitivity analysis, the investment cost of battery is not reduced in the future. The assumption is that investment cost of batteries in period up to 2050 will be the same as in 2020.

Results

In 2030 the installed capacity of battery storage in the *High Cost Battery* scenario will be about 1.7 GW, which is about 2.6GW lower than the *C1 RE Target* scenario. To replace 2.6 GW of battery storage, the model adds about 1GW of domestic gas, while reducing 0.6 GW of imported coal. The capacity of renewable energy is also changed: solar power decreases by 0.2 GW, while wind power increase by 0.1 GW.

In 2040, the battery capacity will decrease by about 2.2 GW in *High battery cost* scenario compared to the *C1 RE target* scenario. In replacement, the capacity of domestic gas thermal increases by 2.6 GW, wind power increases by 0.5 GW, while solar power is reduced by about 2 GW.

In 2050, there are more changes in the power capacity structure. Battery capacity falls by more than 43% compared to *C1 RE target* scenario (32 GW reduction), while 5.8 GW of pumped storage hydro power plants will appear. Imported coal will increase by 2 GW and domestic gas increases by 5 GW compared to *C1 RE target* scenario. Solar decreases by 18 GW, while wind increases by 11 GW and hydro increase 1 GW to ensure RE targets.
The result show that, if the investment cost of battery is high, the wind capacity will be more developed while capacity of solar reduce comparing with *C1 RE target* scenario. That is because of the wind have the hourly generation characteristic more regular than solar, wind power does not need installed battery much as solar

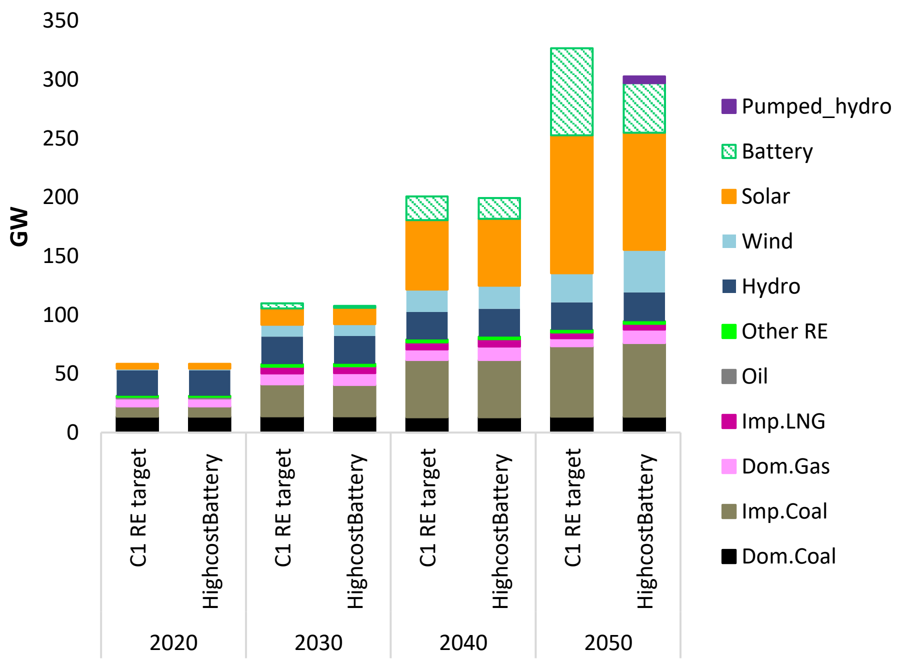


Figure 74: Comparing Installed capacity by power source type in the High cost battery and C1 RE target scenarios.

About the energy generation mix, RE targets are guaranteed as in the *C1 RE target* scenario in all calculated years. The amount of wind energy increases while the solar energy decreases. In 2050, solar generation energy will decrease by 32 TWh, wind energy increase by 29.7 TWh and hydro energy increase by 2.3 TWh. Generation energy of coal and gas-fired thermal power plants have not changed significantly.

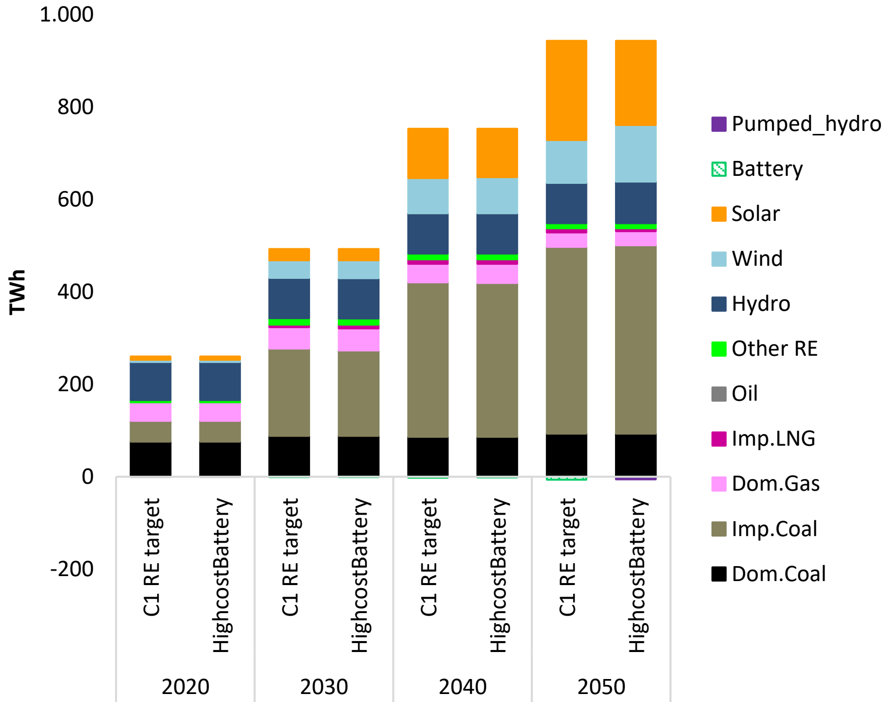


Figure 75: Comparing energy generation by power source type in the High cost battery and C1 RE target scenarios.

Transmission capacity in 2050 on Center_Central – North_Center – North interfaces will increase by 2-3GW, Center_Central – South_Center and Center_Central – Highland interfaces will increase by about 2GW. The reason is that the model chooses to invest more domestic gas in Center_Central and more renewable energy capacity in Highland.

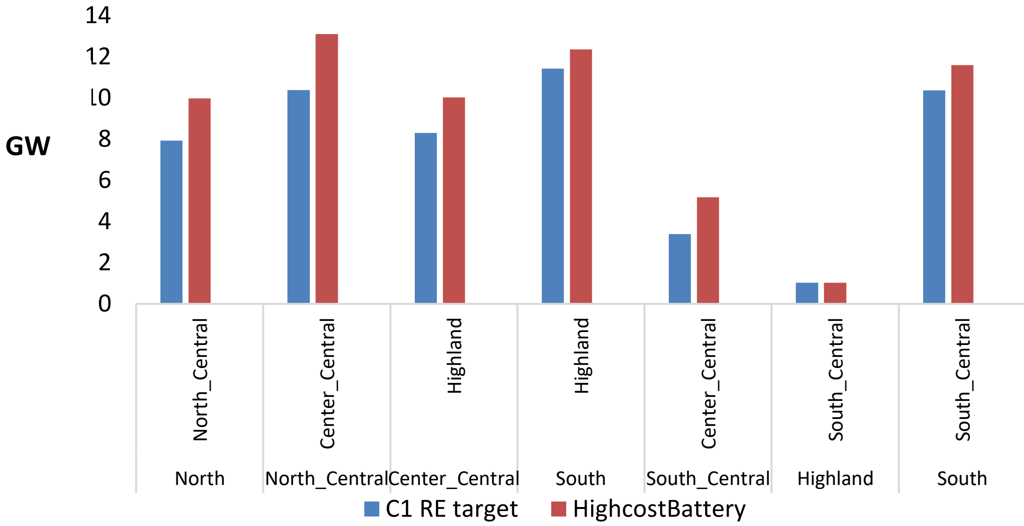


Figure 76: Comparing Transmission capacity between regions in 2050 of the High cost Battery and C1 RE target scenarios.

If the battery investment cost in the period to 2050 does not decrease, the total system cost will be higher than the *C1 RE target* scenario. Significant changes are seen in 2040 and 2050, where the total system cost will increase by 2.3% and 5.9% respectively compared to *C1 RE target* scenario. The main change is due to increased capital costs.

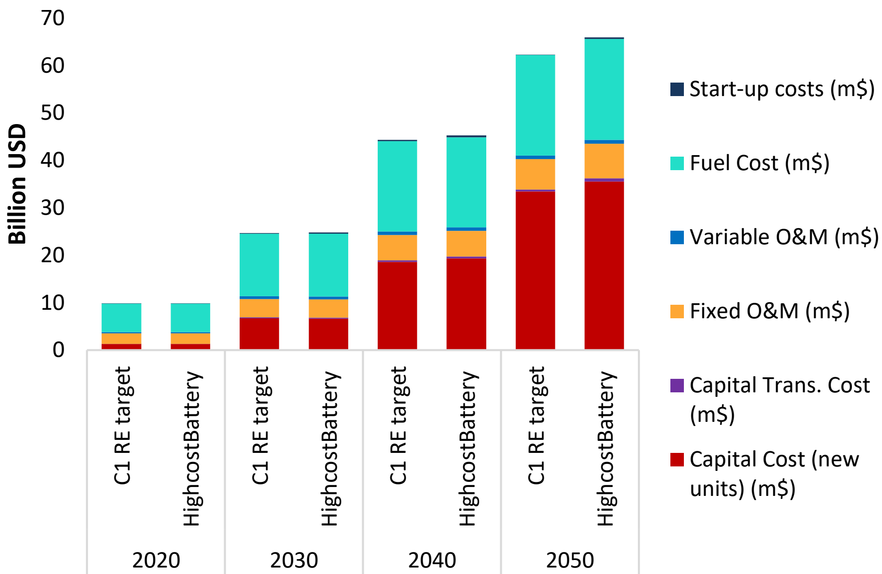


Figure 77: Comparing total system cost of the High cost Battery and C1 RE target scenarios.

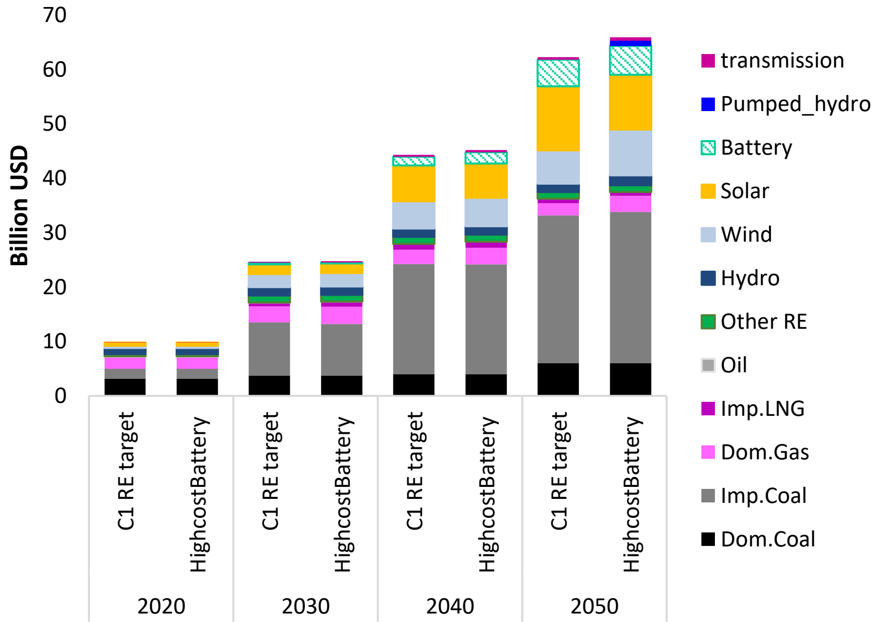


Figure 78: Comparing total system cost of High cost Battery and C1 RE target scenarios by types of source in 2050.

In *High cost battery* scenario, investment cost of domestic gas, battery and pumped hydro make the total system cost higher than total system cost of *C1 RE target* scenario.

In conclusion, if the battery investment cost does not decrease and is kept constant at 2020 level, the battery capacity will decrease by about 2 GW in 2030 and 2040, while a significant change will occur in 2050 with 32GW reduction of battery capacity, compared to the *C1 RE target* scenario. In 2050, pumped storage hydro power plants will appear in the system at a level about 6 GW. The volume of imported coal and domestic gas capacity will increase, solar power will decrease while wind power will increase to ensure RE target.

7.4 Sensitivity analysis on PV potential

Based on the national renewable energy development plan prepared by Institute of Energy (October 2018), the economic potential of solar power in Vietnam is divided into two cases: High case and base case (see below picture). The high case has been included in the calculation in the *C1 RE target* scenario. Therefore, in order to assess the impact when the potential of solar power is lower, potential parameters of the base case will be used for sensitivity analyse. Accordingly, the potential of solar power is expected to fall by more than a half compared to the *C1 RE target* scenario.

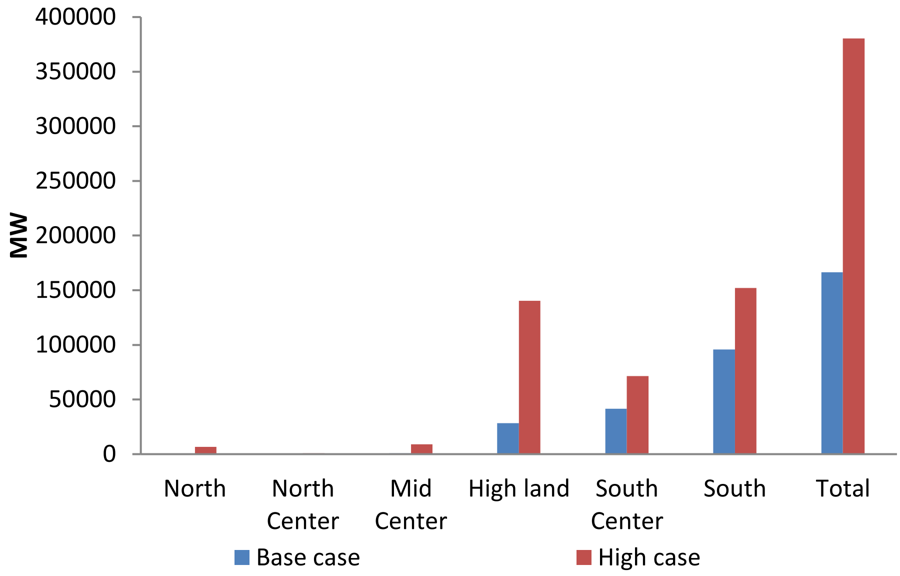


Figure 79: Economic potential of solar power in Vietnam. Source: Draft report of Vietnam Renewable Energy Development Plan (10/2018).

Results

The change in capacity structure will only appear in 2050. The installed capacity of solar power decreases by 5.2 GW and wind power capacity increases by 2.6 GW, at the same time, the capacity of battery reduces 1.2 GW. This result is due to the land cost assumption for solar PV, where 50% of the potential capacity has low land cost and the remaining 50% potential has high land cost. So, with less PV potential, PV solar capacity potential with low land cost is also less compared to the *C1 RE target* scenario.

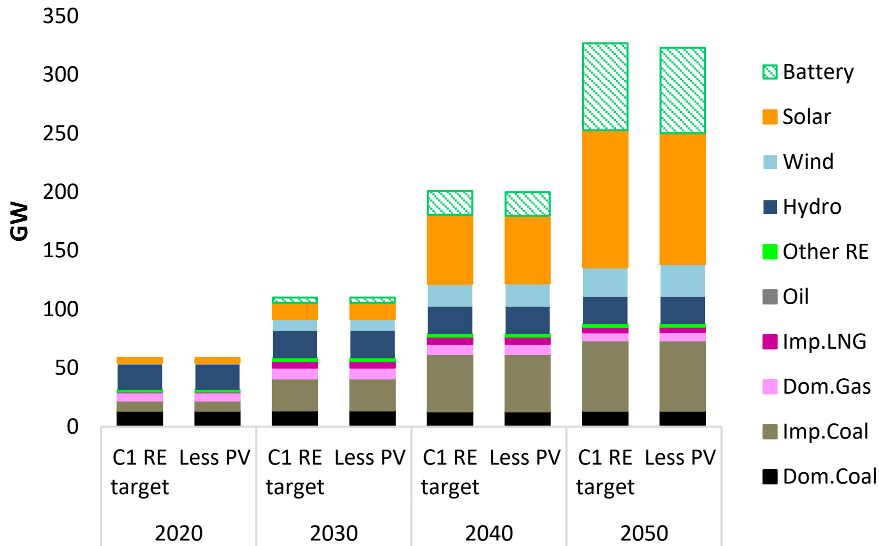


Figure 80: Comparing Installed capacity by power source type in the Less PV and C1 RE target scenarios.

When comparing installed capacity by regions in the *Less PV* scenario in 2050 (Figure 81) and potential of base case, it can be seen that: the installed capacity of solar in each region in the *Less PV* scenario is still smaller than the potential. However, the capacity of solar is different between *C1 RE target* and *Less PV* scenarios in Highland and South Central. In the Less PV scenario, the capacity of solar in Highland is reduced by about 9 GW, while South Central is increased by about 7GW. The increased capacity of wind (about 2.6 GW) occurs in the Highland.

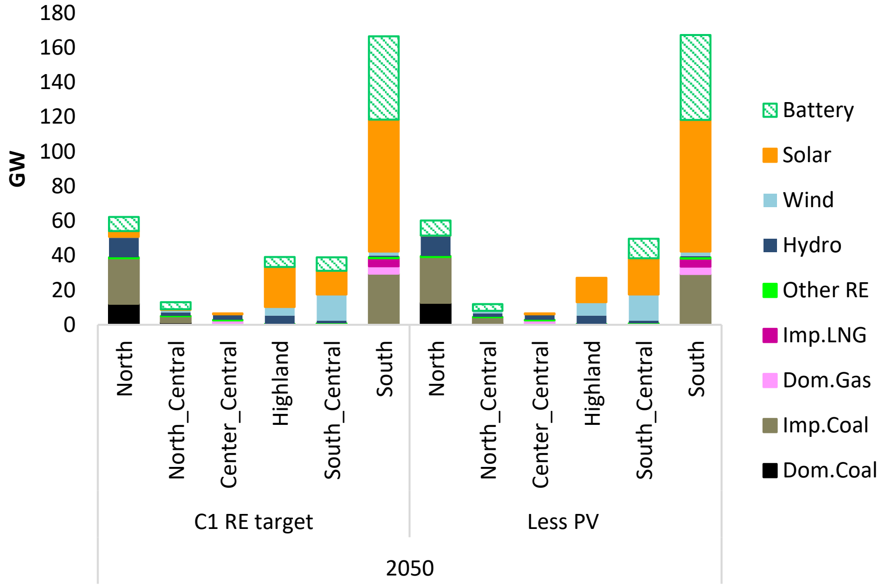


Figure 81: Comparing Installed capacity by power source types and regions in the Less PV and C1 RE target scenarios in 2050.

Analysing the energy generation structure, since the RE target is still applies in the *C1 RE target* scenario, the output of coal and gas power sources have not changed. By 2050, energy generation of solar will decrease by 7.8 TWh and is replaced by an equivalent amount of energy generation from wind power.

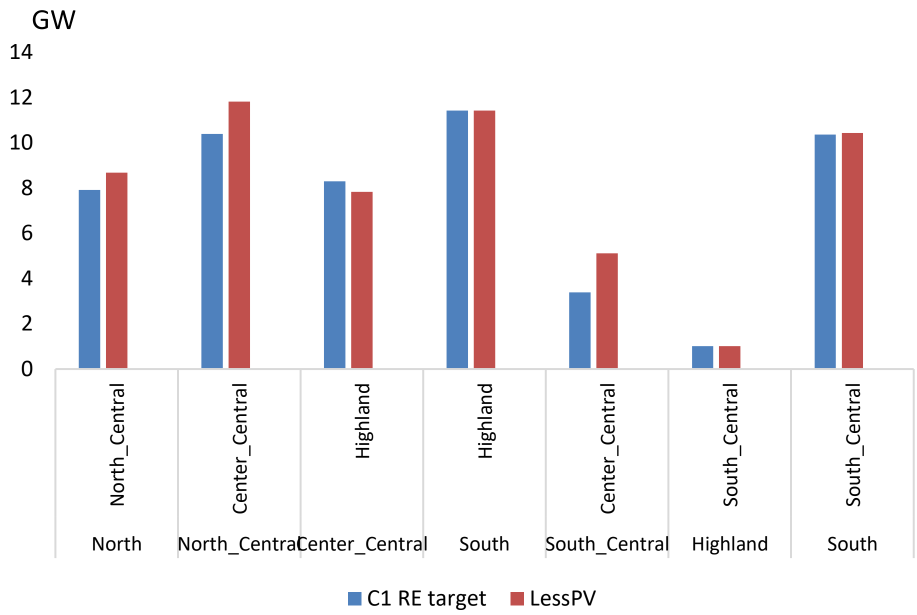


Figure 82: Comparing Transmission capacity between regions in 2050 in the Less PV and C1 RE target scenarios.

The largest change in transmission capacity between regions is the South-Central to Centre-Central interface with an additional capacity of 1.7GW in 2050. This is due to the changing PV solar capacity in Highland and South Central, resulting in higher transmission capacity from South Central to the North.

The total system cost in the *Less PV* scenario will be slightly higher than in the *C1 RE target* scenario. However, the total cost difference is nearly insignificant with a cost increase of about 0.5% in 2050. The cost in the years 2030 and 2040 are almost unchanged.

In conclusion, in the *Less PV* scenario in which the solar power potential is reducing by more than 50%, the capacity of renewable energy sources will only be changed in 2050, where wind power increases by 2.6 GW while solar power decreases by 5.2 GW and battery storage decreases by 1.2 GW. This change will add 0.8-1.7 GW of transmission capacity from South Central to North and results in a 0.5% increase in system cost.

7.5 Sensitivity analysis for less output of hydro

This section studies the change in decisions for the development of the power capacity with less hydro output. For this purpose, a dry year where hydrological parameters at 75% water frequency of hydropower plants has been modelled and compared to the *C1 RE target* scenario.

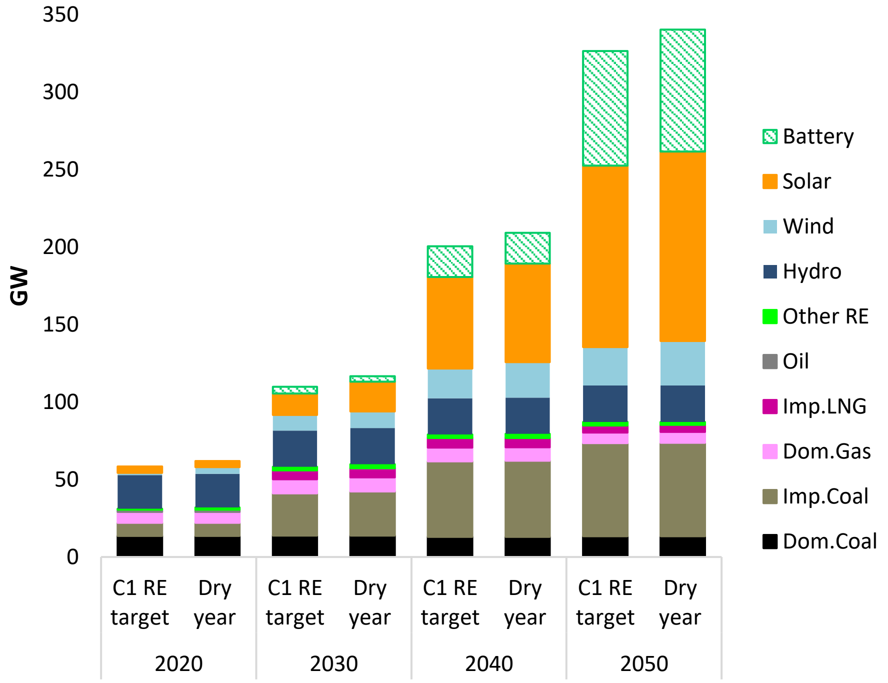


Figure 83: Comparing Installed capacity by power source type in the Dry year and C1 RE target scenarios.

Capacity of imported coal and domestic gas is increased insignificantly in the *Dry year* scenario (only about 0.3 GW in 2030, 2040 and 2050) compared to the *C1 RE target* scenario. Because of the RE target, the capacity of wind, solar and biomass is increased in the *Dry year* scenario. The change in generation capacity mix starts from 2020, with nearly 3 GW of wind and 0.8 GW of biomass additional capacity in the *Dry year* scenario.

Compared to the *C1 RE target* scenario, PV solar increases by about 5 GW in 2030, 2040 and 2050; wind power is increased by about 0.5 GW in 2030 and 3.8 GW in 2040 and 2050; battery capacity is changed significantly in 2050 with an additional 4.6 GW of capacity compared to the *C1 RE target* scenario.

About energy generation, hydro output is reduced by 19.6 GWh in the *Dry year* scenario, renewable energy generates instead in 2040, 2050 with the same generation energy. As an exception, imported coal power generation is increased about 7GWh in 2030. This happens because the RE-target is overfulfilled in 2030 in the *C1 RE target* scenario.

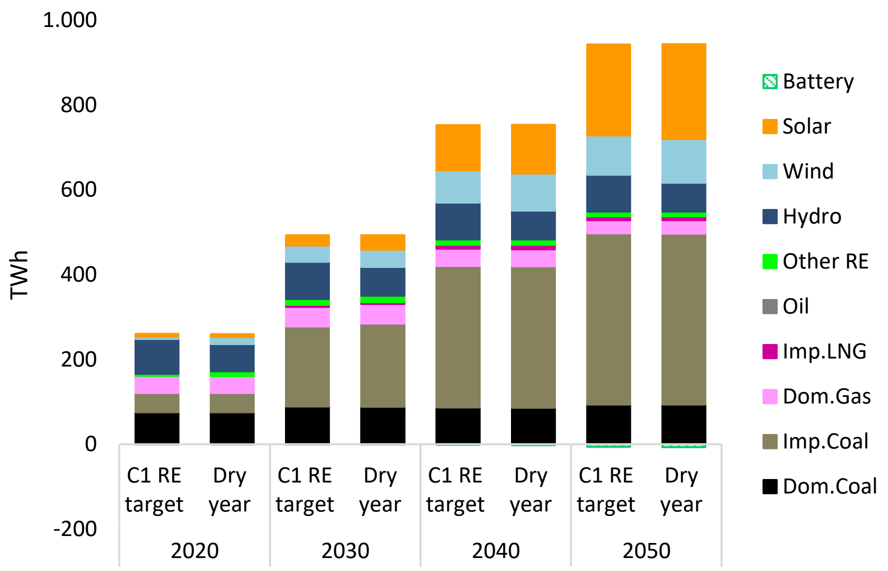


Figure 84: Comparing energy generation by power source type in the Dry year and C1 RE target scenarios.

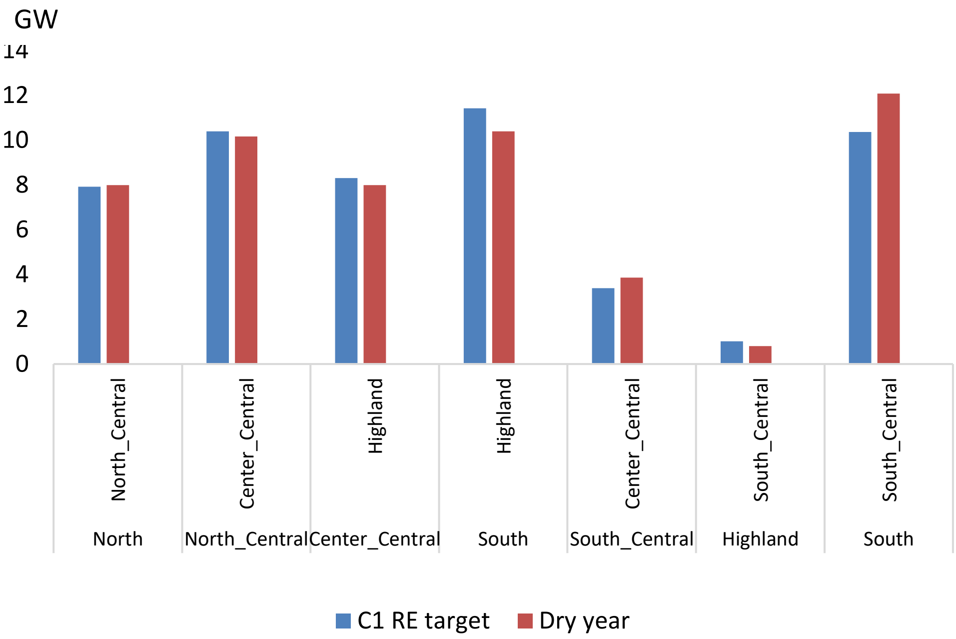


Figure 85: Comparing Transmission capacity between regions in 2050 in the Dry year and C1 RE target scenarios.

Because of increasing capacity of solar and wind in the South Central region in *Dry year* scenario, the transmission capacity in the interface from South Central to South will increase nearly 2 GW compared to the *C1 RE target* scenario. This is the most significant change for the transmission capacity.

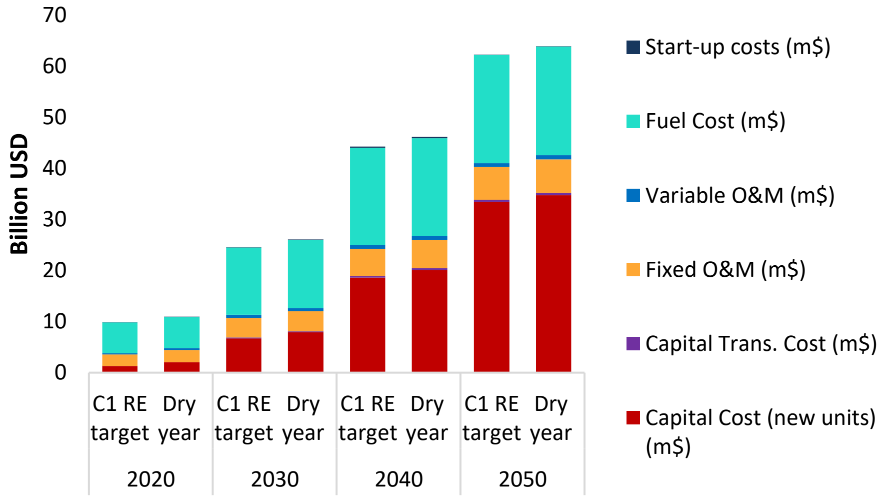


Figure 86: Comparing total system cost in the Dry year and C1 RE target scenarios.

Total system cost of the *Dry year* scenario is higher than *C1 RE target* scenario, with an increase of about 6% of system cost in 2030 and about 3% of total system cost in 2050.

In conclusion, in *Dry year* scenario, the power source development plan will be added more capacity of renewable energy compared to the *C1 RE target* scenario, specifically: 3 GW of wind and 0.8 GW of biomass in 2020; 5 GW of solar PV and 0.5 GW of wind in 2030; 5 GW of solar PV and 4 GW of wind in 2040; 5 GW of solar PV, 4 GW of wind and 4.6 GW of battery in 2050.

7.6 Sensitivity analysis overview

All scenarios for the parameter variation are consistent with least-cost optimal solution. However, the change is not very large because of RE requirement which is implemented in all sensitivity scenarios. The change in capacity mix of each scenario compared to the *C1 RE target* scenario can be seen in Table 15.

Table 15: Summary of parameter Variation Analysis.

No	Scenario	Value variation	Change in capacity mix compared to the *C1 RE target* scenario
1	High fuel prices	Forcasted prices of imported coal and LNG by the Current policy scenario	There is the impact that we in general expect: Higher fuel price, higher RE share. In 2030, imported coal decrease 1 GW, solar increase 3 GW, RE requirement is overfulfilled (35%). In 2050, capacity of renewable energy is changed a little, but the capacity of coal is reduced about 2 GW and capacity of battery is increased by about 3 GW.
2	Low fuel prices	Forcasted prices of imported coal and LNG by the Sustainable policy scenario	Imported coal capacity increases while LNG capacity is unchanged. In 2030, imported coal increases by 1 GW, solar decreases by 0.5 GW, biomass reduces by 0.5 GW. In 2050, capacity of imported coal increases by 1.5 GW and the capacity of battery reduces by 1 GW in the *Low fuel* scenario comparing with *C1 RE target* scenario.
3	No UC improvement	Unit commitment of new power plants will have the same parameters as in 2020	In 2050, the *No UC improvement* scenario has 2 GW of battery storage more than the *C1 RE target* scenario, a decrease of 0.8 GW solar and an increase of 0.8GW wind. In the *No UC improvement* scenario, the system has to add more battery and transmission capacity, the little higher of wind generation will replace some of solar and imported coal.
4	High cost Battery	Investment cost of battery in period to 2050 will be the same one in 2020	Battery capacity decreases about by 2 GW in 2030 and 2040, the significant change will occur in 2050 with a 32 GW reduction of battery capacity compared to the *C1 RE target* scenario. In 2050, pumped storage hydro power plants will appear in the system at a level about 6 GW. The volume of imported coal and domestic gas capacity increases, solar power decreases while wind power increases to ensure the RE target

No	Scenario	Value variation	Change in capacity mix compared to the *C1 RE target* scenario
5	Less PV	Using base case economic potential of solar power (a half of potential of *C1 RE target* scenario)	The structure of renewable energy capacity only changes in 2050, of which wind power increases by 2.6 GW while solar power decreases by 5.2 GW and battery capacity will be reduced by 1.2 GW. This change adds 0.8-1.7 GW of transmission capacity from South Central to North
6	Dry year	Hydrological parameters at 75% water frequency of hydropower plants	More capacity of renewable energy is seen compared to the *C1 RE target* scenario to ensure the RE target, specifically: 3 GW of wind and 0.8 GW of biomass in 2020; 5 GW of solar PV and 0.5 GW of wind in 2030; 5 GW of solar PV and 4 GW of wind in 2040; 5 GW of solar PV, 4 GW of wind and 4.6 GW of battery in 2050

The results of above 5 scenarios of variation parameter show that there will be lots of solar and battery to 2050 in any case. Especially, the High cost battery and the Dry year scenarios are interesting, as they seem to have the largest impact on the results.

In High cost battery scenario, because of RE target, solar power will decrease while wind power will increase (a shift from solar to wind). Even with the high battery costs, battery capacity still appears from 2030 and there are still lot of batteries in 2050 (42GW). Some pumped storage is entering instead of batteries in 2050.

In order to reserve for dry years, the power source development plan should be added more capacity of renewable energy comparing with C1 scenario. In 2020, wind power can be development to 4GW. About 5-10 GW of solar and wind power should be add more in each year 2030, 2040, 2050 to ensure RE target.

8 Discussion and key findings

8.1 Energy efficiency

Different sectors feature with different levels of energy savings, when compared to the baseline demand, with EE devices and measures being cost-effective across all economic sectors. By 2030, EE measures modelled in the *C3 Energy efficiency* scenario can reduce the final energy demand by 8.9%, 11.0%, 22.7% and 13.4% for industrial, commercial, residential and transport sectors respectively, with respect to *C1 RE target* scenario.

In the industrial sector, iron & steel, cement, textile, pulp and paper are the most important subsectors where efficient motors, VSD and efficient boilers/furnaces are key technologies for realizing least-cost EE potential. In the residential sector, efficient technologies and higher performance standards in lighting and cooling devices are needed. In transport sector, fuel economy standards in road transport for car, motorbike and other commercial vehicles help reduce significantly final energy consumption. Modal shift from private to mass transit public transport is also useful in saving fuel use for the transport sector.

With enhanced EE devices, up to 632 PJ of final energy consumption can be saved by 2030 and 1970 PJ by 2050. Moreover, the energy efficient technologies can save annually 76.8 Mt CO_2 by 2030 and 207.4 Mt CO_2 by 2050. The EE measures introduced can save system costs annually from 0.9% to 11.2% in the period 2020-2050. Even though additional investment incurred for EE technologies, a large amount of fuel costs can be saved, thus resulting in an overall reduction of the total system cost. On the other hand, modelling of EE options does include the technology costs (investment, O&M, fuel), yet not the costs associated to the implementation of different measures to promote the EE uptake.

8.2 Energy resources

Domestic fuel resources are all economic sources for future energy development. In both scenarios, domestic resources such as coal, natural gas, crude oil and biomass are all fully utilized. Biomass is a cost-effective fuel for industrial processes and CHP applications. Developments of biomass resources for industrial and power sectors will play a very important role in saving costs and reducing fossil fuel use. Options for biomass co-firing technologies are very attractive in the industrial sector and can deal with current unstable biomass supply in some areas of the country. Solar and wind are major domestic resources when it comes to power production, which will still be available in the period up to 2050. The main differences between the scenario with and without high EE uptake are found in domestic resource allocations among the economic sectors and imported resources.

Despite the significant increases in RE deployment (especially in power sector) in later years, fossil fuel dependency, which accounts for about 80% of the total primary energy supply, is still high in all five scenarios. Imported resources such as coal and natural gas will really be needed to fuel the economy in the period up to 2050. Imported coal is mainly used for power generation. Crude oil and oil products are mainly required for transport activities. Imported LNG will be valuable for industries as well as for the power sector, especially in the *C2 No new coal* and *C4 Combination* scenarios, where new coal investments are restricted. Electricity imports are also utilized at their maximum potential. By 2020, imported fuel dependency will reach about 30% of TPES, and it will increase quickly to 51% to 60% by 2030, then to 58 to 79% in 2050 across scenarios. A combination of RE, EE efforts and a no new coal policy may reduce reliance on imported fuels to 58% by 2050 with some increase in the total system cost.

8.3 Power sector

The historical growth in electricity demand in Vietnam has been very high, due to rapidly increasing electrification rates[12]. More recently, the average annual growth in electricity demand from 2009 to 2017 was 11%. This development has been driven by economic growth with significant expansion in industrial production, though the demand growth surpasses the economic. The continuous growth in Vietnam's power demand even with a high penetration of EE makes it crucial to establish new power generation projects in order to provide a sustainable and stable power supply.

Fuel resources

Several local energy sources are significant but limited, e.g. domestic coal and natural gas, as well as waste, biomass, small and large hydro. With the rapid increase of electricity demand in Vietnam these sources of energy are quickly fully utilised, and three main alternative energy resources emerge and dominate the analysed solutions:

- Wind and solar PV in combination with batteries
- Imported coal
- Imported LNG

[12] More than 98% of households have access to electricity today, compared to just 2.5% in 1976.

When discussing the burden of imported fuels, it is important to clarify whether the focus is on the cost for the imported fuel – or on the amount of imported fuel (PJ). In many situations the cost aspect (USD) may be more important than the technical energy perspective (PJ). Comparing imported coal and LNG, it is clear that LNG is more expensive, but induces lower CO_2 emissions.

Summarizing the analysed power scenarios, one could say that in a least cost development, depending on the focus point, different types of generation come into play (see also Figure 87):

- Achieving a high share of renewable energy in the power sector:
    - Mainly expansion with solar PV and wind
    - Imported coal is preferred over LNG due to lower price
- Achieving dependency on imported fuel (reduction in imported fuel costs)
    - Mainly expansion with solar PV and wind
    - Imported coal is preferred over LNG due to lower price
- Achieving 30% or more CO_2 emission reduction in the power sector (compared to the *C1 RE target* scenario):
    - Mainly expansion with solar PV and wind
    - Imported LNG is preferred over coal due to lower emissions

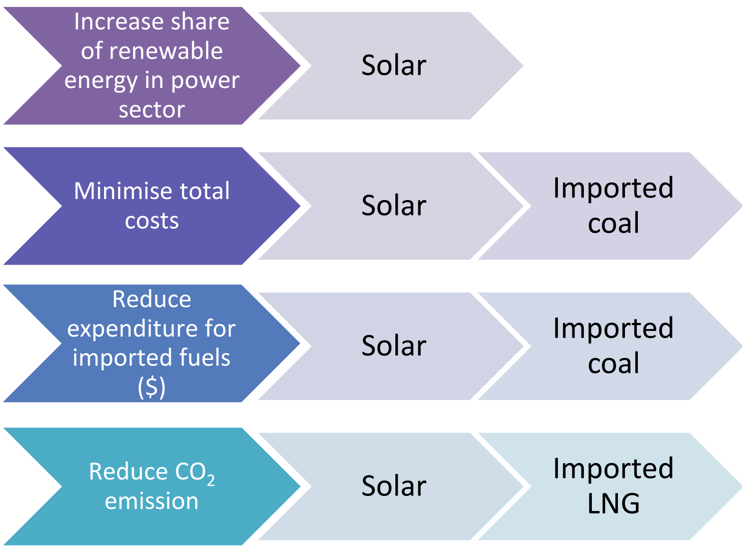


Figure 87: Three types of policy goals and the RE target responses for least-cost solutions.

Energy efficiency

Energy efficiency implementation results in a lower power demand, which increases the RE share. This can be seen, e.g. when comparing the *C2 No new coal* scenario and the *C4 Combination* scenario, where in 2050 the RE share increases from 50% to 59%. A lower power demand also results in lower power sector costs. In the two above mentioned scenarios, the costs decrease from 68 Billion USD to 48 Billion USD, i.e. a 38% decrease.

Renewable energy

Wind and solar power production technologies offer a new cost-effective way to reduce both CO_2 emissions and fuel imports. In all the 5 *Core* scenarios and the 11 *Green power* scenarios, power generation from wind and solar PV play an important role in the Vietnamese power mix.

In 2030, significant expansions in both onshore wind and solar PV are seen in all *Core* scenarios. The share of renewable generation in the *C0 Unrestricted* scenario is the same as in the *C1 RE target* scenario (33%), which is slightly higher than the requirement implemented, indicating that wind and solar generation are least-cost investments from a socio-economic perspective. In the *C2 No new coal* scenario, the generation from imported coal is replaced by wind and solar generation resulting in a 43% RE share, where even offshore wind comes into the power mix. In the *C3 Energy efficiency* scenario and the C4 Combination scenario, RE generation also surpasses the share found in *C1 RE target*, with 37% and 40% respectively.

After 2030, the least-cost expansion in RE is predominantly solar power generation. However, onshore wind expansion has a role in the limited areas with high wind speeds and in some regions also in medium wind speed areas. For example, in 2050, 43% of the generation comes from renewable sources in the *C1 RE target* scenario, hereof 23% solar, 9% hydro, 7% onshore and 3% offshore wind. When increasing the RE share requirement to 80%, the RE generation consists of 54% solar, and 12% onshore wind, other RE shares do not increase. The 289 GW of solar capacity in this case, would still only cover 1.15% of the total land area in Vietnam.

Power system balancing

The incoming variable renewable energy from wind power and solar PV require adequate balancing options in the Vietnamese power system. The least-cost optimization includes investment in balancing options in the forms of transmission lines between regions, batteries which can be optimized independently on volume size and effect (power output capacity) and pumped hydro projects.

Starting in 2030, the least-cost solution for meeting the RE targets involves the utilisation of batteries to balance the system. As a result, by 2050 the total installed battery capacity depending on the scenario is between 73 and 739 GWh storage capacity (32 and 205 GW effect). For the *C1 RE target* scenario, 1.75 MWh storage and 0.63 MW effect of battery is installed per MW solar power. Batteries were found to be a more attractive option than pumped storage solutions, as they are cheaper per MW effect.

With the introduction of larger RE shares in the power system, the transmission capacity in between the region also increases rapidly. By 2050, from 53 GW transmission (all lines summed) in the *C1 RE target* scenarios to 130 GW in the *RE6 80pct* scenario. This transmission is not just used for balancing of the variable RE but also serves to transmit power from regions with high RE resources to the main demand centres.

8.4 Climate impact

CO_2 emissions from the energy sector are increasing quickly at 7.0% p.a. in 2020-2030 and 4.0% p.a. in the whole period of 2020-2050 in the *C1 RE target* scenario. Power generation is the main contributor for the increased CO_2 emissions followed by industrial and transport sectors.
EE measures can reduce the CO_2 emission growth rate in 2020-2050 from 4.0% p.a. in *C1 RE target* scenario to 3.3% p.a. as compared to *C1 RE target* scenario. CO_2 emission reductions are mainly obtained in the power and transport sector.
The introduction of large shares of wind and solar generation are the cheapest alternative to reduce CO_2 emissions from thermal generation, with RE share reaching around 50% of the generation (*EL4 60pct* and further). Further CO_2 reductions are achieved by using imported LNG instead of imported coal.
As compared to the MONRE's BAU emissions, CO_2 emission reductions with REDS's RE targets can fulfill the unconditional target of 8%. Moreover, the RE target and the additional EE efforts in *C3 Energy efficiency* can fulfill the conditional target of 25%.

8.5 Discussion

Wind and solar

The International Renewable Energy Agency (IRENA) has undertaken analysis of the realised costs from thousands of wind and solar projects worldwide. It documents that a strong reduction in investment costs for wind and solar has taken place from 2010 to 2017. The levelized costs of onshore wind and solar PV are now in the same range as traditional fossil fuel plants. In 2010, the levelized cost of a typical PV project was USD 0.35 per MWh, whereas in 2017 it fell to USD 0.10 per MWh. This can be compared to typical costs for fossil fuel-based generation of USD 0.05 to 0.15 per MWh (IRENA, 2018, b).

In this study, the investment costs for solar power have been assumed to decrease from 1.08 USD/kW_{ac} in 2020 to 0.63 USD/kW_{ac} in 2050 (a 42% decrease). This remarkable development is backed by many international reports, including the 2018 World Energy Outlook from the International Energy Agency (IEA, 2018). These decreases in cost are an important driver for the large implementation of wind and especially solar in the model results.

Variable electricity generation from wind and solar power can pose challenges for any power system. To accommodate production from these variable sources, new procedures are required (e.g. for wind and solar generation prognoses, new role for hydro power to balance the system), and investment in new transmission capacity and storage may also be relevant.

While levelized costs for wind and solar are decreasing and competing with traditional generation, they require large capital costs investments, which could be challenging in terms of acquiring financing.

Key aspects that need further research – and where more information will be available when more solar PV parks are installed in Vietnam – is the solar potential and the land cost for solar PV farms. Currently the land costs are assumed to be 6 USD/m^2 for the first half of the total solar potential and the double for the last half.

Rooftop solar has not been considered in this study. However, generation from rooftop solar could supplement utility scale solar power, as it can save on land-use costs, while at the same time requiring lower investments in grid reinforcement as the generation is located at the demand sites. Due to the smaller scale, rooftop solar is generally more expensive than utility scale, which would make utility scale investments the preferred solution in a least-cost optimization.

Storage

As with wind and solar production, batteries see a rapid decrease in costs. Based on the current assumptions, the least-cost analyses will use batteries instead of pumped hydro to balance the system in the scenarios with a high share of renewable energy. The pumped hydro facilities that are used as investment options represent six concrete projects. While comparing pumped storage and batteries by investment per storage capacity (USD/MWh) reveals similar values, comparing them on cost per effect (USD/MW) and in round-cycles efficiency, batteries detain better values (Table 16). The pumped hydro candidates may be further optimised to compete with batteries. The power system seems to prioritise short-term storage.

Table 16: Comparison of pumped storage and batteries, averaged over the 8 projects given as investment options.

	Investment cost kUSD/MWh	Investment cost kUSD/MW	Efficiency %
Pumped storage (average*)	96	887	80%
Batteries (2030/2050)	270/90	500/140	91%/92%

Batteries used for power system balancing are a relatively new technology, which involve several uncertainties. Considerations on the lifecycle assessment of batteries should be taken into account, including an assessment of their impact on environment and the availability of needed resources during their production phase and at the end of their lifetime.

Imported fuels

Due to the large expected increase in demand (both final energy demand and power demand), domestic fuels will not be sufficient to supply the required energy. While renewables can supply a large part of the additional demand in the power sector, the remaining energy generation will be supplied by imported fuels.

In the scenario analysis, coal comes out as the dominating thermal fuel source when CO_2 emission reductions are not prioritised, as its variable generation costs are lower (import LNG has about 3 times higher fuel costs). In recent years, however, coal generation has been met with resistance from the public due to its negative effects on environment and health. Financing difficulties are a further obstacle for development of coal generation. These considerations are not included in the current study and could implicate a large participation of the more expensive but less polluting imported LNG fuel.

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