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Decarbonisation pathways for Southeast Asia

Technical background report

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Decarbonisation pathways for Southeast Asia - Technical background report

Project coordination

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Contents

List of abbreviations

ASEAN	Association of South East Asian Nations
BEV	Battery Electric Vehicles
BF	Blast Furnace
BOF	Basic Oxygen Furnace
CASE	Clean, Affordable and Secure Energy for Southeast Asia
CCS	Carbon Capture and Storage
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
LPG	Liquefied Petroleum Gas
PV	Photovoltaics
RE	Renewable Energy
SAF	Sustainable Aviation Fuels

Executive Summary

Link to the main report

The aspects described in this technical background report form the basis for the main report prepared as part of the same activity within the CASE[1] project. The main report looks at possible future pathways for decarbonising the energy system of the ASEAN region in two scenarios. One scenario focuses more on the use of green gases while the other examines the implications of a stronger focus on electrification. The decarbonisation options of the two scenarios are based on the technologies described here for the different sectors. In addition, this background report provides a summary of the current state of fossil gas in the region.

Current state of fossil gas in the region

Natural gas consumption in the ASEAN region has strongly increased over the past 20 years, mainly due to population and economic growth. To meet the growing regional demand for natural gas, exploration has been accelerated by increasing production volumes, particularly in Malaysia, Indonesia and Brunei Darussalam. However, the discovery of new gas fields has been limited, resulting in a 35% decline in ASEAN reserves between 2010 and 2020. If these trends continue and gas demand keeps rising, the region could become a net importer as early as 2025.

Gas transport by pipeline in the ASEAN region has so far been mainly domestic, with a small proportion of cross-border connections. Given the archipelagic nature of the ASEAN region, liquefied natural gas (LNG) plays an important role in trade and imports, for example from Qatar and Australia. As of March 2023, 11 new LNG regasification terminals are under construction and a further 34 projects are proposed to ensure security of supply despite the likely future net import dependency.

The region is also a net importer of other fossil fuels, particularly oil. Indonesia's large coal reserves and exports have led to a sharp increase in coal consumption and trade in the region, mainly for power generation. The other three CASE countries are net importers of coal, mainly from Indonesia.

Possible options for decarbonisation

Measures to reduce energy demand play a crucial role in reducing greenhouse gas emissions and should therefore be prioritised according to the "energy efficiency first" principle. In addition, technological solutions are needed to switch the remaining energy demand from fossil fuels to renewable energy sources in the relevant sectors.

<u>Power sector</u>

In 2020, 75% of ASEAN's electricity was generated from fossil fuels, which accounted for 36% of the region's total greenhouse gas emissions. To decarbonise the ASEAN electricity system, large-scale integration of renewable energy is needed. This requires significant system flexibility throughout the energy system and the development of short- and medium-term storage as well as demand response. Stationary batteries with a runtime of a few hours and pumped hydro storage with a runtime of hours to days can absorb excess energy and shift it to peak demand periods. Green hydrogen production combined with storage can also provide long-term flexibility to the

[1] CASE: Clean, Affordable and Secure Energy for Southeast Asia, see https://caseforsea.org/ for details on the project.

electricity system through power-to-gas-to-power (P2G2P), where hydrogen is produced during periods of renewable electricity surplus and electricity is generated from hydrogen during periods of renewable electricity shortage. However, this form of storage results in high conversion losses, which makes it comparatively expensive.

Industry

The industry sector is the largest final energy consuming sector in the ASEAN region, with quick growth over the last 15 years (+60%). Heavy industries dominate energy use with non-metallic minerals (mainly cement), petrochemicals, and iron and steel, accounting for 40% of industry energy demand.

The options for decarbonising industry depend on the sub-sectors and processes involved. Overall, most of industrial processes can be electrified, especially mechanical processes where electric motors and machines can be used. Heating and cooling processes can also be largely electrified, with commercial solutions (heat pumps, electric boilers and others) already available for low and medium temperature heating (<400°C), covering most needs in food, textiles and pulp and paper. For higher temperatures, other electric heating technologies (plasma, microwaves, electric arc furnaces, etc.) would be required, some of which are not yet commercially available. Green gases or biomass can therefore be an alternative for some high temperature heating processes (>1000°C), and are also needed as chemical feedstock.

For the decarbonisation of heavy industry in the region, complementary options and processes are needed. For the cement industry, carbon capture and storage is the main alternative under consideration, as it can reduce both energy and process-related emissions. The use of alternative fuels to replace coal in clinker production, such as biomass or hydrogen, could reduce energy-related CO_2 emissions but not process emissions. Decarbonising iron and steel production requires several complementary approaches. The use of alternative fuels such as biomass or hydrogen in existing smelters can reduce the need for fossil fuels, but infrastructure adjustments may be required. Increased scrap recovery and the production of secondary steel through electric steelmaking can provide environmental benefits and lead to a more circular economy. Full decarbonisation of steel production will require investment in direct reduction technologies using hydrogen. Other electricity-based technologies are still in the research and development phase (e.g. electrolytic extraction, fused oxide electrolysis). The chemical industry has great potential to decarbonise its energy-related applications through direct electrification, as these are mainly used for refrigeration and steam (low to medium heat). By applying electrochemistry, alternative routes to chemical synthesis can be used, reducing the need for fossil fuels as both feedstock and energy source.

Transport

Transportation is the second largest final energy consuming sector in the ASEAN region. Road transport, which includes two-wheelers, cars, buses and trucks, accounts for more than 90% of total consumption, with the remainder coming from maritime and air transport. Oil is the main fuel in this sector, accounting for 91% of total transport energy consumption, followed by biofuels (7%). Direct electrification is the main way to decarbonise two-wheelers, cars and short-haul trucks through battery electric vehicles. The future of long-haul transportation is less clear, as hydrogen trucks and buses could find a market due to their greater autonomy and shorter refueling times. Nevertheless, battery-powered trucks and buses are gaining ground, with commercial models already available, and their total cost of ownership likely to be lower in the long term.

The decarbonisation of aviation and shipping will rely mainly on green gases or synthetic fuels. The use of hydrogen-based fuels, such as methanol and ammonia, appears to be the main alternative for shipping. Due to the size and cost of batteries, they are likely to be a viable alternative only for short distances (<200 km).

Next-generation biofuels can also contribute to the decarbonisation of transport, especially in the transition phase to full electrification or in hard-to-electrify cases (e.g., aviation). Biofuels are being promoted in the region, given its large agricultural sector, but sustainability and limited availability are concerns.

Residential

The residential sector accounted for 15% of the ASEAN region's energy consumption in 2020. Approximately 40% of energy demand is met by electricity, mainly for refrigeration, air conditioning, lighting, and electronics. The remainder is split between traditional biomass and oil (LPG), which is mainly used for cooking. Fossil gas use in the residential sector is negligible in the region, as there is virtually no demand for space heating in the region and water heating is already largely electrified. Improving access to clean cooking is one of the United Nations Sustainable Development Goals and can bring significant economic, health and environmental benefits to the populations concerned. Over the past 20 years, progress has been made in the region through access to electrification and LPG. However, to achieve full decarbonisation, fossil LPG will need to be replaced in the future by renewable alternatives, mainly electric stoves. In rural areas, efficient wood stoves could be an alternative.

1 Introduction

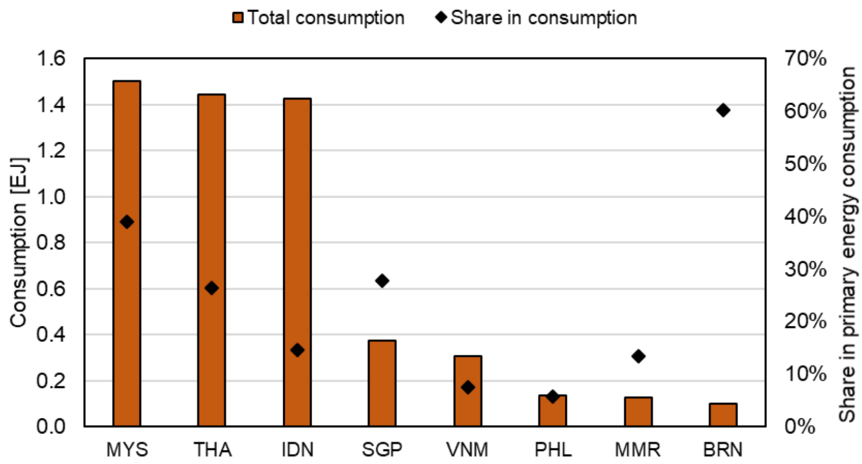
It is often claimed that fossil gas can fulfil the role of a 'transitional' or 'bridging' fuel for various applications on the way to renewable energy systems. Examples include replacing coal in power generation and industrial processes. However, for full decarbonisation, fossil gas will also need to be phased out. Russia's war on Ukraine and its impact on global energy markets, such as rising commodity prices, have added another layer of complexity to the use of fossil gas. In some applications, natural gas could be replaced by alternative green gases, such as low-carbon hydrogen. For other applications direct electrification will be the cheaper and more efficient solution. This report provides the technical background to the main report of the same activity within the CASE project, which discusses two decarbonisation pathways with different priorities for direct electrification and the use of green gases in individual countries of the ASEAN region. The decarbonisation options used as input for the two scenarios in the long-term energy system modelling are based on the technologies described in more detail in this background report, which is structured as follows. The first section describes the current state of fossil gas use, infrastructure and trade in the region. The second section examines possible decarbonisation options for different end-use sectors such as industry, transport, households and the power sector.

2 Current state of fossil gas in the region

2.1 Gas demand

Gas consumption is driven by the three biggest economies of the region: Indonesia, Thailand and Malaysia, which together represent over 80% of gas consumption in the region. In particular, Brunei Darussalam, Malaysia, and Thailand are highly dependent on fossil gas, as gas accounts for 59%, 39% and 28% of primary energy supply, respectively (BP 2022; IEA 2023a). Overall, gas consumption has seen a large growth in the last 20 years, increasing by more than 80%, driven mainly by population and economic growth (ACE 2022).

Figure 1: Fossil gas consumption and share of fossil gas in primary energy consumption in the different ASEAN countries in 2020



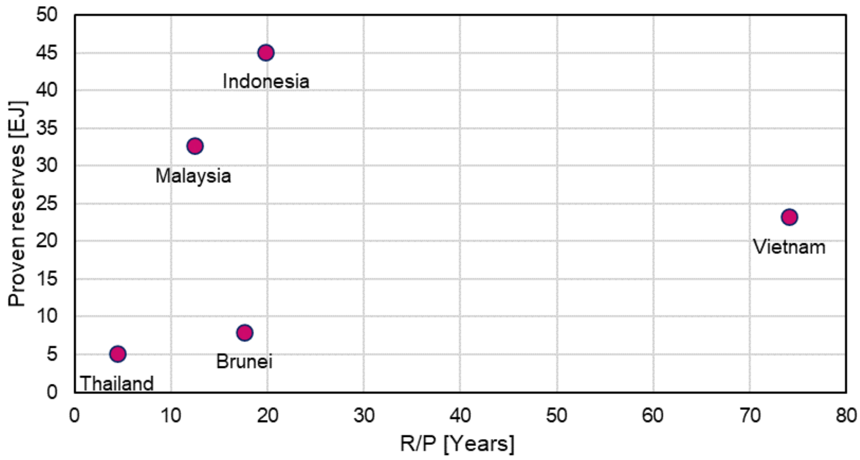
Source: Own elaboration based on (IEA 2023a)

Around half of the gas consumed in the region is used for power generation. With a share of 357 TWh of electricity (32% of total production), gas was the second most important fuel for power generation in the region after coal in 2020 (ACE 2022). In Brunei Darussalam, Singapore and Thailand, gas is even the most important fuel for power generation, accounting for 99%, 98% and 64% of the countries' total electricity mix respectively. Fossil gas is also used in large-scale industry, e.g. petrochemicals, and as an industrial feedstock, e.g. for ammonia production, mainly in Thailand, Malaysia and Indonesia (Franza et al. 2021).

2.2 Production and reserves

The ASEAN region has important fossil fuel resources, including natural gas. Natural gas production increased to 8.1 EJ in 2021, making the region a net exporter. The main producers are Malaysia (2.8 EJ), Indonesia (2.4 EJ) and Thailand (1.3 EJ), which account for 80% of the region's production. Other important producers are Myanmar, Brunei and Vietnam (BP 2022). The most important natural gas reserves (see Figure 2) are located in Indonesia (44.8 EJ), Malaysia (32.7 EJ) and Vietnam (23.3 EJ). The ratio of reserves to production (R/P) shows that Vietnam has reserves for more than 70 years, which is partly due to a lower production rate than its neighbours. The largest producers, Indonesia and Malaysia, have reserves for 12 to 15 years, while Thailand only has reserves for 4.4 years.

Figure 2: Reserves over production ratio (R/P) for natural gas in selected countries of the ASEAN region



Source: Own elaboration based on (BP 2022)

To meet the expected increase in regional gas demand, fossil gas production has been accelerated both by increasing the exploitation level and by boosting the search for new fields. However, the discoveries of new gas fields have been limited and ASEAN reserves have declined by 35% between 2010 to 2020 (ACE 2021). If these trends persist and the gas demand continues to increase, the region could become a net importer as early as 2025 (ACE 2022; IEA 2022).

2.3 Infrastructure and trade

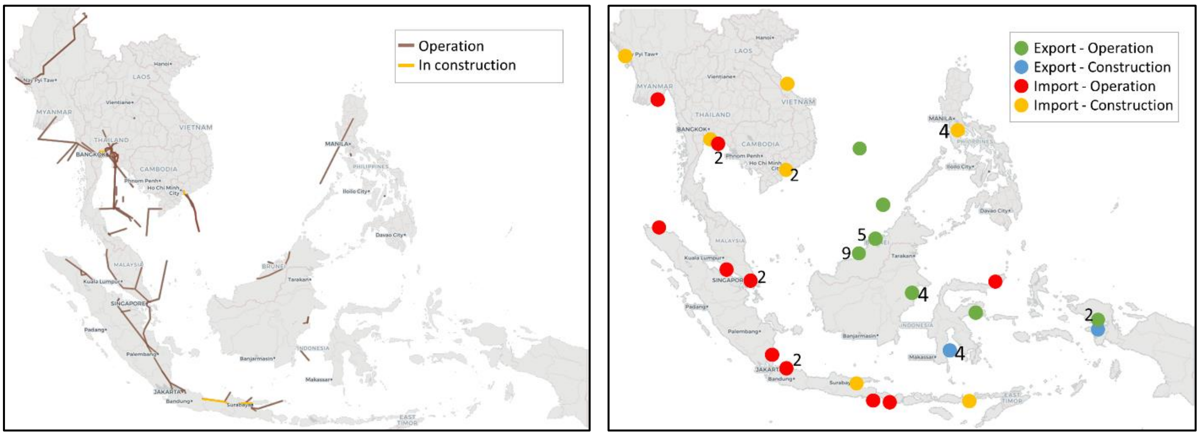
2.3.1 Pipelines and LNG terminals

Fossil gas needs to be transported from production centres, usually located in remote or offshore areas, to gas consumption centres. Gas transport through pipelines in the ASEAN region has been mainly undertaken at the national level (e.g. in Vietnam, Thailand and the Philippines), with low levels of cross-border interconnection (Franza et al. 2021). A more developed gas network can be found in the western part of Indonesia and Malaysia, connecting gas production sites in the South China Sea to Peninsular Malaysia, Singapore, Sumatra and the western part of Java (Jakarta). The main gas pipelines in the region are shown in Figure 3, left side.

Given the archipelago nature of the ASEAN region, liquefied natural gas (LNG) has taken an important role in the region. Up to 2010, all LNG terminals were built for export purposes (liquefaction terminals) in main producer countries (Malaysia and Indonesia), but since 2011 thirteen import terminals have been constructed. The LNG terminals (regasification and liquefaction) are shown in Figure 4 (right).

Figure 3: Main gas pipelines (left), and number of LNG terminals (right) in the ASEAN region in 2022

Main gas pipelines LNG terminals



Source: (Global Energy Monitor 2023a)

The gas exporters of the region have a total of 23 LNG liquefaction terminals (11 in Malaysia, 7 in Indonesia and 5 in Brunei), with 7 additional terminals in construction or proposed. All of them are on the east part of the region (in the islands of Borneo, Sulawesi and Papua). The current liquefaction capacity rises to 3.0 EJ (58.3 MTPA[2]), and is expected to rise to 3.9 EJ (75.6 MTPA, +26%) if all proposed projects are completed.

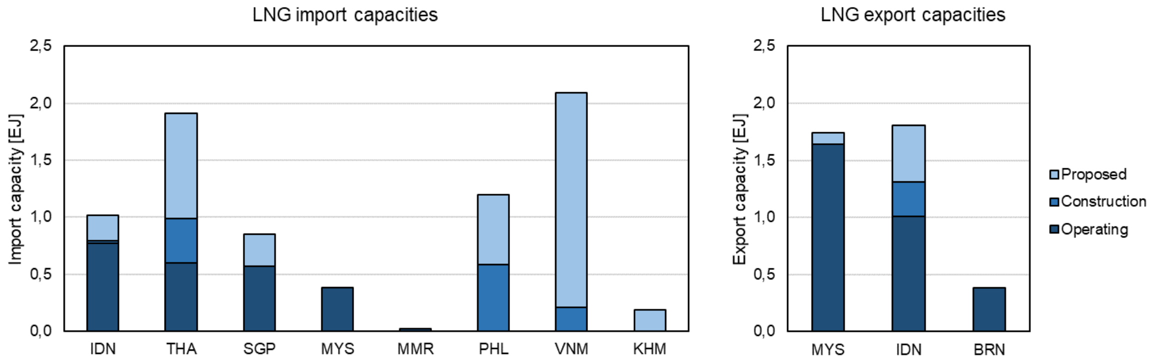
As the region is likely to become a net importer, LNG regasification terminals are promoted to be increasingly important to ensure security of supply. Currently, 13 regasification terminals are operational and 11 terminals are under construction in the region, including 4 in the Philippines and 3 in Vietnam which do not have regasification capacities yet. All countries of the region, with the exception of Brunei, Cambodia[3] and landlocked Laos have at least one LNG regasification terminal in operation or construction. Moreover, there are 34 additional proposed projects[4]. The current regasification capacities in the region rise to 2.3 EJ (45.0 MTPA), and could to rise to 7.7 EJ (147.3 MTPA, +227%) if all proposed projects are completed. This level (7.7 EJ) would represent 1.4 times the fossil gas consumption of 2021, and between 60% and 95% of expected fossil gas demand in 2040. The operational, currently under construction and proposed LNG capacities in the region are shown in Figure 4.

[2] MTPA correspond to million tons per year of LNG liquefaction or regasification.

[3] Cambodia has two proposed LNG regasification terminals, but none in construction yet.

[4] As of March 2023. Not all proposed projects might be actually developed.

Figure 4: Import (left) and export (right) capacities the ASEAN region, in 2022



Source: Own elaboration based on (Global Energy Monitor 2023a)

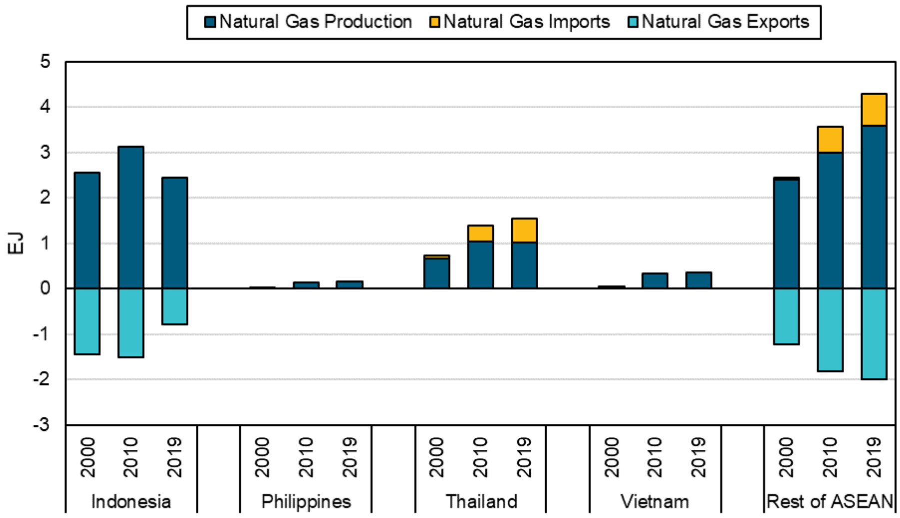
The development of gas infrastructure has been supported by the Trans-ASEAN Gas Pipeline (TAGP) project under APAEC[5], with the aim of creating of a common gas market and increase energy security of the region. Under the TAGP, international (bilateral) pipelines have been developed around the Singapore-Malaysia-Indonesia area and the dedicated pipelines from Myanmar production sites to Thailand. LNG terminals are also included within the TAGP infrastructure scope, with nine out of the thirteen existing import terminals developed within the TAGP framework (APAEC 2020).

2.3.2 Regional and international trade

Regional gas trade is still limited, with countries using mostly local production to meet domestic demand (see Figure 5), such as Vietnam and the Philippines, or exports outside the ASEAN region, such as Indonesia, Malaysia and Brunei. An exception is Thailand, which meets about one fifth of its consumption by imports from neighbouring Myanmar (via pipeline), complemented by LNG imports.

[5] ASEAN Plan of Action and Energy Cooperation, which includes regional collaboration programs in power grids, renewable energy, energy efficiency among others.

Figure 5: Historical evolution of natural gas production, imports and exports for the four CASE countries and the rest of ASEAN

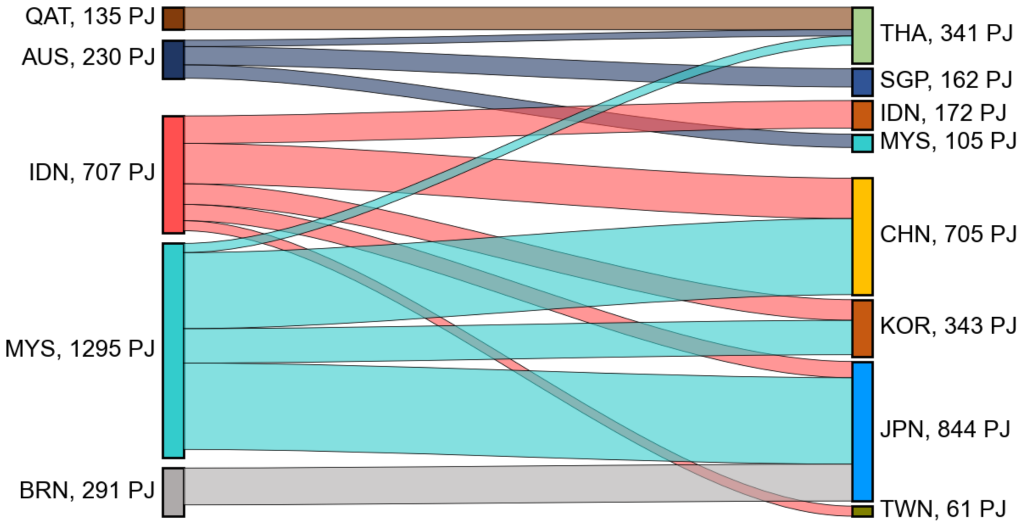


Source: Own elaboration based on (Enerdata 2023)

Given the limited extent of international pipeline capacity, a significant share of both regional and international trade is done via LNG, especially for exports from main producer countries. The main LNG flows (see Figure 6) are exports from Malaysia, Indonesia and Brunei, which reached 2.3 EJ in 2021 (around 30% of the region's production). LNG exports are directed mainly to Asian markets (China, Japan and South Korea). Thailand is the main LNG importer of the region (313 PJ in 2021), followed by Singapore (161 PJ). LNG is also used to transport gas within the region, as is the case of LNG flows from Malaysia to Thailand, and of internal flows within Indonesia or Malaysia, which reflects the geographical constraints of the region[6]. This trend might increase in the future, as LNG gains importance in the region's energy supply.

[6] Smaller LNG flows (<50 PJ) are not included in Figure 6, such as regional trade from Brunei to Thailand and Malaysia, and internal flows within Malaysia.

Figure 6: Main LNG flows to and from South East Asia in 2021 (>50 PJ)



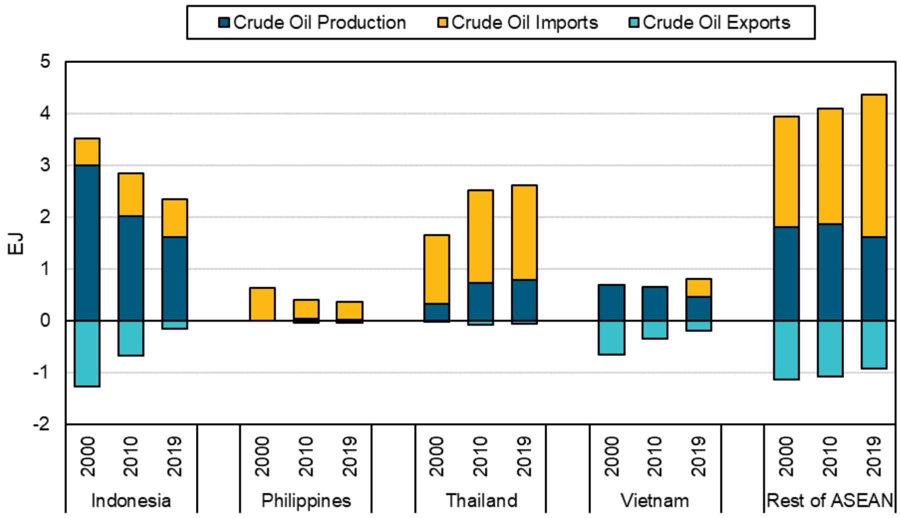
Source: Own elaboration based on (GIIGNL 2022)

2.3.3 Other fossil fuels

Crude oil

All four CASE countries, as well as the aggregated rest of the ASEAN region, imported more crude oil than they exported in 2019 (see Figure 7). In the historic trend from 2000 through 2010 to 2019, exports from Indonesia, Vietnam, and the rest of the ASEAN region have steadily declined, turning both Indonesia and Vietnam, into net importers by 2019 at latest. The Philippines and Thailand were already importers in the past and remain so today. Although Indonesia, Thailand, and Vietnam still produce crude oil domestically, the amount has declined in all countries between 2010 and 2019. Countries from the Middle East and Africa are the main suppliers of crude oil to the region. Given these figures, a shift away from oil, for example through electrification of the transport sector, could help reduce dependency on oil imports, which would otherwise likely increase for all countries in the region as the demand for transport services is expected to grow.

Figure 7: Historical evolution of crude oil production, imports and exports for the four CASE countries and the rest of ASEAN

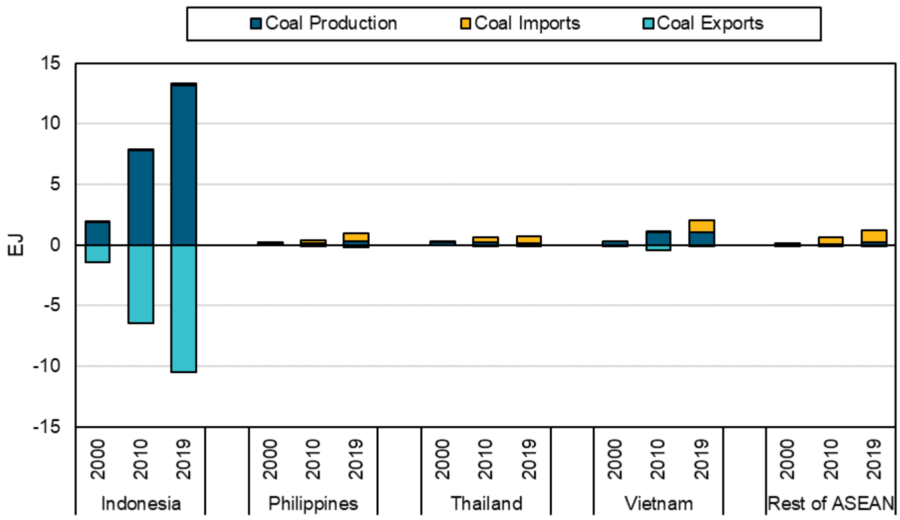


Source: Own elaboration based on (Enerdata 2023)

Coal

In the case of coal (see Figure 8), Indonesia stands out clearly from the other countries as a large producer. With the small exception of Vietnam, the remaining countries produce little or no coal domestically and meet their demand mainly through imports. Between 2000 and 2019, coal production in Indonesia increased sevenfold to 13.2 EJ, of which nearly 80% was exported. These figures show how important the coal industry is to both domestic demand and export revenues. Taken together, the exports exceed the imports of all other countries in the ASEAN, making it the main supplier of coal to other ASEAN countries. Nevertheless, phasing out coal should be a priority, as this is one of the biggest levers to reduce CO_2 emissions globally and thus achieve climate targets (see e.g. IPCC scenarios).

Figure 8: Historical evolution of coal production, imports and exports for the four CASE countries and the rest of ASEAN



Source: Own elaboration based on (Enerdata 2023)

3 Possible options for decarbonisation

The effective decarbonisation of ASEAN economies requires a gradual phase-out of all fossil fuels. To reduce emissions and increase the sustainability of the various sectors of the economy, demand reduction measures should be prioritised in line with the "energy efficiency first" principle. These measures are diverse and include the use of sustainable building materials, improving building insulation to reduce cooling needs, developing public transport to reduce traffic and improving reuse, recycling and recovery practices (circular economy). However, such specific energy efficiency measures are not discussed in detail in this section, which instead focuses on the various technical decarbonisation options in ASEAN in four main sectors: power generation, industry, transport and households.

Renewable green gases such as hydrogen and biogas are expected to play an important role in the decarbonisation of certain demand sectors. However, they will not replace all applications for which fossil gas is currently used. Particular attention is therefore paid to the potential use cases for green gases and how they compare to direct electrification. It is expected that direct electrification will be the leading solution for most use cases, such as low and medium temperature heat for industrial processes or electrification of transport for passenger cars and light commercial vehicles. Green hydrogen and its derivatives are needed where direct electrification is less feasible, e.g. in certain industrial processes or in heavy road transport, long-haul air transport and maritime transport. Biogas can complement direct electrification or the use of hydrogen, e.g. in industrial processes, depending on availability and sustainability. A summary of the decarbonisation options for the main use cases is shown in Table 1.

Table 1: Overview of role of direct electrification and green gases in the decarbonisation of key sectors

✓ denotes mature technologies, ~ medium-maturity, and ✖ low maturity.

The Horizon column denotes the time horizon when decarbonisation options will be available or needed.

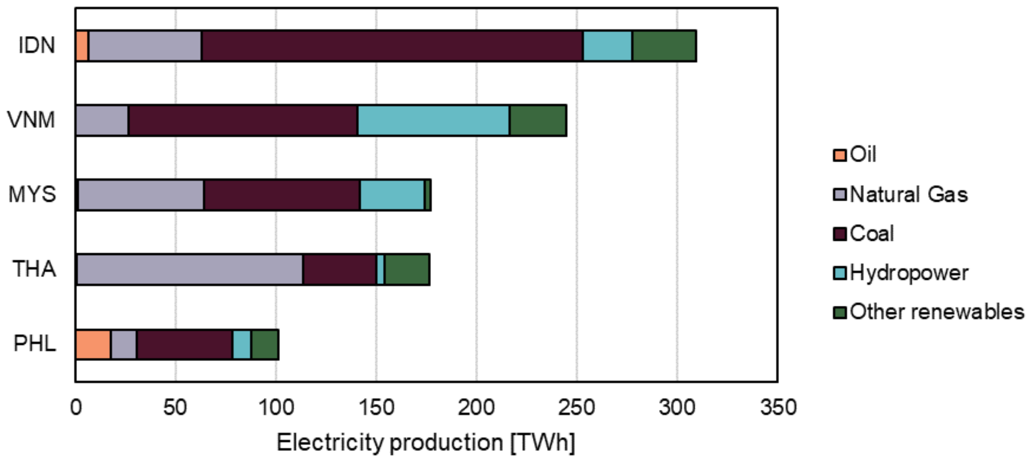
	Use case	H2 and derivatives	Biogas	Electrification	Other	Horizon
Power genera-	**Generation**	No	Yes ✓	-	Renewables,	**Now!**
	Short-term flexibility	No	Yes ✓	-	Generation, DSR, interconnections,	Short/medium
	Long-term storage	P2G2P ~	No	-	Gas/coal w. CCS, hydropower/PHS	Long term
Industry	**Oil refining**	Yes ✓	No	Energy needs	Blue H2 (CCS)	Short term
	Ammonia, Methanol	Yes ✓	No	E-chemistry ~	Blue H2 (CCS)	Short term
	Steel/iron	Yes ~	No	Yes ~	CCS, biomass, new technologies	Medium/long
	Chemicals	Feedstock ~	Uncertain	Yes ~	CCS	Medium/long
	Cement	Uncertain ✖	No	Uncertain ✖	CCS needed, new technologies	Long term
	High-temperature heat	Uncertain ✖	Niche ✓	Yes ~	Biomass	Medium
	Low/medium temperature heat	No	Niche ✓	Yes ✓	Biomass	Short term
Transport	**Aviation**	Yes ✖	No	Niche ✖	SAF (Biofuels)	Long term
	Shipping	Yes ✖	No	Niche ✖		Long term
	Long distance trucks	Uncertain ~	Niche	Yes ~	Railways	Medium
	Buses, Cars, 2/3 wheelers	No ~	Niche ✓	Yes ✓	2nd gen biofuels/biogas	Short term
Res	**Cooking**	No	Niche ✓	Yes ✓	LPG (transition)	Short term

3.1 Power sector

3.1.1 A fossil fuel-dependent sector

ASEAN's electricity generation mix is dominated by fossil fuels. In 2020, fossil fuels generated 75% of total electricity, which accounted for 36% of total GHG emissions in the region (ACE 2022). Coal is the dominant fuel for electricity in Indonesia, Philippines and Vietnam, while Thailand relies on fossil gas (see Figure 9).

Figure 9: Electricity production by source in selected ASEAN countries in 2021



Source: Own elaboration based on (BP 2022)

Electricity demand is expected to increase by a factor of 2 to 3 by 2050, according to prospective scenarios by the International Energy Agency (IEA 2022) and the ASEAN Centre for Energy (ACE 2022), following the economic growth of the region and additional electricity demand coming from cross-sector electrification. This creates a major challenge as the power sector needs to reduce its emissions, while also requiring significant investments in new generation capacities to meet growing demand.

3.1.2 The role of renewables in power generation

Renewable energies (RE) remain the main option to decarbonise bulk power generation. Fossil fuels coupled with carbon capture and storage (CCS) have gained attention in the region, as retrofitting the existing fossil fleet for CCS can lower their emissions and make use of the significant potential for CO_2 storage (IEA 2021b; Zhang et al. 2022). However, CCS is not a fully mature technology, without large-scale deployment yet. It is an energy intensive process[7] and does not provide a solution to other environmental problems in fossil fuel extraction or the emission of other combustion pollutants (EEA 2011). Cost considerations also arise, as conventional power plants combined with CCS will likely be more costly than renewable alternatives (Ordonez et al. 2022). Overall, massive deployment of RE will be necessary.

Currently, RE account for about 25% of total power generation in the region, with the majority coming from hydropower. Vietnam is the largest country for renewables in the region, accounting for the majority of installed capacities in hydropower (21.6 GW, 40% of ASEAN), solar photovoltaics (PV) (16.6 GW, 69% of ASEAN) and wind turbines (4.1 GW, 66% of ASEAN). Nevertheless, the share RE in Vietnamese power generation remains rather low (4% of wind and solar, 35% including hydro in 2020) (IEA 2023a). Thailand has substantial renewable capacities as well, in particular from bioenergy (4.2 GW, 35% of ASEAN) and solar PV (3 GW).

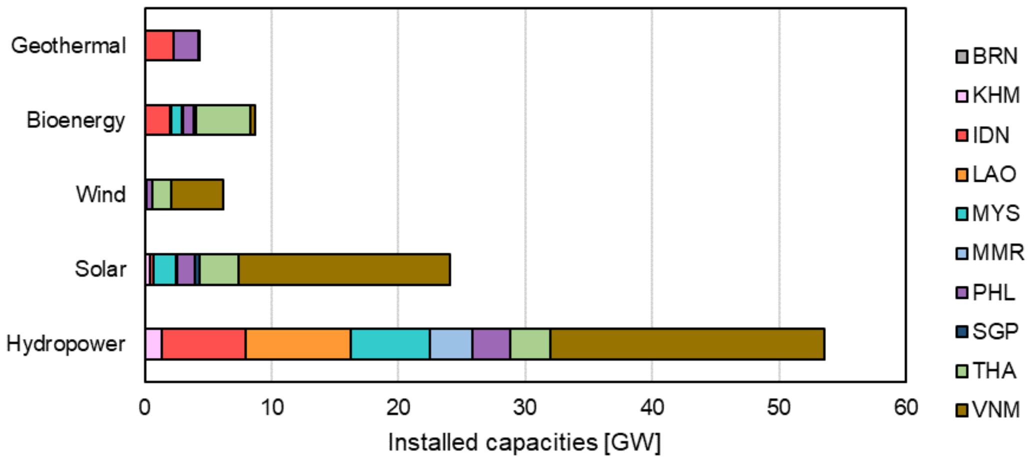
To decarbonise the ASEAN power system, **large-scale integration of RE is required**. The sustainable development scenario of the IEA[8] foresees renewables supplying 85% of total power demand by 2050. To achieve this, massive developments in solar PV, wind, hydropower, and geothermal

[7] 15% – 25 % higher energy demand depending on the particular type of technology used (EEA 2011).

[8] The sustainable development scenario (SDS) is compatible with the Paris Agreement, limiting global warming to 2°C (IEA, ASEAN Energy Outlook 2022). This scenario is more ambitious than scenarios of the ACE 7.

energy are required. Hydropower reaches around 250 GW in 2050, a fivefold increase of 2020 levels. Wind and PV capacities would reach around 750 GW, requiring the annual installation of around 25 GW of these technologies up to 2050, which is close to the current level of installed PV and wind capacities.

Figure 10: Installed capacities of renewable energy sources in the ASEAN countries in 2021



Source: Own elaboration based on (IRENA 2023)

3.1.3 Power system flexibility for renewable integration

In power systems, electricity supply and demand need to be balanced at all times. Power systems make use of **flexibility** such as **dispatchable generation** (coal, gas, hydro), **storage**, cross-border **interconnections**, or **demand response** to adjust for variations in supply or demand or contain unexpected contingencies.

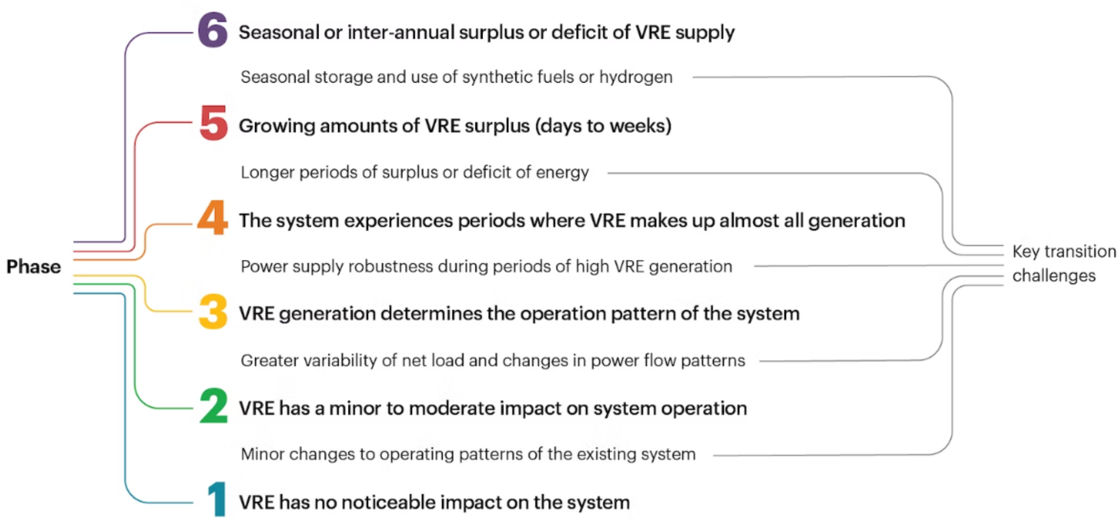
Integrating the vast amounts of variable RE to meet net-zero goals will require significant system flexibility from across the energy system.

Flexibility is needed at different timeframes, from seconds to maintain stability of the system after a contingency, over minutes/hours, to cope with large generation variations such as the PV daily cycle, to weeks and seasons, to ensure supply during large periods of surplus/deficits.

As the share of variable renewable power generation grows over time, the power system will experience different challenges, as explained by the IEA's six phases of renewable integration (see Figure 11). The flexibility solutions to be implemented are thus needed gradually over time but need to be planned in advance to not create barriers for renewables integration. This can be the case of grid expansion and modernization, for which projects can take many years to be completed.

Currently, most ASEAN countries are in Phase 1 or 2 with only low penetrations of variable RE (less than 5% of total production). The large-scale integration of renewables needed to reach a decarbonised power system would move the challenges to Phase 4 or more.

Figure 11: Six phases of variable renewable energy integration, key characteristics and challenges



Source: (IEA 2020)

3.1.4 Enhancing power system flexibility

The first phases of renewable integration (Phases 1 and 2) can be tackled by **grid modernization** and development of interconnections. This is the case of Vietnam, where PV generation has experienced curtailment since 2020, after the rapid surge of solar PV and shortage of transmission capacities (Do et al. 2021).

When renewables start determining the operation of the power system (Phase 3 and 4, when they reach around 10% of total generation), the system will require **more flexible operation of existing thermal and hydro power plants** in the region. In a second step, the development of short and medium duration **storage and demand response** would also be needed. Stationary batteries, with duration of a few hours, and pumped hydro storage, with a duration of hours to days (Silalahi et al. 2022), can absorb surplus power and shift it to times of peak demand.

Phases 5 and 6 of renewable integration will require **long-duration energy storage solutions** to balance weekly and seasonal variability in renewable generation, including dry/wet seasons for hydro or high/low wind generation periods (seasonal fluctuations of power demand (winter/summer) in the ASEAN region are low (IEA 2023b)). Fossil gas with CCS can provide backup power during long periods of low renewable generation, yet high capital costs would require a rather constant operation. Green hydrogen production (or hydrogen derivatives such as ammonia) coupled with storage and hydrogen-based generation can also provide long-term flexibility to the power system, via what is called *Power-to-Gas-to-Power* (P2G2P), with hydrogen being produced during periods of renewable power surplus and power generation from hydrogen during periods of lacking renewable power generation. Green hydrogen production in itself can also provide short term flexibility, as electrolyser operation can be matched with renewable production patterns. Ultimately, the smart charging of battery electric vehicles (BEV) can help to meet rising daily flexibility needs, by matching the (additional) power demand from BEVs with RE generation, in particular solar PV cycles. Vehicle-to-grid can lower the need for stationary batteries.

Ammonia co-firing, a solution to reduce coal CO_2 emissions?

Ammonia (NH3) combustion is a carbon-free process. Co-firing ammonia in coal power plants has been proposed to reduce direct CO_2 emissions in coal generation, allowing existing assets to be retrofitted to continue operation. However, several challenges remain for ammonia co-firing in bulk power generation.

Ammonia co-firing is in early research and development stages. Pilot plants in Japan are testing a 20% ammonia co-firing (energy ratio), with rates of 50% to be trialed by 2028 (BNEF 2022; FAO 2022; IEA 2021a). Co-firing ammonia results in lower efficiencies than pure coal, and also causes higher nitrogen oxides (NO_x) and N_2O emissions. NO_x are major source of environmental pollution, and N_2O is a major greenhouse gas, with a global warming potential 273 times higher than CO_2.

To achieve a net emissions reduction, ammonia would need to be produced through carbon-free processes. Currently, almost all ammonia is produced from steam methane reforming of fossil gas (70%) or coal reforming (30%) (BNEF 2022; FAO 2022; IEA 2021a). Using ammonia for bulk power generation would require large quantities of it. For example, if ASEAN coal plants implemented 20% co-firing (494 TWh, 2020 production), ammonia requirements would surpass 45 Mton, around 7 times current ammonia production in the region (BNEF 2022; FAO 2022; IEA 2021a) and almost 30% of global production in 2020. Thus, green ammonia supply chains (regional or international) would need to be developed at a large scale.

Finally, ammonia co-firing could prove more costly than its alternatives, as co-firing rates would need to be higher than 50% to achieve lower emissions than gas combustion without CCS. BNEF analysis in Japan showed that the LCOE of ammonia co-firing was outperformed by offshore wind and by gas coupled with CCS.

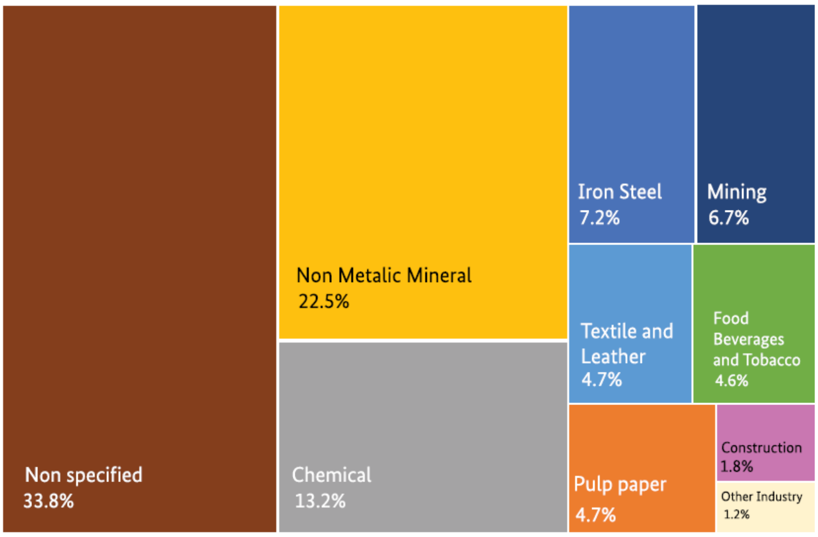
3.2 Industry

The industry sector in ASEAN has experienced rapid growth over the last 15 years, with energy demand increasing by over 60% from 2005 to 2020, reaching 6.3 EJ. Heavy industries dominate energy use with non-metallic minerals (mainly cement), petrochemicals, and iron and steel, accounting for 40% of industry energy demand (ACE 2022).

The energy in industry has many uses: it is used for mechanical purposes in machinery, such as belts, pumps, and mills to cut, grind or transport materials, and for heating and cooling purposes. Around 60 % of energy use comes from the direct combustion of fossil fuels (coal, gas and oil), while the share of electricity is only 23 % (ACE 2022). The majority of energy demand in the industrial sector therefore still needs to be decarbonised.

The options to decarbonise industry, whether through direct electrification or the use of green gases, will depend on the sub-sectors and on the processes involved. Overall, most industrial process can be electrified, especially mechanical processes where electric motors and machines (instead of fuel-based motors) are widely used. For low and medium temperatures (<400°C), there are already commercial solutions (electric boilers, heat pumps and others) for the electrification of heating processes. For higher temperatures, other electric heating technologies (plasma, microwaves, electric arc furnaces, etc.) would be required, which are so far only commercially available in some cases (Madeddu et al. 2020). Therefore, green gases or biomass can be an alternative for some high temperature heating processes (>1000°C) or where they are needed as a chemical feedstock.

Figure 12: Industrial energy demand by subsector in the ASEAN region in 2020

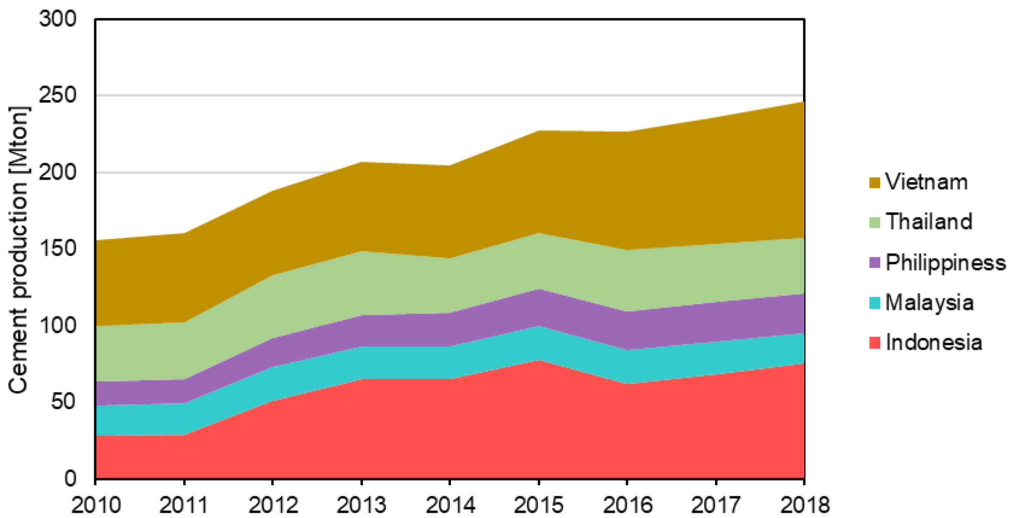


Source: (ACE 2022)

3.2.1 Cement: CCS to capture process emissions

Cement production is one of the top global CO_2 emitters as it accounts for most of direct coal use in the industry sector. Southeast Asia produced 262 million tonnes of cement in 2017, an increase of 66% with respect to 2010. Major producers include Vietnam (34% of the region's production) and Indonesia (29%), which together with Malaysia, Philippines and Thailand account for 94% of the region's cement production (see Figure 13) (USGS 2021).

Figure 13: Cement production in selected ASEAN countries, 2010 to 2017



Source: Own elaboration based on (USGS 2021)

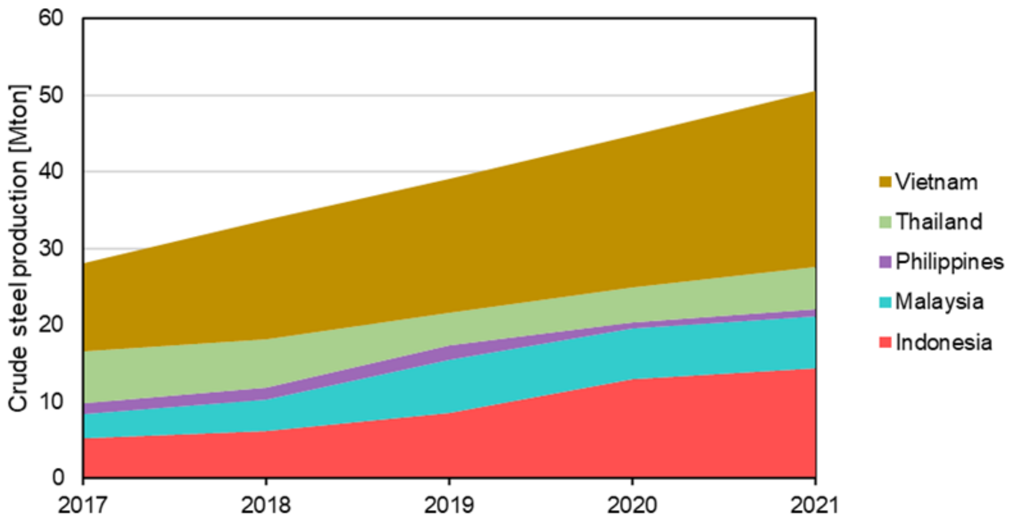
To produce cement, limestone is heated to extremely high temperatures (>1400°C) to produce clinker, in a process known as calcination. Clinker is then grinded and mixed with gypsum and other substances to produce cement. Most of the energy use and CO_2 emissions comes from calcination. To achieve the high temperatures required, burning fossil fuels (often coal) is used. During the process, limestone releases CO_2 molecules. Around two thirds of CO_2 emissions come from process emissions, and one third from energy-related emissions.

To decarbonise the cement industry, CCS is therefore the main envisaged alternative, as it can reduce both energy-related and process emissions. Using of alternative fuels to replace coal in the production of clinker, such as biomass or hydrogen, or even breakthrough technologies[9] like solar concentration (solar clinker (CEMEX 2022)) or plasma (Vattenfall 2019) could reduce energy-related CO_2 emissions but not process emissions.

3.2.2 Iron and Steel: electrification, hydrogen and CCS

The ASEAN region produced 51 million tonnes in 2021 and has experienced rapid growth in recent years. Between 2017 and 2021 production increased by 79%. Production is concentrated in Vietnam and Indonesia, which combined produced 73% of the region's steel (World Steel 2022).

Figure 14: Crude steel production in selected ASEAN countries, 2017 to 2021



Source: Own elaboration based on (World Steel 2022)

To produce steel, processes depend on the type of feedstock. Primary steel, which is made from mined iron ore, follows two stages: first iron ore is reduced to iron, and then the carbon content of iron is reduced to steel grade levels (<1%). Currently, the main process to produce primary steel combines a blast furnace (BF) for iron reduction, which uses coke, and a basic oxygen furnace (BOF) to obtain steel. This process is energy intensive and emits high levels of CO_2, due to the use of coke (a derivate of coal). An alternative route for primary steel is the direct reduced iron (DRI), which uses reducing gases (hydrogen and carbon monoxide) instead of coke. Reducing gases are currently generated from fossil gas or coal, which emits CO_2. The reduced iron is then typically smelted in an electric arc furnace (EAF) (JRC 2022). For secondary steel, which uses scrap metal, the main process smelts steel scrap in an EAF. This process uses mostly electricity but can use additional heat from fossil fuels (mainly natural gas) to melt the scrap.[10]

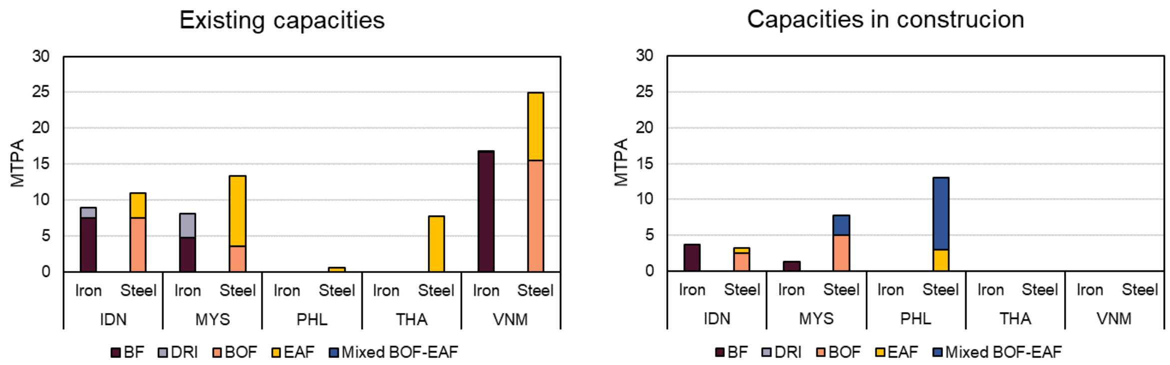
The existing and under construction production capacities in main producers of the region are shown in Figure 15. In the region, primary steel is made in Vietnam, Indonesia and Malaysia, mostly through the BF-BOF route. A minor share of DRI capacities exist Indonesia and Malaysia, thanks to their gas production facilities. Secondary steel using EAF is produced in more countries in the region, with major capacities located in Vietnam, Thailand and Malaysia (Global Energy Monitor 2023b). All planned capacities for iron reduction (i.e., primary steel) rely on BF, which can lock-in

9 These technologies are at the early stage of development with only small-scale demonstrators available.

10 The difference between primary and secondary steel is less well defined, as scrap can be added in BOF or iron pellets in EAF.

emissions for years to come. Significant additions are also planned for EAF or mixed process plants, in particular in the Philippines (Global Energy Monitor 2023b)

Figure 15: Iron and steel production capacities in selected ASEAN countries in million tonnes per annum



Source: Own elaboration based on (Global Energy Monitor 2023b)

The decarbonisation of iron and steelmaking need various complementary approaches. Using alternative fuels in existing BFs, such as biomass[11] or hydrogen, can reduce the need for fossil fuels, but adaptations to the infrastructure might be needed. Increasing scrap metal recovery and making of secondary steel via EAF, which is already an electrified process, can provide environmental benefits and move towards a more circular economy, but the potential is limited to recoverable scrap. To fully decarbonise steelmaking, investments in DRI technologies using green or blue (i.e., with CCS) hydrogen and syngas would be needed. Other electricity-based technologies are still in the phase of research and development (e.g., electrowinning, molten oxide electrolysis) (Madeddu et al. 2020).

3.2.3 Chemical industry: electrifying processes and electrochemistry

The chemical industry uses fossils fuels both as an energy source, for low and medium heat, and as a feedstock. Oil and gas derivatives such as ammonia, methanol, propylene, and ethylene are the building blocks for several products, including plastics, solvents and fertilisers. Most of these products are obtained by applying heat and pressure to produce the necessary chemical reactions (Schiffer et al. 2017).

The chemical industry has great potential to decarbonise its energy-related uses through direct electrification, as they are required mostly for cooling and steam (low to medium heat), while maintaining the thermochemical pathways. Commercially available solutions already exist, such as industrial heat pumps or electric boilers, however their introduction into existing designs and processes might not be as straightforward. Other technologies such as electric steam crackers (used in the petrochemical industry) are not yet fully developed (Madeddu et al. 2020). Biofuels or synthetic fuels can replace fossil fuels as feedstocks and energy carriers in some cases.

However, another paradigm shift is possible for the chemical industry. By adopting **electro-chemistry**, where reactions are driven by electricity instead of thermodynamics, alternative pathways for the synthesis of chemicals can be used which reduce the need for fossil fuels as both feedstocks and energy source. This is the case of hydrogen electrolysis, which separates hydrogen from water

[11] Depending on availability and sustainability

using electricity instead of the traditional pathway of steam methane reforming, which is already a mature technology.

Other molecules could be obtained using similar electrochemical processes, but further research is needed to achieve industrial scale deployment, such as ammonia or methanol which are produced as hydrogen derivatives. Of particular interest is ammonia, which is primarily used for fertilisers and is synthesised through the (thermodynamic) Haber-Bosch process from hydrogen and nitrogen. In ASEAN, the production of ammonia for fertilisers was around 7 Mton in 2021 (5.7% of the world), dominated by Indonesia with over 60% of the region's production, and followed by Vietnam and Malaysia (FAO 2022; IEA 2019; Schiffer et al. 2017). Producing the hydrogen required for fertiliser production through electrolysis only (maintaining the Haber-Bosch process) would require around 45 TWh of electricity, around 3% of the ASEAN's electricity production in 2020, which is more than its current production of solar and wind combined. Alternative electrochemical processes could also be developed for direct synthesis of ammonia (FAO 2022; IEA 2019; Schiffer et al. 2017)

3.2.4 Other industries

Other sectors such as food, textiles and the paper and pulp industries require mostly mechanical processes and low and medium temperature heat. Low and medium temperature heat can be electrified using currently available technologies, such as high-temperature heat pumps (T<150°C) which present a high efficiency, and electric boilers (T>150°C).

Bioenergy can also be used for heating purposes in some of these industries, especially when it is easily available. This is the case of the paper industry which has large amounts of biomass available and already uses part of it for their processes. However, the use of biomass depends on its availability and sustainability and could also be prioritised for high-temperature heat processes (cement, iron and steel, glassmaking) which are harder to electrify.

3.3 Transport

Transport is the second highest sector in final energy consumption in ASEAN, with its energy consumption doubling from 2005 to reach 5.6 EJ in 2020. Road transport, which includes two-wheelers, cars, buses, and trucks represents over 90% of the total consumption, with maritime transport and aviation accounting for the remainder (ACE 2022).

Oil is the main fuel used in the sector, accounting for 91% of total energy use in transport, followed by biofuels (7%). Recently, biofuel shares have grown rapidly with the introduction of blending mandates for biodiesel (notably in Indonesia with B30[12] and Malaysia with B20[13], thanks to their palm oil production) and bioethanol (notably in Thailand with E20 and the Philippines with E10).

Road transport mobility in ASEAN is largely dependent on private vehicle ownership, as alternative transport options such as public transport and train networks are less developed. This has resulted in heavy traffic and high air pollution in many cities. A particularity of the region is the high presence of two and three-wheelers, which represent almost 80% of vehicle sales, more than neighbouring China. However, almost all two and three-wheelers have combustion engines, with low penetration of electric drivetrains, contrary to China where almost 50% of new two and three-wheelers are electric [35].

[12] B30 means a blending with 30% biodiesel. Equivalently, E30 is a 30% blend with bioethanol.

[13] Implementation of B20 mandate in Malaysia, originally planned for 2020, has been delayed.

3.3.1 Decarbonising road transport: mass transit and electrification

To decarbonise the road transport, several complementary solutions are needed. First, developing mass transit reduces the reliance in driving, improving cities' traffic and air quality. Mass transit requires large-scale infrastructure with public support, planning and funding. If mass transit is electrified, such as by electric buses, metro and trains, it can also help remove the reliance on oil.

Second, direct electrification is the main pathway for decarbonisation of two and three-wheelers, cars and short-distance trucks via battery electric vehicles (BEV). Costs of BEVs have declined rapidly, with significant benefits over hydrogen fuel cell vehicles: better energy efficiency, lower total cost of ownership, higher market shares globally and broad public support. Additionally, the high share of two and three-wheelers can be a great opportunity for the region, as they are easier and less costly to electrify due to their smaller batteries and lower charging power.

The future of long-distance transport is less clear as hydrogen trucks and buses can find a marketplace due to their larger autonomy and faster charging (refuelling) times. Nevertheless, battery trucks are gaining momentum, with commercial models already available and potential lower total costs of ownership in the long run (Plötz 2022; TE 2017).

Next generation biofuels will also contribute to decarbonising transport, especially in the transition phase towards complete electrification or aimed only at long-distance trucks. Biofuels are already promoted in the region, given the large agricultural sector (e.g., palm oil, cassava), but sustainability is a concern. Biofuel prices and availability can also be affected by international crisis or weather events that can harm harvests, as was seen during 2022. Considering the limited availability of biofuels, their use should be focused on hard to electrify use cases, such as maritime or aviation.

Finally, compressed natural gas is an alternative fuel to liquid fossil fuels in captive fleets like buses, which allows to reduce (but not remove) CO_2 and emissions and atmospheric pollutants. There have been some implementations in the region (Hokusan 2019). A switch from fossil gas to biomethane can provide sustainable fuel to these niche applications. However, these solutions will need to compete with battery-based alternatives in costs and ease of use.

Challenges remain for all the options. Direct electrification or the use of hydrogen for transport will require the development of sufficiently dense charging infrastructure. Power grids will need to host large numbers of BEV chargers, which will require large investments in infrastructure upgrading and digitalization. The development of a hydrogen recharging network also presents challenges, with complex logistics, strict safety standards and risks of high costs if the demand does not scale. Both options, BEVs and hydrogen vehicles, will require low carbon generation sources (i.e., renewables) to supply the energy needed. Electrification is more efficient in this regard, as the conversion losses of using hydrogen are avoided.

3.3.2 Decarbonising aviation and shipping: green gases and synthetic fuels for the future

The decarbonisation of aviation and shipping will rely mainly on green gases or synthetic fuels. The use of hydrogen-based fuels like methanol and ammonia appears as the main alternative for shipping. The size and costs of batteries make only short routes (<200 km), such as ferries, a viable alternative.

For aviation, industry is currently focused in two decarbonisation routes: sustainable aviation fuels (SAF) and hydrogen. SAFs are currently biofuels-based, with future SAFs expected to be developed from waste and synthetic fuels (ICAO 2022) and are thus of particular interest for agriculture-rich ASEAN. However, producing enough SAFs to meet the expected growth of the sector remains a concern. Hydrogen-based aircrafts are still in research and development phase, with first commercial units expected earliest in 2035 (Airbus 2022).

3.4 Residential

3.4.1 Improving access to clean cooking, a main sustainable development goal

The residential sector in ASEAN accounts for 15% of energy consumption in the region in 2020 (2.6 EJ) (ACE 2022). Around 40% of its energy consumption comes from electricity, with main uses being refrigeration, air conditioning, lighting and electronics, with the remainder split between traditional biomass and oil (liquefied petroleum gas, LPG) used mostly for cooking. The use of fossil gas in the residential sector is region is negligible, as demand for space heating in the region is virtually non-existent, and water heating is already largely electrified.

The use of traditional biomass for cooking denotes the lack of access to clean cooking[14] for a large share of the population, estimated at almost 200 million people in the region (144 million people in CASE countries), see Table 2. This creates numerous burdens on the population, including economic and time loss for families, health problems due to inefficient burning, as well as deforestation.

Table 2: Clean cooking access in the different ASEAN countries

Country	Clean cooking access in 2020	Estimated population without access (million)
Brunei Darussalam	100%	-
Singapore	100%	-
Malaysia	99%	<1 M
Indonesia	**85%**	**41 M**
Thailand	**84%**	**11 M**
Vietnam	**65%**	**34 M**
Philippines	**48%**	**58 M**
Cambodia	37%	10 M
Myanmar	31%	38 M
Lao PDR	9%	6 M

Source: Own elaboration based on (ACE 2022)

Increasing the access to clean cooking is one of the United Nations Sustainable Development Goals (SDG 7, affordable and clean energy access), and can provide significant economic, health and environmental benefits for the populations concerned. Progress has been made in the last 20 years in the region, through the access to LPG and electrification, however a lot is yet to be made to reach the region goal of 100% clean cooking access by 2030.

To fully decarbonise the residential sector, a 100% access to clean cooking is needed. LPG, which is one of the main solutions currently deployed, could have a transition role only, as it is a fossil fuel. Electric cookstoves would need to be massively deployed, with efficient woodstoves being an alternative in rural areas. Another option is the use of household biogas digesters in rural areas, which

[14] Clean cooking considers the use of electricity, (LPG), natural gas, biogas, solar, and alcohol fuels for cooking. Charcoal, coal, crop waste, dung, kerosene, and wood used for cooking are not considered clean fuels.

use manure and organic waste to generate small amounts of biogas. Small scale biogas digesters have been promoted across Asia as they improve waste handling, with high adoption in China and India. In Vietnam, there are around 300,000 small scale digesters in operation, and small-scale installations in Indonesia have been progressing due to government regulations (SNV 2022). Small-scale biodigesters can improve sanitary conditions and reduce odours, but can have high upfront costs for rural and might release methane to the atmosphere due to cracks or spill-overs (Vu et al. 2015).

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