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Peak coal electricity under rapid electricity demand growth conditions: A case study of Indonesia, the Philippines, and Vietnam

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ABSTRACT

Understanding the conditions for peak coal electricity, encompassing peak coal capacity and generation, is relevant for coal-dependent emerging economies yet has received limited attention in the decarbonisation literature. Emerging economies need to reach peak coal amid rapidly growing electricity demand, whereas historical cases of peak coal electricity occurred under stable demand conditions. This study investigates when and how peak coal can be reached in expanding electricity systems by using Indonesia, the Philippines, and Vietnam, coal-dependent emerging economies with coal power plant moratoriums, as cases. We develop approaches for identifying peak coal capacity and generation: the former is determined by utilising coal power plant pipeline data, and the latter by considering the growth of coal substitutes across different scenarios. Additional analysis of total carbon emissions is conducted to understand the climate impact of the scenarios. Our results show that the case countries can reach peak coal capacity between 2026 and 2028 if moratorium policies are implemented. Peak coal generation may be reached in the 2040s or later, depending on the deployment rate and the choice of alternative energy sources. However, reaching peak coal does not necessarily lead to emission reduction. Carbon emissions are projected to continue rising in most scenarios because growth in total electricity generation can outweigh the reductions achieved by substituting coal with lower carbon sources, declining only when coal-powered generation falls sufficiently in absolute terms.

1. Introduction

Many emerging economies rely on coal to meet their growing electricity demand. Yet, coal power plants need to be phased out worldwide to reach the climate mitigation targets of the Paris Agreement (Rogelj et al., 2018). A growing number of studies investigate various aspects of coal phase-out in the electricity system, including constraints (Diluiso et al., 2021; Mirzania et al., 2023; Rentier et al., 2019), socio-political acceptance (Muttitt et al., 2023), policies and pledges (Bi et al., 2023; Jewell et al., 2019; Kalkuhl et al., 2019; Oei et al., 2020), phase-out pathways (Vinichenko et al., 2023), actors (Ohlendorf et al., 2022) and cost (Nacke et al., 2024), with case studies from both developed (Brauers et al., 2020; Isoaho and Markard, 2020; Oei et al., 2020; Rentier et al., 2019) and developing countries (Mirzania et al., 2023; Ohlendorf et al., 2022).

However, less focus has been given to “peak coal”, a phenomenon that occurs before phase-out. Peak coal is defined as a distinct point that marks the end of coal expansion and ultimately the beginning of coal decline (Lægreid et al., 2023). It can be understood as either the maximum installed coal capacity (peak coal capacity) or the maximum electricity generated from coal (peak coal generation) over the entire deployment period. Discussions on coal power in electricity generation often overlook these peak points as many high-income countries are now experiencing a decline in coal capacity and generation (Lægreid et al., 2023), and studies are thus focusing on investigating the acceleration of coal decline. Yet, peak coal remains highly relevant for emerging economies still undergoing coal expansion, as it can help clarify the transition from the current stage of coal expansion to the ultimate goal of coal phase-out and shed light on the technology life cycle of coal (Markard, 2020).

One of the world's centres of coal power growth is Southeast Asia (IEA, 2023a), home to several emerging economies. In this region, aside from economic motives, political factors have encouraged the continuous growth of coal power (Dorband et al., 2020) through the political

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objectives of various actors (Dorband et al., 2020; Jakob et al., 2020; Manych and Jakob, 2021; Ordonez et al., 2021). Supporting policies have attracted international investment in coal power plant projects, particularly from China (Gallagher et al., 2021), further driving coal power expansion in the region. Despite the current expansion, some studies have projected that coal power will peak in the region before 2030 (Chen and Mauzerall, 2021), with slight variations in the peak year across individual countries (Clark et al., 2020). However, these studies primarily focus on peak coal capacity. Considering that countries can still generate electricity from coal power plants after reaching peak coal capacity (Lægreid et al., 2023), analysing both peak coal capacity and generation is crucial for decarbonising the electricity system.

This study aims to understand the conditions enabling peak coal capacity and generation in the expanding electricity systems of coal-dependent emerging economies. It uses three Southeast Asian countries—Indonesia, the Philippines, and Vietnam—as cases. The three countries share a recent history of rapid coal expansion: between 2010 and 2020, coal-powered electricity generation grew by about one and a half times in Indonesia and the Philippines and five times in Vietnam (IEA, 2022a). Coal consumption is expected to grow further as the countries still plan to expand the share of coal-based generation in their electricity systems in the near future (IEA, 2022b). At the same time, the three case countries have announced their aspiration and plans to limit the growth of coal power: Indonesia[1] and the Philippines have announced moratoriums on new coal power plants (President of the Republic of Indonesia, 2022; Philippines Department of Energy, 2020), and Vietnam has issued a plan to reduce coal capacity after 2030 (Prime Minister of Vietnam, 2023). These policies indicate that the countries aim to reach peak coal capacity. Historical precedents of peak coal capacity and generation occurred only during periods when countries experienced stable or declining electricity demand (Lægreid et al., 2023); unlike the three case countries where electricity demand is expected to keep growing rapidly, underscoring the need for other energy sources to substitute coal-based generation (Suzuki et al., 2023).

We ask three research questions in this paper: 1) When can Indonesia, the Philippines, and Vietnam reach peak coal capacity if they meet their pledges and plans? 2) Based on the countries' policies and historic precedents, by when and what electricity mixes could be deployed in the three countries to substitute coal and thus enable peak coal generation? and 3) How do carbon emissions of electricity supply mixes compare to each other and to historical emission levels? To answer the first question, we use coal power plant data from S&P Global Platts (2021) and Global Energy Monitor (2024) and calculate power plant lifetime based on the global average (Global Energy Monitor, 2024) and on lifetime compatible with the Paris Agreement's targets (Cui et al., 2019). To address the second question, we developed two groups of scenarios: policy-based scenarios and empirical scenarios. For the third question, we calculate total carbon emissions for each scenario using the energy-source emission ranges from the IPCC Fifth Assessment Report (Schlömer et al., 2014). We calculate both direct emissions from electricity generation and lifecycle emissions, which additionally include emissions from construction, fuel production, and, where applicable, methane emissions.

Our results show that Indonesia, the Philippines, and Vietnam could reach peak coal capacity by 2030 if their pledges and plans to limit the development of new coal power plants are implemented. Yet, coal capacity is expected to decline only slowly after the peak given the young age of coal power plant fleets. The timing of peak coal generation varies substantially across scenarios, ranging from around the year of peak capacity to beyond 2050, depending on the growth rate and technological choices regarding the deployment of alternative electricity sources. The findings further show that peak coal generation alone is insufficient to decarbonise electricity systems, as total emissions are projected to continue rising in most scenarios amid rapidly growing electricity demand. Emissions fall only in selected policy-based scenarios where coal-powered generation decreases sufficiently in absolute terms.

The remainder of this paper is structured as follows. The next section describes the role of coal in the electricity systems of Indonesia, the Philippines, and Vietnam, and its development over time. Section 3 explains the approaches and general assumptions used to answer the research questions. It is followed by Section 4, which provides details on the country-specific data and assumptions used in the methodological framework. The results are presented in Section 5 and analysed and discussed in Section 6. Finally, we present conclusions and policy implications in Section 7.

2. Coal in the electricity system of Indonesia, the Philippines, and Vietnam

Indonesia, the Philippines, and Vietnam have seen rapid increases in electricity demand since 1990, with demand multiplying by two in the Philippines, eight in Indonesia, and 27 in Vietnam (IEA, 2024). This growth coincided with population growth, rising GDP per capita, and electrification (World Bank, 2024). Fossil fuels have met electricity demand growth: oil until the late 1990s and coal in recent years (Fig. 1A). The three countries have undertaken substantial coal power plant constructions since 2010, with capacity additions reaching almost 12 GW in one year in Indonesia (Fig. 1B). The capacity of operating coal power plants reaches more than 60 GW in Indonesia, 30 GW in Vietnam and 15 GW in the Philippines (Fig. 1C). Coal is expected to continue dominating the electricity systems of the three countries as coal power plants under planning and construction amount to a third of current capacity (Fig. 1C).

Aside from growing electricity demand, coal expansion in Indonesia, the Philippines, and Vietnam has been shaped by a combination of economic and political factors. All three countries produce coal and hold substantial reserves, although the scale of production and reserves varies considerably. Indonesia has the most abundant coal resource, with production of 563 million tonnes and reserves of 156 billion tonnes in 2020[2] (Ministry of Energy and Mineral Resources, 2020). This creates a strong economic interest in sustaining coal demand, and the rising coal consumption for electricity generation in Southeast Asia provides a “lifeline” for the coal industry (Fossum Sagbakken et al., 2021). Political actors in Indonesia, the Philippines, and Vietnam have also perceived coal as an “affordable” option to meet the growing demand and ensure energy security (Dorband et al., 2020; Manych and Jakob, 2021; Ordonez et al., 2021). Governments across the region also prioritised investments in new coal power plants between 2014 and 2018 (Fossum Sagbakken et al., 2021). Government support, combined with less strict environmental regulations in the three countries, has attracted international investors from China (Gallagher et al., 2021), Japan, and Korea (Zhao and Alexandroff, 2019), further enabling coal power expansion.

However, the economic and energy security rationale for coal has become increasingly contested. The costs of generating electricity from solar and wind have already been comparable to or lower than those of coal in the Philippines and Vietnam (Setyawati and Nadhila, 2024). The shift towards cheaper renewable energy could strand coal power plant assets, with potential losses in the scale of billions of US dollars by 2050 (Fazeli et al., 2025). This risk is particularly relevant because many coal power plants in these countries are relatively young, with ages below ten years (Fig. 1B), and have capacities of more than 100 MW (Fig. 1D).

[1] Indonesia's moratorium policy creates some uncertainties, as the regulation still allows for the development of new coal power plants if they 1) support value-added industries or national strategic projects, 2) are committed to reduce greenhouse gas emissions by minimum 35% in ten years, or 3) operate until no later than 2050 (President of the Republic of Indonesia, 2022).

[2] Coal reserve refers to proven, hypothetic, and verified reserves.

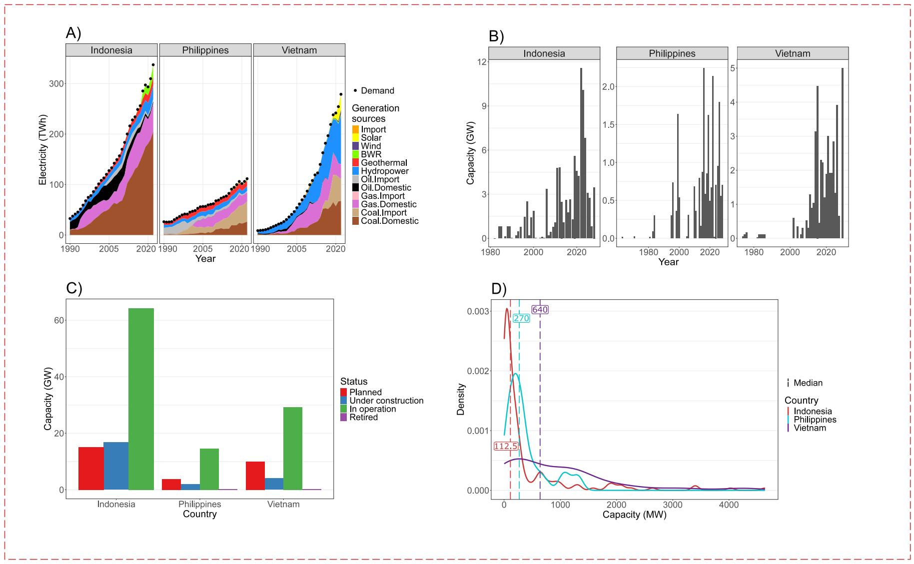

Fig. 1. A) Historical electricity mixes of Indonesia, the Philippines, and Vietnam with the fossil fuel sources specified into domestic and imported sources, B) capacity addition of coal power plants, including the power plants under construction and planning, from 1980 to 2030, C) total capacity of coal power plants with different statuses as of 2024, and D) distribution of the capacity of coal power plants currently in operation with the dashed lines representing median values in MW. (Adapted from IEA (2024), S&P Global (2021), and Global Energy Monitor (2024)).

Furthermore, although the Philippines produced 13 million tonnes of coal in 2020 (Philippines Department of Energy, 2022) and Vietnam produced 45 million (BP, 2020), both countries have become net coal importers, with imported coal accounting for a growing share of their electricity supply (Fig. 1A).

These developments weaken the perceived affordability and reliability of coal and have prompted the countries to pursue strategies such as setting targets to increase domestic coal production and identifying alternative sources for electricity generation (Philippines Department of Energy, 2023; Prime Minister of Vietnam, 2023). At the same time, Indonesia, the Philippines, and Vietnam have announced commitments toward a sustainable energy transition on the international stage by declaring net-zero aspirations (Climate Action Tracker, 2024; Government of Vietnam, 2021), establishing Just Energy Transition Partnerships with several developed countries (European Commission, 2022; The White House, 2022) and signing the Global Coal to Clean Power Transition Statement at COP 26 in 2021 (UK National Archives, 2021). The combination of energy security concerns and international commitments led to the announcement of bans on new coal power plants in Indonesia (President of the Republic of Indonesia, 2022) and the Philippines (Philippines Department of Energy, 2020), as well as to the inclusion of coal phase-out in Vietnam's electricity development plan (Prime Minister of Vietnam, 2023).

3. Methodological framework

Two empirical findings from countries that have reached peak coal electricity (Lægreid et al., 2023) are considered when developing our methodological framework. First, countries reached peak coal electricity under stable electricity demand conditions, whereas in emerging economies, electricity demand is expected to continue to grow rapidly. Second, peak coal capacity and generation do not always coincide, as the latter can occur before, around the same time, or after the former. As such, the methodology must be able to determine peak coal electricity under rapidly growing demand and distinguish between peak coal capacity and peak coal generation.

The approach developed in this paper consists of three steps. First, we analyse peak coal capacity by using coal power plant pipeline data. The pipeline reflects the ongoing development of coal power plants, including those currently operating, under planning, under construction, cancelled, or retired. We then separately determine the likely timing and conditions for peak coal generation by developing policy-based and empirical scenarios for the growth of renewables that could substitute coal-powered electricity generation and thus enable peak coal generation. These two steps address the methodological challenges of determining peak coal under rapidly growing demand. Additionally, we calculate total carbon emissions for each scenario, including both direct and lifecycle emissions, to understand the impact of peak coal electricity on the decarbonisation of electricity systems.

3.1. Peak coal capacity

The year of peak coal capacity is determined by examining currently operating and future coal power plant projects by using datasets from S&P Global Platts (2021) and Global Energy Monitor (2024), which provide capacity data at the power plant unit level. The S&P Global dataset divides power plant units into seven categories, whereas the GEM database divides them into eight (Table 1). To combine the two datasets, we establish equivalence of coal power plant statuses across them, and the statuses in the "Status in this paper" column are used for the rest of this paper. We then check both datasets to ensure there are no

Table 1
The equivalence of coal power plant statuses between statuses used in the GEM database, statuses used in the S&P Global database, and statuses used in this paper. The "Uncertain" status only applies to power plant units without a definite start year of operation after a manual check is conducted.

Status in GEM database	Status in S&P Global database	Status in this paper	
Announced Pre-permit Permitted	Planned, still in development or design	Planned	Uncertain*
Construction	Under construction, physical site work is underway	Under construction	
Operating	In commercial operation	In operation	
Shelved	Delayed after construction starts	Delayed	
	Deferred without construction start	Deferred	
Cancelled	Cancelled	Cancelled	
Retired	Retired	Retired	

duplicate entries, i.e., the same power plant units listed in both the S&P Global and GEM datasets. If the two databases provide different information for the same power plant units, we select the information from the GEM dataset because it is more up-to-date than that from the S&P Global dataset. Furthermore, we also investigate power plant units with statuses of planned, under construction, in operation, and delayed, that have capacities of at least 50 MW and no data on the (planned) start year of operation. These power plant units are then categorised as “Uncertain”.

3.2. Peak coal generation and scenario construction

Peak coal generation is determined by calculating the growth rate of electricity generation from non-coal sources that can replace coal-fired generation. This approach is based on the characteristics of emerging economies, in which electricity demand increases rapidly (Li et al., 2021). We assume that peak coal generation can be reached only when electricity generation from alternative energy sources grows fast enough to meet electricity demand and replace coal-fired generation, marking the substitution phase of the energy transition (Suzuki et al., 2023). The mixes of coal substitutes are explored through policy-based and empirical scenarios.

The two scenario groups are developed based on different growth-rate assumptions for coal substitutes (Fig. 2). Policy-based scenarios use growth rates from the energy plans of the case countries, while empirical scenarios primarily use growth rates from reference countries. The growth rate of the empirical scenarios is complemented by a ramp-up rate, also taken from reference countries. Low-carbon sources are prioritised, and scenarios are constrained by countries' renewable energy potentials. These are further discussed in sub-sections 3.2.1 (policy-based scenarios) and 3.2.2 (empirical scenarios). Policy-based and empirical scenarios use the same electricity demand growth rate and coal generation from countries’ energy plans and the coal power plant pipeline, respectively. Coal generation is calculated using a capacity factor coefficient (α), which determines the amount of electricity a power plant can generate (capacity factor) during its operating time in a year (t) (Equation (1)). The coefficient is used because we do not have data on the operating time of each power plant in each case country.

$$\alpha = Capacity\ factor * t \tag{1}$$

3.2.1. Policy-based scenarios

Policy-based scenarios reflect the countries' future electricity supply plans. The scenarios use electricity demand, coal generation, and low-carbon growth rate data from energy plans of the countries. Low-carbon growth rate refers to the growth rate of renewable sources, including geothermal, hydropower, biomass and renewable waste (BWR), solar, wind, natural gas, and other low-carbon technologies, namely nuclear power. Policy-based scenarios utilise coal power plant pipelines as a constraint to limit coal generation. The six policy-based scenarios are based on renewable energy targets and electricity demand projections, as developed by Dzikrurrokhim and Ahlgren (2026) (Table 2). The “lower” and “higher” terms refer to the ranges of the targets and demand projections, i.e. which targets the countries can achieve and which demand projections the countries will follow. “Proportional adjustment” refers to the adjustment conducted to match electricity generation derived from the target with projected electricity demand. In both renewable target scenarios, it is assumed that the remaining electricity demand will be met through coal, natural gas, and low-carbon technologies proposed by the case countries.

3.2.2. Empirical scenarios

Empirical scenarios are based on empirical data from “reference countries”, a concept borrowed from the feasibility space framework (Jewell and Cherp, 2023). Reference countries are countries worldwide that share one or more characteristics with the case countries and have rapid historical deployment of low-carbon sources.

The low-carbon sources in empirical scenarios include renewables and natural gas. Other low-carbon technologies, such as nuclear power and hydrogen, are excluded because they introduce significant uncertainty due to the absence of historical deployment in the case countries. The growth rate of each low-carbon source in the empirical scenarios is obtained from the reference countries’ normalised five-year growth rate. The five-year period is chosen to avoid extreme variation often found in

Table 2
Scenario taxonomy in the policy-based scenario group. Abbreviation: HD – higher demand, LD – lower demand, PA – proportional adjustment, LRE – lower renewable electricity, HRE – higher renewable electricity. Adapted from Dzikrurrokhim and Ahlgren (2026).

	Proportional adjustment of target	Lower renewable target	Higher renewable target
Higher demand projection	HDPA	HDLRE	HDHRE
Lower demand projection	LDPA	LDLRE	LDHRE

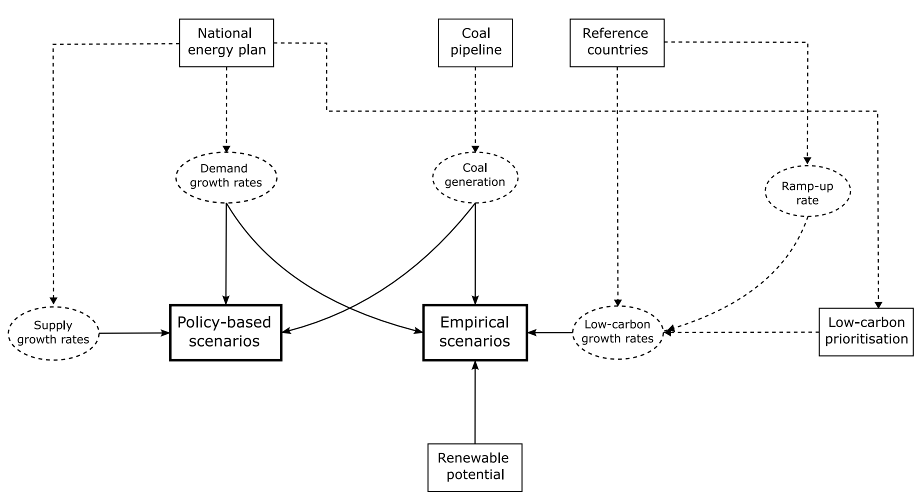

Fig. 2. Summary of the scenario construction process. The squares with solid lines represent data sources and the ovals with dashed lines represent variables taken from the data sources. The dashed lines connect the data sources and the variables taken from them, while the solid lines connect the variables to the scenarios in which they are used.

the annual growth rate, while still providing more detailed observations than a longer period, such as ten years. The normalised five-year growth rate is calculated using Equation (2) (based on Vinichenko et al. (2023)), where GR denotes the growth rate, EG denotes electricity generation, and TES denotes the total electricity system size.

$$\mathrm{GR} = \frac{EG_{YearFinal} - EG_{YearInit}}{\frac{TES_{YearFinal} + TES_{YearInit}}{2}} \tag{2}$$

The calculation yields a list of five-year growth rates, spanning the first to the last year of available data for each reference country. From this data, we take the 95-percentile for each energy source as the growth rate in our scenarios. The 95-percentile value is chosen to account for technological advancements that may lead to a faster growth rate in the future, given that the scenario assumes a constant five-year growth rate over a 20- to 30-year period. At the same time, the 95-percentile can also avoid an outlier growth rate, which may occur when using the maximum value.

The calculated low-carbon growth rate is complemented by a ramp-up rate. The ramp-up rate is based on the S-curve concept, which posits that after take-off, technologies rapidly accelerate before their growth stabilises (Cherp et al., 2021). The application of a ramp-up rate bridges historical and projected data, avoiding an unrealistically high acceleration of growth rates. From among the reference countries, two additional criteria are used to select the country from which the ramp-up rate is derived: for each energy source, the selected reference country (1) must exhibit rapid growth over a short period and (2) must have higher penetrations of the renewable energy source than the case countries. The criteria are applied through visual observations, in which we compare the normalised electricity generation of both the reference and case countries. The rate is then calculated as an annual growth rate by using Equation (3). The 95-percentile of the selected country's annual growth rate is used as the ramp-up rate for each energy source.

$$\text{Annual growth rate} = \frac{EG_{YearN+1} - EG_{YearN}}{EG_{YearN}} \tag{3}$$

The low-carbon growth rate is then constrained by the projected electricity demand and the technical potential of renewable energy in the case countries. Total generation from both renewable and non-renewable sources cannot exceed the projected demand, and each renewable energy source cannot grow beyond its potential. Similar to the renewable potential, we also set an upper limit for natural gas based on the maximum share of gas in the energy plans of the case countries. This limit reflects the capability of the case countries to develop their infrastructure to incorporate more natural gas into their electricity systems.

Prioritisation of low-carbon technologies is introduced to accommodate our assumption that reference countries have only been able to simultaneously develop one or two types of technology rapidly. This prioritisation leads to the division of empirical scenarios into policy-priority scenarios, variable renewable energy (VRE) scenarios, and non-VRE scenarios, each with different low-carbon source constraints, as represented by the priority order (Table 3). The policy-priority scenario derives the priority order from the electricity supply plans of the case countries. It indicates the minimum constraint on energy sources that have the highest share in the plans. The non-VRE scenario prioritises non-VRE sources, i.e., hydropower, geothermal, and BWR, with hydropower as the first priority due to its technological maturity. The VRE scenario prioritises VRE sources, i.e., solar and wind, with solar power as the first priority due to its wider geographical distribution compared to wind power. In all scenarios, natural gas is considered the least prioritised energy source. It only grows when other energy sources have reached their maximum growth limit and projected demand growth exceeds the resulting total renewable generation. Electricity imports are not considered as alternatives due to countries' grid structures and the lack of precedence for large-scale imports in historical data and energy plans.

Table 3
Priority order of low-carbon sources for each scenario of the empirical scenario group. The asterisk on natural gas indicates that, although it is a fossil-fuel source, it is included in the list to emphasise the constraints placed on it.

Scenario name	Priority order (from most to least prioritised)
Policy-priority	Indonesia: solar > BWR > geothermal > hydropower > wind > natural gas* The Philippines: wind > solar > hydropower > geothermal > BWR > natural gas* Vietnam: wind > solar > hydropower > BWR > natural gas*
Non-VRE	Hydropower > geothermal > BWR > solar > wind > natural gas*
VRE	Solar > wind > hydropower > geothermal > BWR > natural gas*

3.3. Emission calculation

The total carbon emissions from policy-based and empirical scenarios are then calculated to assess the impact of peak coal on the decarbonisation of electricity systems. We include both direct and indirect lifecycle emissions, as defined by the IPCC Fifth Assessment Report (Schlömer et al., 2014). The IPCC Report assumes zero direct emissions for BWR and does not consider the carbon absorption effect from fuel vegetation. The direct and lifecycle emissions of each electricity supply technology are given in Table 4.

4. Data and assumptions

4.1. Peak coal capacity and coal generation

Three assumptions for coal power plant lifetime are established: 61 years, reflecting the age of the oldest operating coal power plants in Indonesia, the Philippines, and Vietnam; 38 years, the global average lifetime of coal power plants (Global Energy Monitor, 2024); and 20 years, a lifetime aligned with 1.5-degree pathways under the Paris Agreement (Cui et al., 2019). For coal power plant units that have reached their specified lifetimes by 2024, the year the current dataset was obtained, it is assumed that they will be retired gradually over the next five years, starting with the units of lowest capacity (Montrone et al., 2023). We also assume that power plants under the "uncertain" category will begin operation in the same year as the largest coal power plant units in the plan, which are scheduled to start operation in 2028 for Indonesia, 2026 for the Philippines, and 2029 for Vietnam.

We use the average capacity factor coefficient (α) over the last three years, which represents the latest capacity factor for coal power plants across the three countries, to obtain coal generation data until 2050. We only calculate electricity generation from coal capacity using the 38-year lifetime assumption to account for the absence of historical precedent for policy-driven coal power plant retirements across the three countries. The amount of coal-powered generation from the peak

Table 4
Direct and lifecycle emissions of various electricity supply technologies. Sources: Oil – IEA (2023b), Weisser (2007), other technologies – Schlömer et al. (2014).

Supply technology	Direct emissions (gCO2eq/kWh)	Lifecycle emissions (gCO2eq/kWh)
Coal	670-870	740-910
Natural gas	350-490	410-650
Oil	733-935	500-1200
BWR	0	130-890
Geothermal	0	6-79
Hydropower	0	1-2200
Nuclear	0	3.7-110
Solar	0	18-180
Wind	0	7-56

capacity calculations serves as the upper limit for coal generation in policy-based and empirical scenarios (see Fig. 2).

4.2. Reference countries and low-carbon growth rates

There are two main criteria for selecting reference countries. First, the countries must have had an electricity system size of at least 100 TWh for at least five consecutive years. The five-year criterion is based on the growth rate calculation. Considering the current and projected sizes of the electricity systems in Indonesia, the Philippines, and Vietnam, a threshold of 100 TWh is set to account for the influence of system size on the diffusion rate of energy technologies. Historical analysis of different energy technologies shows that system size negatively correlates with the diffusion rate of technology (Grubler et al., 2016; Wilson et al., 2013; Wilson and Grubler, 2011), suggesting that diffusion in a small system can occur more rapidly than in a larger one. Hence, it is more likely for a smaller system to achieve a growth rate comparable to that of a larger system than vice versa, allowing the reference countries to have larger, not smaller, system sizes than the study countries. Second, the reference countries must have a history of developing at least one out of five renewable energy sources considered in this scenario.

We identified 32 reference countries. All reference countries and their observed periods are listed in Supplementary Table 1. The five-year low-carbon growth rates calculated from these reference countries are shown in Table 5.

4.3. Ramp-up rate

To determine the ramp-up rate that satisfies the two criteria, normalised electricity generation from renewable energy sources in the reference countries and three case countries are presented (Supplementary Fig. 1) and compared. Based on the visual inspection of the criteria, we select the Netherlands, the UK, Thailand, and Argentina as the countries from which ramp-up rates for solar, wind, BWR, and hydropower are derived, respectively. For geothermal power, we select the Philippines' growth rate because its geothermal penetration is higher than that of Indonesia and the other reference countries. The 95th percentile of each source in each country is then calculated and used as the ramp-up rate to avoid extreme acceleration rates that may be difficult to replicate.

4.4. Renewable potential

The renewable potentials used in our calculations are shown in Table 6. We use technical potential rather than feasible potential because the latter depends on a large array of factors (Dupré la Tour, 2023; Fuchs et al., 2012; Jäger et al., 2015; Killingtveit, 2014), and reliable data for all energy sources across the three case countries is not available. The technical potential for Indonesia, the Philippines, and Vietnam is commonly presented in terms of potential capacity (Table 6).

Table 5
The five-year low-carbon growth rate used in the reference scenarios. The growth rate is presented as a percentage of the total electricity system (TES). The equivalent country is the reference country with the closest growth rate to the 95-percentile value for each energy source, as the percentile value calculation may not point to a specific reference country. The equivalent period is the period when the reference country has the growth rate value.

Fuel	Five-year growth rate (% of supply)	Equivalent country	Equivalent period
BWR	2.7%	Germany	2010-2015
Gas	23%	UAE	2012-2017
Geothermal	0.8%	Mexico	2002-2007
Hydropower	16%	Canada	1975-1980
Solar	3.7%	Mexico	2017-2022
Wind	6.1%	Brazil	2012-2017

Table 6
Renewable potential of Indonesia, the Philippines, and Vietnam. Annual potential generation is calculated assuming maximum utilisation of potential capacity. Sources of potential capacity: Geothermal: Indonesia - PLN (2021), the Philippines - Fronda et al. (2021); Hydropower: Indonesia & Vietnam - International Hydropower Association (n.d.), the Philippines - Philippines Department of Energy (n.d.); Solar & Wind: Lee et al. (2020); BWR: Handayani et al. (2022).

Country	Renewable sources	Potential capacity (GW)	Annual potential generation (TWh/year)
Indonesia	Geothermal	30	205
	Hydropower	80	314
	Solar	1052	915
	Wind	50	152
	BWR (Biomass)	33	247
The Philippines	Geothermal	4	22
	Hydropower	16	34
	Solar	1910	2504
	Wind	217	534
	BWR (Biomass)	0.2	0.5
Vietnam	Hydropower	40	154
	Solar	2847	1662
	Wind	311	612
	BWR (Biomass)	1	3

Potential generation is then calculated using the empirical three-year average coefficient for each country and energy source, as with the pipeline's coal capacity (Section 3.2).

5. Results

The coal power plant capacity projection results in similar peak capacity years across lifetimes and countries. Indonesia is projected to reach peak coal capacity in 2026, the Philippines between 2027 and 2028, and Vietnam in 2027 (Fig. 3). The inclusion of coal power plants classified as "uncertain" delays peak coal capacity years to 2028-2030 for Indonesia and 2029-2035 for Vietnam, while the Philippines' peak coal capacity years remain the same (Supplementary Fig. 2). Yet, the decline of coal capacity after the peak year is projected to be slow (Supplementary Fig. 3), with the slowest decline observed under the 61-year lifetime assumption, followed by 38-year and 20-year lifetime assumptions. Even if coal capacity peaks, full utilisation of the remaining capacity could generate coal-fired electricity until 2050 (Fig. 4). Full utilisation of the pipeline capacity would result in higher coal power generation than is presented in the three countries' energy plans.

The results for peak coal generation years show greater variation. Indonesia's policy-based scenarios project peak coal generation by 2030, around the same time as peak coal capacity, enabled by a significant increase in the share of natural gas in electricity supply (Fig. 5). Low-carbon alternatives to reach peak coal generation are developed in the empirical scenarios, which project higher growth of hydropower, biomass, and geothermal than policy-based scenarios. However, not all of Indonesia's empirical scenarios show peak coal generation: a peak is not observed in the policy-priority scenario with a lower demand projection.

The policy-based scenarios for the Philippines also project peak coal generation around the same time as peak coal capacity, achieved mainly through natural gas expansion, except in scenarios where the country achieves its higher renewable targets (LDHRE and HDHRE). On the other hand, the Philippines' empirical scenarios have a less apparent peak than the policy-based scenarios. Coal-powered generation is not projected to decline until around 2050 and the share of natural gas is generally higher than in policy-based scenarios. The non-VRE empirical scenarios exhibit the highest increase in the share of natural gas among the empirical scenarios and the largest proportion of unmet demand.

Vietnam's policy-based scenarios indicate peak coal generation by 2030, around the same time as peak coal capacity, but the main coal substitute varies depending on scenario (Fig. 5). In the scenarios with

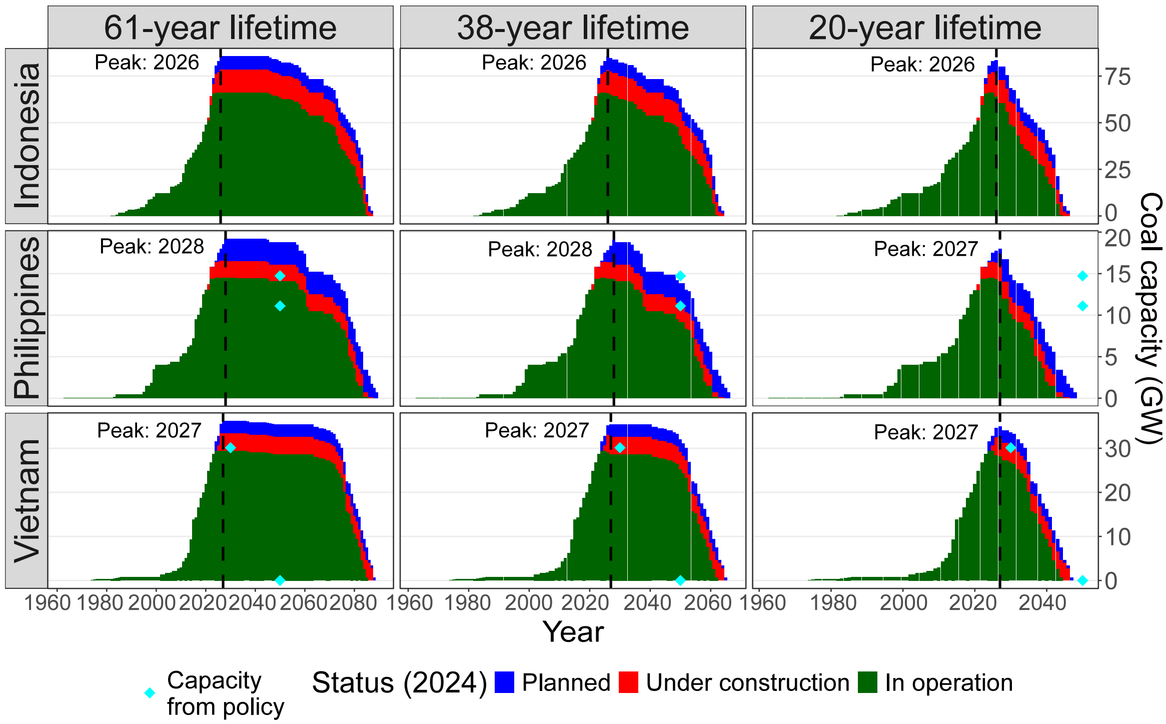

Fig. 3. The historical and projected installed capacity of coal power plants in Indonesia, the Philippines, and Vietnam based on the power plant project (pipeline) data with three lifetime assumptions. Historical data is up to 2022. The "capacity from policy" represents the coal capacity that countries' energy policies aim for. This coal capacity is shown as a range for the Philippines, while Indonesia's is not included due to data unavailability. (Data source: historical pipeline capacity – Global Energy Monitor (2024), S&P Global Platts (2021); planned capacity – Philippines Department of Energy (2023), Prime Minister of Vietnam (2023)).

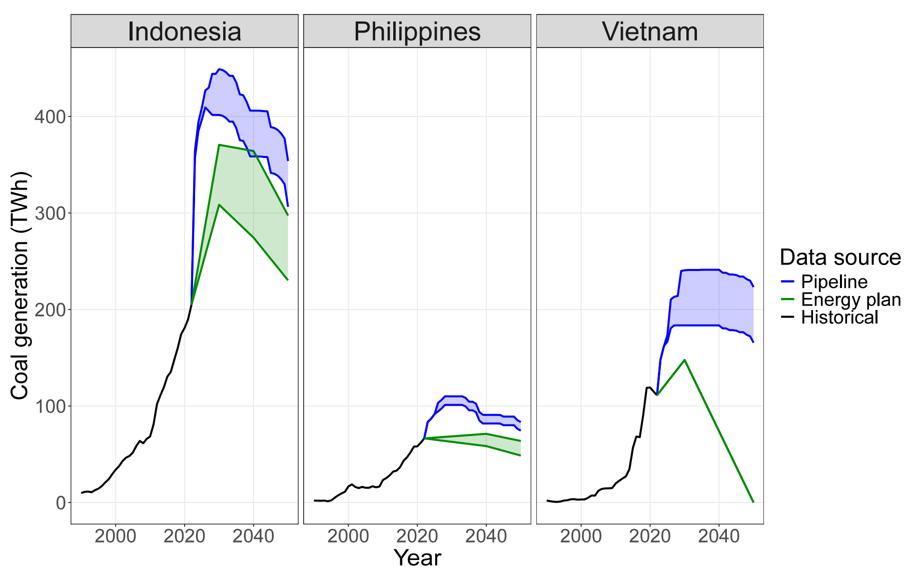

Fig. 4. Coal power generation from historical data (1990-2022), from the coal pipeline, and from the energy plans. The lower range of pipeline projection represents pipeline data, and the upper range represents pipeline data with uncertainty. The energy plan projection is also given in upper and lower ranges for Indonesia and the Philippines. (Data sources: Historical data – IEA (2024), energy plans – President of the Republic of Indonesia (2023), Philippines Department of Energy (2023), Prime Minister of Vietnam (2023).

higher demand projection (HDLRE, HDHRE), coal is primarily replaced by natural gas, with a considerable amount of generation also coming from other low-carbon sources, mainly nuclear and hydrogen. Other policy-based scenarios project declining shares of both coal and natural gas, along with a larger increase in the share of low-carbon sources. On the other hand, all of Vietnam's empirical scenarios show a less apparent peak coal generation, with the peak only appearing after 2040, much later than in the policy-based scenarios.

The emission calculations reveal differences among scenarios within the countries. Indonesia's direct emissions per TWh in the policy-based scenarios exceed those in the empirical scenarios in 2030, but this gap narrows by 2040 and 2050 (Fig. 6). Conversely, empirical scenarios consistently indicate higher lifecycle emissions than policy-based scenarios, with their emissions per TWh following a similar trend across 2030, 2040, and 2050. A similar trend in direct and lifecycle emissions is also evident in Vietnam's policy-based and empirical scenarios. The

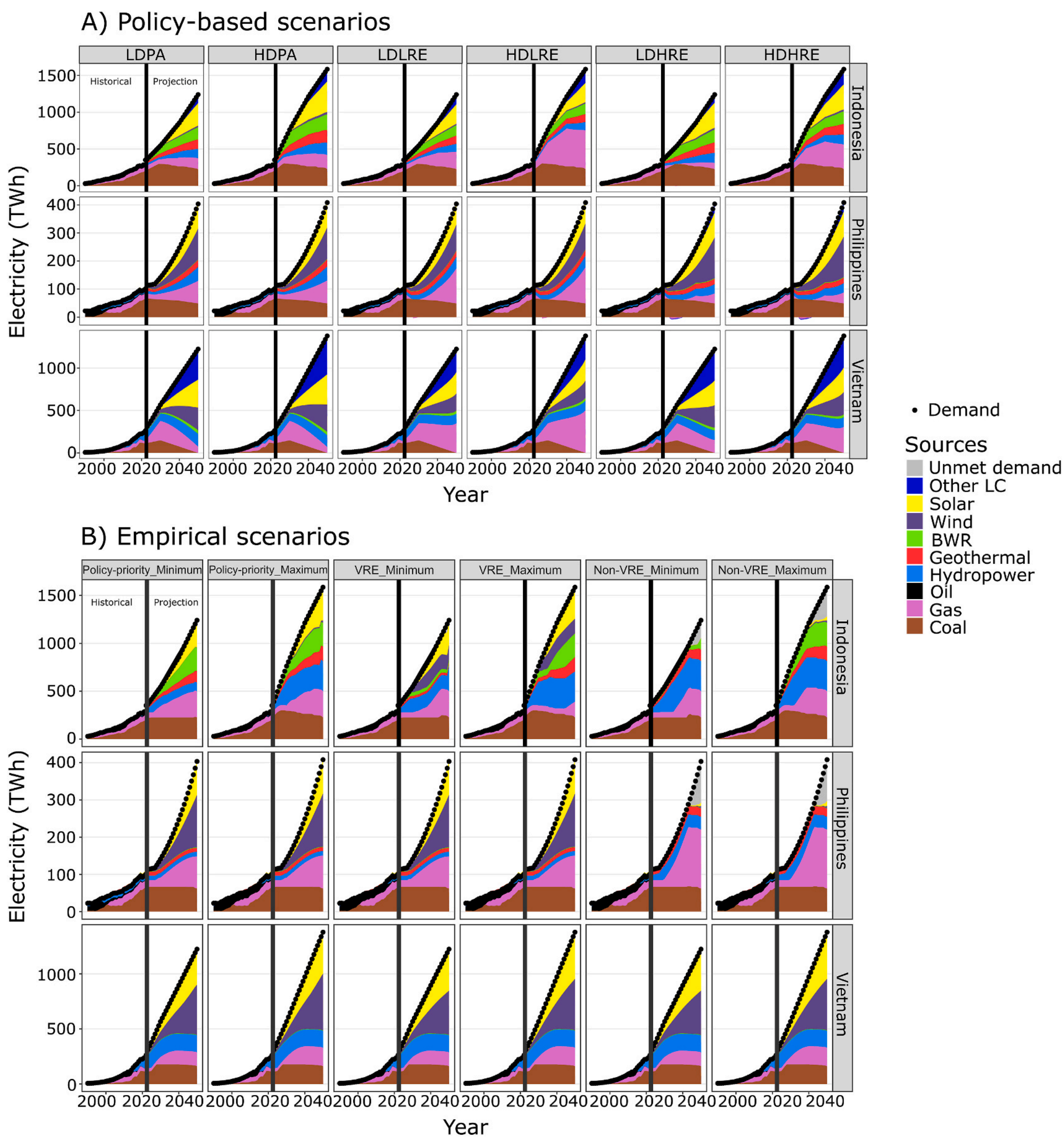

Fig. 5. A) Electricity mixes of policy-based scenarios and B) Electricity mixes of empirical scenarios. Other LC refers to other low-carbon technologies, mainly nuclear power for Indonesia and the Philippines and nuclear power and hydrogen for Vietnam. BWR refers to biomass and renewable waste. The left side of the line shows historical data (1990-2022) and the right side shows scenario projections. For abbreviations of the policy-based scenarios, refer to Table 1. The "minimum" and "maximum" of the empirical scenarios refer to the electricity demand projection (Source for historical data: IEA (2024)).

Philippines shows a different trend as its empirical scenarios have higher direct emissions per TWh in 2030 and 2040 and comparable emissions with policy-based scenarios in 2050. The lifecycle emissions also follow the same pattern as its policy-based scenarios.

The total direct emissions of the scenarios may increase or decrease relative to historical emissions (Fig. 7), with the upper range of the emission projection following the historical line more closely than the lower range. The total lifecycle emissions are shown to increase relative to the historical estimate in most scenarios. A decrease in the total emissions is only observable in some of the Philippines' (PS_HRE) and Vietnam's (PS_PA and PS_HRE) policy-based scenarios, where the absolute generation of coal- and gas-powered electricity is to be reduced.

6. Analysis and discussion

The current literature on peak coal in electricity systems is limited to analyses of past peak coal occurrences, which show that peak coal occurred when electricity demand stabilised (Lægreid et al., 2023). Replicating these historical precedents will be challenging in emerging economies, where electricity demand is expected to continue growing for several decades. This study therefore proposes a new approach for understanding when and how countries with high coal dependence and rapid demand growth can achieve peak coal in their electricity systems. Unlike earlier studies on coal power in Southeast Asia (Chen and Mauzerall, 2021; Clark et al., 2020), this paper explicitly distinguishes between peak coal capacity and peak coal generation. This distinction separates changes in coal power plant size from changes in coal power plant utilisation, allowing the timing and drivers of each peak to be analysed separately before examining whether they lead to lower carbon emissions.

The findings on the peak coal year are in line with those of Clark et al. (2020) and Chen and Mauzerall (2021). The findings also show that peak coal capacity occurs in similar years across various lifetime assumptions, despite the substantial differences among them. This is the case because power plants currently in operation have a much larger cumulative capacity than those with "planned" or "under construction"

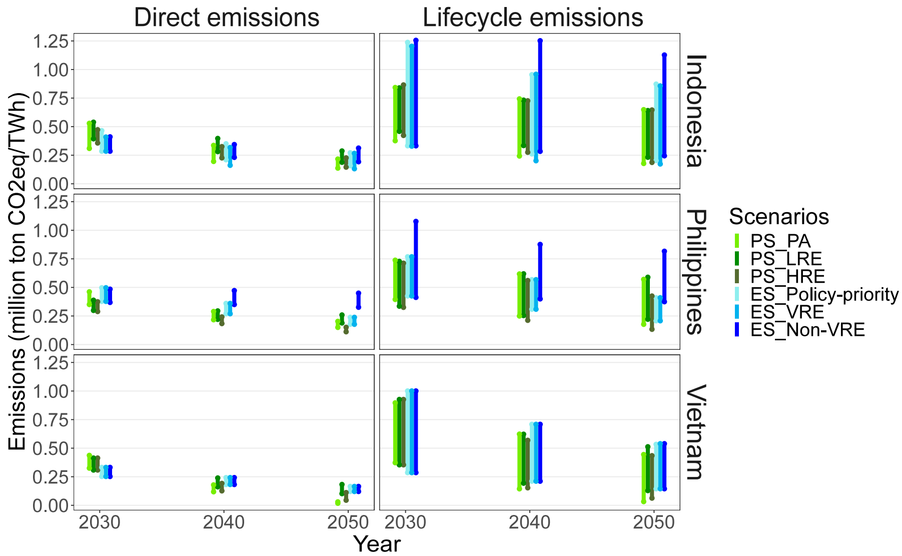

Fig. 6. Direct and lifecycle carbon emissions per generated unit of electricity of the electricity mixes of the constructed scenarios for the selected years of 2030, 2040, and 2050. Green colours represent policy-based scenarios and blue colours represent empirical scenarios. The total emissions range encompasses the lower and upper bounds of emissions from various electricity supply technologies, as well as the lower and upper bounds of demand projections for each scenario. Abbreviations: PS – policy-based scenarios, ES – empirical scenarios, PA – proportional adjustment, LRE – lower renewable energy (target), HRE – higher renewable energy (target), VRE – variable renewable energy. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

status (Fig. 1C), and most of them are under ten years old (Fig. 1B). Thus, phasing out older coal power plants will not substantially accelerate the decline in total capacity. A much faster decline rate can only be achieved if young power plants are forced to retire after 20 years of operation. Yet, even then, it would take 20 years or more from 2024 to phase out coal power plants entirely, a longer timeline than the Indonesian president recently aspired to achieve (Milko, 2024).

Unlike peak coal capacity, the timing of peak coal generation depends on how much electricity coal fleets in the pipeline generate and how quickly coal substitutes expand. This leads to different results between policy-based scenarios and empirical scenarios. Most policy-based scenarios project peak coal generation around the same time as peak coal capacity, generally by 2030, because countries' energy plans already anticipate coal generation levelling off or declining around the time of peak coal capacity. On the other hand, many empirical scenarios project a later and less pronounced peak, typically after 2040, because they anticipate continued coal-fired generation from coal power plants in operation, under construction, and planned. This contrast suggests that halting the development of new coal power plants does not necessarily lead to early peak coal generation in the case countries.

The peak coal generation years from empirical scenarios for Indonesia and Vietnam align with countries' energy outlook reports. Indonesia's National Energy Council (2019) projects peak coal generation around 2045 under the scenario compatible with the IPCC 2-degree limit. Vietnam Energy Outlook (Electricity and Renewable Energy Authority VietnamDanish Energy Agency, 2024) also projects peak coal generation around 2040 under most scenarios. Yet, the net-zero scenario projects peak coal generation around 2030, assuming significantly rapid deployment of solar power from 2030 until it reaches a 75% share of total electricity supply in 2050. Therefore, reaching peak coal generation soon after peak coal capacity depends not only on limiting further coal expansion, but also on whether alternative electricity sources can be deployed rapidly enough to prevent the continued utilisation of the existing coal fleet.

To assess how peak coal affects carbon emissions in electricity systems, this study considers lifecycle carbon emissions alongside direct carbon emissions. The inclusion of lifecycle emissions captures emissions not reflected in direct emissions, particularly for non-VRE sources, such as hydropower and biomass. These energy sources generally have zero direct emissions but can emit substantial amounts of greenhouse gases throughout their lifecycles, including methane and emissions from land-use change (Schlömer et al., 2014).

As the results show, total lifecycle emissions in most scenarios are projected to continue rising until 2050 (Fig. 7), despite scenarios that achieve peak coal generation through the rapid deployment of renewable energy while limiting natural gas development. This indicates that peak coal generation does not automatically lead to decarbonisation in rapidly growing electricity systems. Even when coal is increasingly replaced by renewable energy rather than natural gas, growth in total electricity generation can outweigh the emissions reductions achieved by this substitution. A decrease in emissions is only observable in some of the Philippines' and Vietnam's policy-based scenarios, where coal-powered generation falls sufficiently in absolute terms to offset the emissions effect of electricity system expansion. This suggests that in rapidly growing electricity systems, substituting coal with lower-carbon sources is insufficient if electricity demand continues to grow substantially.

Scenario comparisons also show that VRE sources (solar and wind energy) are vital for simultaneously achieving peak coal generation, meeting growing demand, and limiting emissions growth. This is evident in the non-VRE scenarios for Indonesia and the Philippines, which project significant unmet demand from 2040 onwards, whereas corresponding VRE scenarios do not. At the same time, lifecycle emissions results show important differences among renewable technologies. Scenarios with a larger share of non-VRE sources (biomass and hydropower) can result in higher lifecycle emissions, even when natural gas deployment remains limited, because of their context-dependent lifecycle impacts (Schlömer et al., 2014). These findings highlight the importance of technological choice in decarbonising electricity supply and understanding it in the local context.

This study is not without limitations. One main limitation is that it considers only techno-economic conditions in electricity systems when determining peak coal. Political factors have been shown to pose a significant influence over coal power decisions (Dorband et al., 2020; Jakob et al., 2020; Manych and Jakob, 2021; Ordonez et al., 2021). Furthermore, the study excludes electricity costs, whereas cost variations, as reflected in the levelized costs of electricity across the Southeast Asia region (Setyawati and Nadhila, 2024), may result in electricity

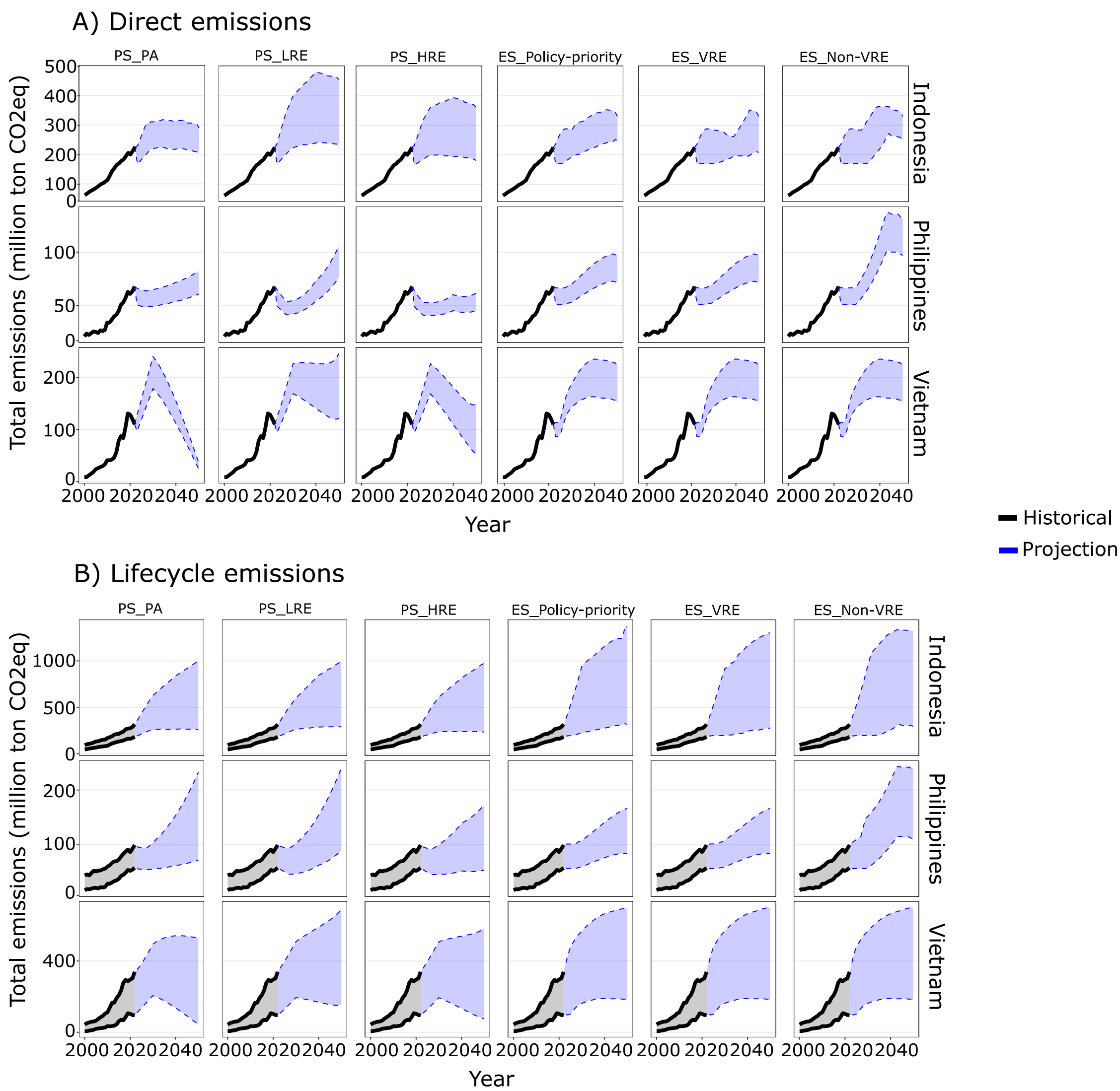

Fig. 7. Calculated emissions of total direct (A) and lifecycle (B) emissions of electricity mixes of the constructed scenarios. The shaded part of each graph represents the range of total carbon emissions. The historical emissions data cover the period from 2000 to 2022. Abbreviations: PS – policy-based scenarios, ES – empirical scenarios, PA – proportional adjustment, LRE – lower renewable energy (target), HRE – higher renewable energy (target). Historical emissions are adapted from Ember.

mixes that differ from those projected in this study.

Other limitations are related to the assumptions used within the methodological framework. Coal-based generation used in the scenario construction is derived from capacity projections with a 38-year lifetime assumption, which is the global average for coal power plant lifetimes. Although this lifetime should reflect a pathway without policy intervention, it has not been observed in the case countries; in reality, coal power plants often operate for longer, with some operating for more than 50 years (Global Energy Monitor, 2024). This suggests that closing down coal power plants after they reach the global average lifetime may also require policy intervention in these countries. Thus, the projection's accuracy may depend on the presence of such interventions.

The empirical scenarios also use very optimistic assumptions. These scenarios assume that the case countries can replicate the 95-percentile growth rate for 20 to 30 years. These optimistic assumptions underscore the urgency with which the countries must develop renewable energy sources in their electricity system to enable peak generation. However, such rapid growth over a long period has not been observed historically. Lower growth rates of renewables and natural gas significantly affect the results of the peak coal generation, as well as the electricity mix conditions that enable those peaks (Supplementary figure 4). This, in turn, also impacts the projected total carbon emissions of systems. A less optimistic set of empirical scenarios would show a later peak and greater carbon emissions.

The estimates of lifecycle emissions should also be interpreted with caution because emission factors vary widely across calculation methods and data sources. This uncertainty is particularly relevant for biomass and hydropower. Biomass lifecycle emissions account for the net carbon flux between biomass combustion and carbon uptake by vegetation and soils, and include carbon-equivalent emissions from nitrous oxide, which vary by biofuel source and land-cover changes (Smith et al., 2014). Hydropower lifecycle emissions primarily originate from fossil fuel combustion during plant construction and methane emissions from the degradation of biomass in the reservoirs (Krey et al., 2014). Because these emission sources are site-specific, the actual lifecycle emissions for each scenario in this study require further investigation, and uncertainties in the emission calculations can lead to different conclusions about overall growth in total lifecycle emissions.

7. Conclusions and policy implications

Reaching peak coal electricity is a crucial step for coal-dependent developing and emerging economies in their transition away from coal. Yet, past coal peaks occurred under stable electricity demand conditions, in sharp contrast to the rapid demand growth in developing and emerging economies. We propose a new methodological framework to understand when and how peak coal electricity can occur under such rapidly growing electricity demand. The framework distinguishes between peak coal capacity and peak coal generation and applies separate approaches to each. The former is analysed using coal power plant pipeline data, and the latter is analysed by considering the growth of coal substitutes through policy-based and empirical scenarios. Additional analysis of total carbon emissions, encompassing both direct and life-cycle emissions, is conducted to understand the impact of peak coal on electricity system decarbonisation. We apply the approaches to Indonesia, the Philippines, and Vietnam, three coal-dependent emerging economies in Southeast Asia that have moratorium policies on new coal power plants.

The results show that the three countries can reach peak coal capacity between 2026 and 2028 if they follow the moratoriums. Yet the installed coal capacity will decline only gradually after reaching its peak. The peak coal generation results show greater variation in peak years, as they depend on the growth and choices of other supply technologies. Policy-based scenarios project reaching peak coal generation around the same year as peak coal capacity, enabled by the expansion of natural gas, another fossil fuel, whereas many empirical scenarios project a later and less pronounced peak coal generation, generally from 2040 onwards, with some scenarios not showing a peak at all. Reaching peak coal generation also does not necessarily lead to decarbonisation of the electricity system. Total emissions are projected to continue rising in most scenarios due to the expansion of fossil-based electricity to meet growing demand. Therefore, decarbonising rapidly growing electricity systems requires coal-powered generation to decline sufficiently in absolute terms to offset the emissions effect of electricity demand growth.

The findings also yield four policy implications for electricity supply planning in Indonesia, the Philippines, and Vietnam. Although country-specific, they are likely to be applicable also to other developing and emerging economies with similar energy system conditions.

1. Although the countries can reach peak coal capacity in the next few years, they are not likely to reach peak coal generation until towards the middle of the century. They thus need to pair coal power plant moratoriums with plans for coal power plant retirement to limit the continued use of coal power for electricity generation.
2. The deployment of VRE technologies (solar and wind power) is crucial not only for reaching peak coal generation but also for limiting carbon emissions. Therefore, their deployment should be prioritised in electricity supply planning. This is particularly important for Indonesia's energy plan, which does not aim to accelerate wind power deployment. Indonesia should review its proposed energy plan and consider increasing the share of wind power in its electricity supply.
3. The electricity supply cannot be decarbonised by relying on natural gas as the main substitute for coal to meet rapidly growing electricity demand. The planned rise in the share of natural gas in the electricity mix will increase both direct and lifecycle emissions, undermining the climate-mitigation benefits of limiting coal growth through reaching peak coal capacity. The countries should thus re-evaluate their energy plans and develop strategies to deploy low-emission substitutes for coal power to meet increasing demand.
4. Policies that limit the development of new coal power plants need to be complemented by measures that reduce fossil-based generation in absolute terms. Although empirical scenarios show that deployment of VRE technologies can enable peak coal generation while limiting natural gas expansion, total carbon emissions, particularly lifecycle emissions, still rise in most scenarios because electricity demand continues to grow. This is a peculiar challenge faced by countries with rapidly expanding electricity systems. Vietnam's energy plan illustrates a pathway in which the share of fossil fuels is reduced over time and eventually phased out. Indonesia and the Philippines should therefore complement coal moratoriums with clearer strategies to reduce fossil-based generation.

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CRediT authorship contribution statement

M. Ridwan Dzikrurrokhim: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Erik O. Ahlgren:** Conceptualization, Resources, Supervision, Writing – review & editing. **Marta Vetier:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: M. Ridwan Dzikrurrokhim reports financial support was provided by European Research Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2026.115532.

Data availability

Data will be made available on request.

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