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Fossil fuel lock-in vs clean power: pathways for the developing Asian region by 2050-2060

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Supplementary material for this article is available online

Abstract

Rapidly growing electricity demand and entrenched fossil-fuel infrastructure in South and Southeast Asia require urgent attention to avoid a long-term lock-in to a high-emissions pathway. National power-sector expansion plans mostly remain supply-side centric and overlook the potential contribution of demand-side efficiency and flexibility. This study addresses this gap by evaluating how four emerging Asian economies can decarbonize their power sectors between 2050 and 2060. Two national-scale models, PyPSA-BD-IDS and PyPSA-TH-IDS, are developed for Bangladesh and Thailand, complemented by a literature synthesis for India and Indonesia, to assess techno-economic feasibility, land use, financial resource mobilization needs, employment, and stranded-asset risk across pledged and higher-ambition scenarios. All four countries can reach clean power systems around mid-century (2050 for Bangladesh, India, and Thailand, and 2060 for Indonesia) through nationally determined pathways. For Bangladesh and Thailand, integrating energy efficiency and demand-side flexibility generates economy-wide ∼7%–33% more jobs, including both direct and indirect, and reduces fossil-fuel dependency and avoids supply-side capacity overbuild. These yield ∼21%–40% lower emissions than the supply-side-only pathway across the milestone years to 2050. The integrated pathway reduces the supply-side financial resource mobilization need by ∼44%–48% and roughly halves land requirements. Published Indian pathways show the same pattern: DSF integration lowers storage needs and system costs, easing lock-in risk. Indonesia, assessed using the literature on a supply-side-only pathway, requires ∼1034 GW installed capacity and ∼€136 billion cumulative investment by 2060. Across all four countries, the predominance of a young coal fleet (227 GW added in the past two decades), unequal investment capacity, and spatially concentrated fossil-sector employment pose special challenges to a just transition. The integrated pathway in Bangladesh and India reduces the need for supply-side annual investment compared to the 2025 investment level, while for Thailand, it is very close but higher than the planned investment level.

1. Introduction

The IPCC Sixth Assessment Report [1] highlights large regional differences in historical and future emissions driven by fossil-fuel infrastructure lock-in. The Asian region is identified with the largest stock of fossil-fuel-driven power infrastructure, locking the region onto high-emission pathways [2]. Limiting warming to well below 2 °C requires rapid, deep reductions in energy-system CO_2 and GHG emissions [3]. However, pathways to zero or net-zero emissions depend on national/regional circumstances [4]. Accelerated action requires a clear understanding of opportunities and challenges reflected in national-scale research and planning. For developing Asian economies pursuing rapid economic growth to deliver wellbeing for all, where electricity demand is expected to rise continually [5, 6], this perspective is essential.

This study examines cases of Bangladesh (BD), India (IN), Indonesia (ID), and Thailand (TH). The power sector is the largest source of national CO_2, contributing ~46.00% in BD, ~47.00% in IN, ~40.00% in ID, and ~35.00% in TH (figure 1) [7–9]. These countries present key structural contrasts that shape transition outcomes in the emerging Asia context (coal-heavy vs gas-heavy systems and lower- vs middle-income contexts). Current per-capita generation (figure 2), in these countries, ranging from 656–2657 kWh, is far below the global average of 3780 kWh [7, 9].

However, demand is rising with income, industrial activity, and electrification. Historical fuel-mix patterns (figure 3) indicate persistent lock-in risks. Bangladesh and Thailand rely on gas, while India and Indonesia remain coal-dependent [7–9]. From 2000 to 2022, fossil-fuel power-sector emissions tripled across the four countries, from ~585 to 1771 MtCO2 (figure 4), driven by coal, which rose from ~461 to 1591 MtCO_2. India's coal emissions increased from ~409 to 1291 MtCO_2, and Indonesia's from ~34 to 260 MtCO_2. Gas emissions reached ~33 MtCO_2 (BD) and ~46 MtCO_2 (TH) in 2022, while oil contributed ~46 MtCO_2. Low-carbon shares remain below the ~41.00% global average: 2.03% (BD), 22.46% (IN), 19.29% (ID), 14.86% (TH) [7].

The central trilemma for developing Asia is how to meet rising demand to meet developmental needs, achieve climate ambitions, and avoid fossil-fuel lock-in. A supply-side-only strategy risks higher cumulative emissions, elevated costs, greater vulnerability to fossil fuel-price shocks, and increased land-use pressures with renewable energy expansion [10]. Integrating EE and DSF can flatten the load curve and shift load, improve renewable penetration, reduce curtailment, and defer or avoid costly capacity additions [11].

1.1. Low-carbon technology portfolio and modeling landscape

Across the four study countries, most capacity-expansion and energy-system models deploy similar low-carbon technology sets (notably solar PV, onshore wind, hydropower, and biomass) on platforms including OSeMOSYS, LEAP, TIMES/TIAM, MARKAL/VEGA, LUT Energy System, EnergyPLAN, GENeSYS-MOD, IDEEA/TIAM-UCL, AIM/Enduse/AIM-CGE/LEAP-NEMO, and PyPSA variants [12–46], summarized in table 1. Country-specific resources appear in selected studies: nuclear in India (and occasionally Bangladesh), geothermal in Indonesia (and in some cases India), and biofuel/biogas in India and Thailand. The predominant emphasis on solar and wind reflects declining technology costs and abundant potential, while hydro and biomass remain constrained by site/resource limitations and competing land/water demands. Nuclear is generally constrained by cost and institutional readiness, while geothermal is concentrated in Indonesia, owing to its rich resource base.

Assumptions regarding storage and system flexibility are highly uneven. Batteries are widely adopted as the 'default' storage choice. In contrast, long-duration storage technologies, such as pumped-hydro energy storage (PHES), hydrogen (power-to-X-to-power), thermal storage, or compressed-air energy storage (A-CAES), appear only sporadically. Demand-side measures (demand response, load shifting, DSF, and end-use efficiency) are often simplified or omitted. Table 2 summarizes these differences. This modeling bias is consequential, as high-renewable mid-century systems require diversified flexibility portfolios to manage diurnal/seasonal variability and reduce the need to overbuild supply-side assets.

Country-level patterns broadly reflect national endowments but still under-represent key options. In Bangladesh, the focus is on solar (including rooftop) and limited wind; DSF is crucial but rarely modeled, despite rising cooling loads. In Thailand, solar and biomass dominate, with moderate wind and limited hydro growth; DSF remains underutilized. In India, large-scale solar and wind dominate, with hydro, biomass, nuclear, and PHES in selected studies; hydrogen and long-duration storage appear in advanced scenarios. In Indonesia, geothermal is strong, alongside solar and hydro; wind plays a smaller role; PHES and hydrogen appear in longer-term pathways.

1.2. Knowledge gap and research questions

IPCC AR6 [47] highlights both demand-side mitigation and supply-side transformation as critical, yet nationally grounded, integrated demand-supply evidence for developing Asian power systems remains limited and is identified as a knowledge gap in global assessments and the Global Stocktake. The systematic underrepresentation of demand-side solutions across existing models leaves a major gap that this study addresses. Stranded-asset risks and fossil-sector employment impacts are also examined, guided by two research questions: (a) how can a zero-emission power system be achieved using clean energy sources under national pledges? (b) What challenges constrain emission reduction, what strategic pathways exist, and what socioeconomic implications must policymakers address?

Investment decisions made today in Asia's fastest-growing power markets will determine emissions trajectories for decades, making this research urgently relevant to the Paris Agreement targets. The contributions of this study are -

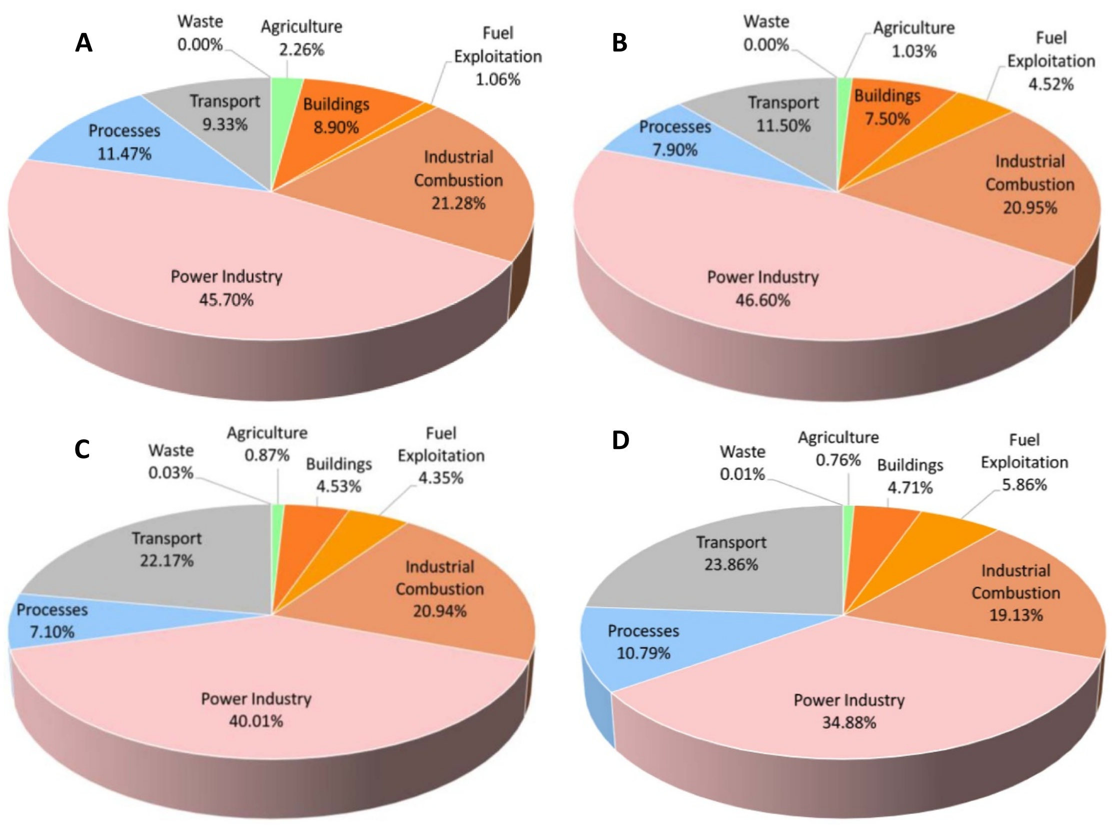

Figure 1. Sectoral emissions of the selected Asian countries (A) Bangladesh; (B) India; (C) Indonesia; (D) Thailand. Data Source: [5, 7, 9].

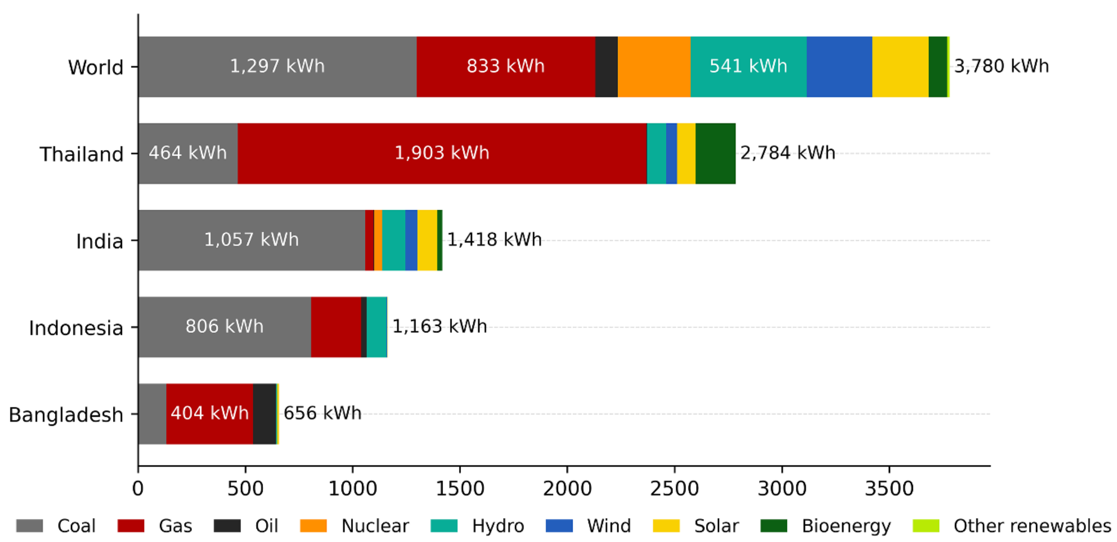

Figure 2. Per capita electricity generation by sources. Data Source: [7, 9].

i. Implementing PyPSA-BD-IDS and PyPSA-TH-IDS with explicit EE and DSF under pledged and ambitious scenarios. Presenting comparable pathways for India and Indonesia using information as available from the published literature.

ii. Providing a data-rich comparative framing of four emerging power systems in Asian countries: capacity, investment, land, affordability, and employment impacts of integrated demand–supply strategies for decarbonization, thus offering a policy-relevant assessment beyond emissions alone.

iii. Analyzing zero-carbon transition challenges and barriers in the power sector.

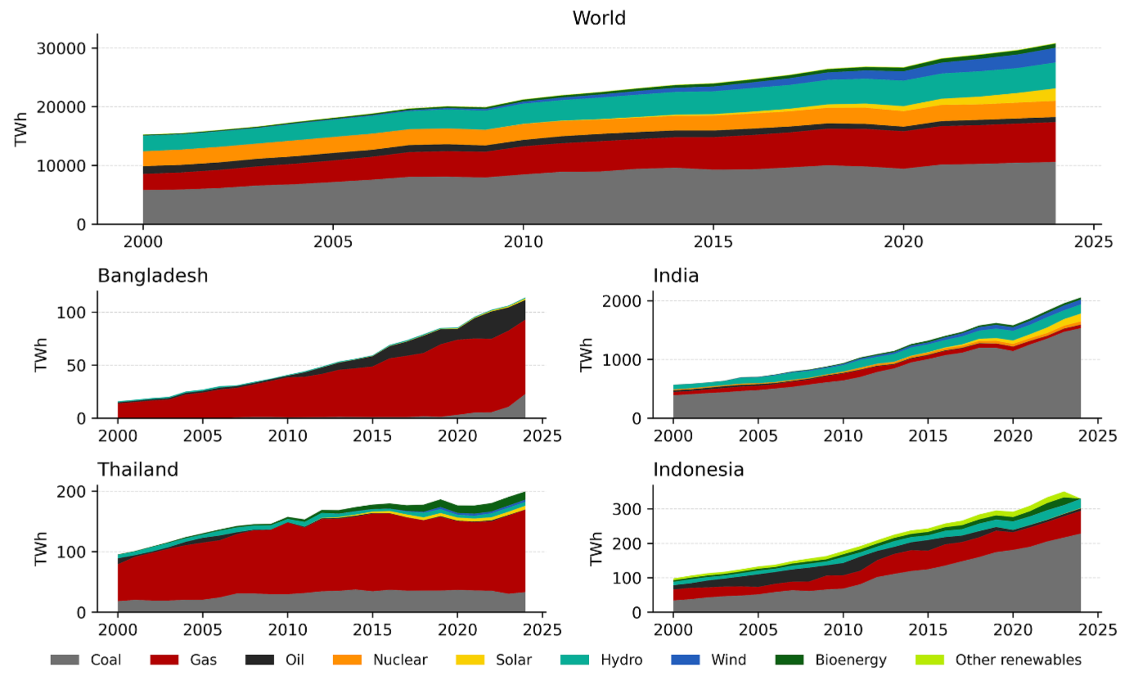

Figure 3. Historical fuel-mix of power generation.
Data Source: [5, 7].

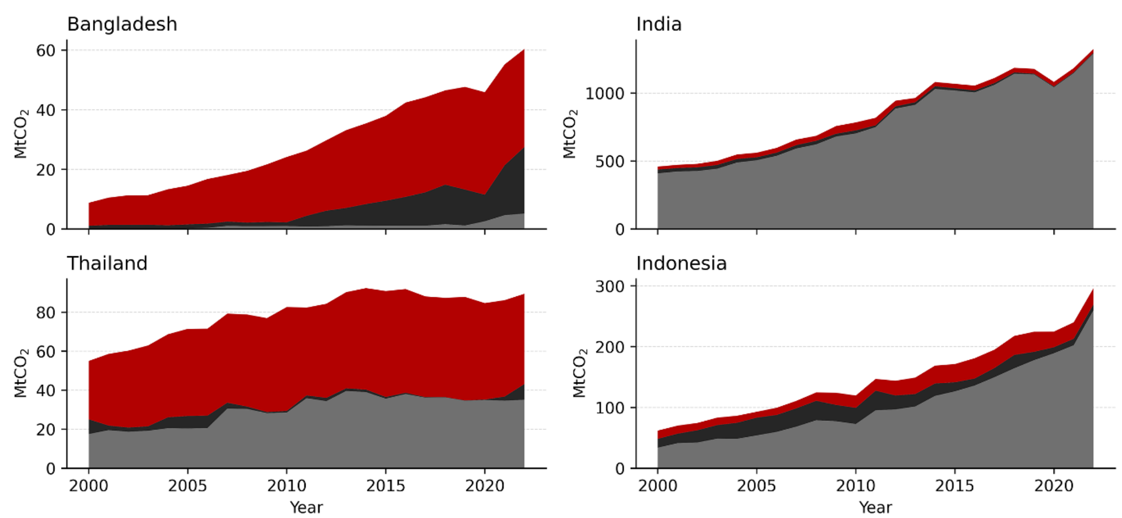

Figure 4. Fossil-fuel-specific emission trajectories.
Data Source: [5, 7, 9].

2. Methodology

A notable gap in existing model-based power sector decarbonization studies is the limited representation of EE and DSF, as most of the studies focus primarily on supply-side expansion. This study uses an integrated national demand–supply modeling framework, PyPSA-BD/TH-IDS (Integrated Demand–Supply) [42, 48], to simulate long-term power-sector pathways for Bangladesh and Thailand, while synthesizing nearly comparable evidence from the literature for India and Indonesia. The framework builds on PyPSA and PyPSA-Earth by adding country-specific data and integrating end-use efficiency, DSF, renewable generation, storage, and transmission modules. PyPSA-BD-IDS resolves Bangladesh across nine spatial nodes, and PyPSA-TH-IDS resolves Thailand across 77 spatial nodes, each at full hourly resolution (8760 h per scenario year). Figure 5 shows the modeling workflow. The objective function and constraints (capacity expansion, demand–supply balance, storage operation, emissions limits, and power flow) follow standard PyPSA formulations, presented in supplementary materials. DSF is represented as an aggregate, system-wide intraday load shift rather than a sector-specific intervention. Sector-scale intervention

Table 1. Summary of model-based low-carbon power generation sources in the reviewed literature.

Models	Hydro	Solar	Wind	Biomass	Biofuel /Biogas	Geothermal	Nuclear
OSeMOSYS	ID, IN, BD,	ID, IN, BD,	ID, IN, BD,	ID, IN,	IN,	ID, IN,	ID, IN, BD
LEAP	ID, IN, BD, TH	ID, IN, BD, TH	ID, IN, BD, TH	ID, IN, BD, TH	ID,	ID	ID, IN, BD
Times	ID, IN, BD,	ID, IN, BD	ID, IN, BD	ID, BD		ID,	ID, IN, BD
MARKAL	BD,	IN, BD	IN, BD	BD			IN, BD
LUT Energy system model	IN, BD	IN, BD	IN, BD	IN, BD	IN,	IN, BD	IN, BD
EnergyPLAN	ID	ID				ID	
VEDA-TIMES, PowerGen-ABM	ID	ID	ID	ID		ID	ID
MoMANI-OSeMOSYS	ID	ID	ID			ID	ID
GENeSYS-MOD	IN	IN	IN	IN		IN	IN
IDEEA, TIAM–UCL	IN	IN	IN	IN			IN
AIM/Enduse, AIM/CGE, LEAP-NEMO	TH	TH	TH	TH			
LEAP-NEMO	TH	TH	TH	TH	TH		

Source: Authors' compilation

Table 2. Representation of storage technologies and flexibility options in reviewed models.

Models	Battery	Hydrogen	PHES	A-CAES	GS	TES	CCS	BECCS
OSeMOSYS	ID							
LEAP	ID, IN, TH	TH	IN					
Times	ID, IN	IN	ID, IN					ID
MARKAL		IN						
LUT Energy System model	IN. BD		IN, BD	IN, BD	IN. BD	IN, BD		
VEDA-TIMES, PowerGen-ABM	ID		ID					ID
AIM/Enduse, AIM/CGE, LEAP-NEMO		TH					TH	
LEAP-NEMO		TH					TH	
TIAM–UCL							IN	

Source: Authors' compilation

will ultimately be important for implementation. For DSF, the assumed magnitude is set endogenously by the curtailment obtained as output from the supply-side-only 100% clean scenario model run. The detailed formulation is provided in the supplementary materials. This study uses a single-pathway, least-cost optimization with fixed input values, rather than a range of pathways sensitive to alternative input values. This deterministic approach is standard in long-term capacity-expansion modeling and is used in comparable PyPSA-based national studies [42, 48]. A full sensitivity analysis of the discount rate, technology-cost trends, demand growth, and fuel prices is left for future work. As this study used only one discount rate and did not perform a sensitivity check, our reported results for Bangladesh and Thailand on relative and absolute savings in supply capacity expansion under the integrated-pathway, compared to the supply-side pathway, remain sensitive to the chosen discount rate. A sector-resolved formulation separating industrial load shifting, residential smart-appliance response, and electric-vehicle charging would require consumer-category load profiles for implementation purposes. However, at the national scale, such consumer-specific load curves are not publicly available. Such disaggregation is therefore deferred to future work, where access to end-use load data would enable sector-specific flexibility analysis and more granular, technology-level policy guidance.

2.1. Scenarios

For both Bangladesh and Thailand, the model evaluates long-term pathways consisting of a 2019 policy-frozen reference trajectory and forward-looking scenarios. Bangladesh includes eight scenarios, and Thailand includes ten, grouped into: (a) Pledged Action Scenarios reflecting national plans, and (b) Higher Ambitious Action Scenarios consistent with full clean-energy transitions. Each country's sce-

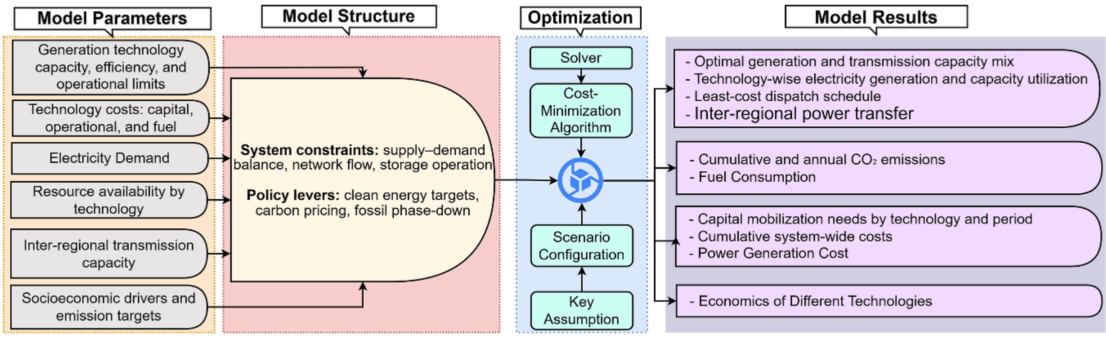

Figure 5. Flowchart of PyPSA-TH-IDS and PyPSA-BD-IDS methodology.

nario set spans both supply-side-only pathways and integrated demand–supply pathways incorporating EE and DSF. Detailed scenario definitions, model inputs, and cost assumptions are provided in the supplementary material (tables S1–S9). For India and Indonesia, this study maps published model outputs using the same socio-economic taxonomy to enable cross-country comparability. For India, the assessment covers both supply- and demand-side interventions [22]; for Indonesia, due to demand-side data limitations in the source study [45], the assessment reflects only a supply-side pathway.

The four cases do not share a single set of harmonized input values: cost base years, discount rates, target years, and demand-side representation differ across the countries. Comparability is therefore established at the level of derived indicators computed under a common taxonomy, not at the level of inputs. This is consistent with the growing call to keep national models transparent and to apply an explicit comparability check before drawing regional-scale conclusions [49, 50]. The underlying economic parameters for all four countries (technology costs, discount rates, and carbon-price treatment) are compared in supplementary table S9.

2.2. Indicators and outputs

The PyPSA-BD/TH-IDS model reports the capacity mix and generation by technology. The emissions trajectories and a consistent set of socio-economic indicators, such as investment needs, generation costs, land requirements for renewable siting, employment creation potential, and exposure to stranded-asset risks, are calculated based on alternative capacity expansion scenarios and generation mixes. Employment is estimated by applying technology-specific direct-job intensity factors (jobs MW^{-1}) for installed capacity, together with efficiency-driven jobs estimated per unit of energy saved (jobs GWh^{-1}) [51, 52]. These factors, their manufacturing, construction, and operation split, and their sources are reported in supplementary table S11. The efficiency-driven factor of 9.04 jobs GWh^{-1}-saved comprises 0.04 direct and 9.0 indirect jobs GWh^{-1}, whereas the technology factors applied to installed capacity are direct jobs only. The employment gains attributed to EE and DSF are therefore dominated by indirect jobs, which carry greater uncertainty than direct capacity-based factors, and the reported employment advantage of the integrated pathways should be read as indicative. Land requirements are obtained by applying a single baseline land-use density to the installed capacity of the specific technology: fixed-tilt, ground-mounted utility-scale PV for solar, and the standard configuration of conventional onshore wind arrays. The reported cost and investment figures represent the supply-side system costs—generation, storage, and transmission—required to meet the imposed EE and DSF targets at least-cost. They exclude the deployment costs of EE and DSF measures (metering, retrofits, demand-response programs, incentives), which fall outside the cost boundary of this study. Accordingly, the figures indicate a reduction in supply-side investment rather than a net societal saving. The findings directly inform the NDC design and revisions, as well as power-sector investment decisions, to avoid long-term fossil-fuel lock-in. The integrated demand–supply evidence generated here addresses a gap explicitly identified in IPCC AR6 [47], with relevance extending beyond the four study countries to all developing economies facing similar structural energy transitions. Since the central objective of this study is a macro-level assessment of decarbonization pathways, the spatial justice risks associated with transition have been evaluated indicatively rather than through a composite index.

3. Results

3.1. Insights from the power sector model

The results combine model-based pathways for Bangladesh and Thailand with published scenario evidence for India and Indonesia, extended by calculating associated socio-economic dimensions.

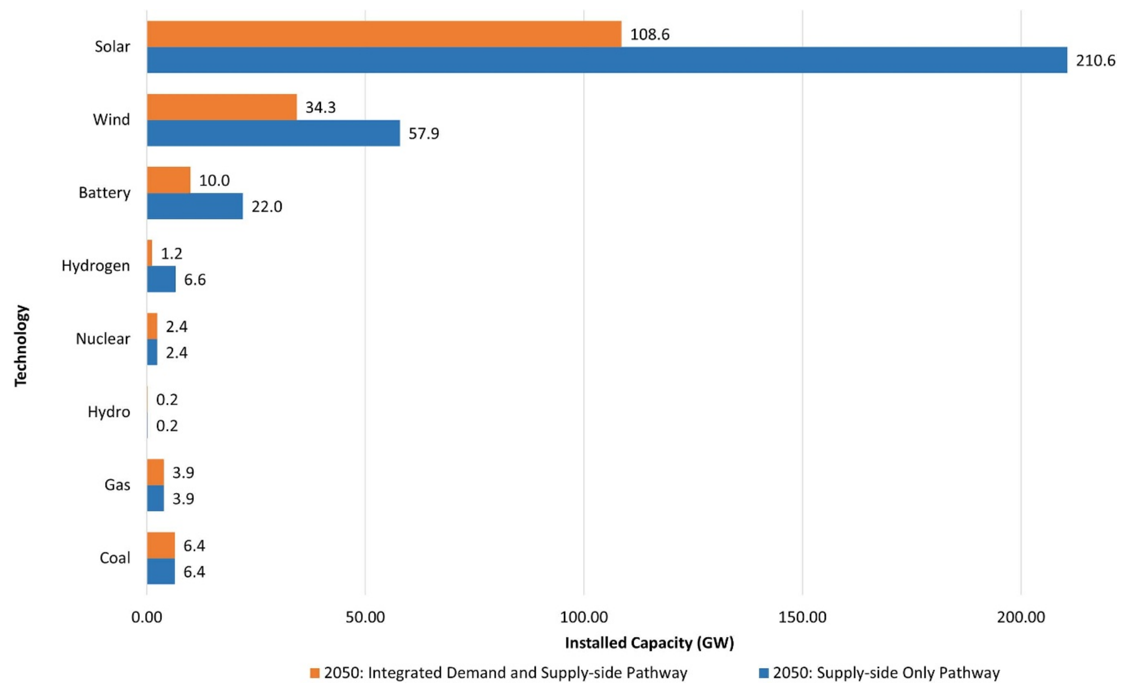

Figure 6. Model-based generation capacity expansion in Bangladesh in 2050.

3.1.1. Bangladesh

By 2050, Bangladesh can achieve a fully clean power system under both supply-side-only and an integrated pathway, but with markedly different system configurations. The supply-only case requires ~310 GW of installed capacity to generate ~440 TWh (figure 6), largely from ~211 GW of solar and ~58 GW of wind, supported by ~22 GW of batteries and ~6.6 GW of hydrogen. Under integrated EE + DSF, total installed capacity drops to 167 GW, delivering 246 TWh, a ~46.00% reduction that significantly reduces renewable overbuild and storage needs. The supply-only pathway requires ~3695 km^2 of land (~2.50% of the national area), dominated by utility-scale solar. The integrated pathway reduces this to ~1960 km^2 (~1.33%), a reduction of ~47.00%, which is significant in a densely populated country.

Achieving 100% clean power under supply-only planning requires ~€257.50 billion in cumulative investment, whereas integrated planning lowers this to €144.60 billion, saving ~44% by reducing capacity expansion and the size of storage fleets. Average generation costs fall from 57.30 € MWh^{-1} (supply-only) to 49.00 € MWh^{-1} (integrated). Employment creation also favors the integrated pathway. The integrated pathway yields ~7.34 million gross jobs by 2050, compared with ~6.88 million under the supply-only case, largely from labor-intensive efficiency measures and associated supply chains.

Emissions trajectories (figure 7) further highlight the benefits of demand-side action. In the policy-frozen reference case, CO_2 emissions rise to 100 Mt (2030), 170 Mt (2041), and ~200 Mt (2050). Supply-only measures reduce these to 63.6 Mt (2030) and 90.98 Mt (2041). Integrating EE + DSF achieves deeper reductions: 49.3 Mt (2030) and 61.3 Mt (2041). All clean-energy scenarios reach zero emissions by 2050, but integrated pathways deliver lower near-term emissions, providing earlier climate and health benefits.

The modeled hourly energy balance (supplementary figure S1) shows why demand-side flexibility matters. Solar output peaks around midday and can exceed demand, while demand peaks in the evening after solar falls—the characteristic midday-surplus, evening-peak (duck-curve) shape [53]. Under the supply-side-only pathway, the midday surplus is largely absorbed by battery and electrolyzer charging. This mismatch would otherwise lead to renewable curtailment and a steep evening ramp-up, requiring additional storage and overbuilt capacity. Under the EE + DSF pathway, however, part of the evening and night demand is shifted into the midday surplus, sharply reducing the need for battery and electrolyzer charging as demand itself becomes the primary source of flexibility. Storage therefore substitutes for the flexibility that demand-side measures can provide directly, explaining the lower hydrogen capacity requirements alongside the reductions in overall storage and generation capacity.

3.1.2. India

In the case of India, our assessment draws on the published analysis of Lugovoy *et al* [22], which models a zero-carbon electricity system for 2050 using

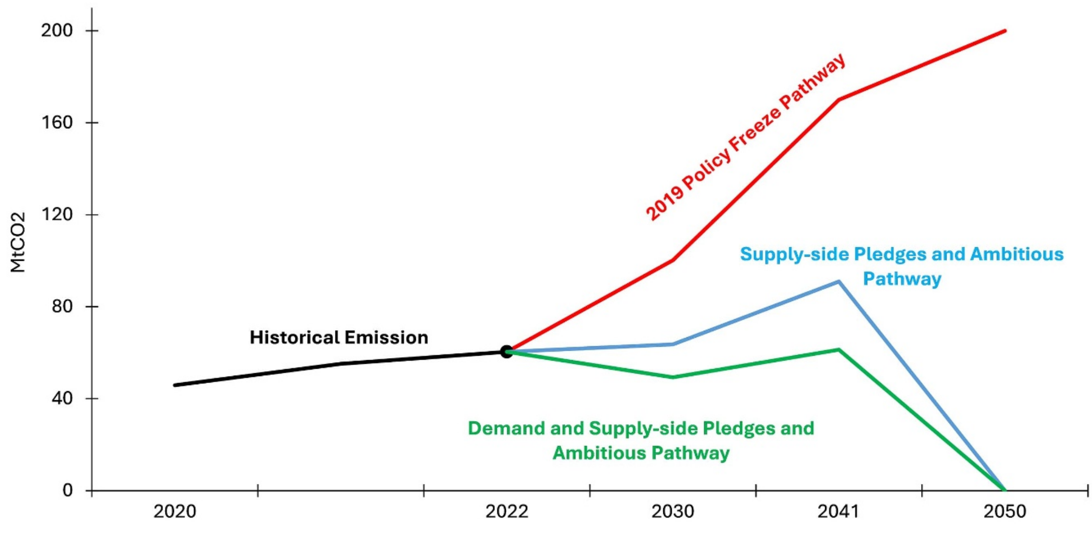

Figure 7. Alternative emission pathways in Bangladesh: Pledges and ambitious.

the IDEEA (InDian zEro carbon Energy pAthways) model. The model evaluates 153 scenarios across alternative generation, balancing, and demand-side options, including DSF options. By 2050, India's installed capacity rises to ∼2531 GW, more than four times the 2020 level. Solar dominates with 1728 GW (∼68.00% of total), followed by 503 GW of wind, 71 GW of biomass, 90 GW of hydro, 54 GW of nuclear, and ∼85 GW of residual fossil capacity. Generation is led by 2483 TWh of solar (41.00%), 915 TWh of wind (15.00%), and 221 TWh of hydro and biomass, while thermal output declines to 259 TWh.

Achieving this requires a cumulative investment of €1896.00 billion, averaging ∼1.94% of 2024 GDP per year over 2025–2050. Solar accounts for €775.00 billion, and wind for €507.00 billion. This underscores the scale of financial resource mobilization necessary for India's transition. However, integrating DSF (40%–60% intraday load flexibility) reduces storage requirements by 3–6 times and lowers system-wide levelized electricity costs by up to 40% compared to supply-side-only pathways.

India's total land requirement reaches ∼44 170 km^2 (1.34% of the national territory), dominated by ∼24 540 km^2 for solar and ∼12 575 km^2 for wind. While manageable at the national scale, concentrated siting pressures require strong governance to address land rights, environmental safeguards, and social acceptance. These capacity additions translate into ∼57.18 million gross jobs by 2050, with solar contributing ∼47.09 million and wind, hydro, and residual thermal adding a further ∼8 million combined.

3.1.3. Indonesia

For Indonesia, this study uses the published results from Kanugrahan and Hakam (2023) [45], focusing on the Advanced (ADV) scenario, achieving 100% clean electricity by 2060. Indonesia's assessment reflects only a supply-side pathway, as the source study does not include demand-side interventions. In 2060, total installed capacity expands to ∼1034.25 GW to supply 1674.14 TWh of demand, around an 11-fold increase from 2030 (95.60 GW). Solar becomes the largest technology at 697.88 GW (966.98 TWh), followed by hydro at 75 GW (322.10 TWh), geothermal at 29.5 GW (210.43 TWh), wind at 50 GW (61.27 TWh), and nuclear at 15.7 GW (110.82 TWh). Fossil fuel use falls to negligible levels. Battery storage reaches ∼63.00 GW to ensure reliability.

Under the modeled ADV scenario in the study, the supply-side investment needs total ∼€136 billion in 2060. Employment effects as calculated using factors mentioned in table S11 by postprocessing are substantial, reaching ∼24.47 million jobs by 2060, dominated by solar (∼19.02 million), with additional roles in gas (∼0.15 million), coal (∼0.48 million), hydro (∼2.08 million), geothermal (∼0.33 million), wind (∼0.41 million), battery storage (∼1.77 million), and nuclear (∼0.22 million). Estimates using country-level factors (table S12) land requirements total ∼16 800 km^2 (0.88% of land area), led by solar (∼9900 km^2). However, this land requirement is <1% of the national territory, but competing land uses—forests, agriculture, and biodiversity—require careful planning.

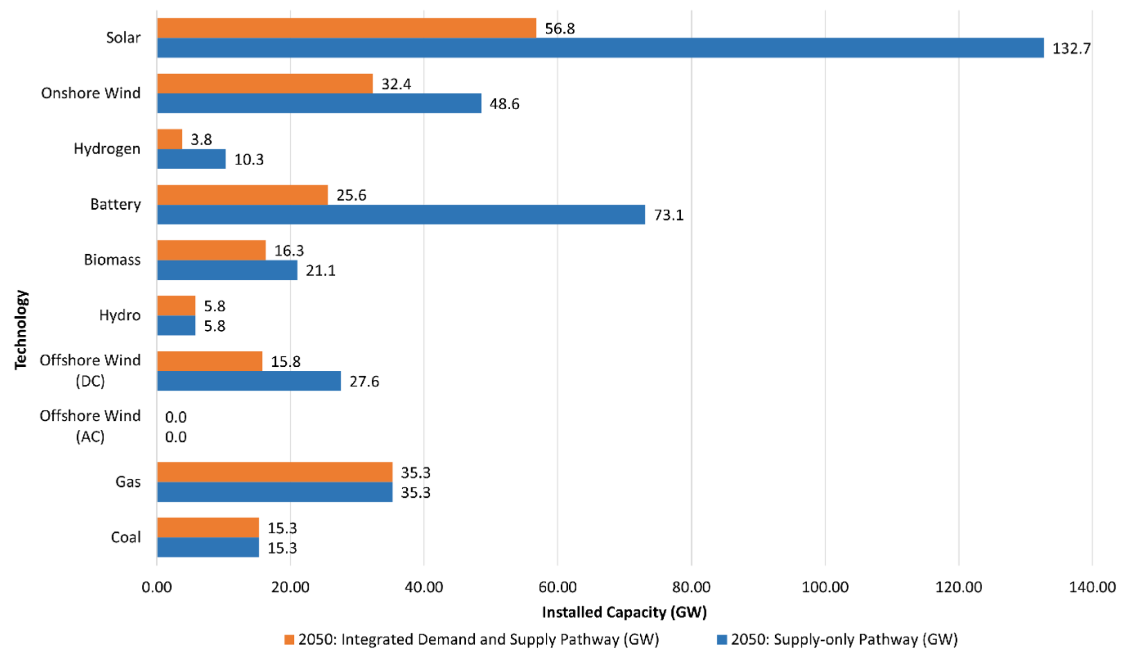

Figure 8. Model-based generation capacity expansion in Thailand in 2050.

3.1.4. Thailand

By 2050, Thailand can achieve a fully clean power system through both supply-only and integrated pathways, but the system size and cost vary sharply between them. In the supply-only pathway, total installed capacity reaches ∼370 GW to supply ∼523.5 TWh, including ∼132.7 GW of solar, ∼48.6 GW of onshore wind, ∼27.6 GW of offshore wind, ∼18.1 GW of biomass, ∼23.1 GW of batteries, and ∼20.1 GW of hydrogen (figure 8). Under the integrated EE + DSF pathway, capacity requirements drop to ∼207 GW, supplying ∼261.8 TWh, a ∼163 GW reduction from lower demand and improved load alignment. Thailand's modeled hourly energy balance is shown in supplementary figure S2 and shows the same pattern as in Bangladesh. In the supply-side-only pathway, midday solar output exceeds demand and is absorbed partly by curtailment and partly by battery and electrolyzer charging; under EE + DSF, shifted demand absorbs the surplus instead, and both curtailment and midday charging withdrawals decline.

The supply-only clean pathway requires ∼5613 km^2 (∼1.09% of the national land area), mainly for utility-scale solar and wind. With EE + DSF integration, land requirements fall to ∼3153 km^2 (∼0.61%), a reduction of ∼2460 km^2. A supply-only approach needs €230.31 billion in cumulative investment, while the integrated pathway requires €120.19 billion, saving ∼€110.00 billion by reducing both renewable overbuild and storage capacity. Average generation costs decline from 70.33 € MWh^{-1} in supply-only planning to 65.17 € MWh^{-1} in the integrated approach. The integrated pathway generates ∼2.37 million more jobs than the supply-only pathway (∼7.07 million). This rise is driven by labor-intensive efficiency measures such as audits, retrofits, and appliance upgrades—alongside ongoing renewable and storage deployment.

CO_2 emissions in the 2019 policy-frozen reference case (figure 9) rise from 94 $MtCO_2$ to 135 $MtCO_2$ in 2050. Supply-only pathways reduce emissions to 103 $MtCO_2$ (2030), 62 $MtCO_2$ (2037), and 29 $MtCO_2$ (2045) before reaching zero in 2050. Integrated pathways achieve substantially stronger reductions, ∼21%–40% deeper mitigation relative to supply-only, and 22%–86% reductions relative to the reference. This abatement signals a structural break from fossil-fuel lock-in—gas-based generation is progressively displaced by renewables, with fossil fuel dependence declining substantially faster than in supply-only pathways.

Table 3 consolidates the five transition-pathway indicators—installed capacity, land requirement, cumulative supply-side investment, employment, and stranded-asset risk—for all four countries under a single common taxonomy. The comparable result is the within-country contrast between supply-side-only and integrated (EE + DSF) pathways, available for Bangladesh and Thailand; India and Indonesia are reported as literature-based contextual cases.

3.2. National perspective of the transition challenges

Given model-based insights and technoeconomic feasibility assessments for the transition to zero carbon by 2050–2060 for Bangladesh, India, Indonesia,

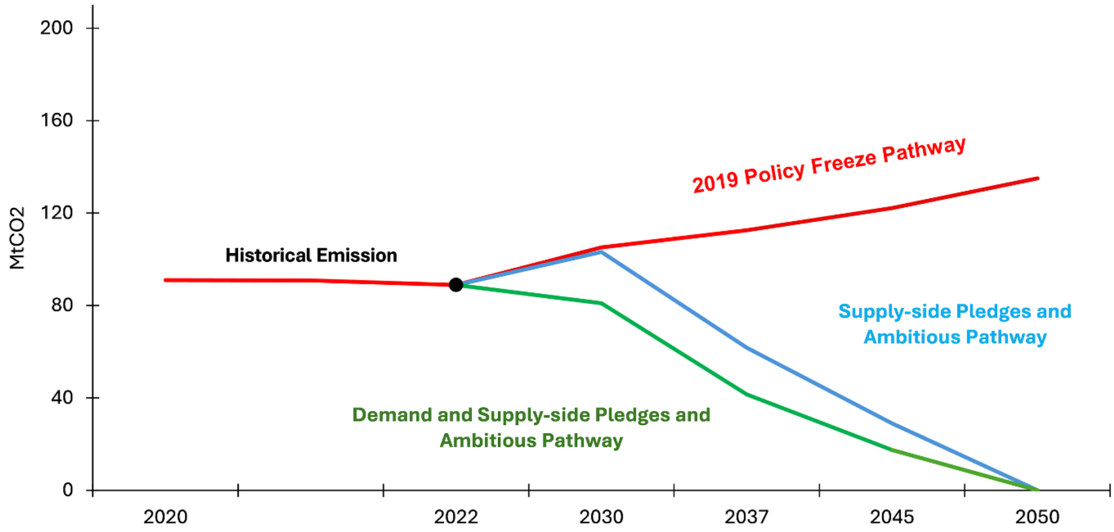

Figure 9. Alternative emission pathways in Thailand: Pledges and ambitious.

Table 3. Summary of indicators used across four countries in this study.

Country	Scenario/source basis	Target year	Capacity	Land requirement	Cumulative supply-side investment	Employment	Stranded assets
Bangladesh	Supply-side only	2050	∼310 GW	∼3695 km^2	€257.50 bn	∼6.88 million jobs	∼€0.024 bn
	Integrated EE + DSF		∼167 GW	∼1960 km^2	€144.60 bn	∼7.34 million jobs	
India	Literature-based IDEEA scenario [22]	2050	∼2,531 GW	∼44 170 km^2	€1,896 bn	∼57.18 million jobs	€60–70 bn
Indonesia	Literature-based ADV supply-side pathway [45]	2060	∼1034.25GW	∼16 800 km^2	€136 bn	∼24.4 million jobs	€23.32 bn
Thailand	Supply-side only	2050	∼370 GW	∼5613 km^2	€230.31 bn	∼7.07 million jobs	∼€2.77 bn
	Integrated EE + DSF		∼207 GW	∼3153 km^2	€120.19 bn	∼9.44 million jobs	

Note: Scenarios reported for Bangladesh and Thailand are based on the models developed in this study. Final supply-side installed capacity, cumulative investment, employment, land use, and stranded-asset values are all derived from the model outputs. For India, installed capacity is taken from the source study, whereas investment, employment, and land-use values are calculated by post-processing using factors presented in tables S11 and S12. For Indonesia, supply-side installed capacity and cumulative investment are adopted directly from Kanugrahan and Hakam (2023) [45], while employment and land-use values are calculated by post-processing using factors presented in tables S11 and S12.

and Thailand, it is essential to examine their current fossil-fuel power fleets and associated transition challenges. Currently, of the global operational coal capacity of 2193 GW, India and Indonesia account for ∼11.00% and ∼2.60%, while Thailand and Bangladesh each account for ∼0.30%. In contrast, China has 54.00%, the US 8.60%, and Germany 1.40%. Of the global oil and gas operational capacity of 2169 GW, India and Indonesia each account for ∼1.20%, while Thailand and Bangladesh account for ∼0.90% and ∼1.80%, respectively. For China, it is 7.60%; for the U.S., 26.00%; and for Germany, 1.60% [54]. Thus, while India and Indonesia follow China in global coal dependence, Thailand and Bangladesh contribute comparatively little to global coal use. In oil and gas, India, Indonesia, and Thailand follow the U.S., China, and Germany, whereas Bangladesh's share exceeds that of Germany. The four study countries follow different transition pathways shaped by national contexts. Currently, India's and Indonesia's national power sectors remain highly coal-dependent, with a ∼45.00% share [55, 56], whereas Bangladesh's

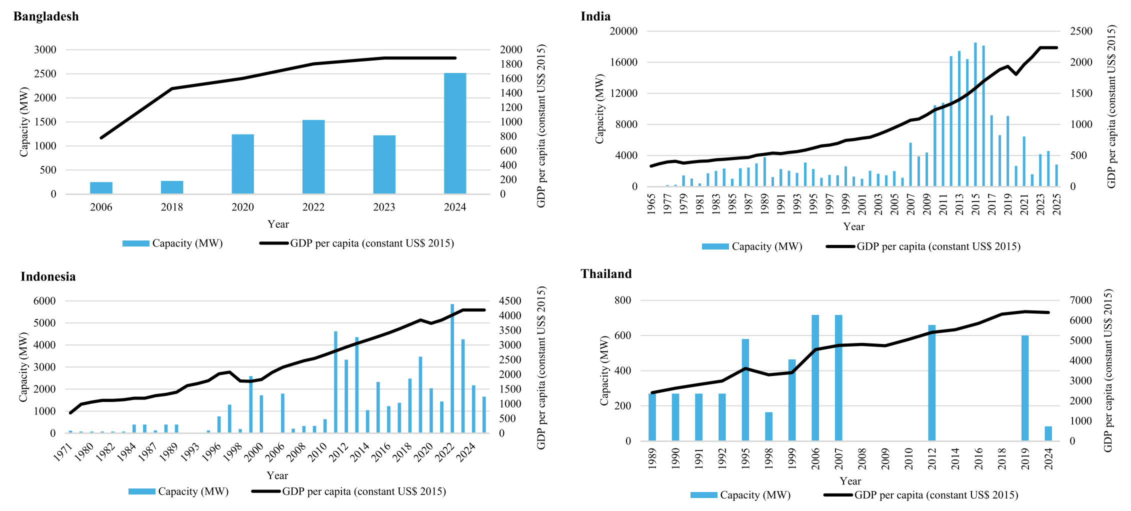

Figure 10. Coal capacity and GDP growth in the selected four countries.

and Thailand's installed capacity is dominated by natural gas at ~45.00% and ~65.00%, respectively [57, 58].

3.3. Tracing history: coal peak and economic growth

Historically, a gap of ~120 years on average between the commissioning of the first coal plant and the attainment of the national coal peak happened in the US, Germany, and the Netherlands. Periods of highest GDP growth in the U.S., Germany, and the Netherlands closely coincided with expansions in coal capacity [59, 60]. Coal capacity peaked at ~318 GW in the U.S. (2011), ~50 GW in Germany (1995), and ~10 GW in the Netherlands (2014) [61, 62]. If a similar trajectory is based on the technical retirement age assumed for Bangladesh, India, Indonesia, and Thailand, their coal peaks would occur around mid-century [59, 60, 63, 64]. However, early retirement for the energy transition would need support and strengthening of finance initiatives, such as the Just Energy Transition Partnerships, to address challenges like early termination of power purchase agreements (PPAs) and obligations under investment contracts, in addition to exploring new financial pathways, such as debt swaps [65].

3.4. Conundrum of low-carbon pledges versus aspirations for development

The aspiration to achieve developed-country status while meeting low-carbon commitments creates significant concern for the four study countries. Bangladesh's economic growth has been driven by expanding manufacturing and services, supported by ~25 GW of installed capacity (~45.00% of which is gas). To reach its 2041 developed-country target, capacity must rise to ~61 GW [66, 67], still well below the combined ~215 GW of fossil capacity in Germany and Japan in 2025 [54]. Bangladesh's first NDC (2015, updated 2020) pledged a 21.85% GHG reduction by 2030, requiring >95.00% mitigation from the energy sector [68].

India aims to achieve developed-country status by 2047. Its updated NDC commits to a 45.00% reduction in GDP emission intensity, 50.00% non-fossil electricity by 2030, and net zero by 2070, requiring large-scale technological, efficiency, structural, and behavioral shifts [69].

Indonesia targets developed-country status by 2045, but to date, it remains heavily coal-dependent. Its enhanced NDC targets 31.89% unconditional and 43.20% conditional GHG reduction below BAU [70] and its draft SNDC introduces revised 2030 and 2035 climate goals that reflect stronger ambition.

Thailand's National Strategy (2018–2037) aims to achieve developed-country status by 2037. Its 2022 NDC update raises its GHG reduction target from 20.00% to 30.00% by 2030 [71]. Thailand further strengthened its ambition through its revised Long-term low greenhouse Gas emission development strategy, which advances carbon-neutrality to 2050 and net-zero GHG emissions to 2065 [72].

3.5. Young coal fleet, global call, and modeled coal phase-out

The four selected countries have added 227 GW of coal capacity (figure 10) in the past two decades [73–75], compared with ~50 GW during the 1985–2004 period. Figure 10 further shows that these coal capacity additions closely track rising GDP per capita in each country, underscoring the intertwining of recent economic growth with coal-based power. The challenge for these countries is the new physical and financial burden of young coal plants becoming stranded assets in a fully clean power future [76]. This burden is quantified as the cost of early retirement—the stranded-asset value of coal capacity retired before the end of its technical life under the modeled clean-power pathway (table 3). For Bangladesh and Thailand, these values are model-based, representing the unrecovered capital of fossil-based plants valued at plant CAPEX (Tables S3, S4) scaled by the remaining technical lifetime at the point of retirement (∼€24 million and ∼€2.77 billion, respectively). For India and Indonesia, the figures are drawn from published source studies. All estimates are reported as direct capital losses to investors and operators and exclude wider social costs. A full cost-of-inaction estimate would require climate-damage valuation beyond the power-system optimization framework used here and therefore lies outside the scope of this study. A rapid coal phase-out scenario underlines the urgency of the current regional challenge and how it can be reflected in global climate negotiations [77, 78].

India and Indonesia, endowed with abundant coal reserves and facing rising demand, confront the additional challenge of leaving these reserves in the ground. Renewable energy potential, coal reserves, and the corresponding power plant installations in these two nations are unevenly distributed across states and provinces. Supplementary table S10 provides a snapshot of this challenge for justice in transition, indicating the need for a separate research agenda that maps the spatial overlap and divergence between clean energy expansion and fossil-sector transition risks.

3.6. Enabling conditions, policy pathways, and way forward

Decarbonizing the power sector in Bangladesh, India, Indonesia, and Thailand depends as much on policy, technological, institutional, and financial conditions as on resource access and techno-economic-socio-political feasibility. A phased, justice-oriented strategy must combine the strategic implementation of demand-side actions and investment in clean energy sources with a planned retirement schedule for fossil fuel assets and targeted support for affected workers. This study provides indicative policy recommendations based on model outputs. For implementation, a more granular study can build on this work, with timelines, dated targets, and sequencing co-designed through science–policy dialogue and stakeholder consultation. This study answers some questions while raising others that warrant detailed follow-up research.

For Bangladesh, the findings show that EE and DSF can avoid capacity overbuild and reduce near-term financial resource mobilization needs, strengthening the case for deeper enabling policies to implement demand-side solutions. Enabling measures span stricter appliance efficiency standards and labels benchmarked against international minimum energy performance standards and comparative-labeling programs; effective building energy codes; and rollout of advanced metering, dynamic tariffs, and demand-response programs to tap flexible loads in cooling, pumping, cold chains, industry, and EVs [79]. IoT technologies and market-based instruments that directly target the midday solar surplus and evening peak can reduce curtailment and excess RE expansion (figure S1). Barrier analysis for Bangladesh identifies weak efficiency standards, benchmarking, and energy-management regulation, alongside skilled manpower and information gaps, as foundational drivers of low efficiency uptake, so standard-tightening should be packaged with capacity-building rather than pursued alone [80]. Gradual tariff and subsidy reform, with safeguards for low-income users, can sharpen efficiency incentives [36, 67]. De-risked finance via concessional credit, standardized contracts, green bonds, and blended finance is needed to overcome upfront-cost barriers [81]. GIS-based planning and multi-use siting (rooftops, industrial estates, agrivoltaics, floating PV), supported by a multi-agency transition task force managing planning, retirement schedules, decommissioning funds, and worker reskilling, can align investment with long-term clean-energy goals [42].

In India, governance of a just coal transition is central. Key priorities include transparent coal-retirement pathways consistent with the national net-zero target [78]; a national just-transition commission to coordinate ministries, utilities, and affected communities [69, 82]; integration of labor, social protection, and regional development measures [21, 75]. Grid modernization and flexibility, including expanded transmission to resource-rich regions, and large-scale storage, are prerequisites for integrating high variable-renewable shares [22]. The model further shows that demand-side flexibility can reduce storage needs three- to six-fold and system costs by up to 40%, so scaling time-of-use tariffs and demand response is as decisive as supply-side build-out [53, 83]. Stable renewable-energy procurement frameworks and support for domestic manufacturing of solar, wind, storage, and grid equipment can attract capital and reduce import dependence [20, 29]. Scaling finance will require deeper green-bond markets, blended-finance and risk-sharing instruments, and strong, independent regulation to protect both investors and consumers [84].

In Indonesia, a large expansion of solar, hydro, geothermal, wind, and storage can deliver near-zero-emission electricity at manageable cost, provided coal phase-out is planned over time. Core enabling conditions are a clear ‘no new unabated coal’ policy and a managed phase-out of existing plants, backed by predictable retirement schedules, compensation mechanisms, and strategies to repurpose sites and grid assets [74, 85]. Accelerated geothermal and storage development (and, where appropriate, hydrogen), together with carbon pricing, tariff reform, and progressive integration of CO_2 costs into planning, can shift incentives toward low-carbon options and help capitalize transition funds [77, 86, 87]. Strengthening inter-island transmission, land-use governance for forests and biodiversity, and spatial planning for renewable zones are equally critical [15]. International coal-transition and climate-finance facilities can help connect coal-asset resolution with clean-energy investment and employment transitions [18, 87]. Assessing the potential contribution of demand-side integration in Indonesia requires dedicated future research.

In Thailand, model results show that integrating renewable expansion with EE and DSF can achieve a fully clean power system with lower capacity, costs, and land requirements, while creating more jobs than a supply-only pathway. Key demand-side measures are tighter and better-enforced efficiency standards and building codes, large-scale rollout of smart meters and dynamic tariffs, and systematic DSF to tap flexible loads in buildings, industry, and transport [32, 48], aligned with the intraday solar-surplus/evening-ramp pattern shown in Figures S1 and S2. Refined Feed-in-tariffs, direct PPAs, green-bond frameworks, and public–private partnerships are key supply-side enablers [31, 34]. A dedicated transition task force coordinating energy, land-use, and labor agencies, alongside GIS-based planning, rooftop PV, agrivoltaics, green hydrogen, and long-duration storage strategies, can ensure a sustainable transition [33, 48, 88].

Across the modeled pathways, the 2050 systems are dominated by inverter-based resources. In Bangladesh's integrated pathway, synchronous capacity is limited to nuclear and hydro, so the instantaneous non-synchronous share approaches 100% at midday. Thailand retains a larger synchronous base through biomass and hydro, but both systems operate well above demonstrated non-synchronous penetration levels, a system-operation condition distinct from the annual clean-energy shares reported in this study. A recent operational precedent is the all-island Irish system, where EirGrid and SONI raised the System Non-Synchronous Penetration (SNSP) limit from 50% to 75% through five incremental operational trials, adopted 75% as formal policy in 2022, and now target operation at up to 95% SNSP by 2030 and close to 100% by 2035 [89, 90]. Grid codes mandating grid-forming capability, procurement of synchronous condensers, and markets for inertia and fast frequency response are therefore enabling requirements alongside generation build-out in all four countries [90].

Looking ahead, scaling investment and aligning domestic reforms with international support are prerequisites for an accelerated transition. Cumulative pathway investment is therefore expressed as an average annual requirement and compared with current annual power-sector investment, over 2026–2050 for Bangladesh, India, and Thailand and over 2026–2060 for Indonesia (supplementary table S13). Bangladesh requires ∼€10.3 billion per year under the supply-side-only pathway and ∼€5.8 billion per year under the integrated pathway, compared to ∼€6.89 billion invested in 2025 [91], or ∼1.5 and ∼0.8 times the 2025 level, respectively. In modeled Thailand pathways, the annual investment requirement up to 2050 is ∼€9.2 billion per year under the supply-side-only pathway and ∼€4.8 billion per year under the integrated pathway. We compare these numbers for Thailand with the proposed ∼€4.56 billion per year for supply-side expansion until 2030 in the Power Development Plan of Thailand [92, 93] and not with 2025 values as done for other country contexts. The Indian integrated demand–supply pathway requires ∼€75.8 billion per year, compared with €101.87 billion in 2025 [94], or ∼0.7 times the 2025 investment level. Indonesia requires ∼€3.9 billion per year under its supply-side-only pathway, compared with €3.14 billion in 2025 [95], representing a marginal increase of ∼1.2 times. Among the four countries, only Thailand requires a substantial increase in annual investment, although demand-side integration lowers this requirement from ∼6.4 to ∼3.3 times the 2025 level. Indonesia requires a marginal increase of ∼1.2 times under its supply-side-only pathway, and Bangladesh exceeds the 2025 level (∼1.5 times) under supply-side-only planning. For India and Bangladesh under the modeled integrated pathway, the annual investment requirement in the supply-side, going forward, falls below the 2025 current annual investment level, indicating that the financing challenge is primarily one of redirecting existing power-sector flows towards enhancing clean capacity and integrating demand-side solutions.

4. Conclusion

In this study, model-based power-sector planning for two coal-dependent (ID, IN) and two gas-dependent (BD, TH) economies in South and Southeast Asia confirms that fossil-fuel-free clean power systems are achievable by 2050–2060. Integrating demand-side solutions eases this transition by reducing the need for supply-side investment mobilization and land conversion requirements, while creating new jobs. In Bangladesh, the IDS pathway lowers investment need by ∼€112 billion, halves land use, and creates ∼0.46 million more jobs than supply-only planning. Thailand's investment requirements fall from €230 billion to €120 billion; land needs drop by ∼2460 km^2, and employment rises by ∼2.4 million. India's mid-century power system (∼2531 GW, including ∼1728 GW of solar) requires ∼€1.90 trillion and ∼44 000 km^2 of land, underscoring the scale of mobilization required. Indonesia's pathway expands capacity 11-fold to ∼1034 GW by 2060, with ∼63 GW of storage and ∼€136 billion in cumulative investment, driven by solar, hydro, and geothermal.

However, we acknowledge that this study has several limitations that a future targeted research agenda could address. These include developing a modeled pathway for Indonesia that integrates EE and DSF. Because the supply-side-only and integrated pathways differ substantially in capital intensity, both the absolute investment figures and the relative savings reported between them are conditional on the assumed discount rate. Sensitivity analysis can yield multiple pathways by varying the point-estimate discount rate and cost assumptions. Including carbon prices in the models would yield additional plausible pathways. To implement the recommendations, DSF management will need granular, sector-disaggregated load data. Technology-specific land-use densities for solar and other clean energy technologies would support more granular supply-side technology choices. To go beyond current NDC targets, endogenizing the cost of EE/DSF deployment in the model can provide a range of values for the optimal scale of these demand-side solutions. Just-transition costs, currently represented only by stranded-asset costs, need to be broadened to capture the full social costs and benefits. A further limitation is that PyPSA-BD/TH-IDS resolves energy and power balances only and does not represent frequency stability, system inertia, rate of change of frequency, fault level, or limits on instantaneous non-synchronous penetration; the pathways therefore establish energy and cost feasibility rather than operational feasibility at sub-hourly timescales, and testing the latter requires dedicated power-system dynamic studies.

Across countries, structural challenges shape the feasibility of transitions. 227 GW of coal capacity added in the past two decades creates substantial stranded-asset risks, ∼€23.32 billion in Indonesia, €60–70 billion in India, and in Bangladesh (∼€24 million) and Thailand (∼€2.77 billion). Addressing young operational coal fleets in line with the global call for coal phase-out and phase-down requires strategic decisions. While the renewable-energy sector will create millions of jobs, losses across the coal-thermal value chain will not be instantly offset on a one-for-one basis, given differences in skills and locations, underscoring justice and equity concerns [96]. Future research needs to examine how transitions drive employment outcomes for coal-dependent workers and communities within a justice framework and may develop a Spatial Just Transition Index through harmonized state/province-level mapping of coal employment, plant-retirement exposure, mining dependence, renewable-resource potential, grid infrastructure, and socio-economic vulnerability, especially for India and Indonesia, to locate where fossil-sector job losses coincide with weak renewable-resource endowments.

Overall, the comparative evidence confirms that by committing to IDS pathways, emerging Asian economies can expand their clean power systems at lower cost, with less land, and with lower emissions. Their success hinges on: (i) early, large-scale deployment of EE and DSF to better optimize system size; (ii) timely, well-planned coal and gas phase-down backed by dedicated just-transition institutions and social protections for workers and affected regions; (iii) scaling-up of investment through domestic reforms and international climate finance; and (iv) robust frameworks for land-use governance, grid modernization, and diversified storage. The comparative evidence across four structurally diverse emerging economies offers transferable insights for decarbonization planning globally, informing the Global Stocktake, NDC design, and climate finance allocation, and ensuring that the clean power transition is both fast and just.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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