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National scale electricity sector model to strategize national clean energy transition

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ABSTRACT

This study develops an open-source model adapted from Python for Power System Analysis (PyPSA), to analyze transition pathways through 2030 and 2050, validated against 2019 national data for Thailand's fossil fuel-dominated power sector. Utilizing 30 km × 30 km resource potential, hourly demand data, national policies, and energy strategies, PyPSA-TH (Thailand) evaluates ten scenarios. Pledged and higher ambition scenarios integrate supply-side renewable energy expansion with demand-side energy efficiency, flexibility, and regional hydro imports. In 100% clean energy scenarios (2050), model results project an installed capacity of 369.71 GW (7.4-fold higher than 2019), primarily driven by solar (132.74 GW), wind (76.10 GW), and battery storage (83.44 GW), generating 523.5 TWh. 100% clean energy supply combined with energy efficiency and demand-side flexibility scenario indicates a need for an installed capacity of 207.10 GW, where solar drives the key share (56.82 GW), followed by wind (48.14 GW) and battery storage (25.61 GW). Combining supply- and demand-side measures reduces power generation costs to €0.065/kWh, from €0.070/kWh with supply-side interventions alone. Demand-side strategies lower land requirements to 3152.64 km^2 (0.61% of Thailand's land) from 5612.87 km^2 (1.09%) compared to supply-side-only measures and investment needs for capacity expansion rises by 48%, generating 9.43 million new jobs, 1.33 times more than supply-side-only pathways. The emission pathway associated with supply-plus demand-side strategies provides clear near-term benefits compared to supply-side-only planning strategies. PyPSA-TH's transparent and reproducible framework is useful in deriving policy guidelines, including green financing and land-use management, to achieve a sustainable energy future for Thailand and similar developing nations.

List of Abbreviations

AC	Alternating Current
ACEEE	American Council for an Energy-Efficient Economy
AEDP	Alternative Energy Development Plan
AIM/CGE	Asia-Pacific Integrated Modeling/Computable General Equilibrium
AIM/Enduse	Asia-Pacific Integrated Model/Enduse
ASEAN	Association of Southeast Asian Nations
BAU	Business As Usual
BESS	Battery Energy Storage System
BECCS	Bioenergy with Carbon Capture and Storage
CAES	Compressed Air Energy Storage
CASE	Clean, Affordable and Secure Energy for Southeast Asia
CCS	Carbon Capture and Storage
CCGT	Combined Cycle Gas Turbine
CESER	Cybersecurity, Energy Security, and Emergency Response
C&I	Commercial and Industrial
CO2	Carbon Dioxide
CS	Carbon Sequestration
DC	Direct Current
DEDE	Department of Alternative Energy Development and Efficiency
DSF	Demand-Side Flexibility
EE	Energy Efficiency
ECSO	Energy Community Secretariat Office
EEDP	Energy Efficiency Development Plan
EGAT	Electricity Generating Authority of Thailand
ELD	Efficient Low Demand
EEP	Energy Efficiency Plan
EPPO	Energy Policy and Planning Office

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ERC	Energy Regulatory Commission
EUR	Euro
EV	Electric Vehicle
FOM	Fixed Operation and Maintenance
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information System
GW	Gigawatt
HASS	Higher Ambitious Action Scenario
HH	High Hydrogen
HRE	High Renewable Energy
HVAC	Heating, Ventilation, and Air Conditioning
kV	Kilovolt
km	Kilometer
LAES	Liquid Air Energy Storage
LEAP	Low Emissions Analysis Platform
NEMO	Next Energy Modeling system for Optimization
LRE	Low Renewable Energy
LULUCF	Land Use, Land-Use Change and Forestry
LT-LEDS	Long-Term Low Emission Development Strategy
MA	More Ambitious
MARKAL	MARKet ALlocation
MEA	Metropolitan Electricity Authority
MF	Market Flexibility
MRE	Moderate Renewable Energy
MSW	Municipal Solid Waste
MW	Megawatt
MWh	Megawatt-hour
NCSA	National Clean Energy Scenario Analysis
NDC	Nationally Determined Contribution
NEP	National Energy Plan
NZE	Net Zero Emissions
O&M	Operation and Maintenance
OSM	OpenStreetMap
PAS	Pledged Action Scenario
PDP	Power Development Plan
PEA	Provincial Electricity Authority
PHES	Pumped Hydro Energy Storage
PV	Photovoltaic
PVBESS	Photovoltaic with Battery Energy Storage System
PyPSA	Python for Power System Analysis
PyPSA-TH	Python for Power System Analysis – Thailand
RC	Regional Cooperation
REF	Reference
RE	Renewable Energy
SSP	Shared Socioeconomic Pathway
TES	Thermal Energy Storage
TH	Thailand
THB	Thai Baht
TIEB	Thailand Integrated Energy Blueprint
TNB	Tenaga Nasional Berhad
UK	United Kingdom
USA	United States of America
VOM	Variable Operation and Maintenance

1. Introduction

Decarbonization of the power sector is a necessary goal to mitigate climate change, but how soon and in what ways it can be achieved in Asia is an important research question, given that region's rapid economic growth and energy demand are absolute necessities to sustain human wellbeing in the coming decades. However, challenges vary country-wise in Asia. In Thailand, as of January 2025, fossil fuels (67%) dominate as the primary energy carrier for the power generation sector, with gas and coal each accounting for 55% and 12% of the installed capacity [1]. The Provincial Electricity Authority (PEA) [2] reports that 99.73% of Thai households have access to electricity, with a goal of achieving 100% by 2025, while annual electricity demand growth has ranged between 1.25% and 5.17% over the last ten years [3]. Thailand's political commitment is to achieve carbon neutrality by 2050 and net-zero emissions by 2065, as pledged at the 26th Conference of the Parties (COP26) [4,5]. Given the urgency of aligning national energy strategies with global climate goals [6] there is a need for strategic energy sector planning to harmonize economic expansion with global environmental sustainability.

PyPSA [7] can be customized to help in analyzing the electricity sector expansion strategies with country-specific policy strategies. Customization of the PyPSA model has proven effective across diverse geopolitical settings, such as Bangladesh [8,9], India [10], the United Kingdom (UK) [11], South Africa [12], Kazakhstan [13,14], Vietnam [15], and Germany [16,17]. This study develops the PyPSA-TH model, a customized version of PyPSA-Earth [18], to handle high-resolution spatial and temporal data. This is essential for developing precise and adaptable energy system frameworks that address Thailand's geographic, infrastructural, and policy challenges. It can also help in formulating strategic scenarios aligned with national renewable energy (RE) integration through supply-side interventions, energy efficiency (EE) targets and demand-side flexibility (DSF), as summarized in Tables 1 and 3. This modeling framework is explicitly tailored to support strategic planning for capacity expansion, renewable integration, and emissions reduction, providing crucial insights into the power sector and some broader socio-economic impacts to guide policymakers in Thailand's transition toward a cleaner energy future through integrated supply- and demand-side interventions.

Being open-source, PyPSA-TH promotes collaborative development, enabling enhancements through contributions from both the local and global research communities, which opens up the possibility of continuous improvement and accessibility in energy modeling. By integrating updated datasets from OpenStreetMap [1], tailored information from key Thai entities, notably the Electricity Generating Authority of Thailand (EGAT) [33], the Provincial Electricity Authority (PEA) [34], Metropolitan Electricity Authority (MEA) [35], Thailand's Energy Policy and Planning Office (EPPO) [3], the Ministry of Energy, Department of Alternative Energy Development and Efficiency (DEDE) [36] and supplementary web-based statistics, such as exact power plant coordinates (latitude/longitude), PyPSA-TH provide a detailed and accurate depiction of Thailand's current power system and future goal oriented pathways.

This study addresses key questions: 1) How can strategic pathways for expanding electricity generation capacity and reducing emissions in Thailand's power sector be formulated using multiple granular-scale data sources? 2) What are the implications of transition pathways for broad socio-economic variables like investment, job creation, and land use? 3) Requirement and role of energy storage over time to support the transition through enhanced penetration of RE resources?

This article's key contributions include.

i. Development of PyPSA-TH, customized to capture Thailand's geographic, infrastructural, climatic, and power sector characteristics.
ii. Incorporation of high spatial and temporal scale resolution to model renewable energy variability and optimize grid performance.
iii. Integrated optimization of both investment and operational decisions within the PyPSA-TH model, providing a foundation for long-term energy system planning.
iv. Enhancement of model precision through country-specific official datasets obtained from EGAT, EPPO, and national strategies of the energy sector.
v. Establishment of PyPSA-TH as an open-source tool, ensuring transparency, reproducibility, and the potential for ongoing global collaboration.
vi. To understand how strategically national priorities be achieved through energy supply-side and demand-side interventions to achieve the least-cost solutions while meeting the growing demand while not over burdening the additional financial resource mobilization need.

Table 1
Evolving demand and supply-side targets for Thailand's energy sector.

Official Policy Documents	Year	Key Targets
Energy Efficiency Development Plan (EEDP) 2011–2030	2011	- 25% energy intensity reduction by 2030 relative to 2005 levels. The focus is on energy conservation across industry, transport, and buildings. Aimed to reduce energy expenditure and emissions through technology and incentives.
Energy Efficiency Plan (EEP) 2015–2036	2015	- Updated the 2011 EEDP, aiming for a 30% reduction in energy intensity by 2036. Promoted efficiency in residential, commercial, and industrial sectors. Introduced stricter standards in residential, commercial, and industrial sectors and incentives to support sustainability goals.
Thailand Integrated Energy Blueprint (TIEB)	2015	- Integration of five plans: PDP, EEP, AEDP, Oil Plan, and Gas Plan into a 2015–2036 strategy. Balancing energy security, economic growth, and environmental protection. Encourage diversification of energy sources and ASEAN energy cooperation.
Power Development Plan (PDP) 2015–2036	2015	-15–20% RE in the power mix by 2036, reducing reliance on natural gas. Promote cleaner coal technologies and enhance grid reliability. Focus on integration with ASEAN power markets for energy trade.
Alternative Energy Development Plan (AEDP) 2018–2037	2018	- Target to achieve 30% RE in the total share of energy consumption by 2037. Prioritize solar (6 GW), wind (3 GW), and biomass (5.5 GW) capacity. Encourage community-based projects and private sector investment in renewables.
Long-Term Low Emission Development Strategy (LT-LEDS)	2021	- Provided a roadmap for carbon neutrality by 2050 and net-zero emissions by 2065. Focused on renewables, EE, and transport electrification. Aligned with Thailand's Paris Agreement commitments.
National Energy Plan (NEP) 2023	2023 (pending approval)	- Unified all energy plans into a framework supporting carbon neutrality by 2050. Target over 50% renewable energy share by the 2040s and 30% energy consumption by 2030. Emphasizes energy storage, private investment, and green technologies.
Power Development Plan (PDP) 2024–2037 (Draft)	2024 (draft)	- Increased renewable energy target set to 51% of power generation by 2037. Prioritized solar-plus-storage, wind, and biomass for grid stability. Introduced Direct Power Purchase Agreements (PPAs) to enhance private sector participation.

Source: Authors' compilation

2. Thailand electricity sector: overview and policies

Thailand's electricity market operates under the Enhanced Single Buyer (ESB) model, with a total installed power plant capacity of 53.87 GW as per the annual energy statistics report 2024 of the Ministry of Energy (MoE) [37]. This is distributed among the EGAT, which owns approximately 30% (16.23 GW), and private producers, including Independent Power Producers (IPPs) own 33% (17.65 GW), Small Power Producers (SPPs) own 18% (9.48 GW), and Very Small Power Producers (VSPPs) own 8% (4.28 GW). An additional 11% (6.23 GW) of installed

Table 2
Summary of literature on Thailand's clean energy transition.

Ref	Year	Model Used	Brief Description
[19]	2050	LEAP-NEMO	Assesses Thailand's prospects for reaching net-zero emissions by 2050 through a decarbonized energy system. It models reference (REF), more ambitious (MA), and net-zero emission (NZE) scenarios. The NZE scenario features a 25% share of renewables in final energy use, 71% in electricity generation, an 80% penetration of EVs, and the deployment of natural gas power plants equipped with carbon capture and storage (CCS) to achieve greenhouse gas reductions exceeding the country's NDC commitments.
[20]	2050	AIM/CGE	Analyzes Thailand's power sector decarbonization efforts to achieve carbon neutrality and net-zero GHG by 2050. The power sector is disaggregated into renewable and fossil-based sources to assess economy-wide impacts. The Carbon Neutrality 2050 (CN2050) scenario projects renewable energy at 74% of electricity generation by 2050, with CCS and Bioenergy with Carbon Capture and Storage (BECCS) technologies deployed, leading to gross domestic product (GDP) gains until 2040 but losses from 2045 to 2065 due to higher costs.
[21]	2050	AIM/Enduse	Investigate Thailand's energy system transition for the 1.5°C target and net-zero CO_2 by 2050. Scenarios vary CO_2 taxes (\$500–\$1000/tCO_2), renewables (31%–60% electricity), CCS, and nuclear. Results show that High taxes, CCS, renewables, and EVs achieve near net-zero, requiring taxes above \$1000/tCO_2 for full success.
[22]	2050	AIM/Enduse	Studies Thailand's shift to a carbon-neutral power sector by 2050. Compares business as usual (BAU) (93 MtCO_2 in 2010 to 223 MtCO_2 by 2050) with carbon neutral (CN2050) scenarios. CN2050 utilizes efficiency, achieving 65%–66% solar/wind energy, and CCS/BECCS, which cuts emissions by 53%–89% by 2030 compared to BAU.
[23]	2050	AIM/Enduse	Assesses Thailand's net-zero GHG by 2050 without CCS/BECCS. It emphasizes energy service demand reduction (e.g., 25% lower cooling/lighting by 2050, 15% lower transport demand) and green hydrogen (11.3% of final energy by 2050). In the NZE-GHG scenario, solar (40%, 64 GW) and wind (8.6%, 40 GW) dominate power generation, with hydrogen at 10%, offsetting emissions via Land Use, Land-Use Change, and Forestry - LULUCF (90 MtCO_2e removal).
[24]	2050	AIM/Enduse	Explores Thailand's net-zero GHG by 2050, emphasizing green hydrogen. NZE-HH (High hydrogen) scenario features 50 GW of electrolyzers, 107 GW solar, 43 GW wind, 50M m^3 water, and \$122 billion investment (2031–2050). GHG emissions drop 63% from BAU by 2050, with hydrogen aiding hard-to-abate sectors (transport, industry) and power stability, alongside renewables and CCS, reducing air pollutants significantly.
[25]	2050	LEAP	Examines Thailand's goal of achieving carbon neutrality by 2050. Classic scenario, emphasizing clean technologies such as renewables, green hydrogen, Carbon Capture, Utilization, and Storage (CCUS) with 28.5 GW prosumer capacity and 9.5 MToE hydrogen demand, requiring

(*continued on next page*)

Table 2 (*continued*)

Ref	Year	Model Used	Brief Description
			30 $MtCO_2eq$ carbon offsets; and Orchestra, focusing on energy management, decentralization, and a prosumer market (32.5 GW capacity), achieving neutrality with minimal offsets via higher efficiency (45% GHG reduction vs. 35% in Classic).
[26]	2050	Multi-period Linear Programming	Proposes Thailand's electricity carbon neutrality by 2050, integrating Photovoltaic (PV) BESS and hydrogen blending (0%–75%) in gas. Results show PVBESS dominates in lower hydrogen scenarios (e.g., 121,000 MW at 0% H_2), while higher hydrogen blends (75%) reduce PVBESS need (63,000 MW) and land use (1662 km^2 vs. 3192 km^2 at 0%), with combined cycle gas turbine (CCGT) capacity increasing (25,200 MW at 75% H_2).
[27]	2050	LEAP	Assesses Thailand's energy sector GHG reduction beyond NDC by 2050. BAU emissions rose from 217,842.5 Gg CO_2eq in 2010 to 817,631.0 Gg CO_2eq by 2050. Mitigation (MT1 by RE, EE) cuts 54.5%, MT2 (plus CCS) cuts 67.7%. Extended to 2050, emissions drop to 569,099.3 Gg CO_2eq (30.3% below BAU). Co-benefits include reduced GHG intensity (67.7% in MT2) and air pollutants (e.g., 55.9% PM2.5 reduction in MT2).

Source: Authors' Compilation

capacity is imported from neighboring countries. EGAT and VSPPs primarily own the renewable installed capacities supported by the Adder and Feed-in Tariff (FiT) programs. EGAT solely owns the transmission infrastructure, while distribution is handled by two utilities: MEA, covering Bangkok and its surrounding areas, and PEA, responsible for other provinces. The power sector is overseen by the Thai Energy Regulatory Commission (ERC) as presented in Fig. 1.

In electricity generation, over the years 2014–2023, natural gas dominates (Fig. 2), but the share declined from 64.7% in 2014 to 58% in 2023. Coal and Lignite share also reduced from 20.2% to 13.6% [33]. Contribution of RE more than doubled, rising from 4.9% to 10.4%, while share of imported energy from Lao PDR and the EGAT-TNB (Tenaga Nasional Berha) interconnection system nearly doubled from 6.6% to 14.7%. Hydro and oil maintained minimal shares, both contributing less than 3% and 1%, respectively. The per capita energy consumption has increased to 3087.40 kWh from 2659.84 kWh, showing around 13.8% growth over 9 years [3].

Thailand's energy policy has evolved significantly over the past decade. Table 1 summarizes the key integrated energy plans announced from 2011 to 2024, highlighting Thailand's current and future energy sector perspectives. These plans, including the Thailand Energy Efficiency Development Plan (EEDP) [39], Integrated Energy Blueprint (TIEB) [40], Power Development Plans (PDP) [41,42], the National Energy Plan (NEP) [43], Alternative Energy Development Plan (AEDP) [28], Long-Term Low Emission Development Strategy (LT-LEDS) [31], demonstrate a commitment to increasing RE penetration, enhancing EE, and the intention of aligning with global climate goals such as carbon neutrality by 2050.

3. Literature review

Thailand's clean energy transition is driven by global climate goals and its Nationally Determined Contributions (NDCs). This has spurred research on power sector transition. Studies using models like The Low Emissions Analysis Platform (LEAP), LEAP-NEMO (Next Energy Modeling system for Optimization), Asia-Pacific Integrated Modeling/Computable General Equilibrium (AIM/CGE), AIM/Enduse, and multi-period linear programming explore pathways to carbon neutrality or net-zero emissions or clean energy transition by 2050, focusing on RE, EE, electric vehicles (EVs), carbon capture and storage (CCS), and green hydrogen assess technology integration, economic impacts, and co-benefits like reduced air pollution. These are summarized in Table 2.

Table 3
Scenario details: Supply (S) side and Demand (D) side interventions and assumptions.

Scenario Name	Year	Narrative and Assumptions	Scenario Acronyms/ Cluster	
Reference Scenario	2030, 2037, 2045, and 2050	Continuation of traditional planning without significant transformation in the power sector.	Reference	
Scenario-I	2030	The key assumption is having a 30% share of the RE (hydro, biomass, solar, and wind) in the generation mix. This scenario is both policy (AEDP 2018) [28] and government-commitment-driven (accelerating renewable energy) [29].	LRE (S)	PAS
Scenario-II	2030	Scenario I plus 19% energy efficiency, calculated with a year-by-year 1.67% increase based on EEP 2015 [30], rounded to 19% for 2030.	LRE (S), ELD (D)	
Scenario-III	2037	56.6% share of renewable energy, calculated on a year-by-year scale of 3.80% from 2030, based on LT-LEDS [31].	MRE (S)	
Scenario - IV	2037	30% energy efficiency, considering EEP 2015, maintaining Scenario III's renewable energy mix.	MRE (S), ELD (D)	
Scenario - V	2045	71% share of renewable energy, calculated on a year-by-year scale of 0.6% from 2040, based on LT-LEDS. The coal phase-out has been implemented.	HRE (S)	
Scenario - VI	2045	43% energy efficiency in addition to Scenario V, with a year-by-year increase of 1.67% based on AEDP 2018, rounded to 43% for 2045.	HRE (S), ELD (D)	PAS, HAAS
Scenario - VII	2050	The entire generation mix is from local renewable and alternative clean sources, exploring the socio-economic context of the clean energy transition.	HRE (S)	HAAS
Scenario - VIII	2050	100% clean energy with a 10% demand-side load shift (DSF) (evening peak to daytime) to utilize excess solar and renewable power, reduce storage dependence, and minimize curtailment losses, assuming consumer acceptance of behavioral changes.	HRE (S), DSF (D)	HAAS
Scenario - IX	2050	50% energy efficiency on top of Scenario VIII, calculated with a 1.67% year-by-year increase based on AEDP.	HRE (S), DSF (D), ELD (D)	HAAS
Scenario - X	2050	-In addition to Scenario VIII (10% DSF, 100% clean), the entire generation mix will comprise local and imported renewable and alternative clean sources, including imported hydro from Lao PDR and Malaysia, to enhance energy security.	HRE (S), DSF (D), RC (D)	HAAS

Note: Although Thailand officially didn't commit to a coal phase-out but like many studies [20,22,23,25,32], in this research, we explore the coal phase–out pathways.

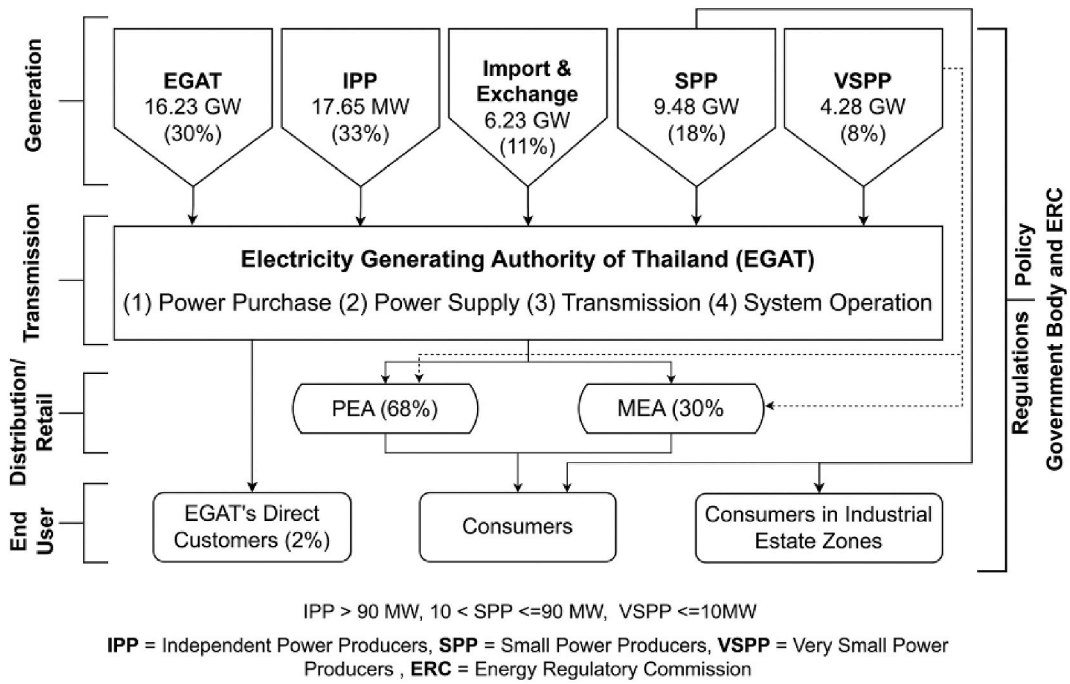

Fig. 1. Structure of Thailand's power sector.
Source: Author presentation based on Thai power sector regulation study [37] and data from EPPO [3]

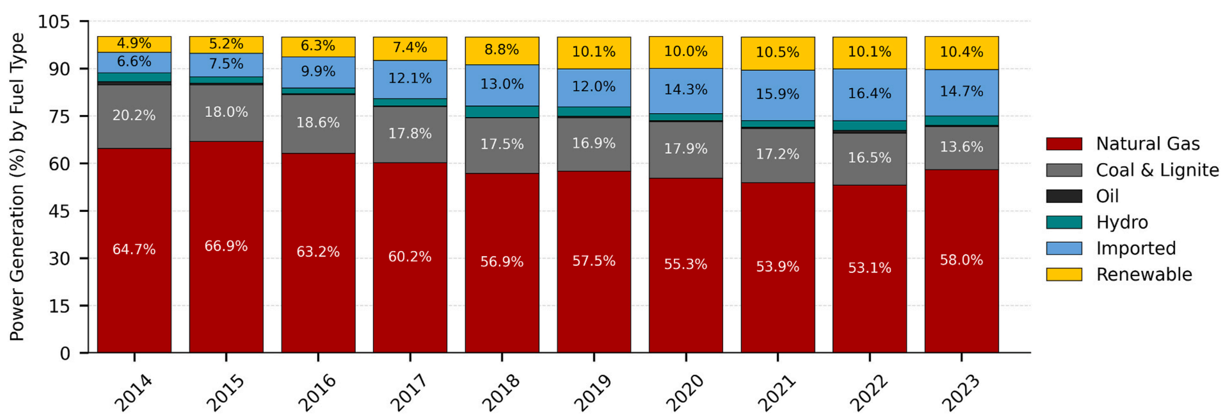

Fig. 2. Thailand's power generation share by fuel-type.
Source: Author's compliation with data from EGAT Annual reports 2014–2023 [38]

LEAP ([7,13,15]), AIM/Enduse ([9–12]), AIM/CGE ([8]), and multi-period linear programming ([14]), which address long-term, sector-wide or macroeconomic scenarios. PyPSA-TH uses the open-source PyPSA framework to model Thailand's power system with high-resolution techno-economic details by integrating spatial data on solar and wind resource potential at a 30 km × 30 km resolution, alongside detailed grid topology, land use constraints, and transmission infrastructure, enabling precise mapping of renewable energy deployment and hourly load data. It emphasizes hourly dispatch, offering finer granularity than the aggregated (annual or monthly dispatch) approaches of prior studies. PyPSA-TH's open-source design enhances transparency and reproducibility, fostering global collaboration. It bridges long-term decarbonization objectives with short-term operational strategies, delivering actionable insights for capacity expansion, grid stability through storage facilities, and quantification of socio-economic impacts. This provides more detailed information and can help decision-making for advancing Thailand's clean energy transition in a phased manner.

4. Methodology

PyPSA-TH builds on PyPSA-Earth's [18] global energy modeling capabilities, integrating data from Thailand's official sources to address the country's clean energy transition. PyPSA is excellent in power system analysis by integrating steady-state network modeling with multi-period linear optimization. Its key features include the ability to model diverse components, such as conventional generators, renewable sources (including hydro, biomass, solar, and wind), storage systems, and interconnections, with high spatial and temporal resolution, enabling precise simulation of energy flows and generation variability. PyPSA enables the simultaneous optimization of both investment and operational decisions while efficiently managing large-scale networks and long time series data, making it particularly well-suited for modeling complex energy transitions, an advantage over tools like LEAP or MARKAL, which do not offer the same level of detail in network structure and temporal resolution.

The modeling framework, illustrated in Fig. 3, unfolds in four stages:

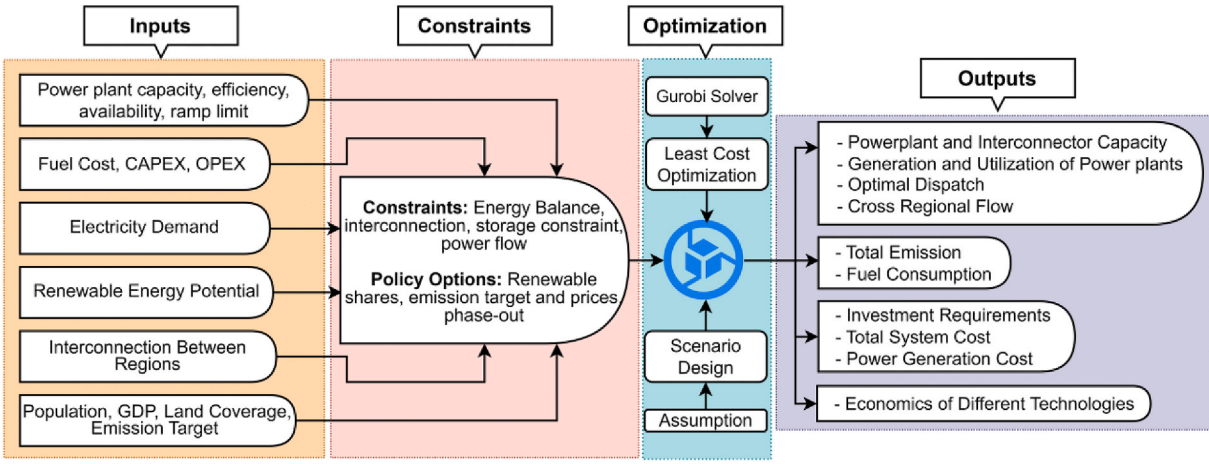

Fig. 3. Flowchart of PyPSA-TH methodology.

Inputs, Constraints, Optimization, and Outputs. Input includes detailed datasets on power plant capacities, fuel costs, electricity demand, and renewable energy potentials (e.g., solar, wind, as presented in Fig. 4), as well as socio-economic indicators such as population and GDP. Constraints ensure system feasibility, enforcing energy balance and policy targets. The Optimization stage utilizes the Gurobi solver to minimize total system costs across various scenarios, taking into account renewable expansion and fossil fuel phase-out assumptions. Outputs provide critical insights, including optimal generation capacities, cross-regional flows, total emissions, investment requirements, and system costs, thereby providing a foundation for informed policy formulation.

PyPSA-TH's open-source nature enables transparency, reproducibility, and global collaboration, allowing continuous updates and community-driven enhancements. The mathematical formulations, comprising the objective function and constraints for energy balance, storage, and power flow, are based on established PyPSA methodologies from the literature and are presented in Appendix A. Through these features, PyPSA-TH offers an adaptable framework for designing sustainable energy strategies tailored to Thailand.

4.1. *Inputs for the PyPSA-TH model*

Context-specific basic geographic data: The Grid Topology represents the physical structure of Thailand's power network, comprising of the transmission lines, buses, and substations. This data is sourced from OpenStreetMap (OSM) [45]. The regional electricity demand profiles provide electric demand data that varies across 77 regions and were collected from PEA [34] and MEA [35].

Technology details: The installed capacity data represents the capacity of all power plants in Thailand, and the efficiency rates of the plants obtained from the EGAT annual reports 2001–2023 [33].

Economic Data: The economic parameters encompass fuel costs, investment expenditures, and both fixed and variable operation and maintenance (O&M) costs, representing the capital required for constructing new generation and transmission infrastructures. The sources of these data are from the EGAT annual report 2023 [33] and a study by Clean, Affordable and Secure Energy for Southeast Asia (CASE) and EPPO, Ministry of Energy, Thailand [46].

Policy and targets: The renewable energy targets define Thailand's intended share of renewables in electricity generation, as specified in the AEDP 2015 [34] and LT-LEDS [31].

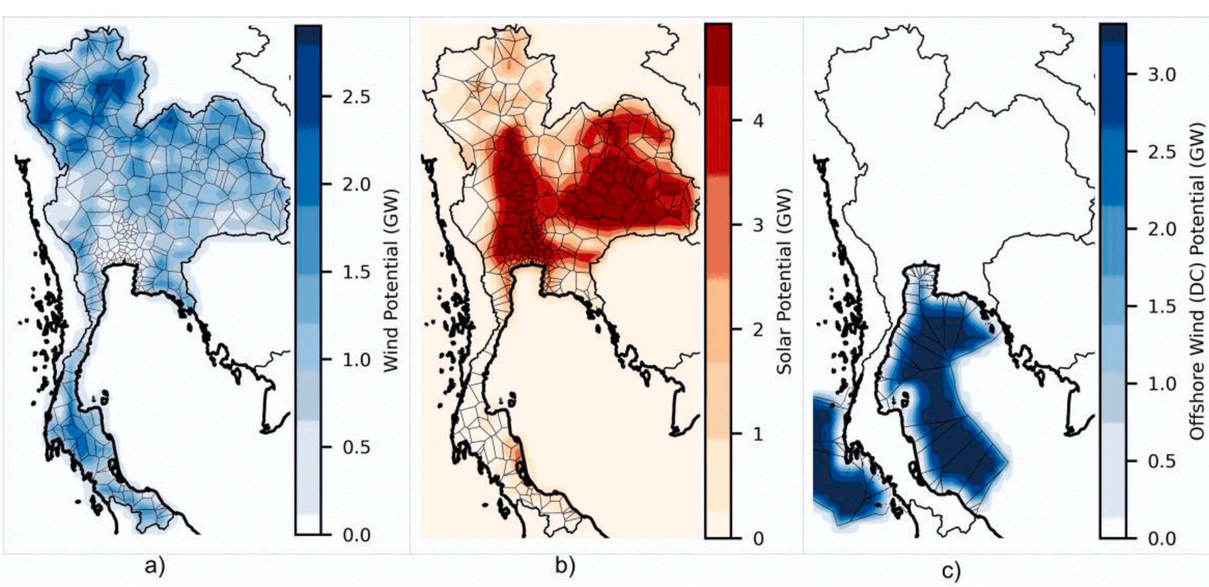

Fig. 4. Renewable energy potential a) onshore wind, b) solar, and c) offshore wind (DC).
Source: Authors compilation through PyPSA-TH model using ERA5 reanalysis data [44]

4.2. Scenarios

This study presents a policy-focused framework for Thailand's energy sector transition by 2050, detailed in Table 3, through ten scenarios (S-I to S-X) clustered into Low Renewable Energy (LRE, ≤40%), Moderate Renewable Energy (MRE, 40%–70%), High Renewable Energy (HRE, >70%), Efficient Low Demand (ELD), Demand-Side Flexibility (DSF), and Regional Cooperation (RC). Aligned with the AEDP, EEP, and LT-LEDS, the scenarios are grouped into Pledged Action Scenario (PAS), reflecting existing commitments, and Higher Ambitious Action Scenario (HAAS), targeting ambitious higher renewable energy in the generation mix and advanced demand-side measures like higher energy efficiency (EE) and demand-side flexibility (DSF).

PAS integrates supply- and demand-side interventions rooted in established policy frameworks. On the supply-side, emphasis is placed on scaling RE integration as outlined in the AEDP and LT-LEDS. Scenarios I, III, V, and VI emphasize a progressive increase in renewable energy shares, starting at 30% in 2030 (S-I, LRE) and reaching 71% by 2045 (S-V, HRE), incorporating solar, wind, biomass, and hydro. On the demand-side, energy efficiency measures, as per the EEP, are applied in Scenarios II, IV, and VI, which integrate efficiency gains of 19% (2030) and 30% (2037), respectively, which might be achieved through policies such as energy-efficient building codes, industrial retrofit programs, and appliance standards. These interventions aim to curb energy demand growth, optimize resource utilization, and support the integration of renewable energy by reducing peak loads.

HAAS builds on PAS by introducing higher and more ambitious targets to achieve a clean power sector by 2050, emphasizing both supply-side and demand-side innovations. On the supply-side, Scenarios VII, VIII, IX, and X target 100% renewable energy, leveraging a mix of local and imported clean energy sources. These scenarios require transformative policies, such as accelerated renewable energy auctions, public-private partnerships for energy storage, and regional grid interconnections to enhance energy security and reduce curtailment. The demand-side incorporates advanced interventions, notably in Scenarios VIII, IX, and X, which integrate a 10% demand-side load shift (DSF) to align evening peak demand with daytime renewable energy availability. This might be supported by policies promoting time-of-use tariffs, smart metering, and consumer incentives for behavioral changes, reducing reliance on storage and enhancing system efficiency. Additionally, S-IX and S-X target 50% energy efficiency, which is assumed to be possible through comprehensive demand-side management programs, including sector-wide retrofits (e.g., upgrading industrial facilities with energy-efficient motors and insulation in manufacturing plants), digital energy management systems, efficient devices (such as lighting, energy-efficient HVAC systems, smart thermostats, and high-efficiency appliances like inverter-based refrigerators and washing machines) integration, and public awareness campaigns. Scenario X further incorporates regional cooperation, fostering policy alignment with neighboring countries to facilitate clean energy trade and bolster energy resilience.

5. Results

5.1. Model validation

The PyPSA-TH model has been validated and tested using actual power sector data from 2019 to ensure that the baseline year accurately representing the latest pre-pandemic condition of Thailand's electricity sector. To simplify the modeling simulation, the power sector of Thailand has been divided into 77 load points (Figure B1a), which include 231 buses and 341 generators with 18 carriers. The assumptions and data considered for the model are derived from national energy sector planning reports of the EGAT, DEDE, EPPO, MEA, and PEA, offering a robust basis for future scenario building. Cost assumptions such as capital expenditures (CAPEX), fixed and variable operation and maintenance (FOM and VOM) expenses, and technology lifespans are obtained from the Thai Energy Transition Report [47] and the EGAT annual reports 2019 [48], across the scenarios ensuring consistency with prevailing market conditions in Thailand (Table B1) [47,48]. The spatial distribution of installed capacity across the country for different scenarios is presented in Appendix B through figures B2 (S-I, S-II, and S-III), B3 (S-IV, S-V, and S-VI) and B4 (S-VII, S-VIII, S-IX, and S-X).The validation of the PyPSA-TH model against EGAT's 2019 transmission network data (Table 4 and Figure B1 b) demonstrates a high degree of alignment, underscoring the model's accuracy in representing Thailand's transmission infrastructure. The total transmission line capacity in the PyPSA-TH model is 1.24% lower than the EGAT-reported figure, with variations across voltage levels remaining within acceptable margins. For instance, at 230 kV, the PyPSA-TH model records a line length of 14,814.68 km compared to EGAT's 15,357.71 km, while at 500 kV, it slightly exceeds EGAT's data with 7437.49 km versus 6575.18 km. These minor discrepancies indicate close correspondence, particularly when aggregated across all voltage levels, where the modeled total is 35, 540.79 km compared to EGAT's 35,981.45 km. This validation confirms the reliability of the PyPSA-TH model for future transmission network planning and optimization.

The total power generation (Table 5) in 2019 was estimated at 213.13 TWh by PyPSA-TH, showing a 2.97% deviation from the official data of 219.65 TWh, including the off-grid power generation collected from the 2109 energy balance report of DEDE [36], which is based on the data of annual reports from EGAT, MEA, and PEA. Gas-fired power plants account for 55.79% of the model results and 55.14% of the official data, followed by coal at 14.51% and 15.44%, respectively. Hydropower, including imports, contributes 14.24% in the model and 14.41% in the official statistics. Solar and wind generation are slightly overestimates by the model, showing 2.84% and 2.01% contribution, compared to 2.34% and 1.67% in the official data. Biomass (fuel includes fuel woods, paddy husk, bagasse, and agricultural waste) accounts for 8.40% of the model and 8.70% in the official statistics. In contrast other renewable sources, such as municipal solid waste (MSW) and biogas, are consistent at approximately 1.8%. These comparisons demonstrate the accuracy of PyPSA-TH in replicating national generation trends and the model's potential for energy system planning. The scenario comparisons are illustrated at Table 6.

5.2. Scenario-I

By 2030, the total installed capacity is projected to reach 107.67 GW, with gas leading with 39.13 GW (36.34%), followed by solar at 24.75 GW (22.98%) and coal at 18.28 GW (16.98%). Renewable sources, solar (24.75 GW, 22.98%), onshore wind (6.84 GW, 6.35%), hydro (4.09 GW, 3.80%), and biomass (4.13 GW, 3.84%), collectively contribute 77.46 TWh (30.00%) to the generation mix. Fossil fuels dominate generation, with gas 116.18 TWh (45.74%), coal 55.23 TWh (21.74%), and oil 4.73 TWh (1.86%). Emerging technologies such as offshore wind (0.006 TWh, <0.01%), battery storage (0.90 TWh, 0.35%), and hydrogen (0.45 TWh, 0.17%) provide initial system flexibility. Current hydrogen projects, such as the 300 kW pilot at Lam Takhong [49,50], operates at the demonstration stage, but with promise for significant potential in scaling up as EGAT is assessing [51] the feasibility of blending hydrogen (both green and blue) with natural gas at a 5% ratio for power plants, with targeted plans for implementation between 2031 and 2040.

5.2.1. Key insights

- The power system installed capacity expansion by 61.59 GW over the 2019 base case, with solar contributing 21.77 GW (35.34% of new capacity), onshore wind 5.33 GW (8.6%), and biomass 0.72 GW (1.17%). This marks an early reliance on solar and wind, although gas (10.17 GW) remains with significant share, reflecting a transitional phase to support the integration of renewable energy.

Table 4
Comparative overview of transmission line lengths at varying voltage levels.

Voltage Level (kV)	69	115	132	230	300	500	Total
Length (km): EGAT	18.80	13997.98	8.71	15357.71	23.07	6575.18	35981.45
Length (km): PyPSA-TH	22.17	13244.30	3.52	14814.68	18.63	7437.49	35540.79

Source: EGAT transmission system [30].

Table 5
2019 power generation capacity: Official statistics vs. PyPSA-TH model-based results.

Fuel	Official Statistics		Model-Based Estimates	
	TWh	Share (%)	TWh	Share (%)
Gas	121.12	55.14	118.90	55.79
Coal	33.92	15.44	30.93	14.51
Oil	1.07	0.49	0.86	0.40
Hydro	31.66	14.41	30.36	14.24
Solar	5.15	2.34	6.05	2.84
Wind	3.67	1.67	4.29	2.01
Biomass	19.11	8.70	17.90	8.40
Other RE	3.96	1.80	3.85	1.81

Note: The hydro capacity includes imports from LoaPDR and Malaysia. For the ease of modeling configuration, the imported power has been merged based on the fuel type (hydro).

- Land requirements total 1756.37 km^2 (0.34% of the total land), with solar occupying 435.4 km^2 (24.8%) and onshore wind 171.63 km^2 (9.8%). These estimated land areas account for 0.08% and 0.03% of the total national land respectively.
- Total investment requirement amounts to €54.83 billion, with share of solar at 24.5% (€13.43 billion), for coal at 26.2% (€14.39 billion), and for gas 15.2% (€8.35 billion).
- The transition is expected to generate 1,073,367 new jobs, with solar contributing 593,232 (55.3%), onshore wind contributing 43,706 (4.1%), and battery storage contributing 153,988 (14.3%), underscoring the labor potential of renewable technologies.

5.3. Scenario-II

Installed capacity totals 91.00 GW, with gas share 35.27 GW (38.76%), solar 20.62 GW (22.66%), and coal 13.16 GW (14.46%). Renewables contribute 62.14 TWh (30.00%), with gas (101.72 TWh, 49.45%) and coal (39.62 TWh, 19.26%) leading generation, moderated by EE-induced demand reduction.

5.3.1. Key insights

- The modeled expansion of installed capacity is 44.92 GW over the base case (2019), with solar (17.64 GW) and gas (6.31 GW). This is 16.67 GW (27.06%) lower than Scenario I's capacity expansion. EE reduces helps in reducing the additional need for new capacity, shifting reliance from Scenario I's broader mix to efficiency-optimized growth.
- Land requirements is 1186.50 km^2 (0.23% of the total land), 32.4% less compared to Scenario I. Solar energy accounts for 352.8 km^2 (29.7%) and onshore wind accounts for 142.97 km^2 (12.0%), representing 0.06% and 0.02% of the total land requirement respectively.
- Investment requirement for capacity expansion is €38.97 billion, 28.92% below Scenario I. Of this need for solar is €10.88 billion (27.91%), for coal €8.34 billion (21.40%), and for gas €5.18 billion (13.29%).
- Employment can rise by1.50 million, a 40.66% increase over Scenario I, with solar contributing 0.68 million jobs. The 19% EE improvement adds 0.43 million jobs, showcasing the huge employment creation potential of energy efficiency programs.

5.4. Scenario-III

Installed capacity rises to 186.94 GW, with solar (71.30 GW, 38.14%) overtaking gas (43.16 GW, 23.08%) and coal at 15.28 GW (8.17%). The battery storage reaches 14.88 GW (7.96%). Renewables generate 190.92 TWh (56.6%), surpassing fossil fuels (gas 96.10 TWh, coal 18.63 TWh, and Oil 1.38 TWh).

Table 6
Summary of the key outcomes across the scenarios.

Indicators	Supply-side-only scenarios				Integrated demand and supply-side scenarios					
	S-I	S-III	S-V	S-VII	S-II	S-IV	S-VI	S-IX	S-VIII	S-X
	LRE (2030)	MRE (2037)	HRE (2045)	HRE (2050)	LRE + ELD (2030)	MRE + ELD (2037)	HRE + ELD (2045)	HRE + ELD + DSF (2050)	HRE + DSF (2050)	HRE + DSF + RC (2050)
Total installed capacity (GW)	107.67	186.92	255.64	369.71	91.00	130.34	174.18	207.11	347.62	353.89
Power demand (TWh)	254.02	337.30	441.54	523.50	205.75	236.15	251.68	261.75	523.50	523.50
Power generation cost (€/MWh)	105.75	87.14	81.62	70.33	94.48	82.49	74.68	65.17	68.02	67.35
Emissions in reference scenarios ($MtCO_2$) (year)	105.16 (2030)	112.59 (2037)	122.14 (2045)	135.02 (2050)						
Emissions across scenarios ($MtCO_2$)	103.19	61.74	28.96	0.00	80.99	41.48	17.48	0.00	0.00	0.00
Land requirement (km^2)	1756.29	3316.23	3919.31	5612.98	1186.43	1771.49	2220.51	3152.65	5532.88	5590.58
Jobs created (Millions)	1.07	2.80	4.52	7.07	1.51	3.71	6.24	9.44	6.58	6.76
Job losses from the fossil fuel phase-out			79,515.00 (Coal Only)	23,628 (Gas Only)						
Stranded assets due to fossil fuel (coal and gas) phase-out (€ billion)			1.96 (Coal Only)	0.81 (Gas Only)						

Source: PyPSA-TH Model-based results

5.4.1. Key insights

- Expansion reaches 140.84 GW compared to the 2019 level, with solar (68.32 GW, 48.50% of new capacity) share rising. The wind, biomass, and battery storage expand by 16.94 GW, 7.25 GW, and 14.88 GW.
- Land requirement is 3316.42 km^2 (0.64% of the total land), 88.8% more than Scenario I. Solar requires 1366.4 km^2 (41.2%), onshore wind at 545.47 km^2 (16.5%), and biomass 193.58 km^2 (5.8%), representing 0.26%, 0.10% and 0.03% of the total land respectively.
- Investment need totals €116.87 billion, 113% above Scenario I, for solar €38.11 billion (32.6%), onshore wind €19.15 billion (16.38%), biomass €10.63 billion (9.09%), and battery storage €15.58 billion (10.76%).
- Employment reaches 2.80 million, 161% more than Scenario I, in solar (1.86 million jobs, 66.5%) and onshore wind (0.14 million jobs, 5.0%).

5.5. Scenario-IV

Installed capacity increases to 130.34 GW, with solar (42.42 GW, 32.54%) and gas (34.57 GW, 26.52%) leading. Onshore wind continues to grow in capacity, reaching 11.66 GW, while biomass capacity decreases slightly compared to scenario III (9.82 GW) due to demand reduction by EE. Renewables contribute 133.67 TWh (56.6%), with solar energy accounting for 72.78 TWh, wind energy for 37.32 TWh, and biomass for 25.69 TWh, while the total demand reaches 236.15 TWh.

5.5.1. Key insights

- Optimum capacity expansion totals 84.26 GW over the 2019 base case. Of this, solar 39.44 GW, onshore wind 10.15 GW, and biomass 6.41 GW emerge as the key fuel sources, while battery storage plays a key role with an expansion of 10.68 GW. EE helps in reducing total capacity needs by 30.3% from Scenario III's 186.94 GW, optimizing resource use.
- Land use requirement totals 1771.68 km^2 (0.34% of the total land), 46.6% less than Scenario III, for solar 788.8 km^2 (44.5%), wind 326.83 km^2 (18.45%), representing 0.15% and 0.06% of the total land requirement, respectively.
- The required investment in supply expansion is €70.02 billion, 40% below (due to efficiency improvement in end use) Scenario III, for solar (€22.00 billion, 31.4%) and biomass (€9.40 billion, 13.42%) emerging as the dominant sources.
- New jobs from this scenario reach 3.71 million, 32.65% above Scenario III, led by solar and battery storage (2.23 and 0.48 million, respectively) sectors EE's higher job creation potential.

5.6. Scenario-V

Installed capacity reaches 255.68 GW, with solar (92.29 GW, 36.09%), onshore (27.27 GW, 10.66%), and offshore wind DC (21.41 GW, 8.37%) prominent. Renewables generate 313.51 TWh (71%), with coal generation phased out. The total demand reaches 441.54 TWh.

5.6.1. Key insights

- The expansion totals 209.56 GW compared to the 2019 level, 48.8% above Scenario III, with solar (89.31 GW, 42.62%), onshore wind (25.76 GW, 12.29%), offshore wind DC (21.14 GW, 10.08% biomass (14.2 GW, 6.7%) and battery storage (36.92 GW, 17.62%).
- Land use rises to 3919.46 km^2 (0.76% of the total land), 121% more than Scenario IV, with solar at 1786.2 km^2, onshore wind 829.472 km^2, offshore wind DC 528.54 km^2, and biomass 379.14 km^2, representing 0.34%, 0.16%, 0.07% and 0.10% of the total land area, respectively.
- The total investment needs is €166.85 billion, for solar (€43.82 billion), onshore wind (€27.20 billion), offshore wind DC (€20.19 billion) and biomass (€19.69 billion).
- The employment opportunity reaches 4.5 million, slightly above Scenario IV, with solar (2.43 million jobs, 53.8%), onshore wind (0.22 million jobs, 4.92%), and hydro (0.43 million jobs, 9.5%).

5.7. Scenario-VI

Installed capacity reaches 174.18 GW, with solar (47.34 GW, 27.18%), gas (36.57 GW, 21.00%), onshore wind (21.73 GW, 21.47%), offshore wind DC (11.92 GW, 6.84%), biomass (14.13 GW, 8.11%), battery (20.24 GW, 11.62%) leading. Renewables contribute 181.80 TWh (71%), while enhanced by EE, the total demand reached 251.68 TWh.

5.7.1. Key insights

- Capacity expansion reaches 128.1 GW compared to 2019 level, 38% lower than the scenario-V. Solar (44.36 GW, 34.62%), onshore wind (20.22 GW, 15.78%), offshore wind DC (11.92 GW, 9.30%), biomass (10.72 GW, 8.36%) and battery storage (20.24 GW, 15.80%) dominate the expansion.
- Land requirement is 2518.70 km^2 (0.49% of the total national land), 35.7% less than Scenario V, with solar at 887.2 km^2 (35.22%) and onshore wind at 651.08 km2 (25.85%), offshore wind DC 298.10 km2 (11.84%) and biomass 286.22 km^2 (18.84%), representing 0.17%, 0.12%, 0.05% and 0.05% of the total land area, respectively.
- Investment need reaches 105.26 billion, for solar (€21.76 billion), onshore wind (€21.35 billion), offshore wind DC (€20.19 billion), and biomass (€14.16 billion). Investment is also needed for battery storage (€13.90 billion).
- Employment creation increases to 6.23 million, 37.95% above Scenario V, with solar (3.15 million jobs) dominating the job creation, followed by battery storage and biomass, 1.29 million and 0.43 million, respectively.

5.8. Scenario-VII

Installed capacity reaches 369.71 GW, with solar dominating at 132.74 GW (35.90%), followed by onshore wind at 48.55 GW (13.13%), offshore wind DC at 27.55 GW (7.45%), and biomass at 18.15 GW (4.91%). Battery storage (23.11 GW, 6.25%) and hydrogen (20.11 GW, 5.44%) ensure system stability. Renewables generate 525.50 TWh with solar contributing 205.54 TWh (39.12%), onshore wind 90.39 TWh (17.20%), and biomass 91.69 TWh (17.45%). Fossil fuel (coal, gas, oil) is phased out.

5.8.1. Key insights

- Capacity expands by 323.63 GW over the 2019 base case, with solar adding 129.76 GW (40.08%), onshore wind 47.04 GW (14.53%), offshore wind DC 27.55 GW (8.51%), and biomass 17.64 GW (5.45%). Battery storage (73.11 GW, 22.60%) and hydrogen (10.32 GW, 3.19%) support grid reliability.
- Totals 5612.88 km^2 land requirement (1.09% of the total land), with solar occupying 2595.2 km^2 (46.24%), onshore wind 1514.69 km^2 (26.99%), offshore wind DC 688.762 km^2 (12.27%), and biomass 470.98 km^2 (8.39%), 0.50%, 0.29%, 0.13% and 0.09% of the total land area, respectively
- Investment requirement reaches €230.32 billion, for solar (€58.20 billion, 25.27%), onshore wind (€47.47 billion, 20.61%), offshore wind DC (€43.76 billion, 19.01%), and biomass (€23.58 billion, 10.24%). Battery storage (€42.97 billion, 18.66%) and hydrogen (€10.78 billion, 4.68%) reflect significant grid support costs.

- New jobs total 7.07 million, with solar generating 3,535,960 jobs (50.01%), onshore wind 385,728 jobs (5.45%), and biomass 324,576 jobs (4.59%). Battery storage and hydrogen add 2,054,391 jobs (29.05%) and 38,184 jobs (0.54%), respectively, highlighting the employment potential of clean energy transition.

5.9. Scenario-VIII

Installed capacity totals 347.62 GW, with solar at 132.74 GW (38.19%), onshore wind at 48.55 GW (13.97%), offshore wind DC at 27.55 GW (7.93%), and biomass at 18.15 GW (5.22%). Battery storage rises to 58.33 GW (16.78%) to manage shifted loads, while hydrogen drops to 6.01 GW (1.73%). Generation reaches 523.50 TWh, with solar at 205.64 TWh (39.28%), onshore wind at 70.93 TWh (13.54%), and biomass at 72.14 TWh (13.78%).

5.9.1. Key insights

- Supply capacity expansion reaches 301.54 GW over the 2019 level, with solar (129.76 GW, 43.03%), onshore wind (47.04 GW, 15.60%), offshore wind DC (27.55 GW, 9.14%), and biomass (14.64 GW, 4.85%). Battery storage expands by 58.33 GW (19.34%) which is less than Scenario-VII reflecting the impact of DSF, while hydrogen adds only 6.01 GW (1.99%).
- Land Use requirement totals 5532.77 km^2 (0.1.07% of the total land), slightly below Scenario VII, with solar at 2595 km^2 (46.9%), onshore wind at 1514.68 km^2 (27.38%), and offshore wind DC 688.76 km^2 (12.45%). Biomass uses 390.88 km^2 (7.06%), 0.50%, 0.29%, 0.13% and 0.07% of the total land requirement respectively.
- Investment requirement reaches €213.12 billion, solar accounting for (€58.20 billion, 27.31%), onshore wind (€47.47 billion, 22.27%), battery storage (€34.29 billion, 16.01%), biomass (€19.57 billion, 9.18%) and offshore wind DC (€43.76 billion, 20.53%), and hydrogen €6.28 billion (2.94%).
- New job creation totals 6.58 million, with solar (3.53 million jobs, 53.71%), onshore wind (3.85 million jobs, 5.86%), and battery storage (1.64 million jobs, 24.9%).

5.10. Scenario-IX

Installed capacity drops to 297.11 GW due to contribution of EE in demand side, in supply side with solar 132.74 GW (44.67%), onshore wind at 38.25 GW (12.87%), offshore wind DC at 27.55 GW (9.27%), and biomass at 15.15 GW (5.10%). Battery storage (25.62 GW, 8.62%) and hydrogen (3.82 GW, 1.29%) support the system. Generation totals 261.75 TWh (100%), with solar at 87.18 TWh (33.31%), onshore wind at 30.86 TWh (11.79%), and biomass at 66.71 TWh (25.49%).

5.10.1. Key insights

- Expansion Totals 207.11 GW over the base case, with solar (56.82 GW, 27.43%), onshore wind (32.35 GW, 15.62%), offshore wind DC (15.79 GW, 7.62%), and biomass (16.32 GW, 7.88%). Battery storage adds 25.62 GW (12.37%), reduced from Scenario VIII due to EE.
- Land requirement decreases to 3152.64 km^2 (0.61% of the total land), with requirement for solar 1076.8 km^2 (34.16%), onshore wind 993.05 km^2 (31.50%), offshore wind DC 394.86 km^2 (12.53%), and biomass 344.70 km^2 (10.93%), accounting for 0.20%, 0.19%, 0.07% and 0.06% of the total land area, respectively.
- Investment totals €120.19 billion, for solar (€24.15 billion, 20.01%), onshore wind (€31.13 billion, 25.89%), offshore wind DC (€25.09 billion, 20.87%), and biomass (€17.26 billion, 14.35%). Battery storage (€15.06 billion, 12.53%) and hydrogen (€3.99 billion, 3.32%). This scenario reflects savings due to EE.
- New jobs increase to 9.43 million, with solar (4.42 million jobs), onshore wind (0.55 million jobs), offshore wind DC (0.83 million jobs), and biomass (0.55 million jobs). Battery storage (2.80 million jobs) and hydrogen (0.20 million jobs) contribute to employment gains.

5.11. Scenario-X

Installed capacity reaches 353.89 GW, with solar 132.74 GW (37.51%), onshore wind at 48.55 GW (13.72%), offshore wind DC at 27.55 GW (7.78%), and hydro increases to 11.59 GW (3.27%) due to imports. Biomass (15.15 GW, 4.28%), battery storage (58.33 GW, 16.48%), and hydrogen (6.01 GW, 1.70%) complete the mix. Generation totals 523.50 TWh, with solar at 199.64 TWh (38.13%), hydro at 51.08 TWh (9.76%), and onshore wind at 66.93 TWh (12.78%).

5.11.1. Key insights

- Expansion Totals 307.81 GW over the 2019 base case, with solar (129.76 GW, 42.16%), onshore wind (47.04 GW, 15.28%), offshore wind DC (27.55 GW, 8.95%), and hydro (8.48 GW, 2.75%). Biomass adds 14.64 GW (4.76%), and battery storage (58.33 GW, 18.95%) ensures stability.
- Total land requirement is 5590.48 km^2 (1.08% of the total land), solar 2595.2 km^2 (46.42%), onshore wind 1514.69 km^2 (27.09%), offshore wind DC 688.76 km^2 (12.32%), and biomass 390.89 km^2 (accounting for 6.99%), 0.50%, 0.29%, 0.13% and 0.07% of the total land requirement respectively. For Hydro capacity requirement is 84.8 km^2 (1.52%), reflecting minimal local land use due to power imports.
- Investment reaches €220.87 billion, for solar (€58.21 billion, 26.35%), onshore wind (€47.48 billion, 21.49%), offshore wind DC (€43.77 billion, 19.81%), and battery storage (€34.58 billion, 15.65%). Biomass (€19.57 billion, 8.86%) and hydro (€10.97 billion, 4.96%).
- New jobs total 6.75 million, in solar (3,535,960 jobs, 52.32%), onshore wind (385,728 jobs, 5.71%), offshore wind DC (655,702 jobs, 9.70%), and biomass (269,376 jobs, 3.99%). Hydro (235,320 jobs, 3.48%) and battery storage (1,653,123 jobs, 24.46%).

6. Discussion

6.1. Model-based results

The results from the PyPSA-TH model are compatible with the socio-economic pathway (SSP) framework, Middle of the Road scenario (SSP 2.6, estimated global warming of approximately 2.6°C by the end of the 21st century) [52]. The installed capacity for Thailand is modeled to grow 7.4 times (S-VII, 2050) compared to the 2019 level to meet a 2.4-times higher load than the 2019 load. Fig. 5 and B5 show the installed capacity and the share of various energy carriers. The fossil fuel plants in 100% clean energy scenarios (S–VII to S–X) do not reach their technical retirement life. That is why it is found (Figure B5) that installed coal capacity, although at a minimal level of 4.13%, still exists in 2050, like gas, with an installed capacity of 9.54%.

However, it is worth noting that in the 100% clean energy-based power system for Thailand, such as Scenarios V-II to S–X, the generation from fossil fuel plants is zero, as shown in Fig. 6 and B6. In modeled generation results, 2037 is the last year with 5.52% of generation from coal and 0.41% of oil generation, while gas plant generation continues until 2045.

One important observation from this study is that the long-term plan for installed capacity and, hence, the generation will vary significantly depending on how various intervention strategies are chosen at any point in time. Strategic planning can be done by focusing only on supply-side capacity expansion plans. Alternatively, it can be achieved through a strategic mix of supply-side capacity expansion integrated with demand-side interventions such as end-use energy efficient appliance

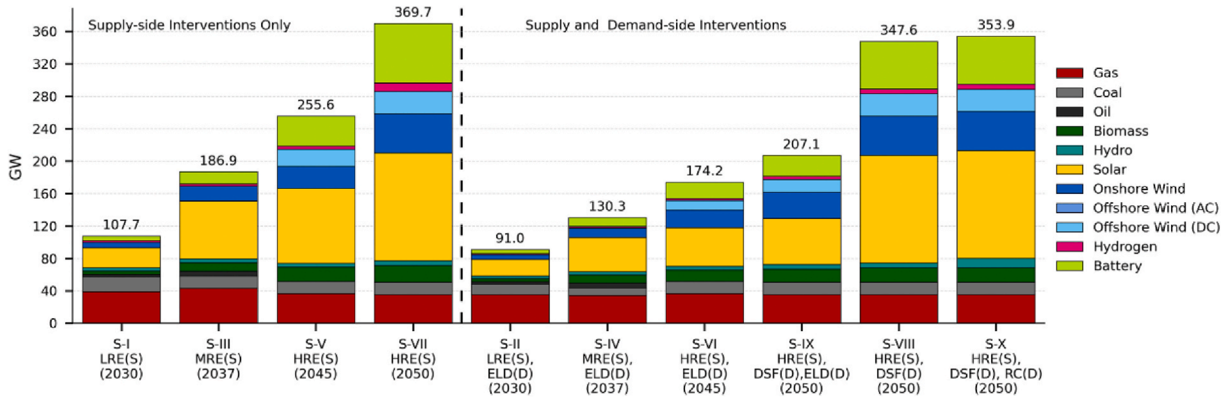

Fig. 5. Modeled installed capacity over scenario years.

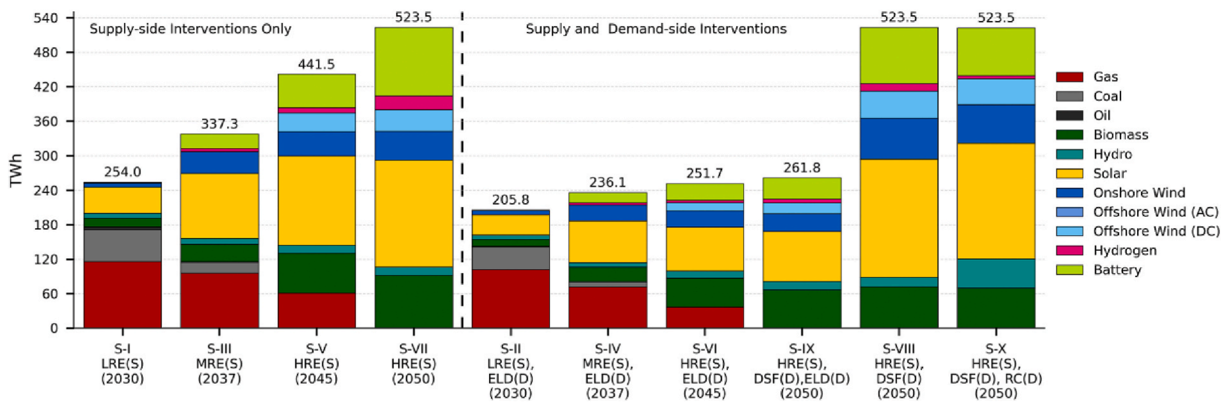

Fig. 6. Modeled power dispatch across the scenarios.

diffusion and the introduction of demand-side flexibility (DSF) and clean energy import plans.

If we compare the near-term scenario of 2030 (S-I and S-II), the S-II scenario, which include demand-side interventions, require 49 TWh less generation (Figs. 6) and 16 GW less installed capacity (Fig. 5) addition compared to S-I. Similarly, in the long-term scenario of 2050, compared to supply-side-only expansion scenarios (S-VII), the demand-side integrated supply-side scenario (S-IX) requires around 261 TWh less generation (Fig. 6) and approximately 162 GW less installed capacity (Fig. 5). This relatively low installed capacity and generation need in EE and/or DSF scenarios is driven by increased productivity of energy input at the end-user service provision level and/or shifting of the evening peak demand to daytime renewable energy available hours reducing curtailment need as well. Market forces drive the rapid expansion of solar in the optimal solutions across the scenarios, as the assumed capital cost in the model declines from 616.79 €/kW in 2030 to 448.57 €/kW in 2050. In Thailand, the need for offshore wind (DC) increases in model results as the demand for higher clean energy installed capacity increases with a gradual phase-down of generation from fossil fuel capacities. Regional cooperation in terms of importing hydropower generated in the neighboring countries, along with the demand-side shift, reduces the need for storage margin by 18.59 GW.

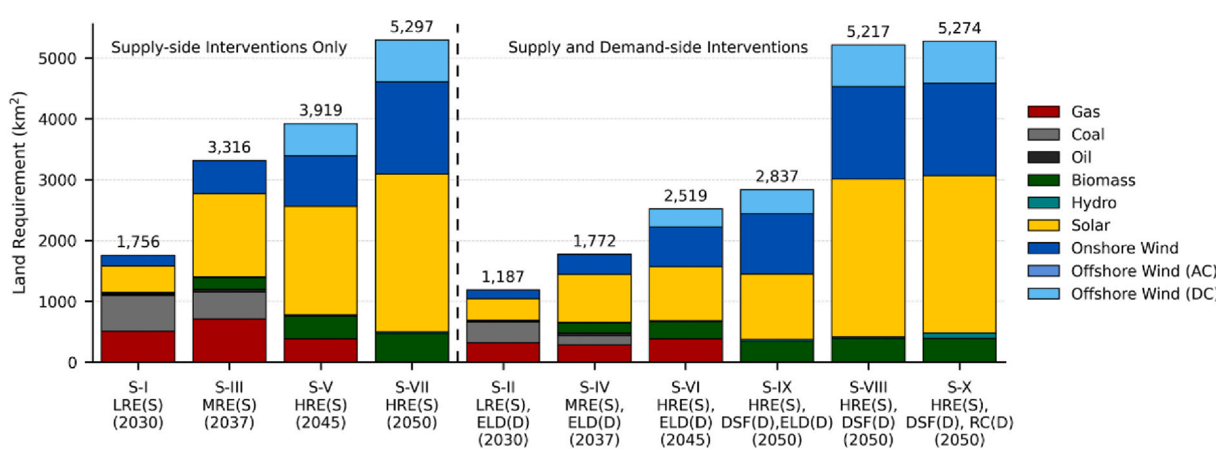

Fig. 7. Land requirement under various alternative scenarios.

6.2. Land requirements across the scenarios

Many argue that a major roadblock in renewable capacity expansion is the availability of land [53]. To understand the total land requirements (Fig. 7) for power sector installed capacity expansion, this study considered the land intensity (km^2/MW) values derived for each energy carrier type specifically for Thailand available in the published literature [24,54–56]. The PyPSA-TH model utilizes the land intensity value, as presented in Table 7, to determine land requirements under various scenarios.

The total land requirements in the near to medium-term PAS scenarios, with only supply-side capacity expansions (S-I and S-III), reach 1756.36 km^2 and 3316 km^2 (0.34% and 0.64% of the total land area, respectively), dominated mainly through coal capacity expansion in S-I followed by gas and solar capacity expansion, while in S-III, by solar capacity followed by gas, wind and coal. On the other hand, the scenarios with demand-side energy efficiency improvements exhibit a lower land footprint, a 32% reduction in S-II compared to S-I, and a 47% reduction in S-IV compared to S-III.

In long-term HAAS scenarios, which are dominated by a high share of clean energy, for example, 71% in S-V and S-VI in 2045, S-V requires around 3920 km^2 (0.76% of total land area) of land with only supply-side interventions, while 36% less land is required with demand-side interventions in S-VI with the same RE energy levels. This reflects that having demand-side interventions implemented not only the total energy demand reduces but required installed capacity reduces there by reducing the pressure on land requirement. A 100% clean energy scenario, without demand-side intervention, shows 5612.88 km^2 (1.09% of Thailand's total land) of land requirements, which is almost 44% higher than S-IX, which incorporates demand-side efficiency and flexibility. During this transition period, solar and wind dominate the demand for land use, peaking at 2595.2 km^2 and 1514.68 km^2, respectively, in scenario VII.

One key challenge of this transition might be to ensure that the required land does not compete with productive agricultural lands or lands that are currently in productive use in other services. However, studies show that in Thailand, an estimated 12,351 km^2 of unused land is available [22,52]. HRE scenarios with the maximum land requirement require 45.44% (S-VII) of this unused land. It can be concluded that sufficient land is available to achieve a fully clean energy system. But we understand that a more nuanced analysis of exact location of land availability, corresponding transmission network availability, land transfer, land rights, etc. is needed to provide more practical guidelines for policy and actions to implement transitions. This we see as a future research agenda.

6.3. Job creation potential

Direct job creation parameters (jobs/MW) and job distribution across sectors, manufacturing (MF), construction and installation (C&I), and operation and maintenance (O&M), which are used in this study, are presented in Table 8. Fig. 8 illustrates the total job creation potential broken down by sectors under modeled scenarios to reflect how it varies under supply-side-only interventions vis-a-vis supply plus demand-side interventions. The job creation due to the incorporation of demand-side energy efficiency in scenarios II, IV, VI and IX are calculated based on the combined effect of direct (0.04 jobs/GWh energy saved) and indirect (9.0 jobs/GWh energy saved) job [57,58] creation potential of EE both upstream and downstream of supply chain.

By 2030, in scenario S-I, supply-side capacity expansion has potential to generate 1.07 million jobs, reflecting a 12.33% growth rate compared to the 2019 level. However, in scenario S - II, due to the demand-side energy efficiency related services and products, job creation potential is higher (1.41 million, around 31% higher compared to S-I).

Similar features are observed in medium-term (2037) and long-term (2045 and 2050) scenarios, where demand-side EE improvements and DSF consistently enhance job creation potential. In the 100% clean energy scenario (S-VII), supply-side expansion alone yields 7.06 million new jobs. However, when demand-side EE and DSF are integrated, total job creation rises to 9.43 million, a 1.33-fold increase. As RE penetration and storage capacity expand over the long term, job creation increases in solar and storage sectors, with 4.42 million and 2.80 million jobs, respectively, in Scenario IX, followed by offshore wind DC, biomass, and hydropower.

The construction and installation sectors emerge as the primary drivers of job creation across all scenarios. In the clean energy transition, supply-side expansion alone generates 3.99 million jobs, while integration with demand-side interventions elevates this Figure to 5.26 million. These findings align with prior research by the American Council for an Energy Efficient Economy (ACEEE) [63], which highlights the construction sector and retrofit projects as key areas of EE-driven job growth.

6.4. Investment and need for financial mobilization

A sector expansion plan needs matching investments and financial resource mobilization as primary enabling conditions. Fig. 9 illustrates the additional financial resource mobilization need (during 200–2050 in billion euro (€) for capacity expansion over and above the base case (the year 2019 in this study) for Thailand's energy transition under various scenarios.

Scenarios emphasizing supply-side interventions alone exhibit significantly higher need for financial mobilization. In the near-term scenario (S-I, 2030), the financial mobilization need for capacity expansion amounts to €54.82 billion. This requirement escalates to €230.31 billion (i.e., 1.94% of the 2024 Thailand's GDP each year starting from 2025) in Scenario VII (2050). This means 4.18-fold increase, reflecting the capital-intensive nature of achieving a 100% clean energy system through a supply-side-only intervention strategy. In contrast, the integration of demand-side EE in low-demand scenarios (S-II, S-IV, S-VI, S-IX) substantially reduces investment needs by 29%–48%. For instance, investment requirements decrease from €116.87 billion in S-III to €70.02 billion in S-IV (1.67-fold less for 30% EE) and from €230.31 billion in S-VII to €120.19 billion (1.01% of 2024's GDP of Thailand in each year from 2025) in S-IX (1.91-fold lower for 50% EE and 10% DSF). These reductions alleviate financial burden on the energy sector, thereby creating opportunities for investment in other economic sectors. The 10% demand-side load shift (DSF) in S-VIII results in a 7.5% reduction in investment need (€213.112 billion vs. €230.311 billion in S-VII) through aligning end use demand with renewable generation, thereby reducing additional storage need. Without even going into the details, the maximum investment need is in scenario VII, which is approximately €230 billion over a period of 2019–2050. If we look into Thailand's recent investment in renewable and alternative clean energy between 2019 and 2023, it amounts to €4.34 million (160.82 million THB) [64].

Across all scenarios, solar energy emerges as the dominant driver of

Table 7
Land use intensity of energy carriers for Thailand's power sector.

Carrier	Biomass	Coal	Gas	Offshore Wind (AC)	Offshore Wind (DC)	Oil	Onshore Wind	Hydro	Solar
Land requirement (km^2/MW)	0.027	0.049	0.050	0.025	0.025	0.007	0.032	0.010	0.020

Source: Authors' compilation from source [24,54–56].

Table 8
Breakdown of sectoral job creation potential (%).

Sector	Carrier										
	Biomass	Coal	Gas	Offshore Wind (AC)	Offshore Wind (DC)	Oil	Onshore Wind	Hydro	Solar	Battery	Hydrogen
Direct jobs (jobs/MW)	18.4	16.74	2.37	23.80	23.8	2.30	8.20	27.75	27.25	28.10	3.70
Manufacturing (% of direct jobs)	15.76	32.26	39.24	65.55	65.55	39.24	57.32	31.55	24.59	60.14	60.00
Construction and installation (% of direct jobs)	76.09	66.91	54.85	33.61	33.61	54.85	39.02	66.65	71.56	38.43	25.00
Operation and maintenance (% of direct jobs)	8.15	0.84	5.91	0.84	0.84	5.91	3.66	1.80	3.85	1.42	15.00

Source: Authors' compilation from sources [59–62].

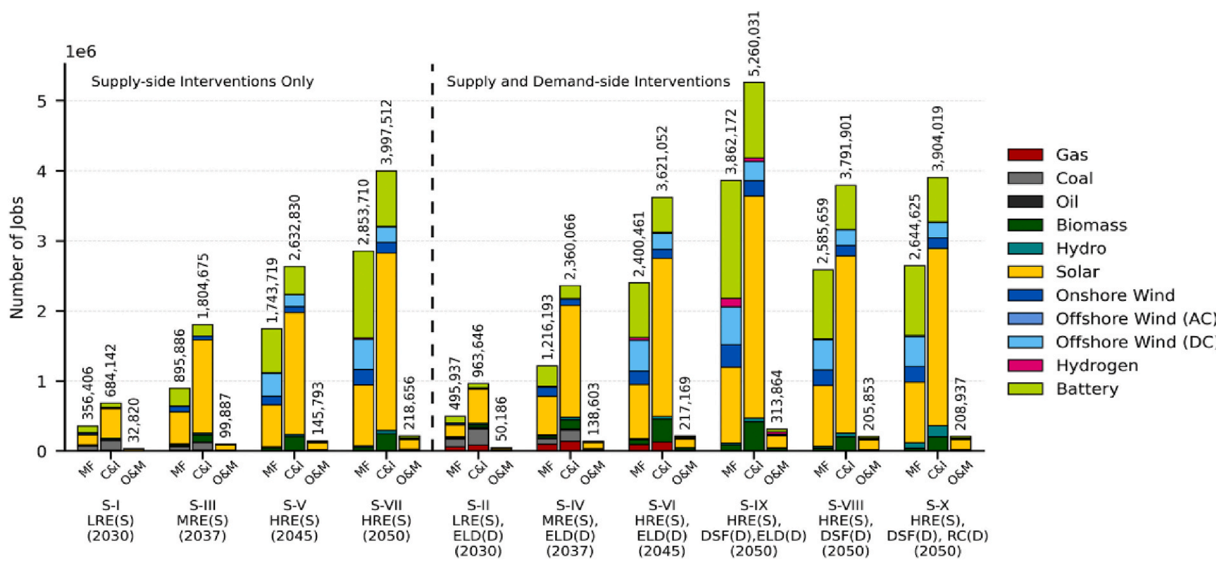

Fig. 8. Job creation potential in various scenarios with energy sector specific breakdown.

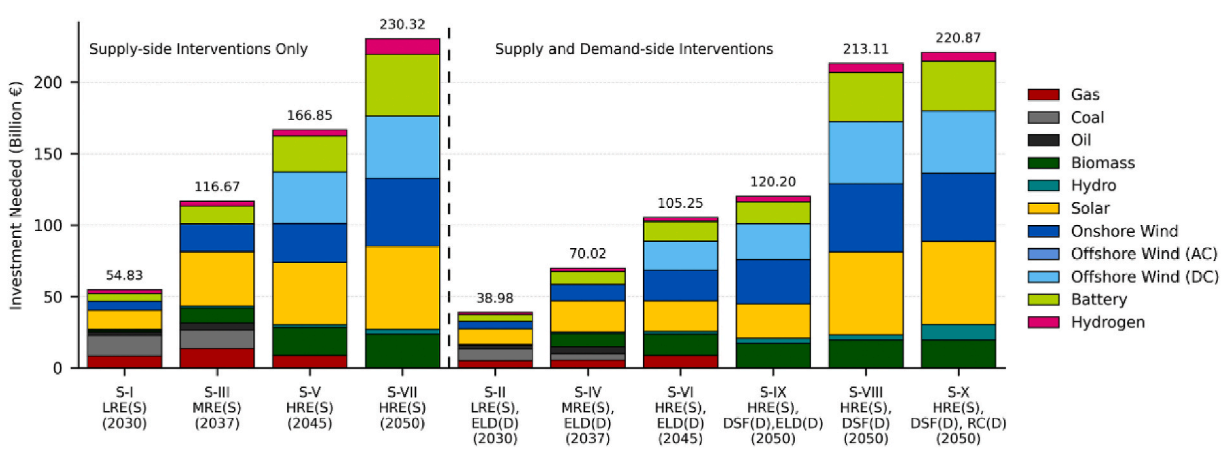

Fig. 9. Investment requirement across the scenarios: Model results.

investment requirements. In S-I (2030), solar capacity expansion necessitates €13.427 billion, which increases 4.34-fold to €58.206 billion in S-VII (2050), followed by onshore wind and offshore wind requiring €47.477 billion and €43.769 billion, respectively, in S-VII. However, demand-side interventions (EE and DSF) significantly help in moderating the financial mobilization need in supply capacity expansion. In S-IX, which incorporates both EE and DSF, the investment need for solar power is 1.91 times lower than in S-VII.

Battery storage represents another critical area of investment, with requirements increasing 7.97-fold from €5.395 billion in S-I to €42.979 billion in S-VII. Compared to the supply-side expansion only scenario (S-VII), demand-side interventions help moderate this growth, to 6.36-fold in S-VIII (with DSF) and 2.79-fold in S-IX (with EE), highlighting the cost-saving potential of demand-side measures in managing storage needs.

6.5. Power generation costs across scenarios

What matters for the social acceptance of any transition is the cost burden on the consumers. It does vary proportionately with the generation cost. Each of the scenario-specific optimum solutions of the transition pathway can be defined by costs per unit of generation, thereby making them comparable through cost-effectiveness criteria. This section analyzes the power generation costs (Fig. 10) for ten scenarios (S-I to S-X). Power generation costs (€/MWh) vary across scenarios depending on the scale of renewable integration on the supply side and if integrated with energy efficiency (EE) and demand-side flexibility (DSF). Costs with and without regional cooperation in power trade also matter.

With a high initial cost of renewable energy and lower integration in the generation mix, the power generation cost with supply-side expansion only scenario in the near term (2030) is higher €105.75/MWh (S-I). This is reduced by 20% when demand-side EE is integrated with RE penetration. As the capital cost of solar, wind, hydro, biomass, and storage technologies decline with time (2030–2050), as presented in Tables 7–9, increasing RE shares in the generation mix, do not lead to higher power generation cost and model-based optimal mix shows a generation cost of €70.33/MWh in scenario S-VII. The power generation cost further reduces with demand-side interventions (EE and DSF), resulting in €65.17/MWH, the lowest is in scenario S-IX. A 10% demand-side shift with 100% clean energy costs 68.02/MWh, while the regional cooperation through import of hydroelectricity reduces the price to €67.35/MWh.

The modeled power generation cost with integrated supply and demand-side intervention in the clean energy transition is €65.17/MWh (2.45 Baht/kWh), which is 1.72-fold less than the current residential tariff (4.22 Baht/kWh for over 250 kWh monthly consumption [65]), ensuring a more affordable electricity price in future.

6.6. Coal phase-out and fossil fuel phase-down

This subsection assesses the economic and operational consequences of phasing down/out of fossil fuel-based power plants in Thailand's electricity sector, as modeled by PyPSA-TH across scenarios S-I to S-X, aligning with the country's 2050 clean energy goals.

Fig. 6 indicates that coal plants are phased out of generation capacity after 2037 (S-VI). The model-based optimum installed capacity in 2037 is 15.28 GW (Fig. 5). It is to be noted that 6.7 GW is coming from 22 currently operational plants, of which 4.75 GW do not reach their technical retirement lifetime. However, plants with a capacity of 1.95 GW after 2037 reach the technical end of their life. The remaining 8.58 GW represents a model-based optimal additional capacity expansion requirement by 2037 due to the constraint imposed in the model on the RE capacity target of the country. In 2037, phasing out of 4.75 GW coal capacity require early retirement of plants with a remaining technical lifetime of 2–29 years. This is considered as stranded asset. We calculate the cost of this stranded asset at €1.96 billion (at 2019 capital cost value), and a projected loss of around 79,515 jobs, reflecting unrecovered investments and the economic trade-off of accelerating Thailand's shift to renewables by phasing out existing coal plants. If any new coal plant is built by 2037 in line with the modeled optimum capacity under RE constraints, which is 8.58 GW, then this is going to be additional stranded asset.

Likewise, if gas plants are required to cease power generation after 2045 to achieve a fossil-free system, 35.28 GW of capacity becomes stranded (Fig. 5). Of this, 28.94 GW are currently operational, and 6.34 GW are in the pipeline and included in the model results. Within the operational capacity, 9.97 GW becomes stranded with the remaining 1–5 years of technical life, while 18.96 GW reach their technical retirement age, giving rise to a stranded asset cost of €0.81 billion in 2045, along with a projected loss of approximately 23628 jobs. The total stranded asset cost for coal and gas is €2.77 billion, reflecting the financial risks of fossil fuel investments amid a rapid clean energy transition driven by national policies such as the LT-LEDS and global net-zero goals.

6.7. CO_2 emission pathways

The CO_2 emission pathways under ten scenarios, as modeled by PyPSA-TH, are presented in Fig. 11 vis-à-vis the 2019 frozen policy pathway. The future emission trajectories for Thailand under pledged and ambitious emission reduction scenarios illustrate how emissions are driven by shifting goals and strategies. Starting from a 2019 emission of 93.83 $MtCO_2$, (the reference scenario) continues to grow with no additional policy interventions and can increase 43.8% reaching 135.02 $MtCO_2$ by 2050, driven by a continued reliance on fossil fuels and a projected 2.4-fold rise in electricity demand.

In contrast, meeting the same demand through the modeled scenarios and pathways help in sharp decline in emissions relative to the reference scenario. However, in the near term, by 2030, emissions are marginally reduced by 1.87%, with more substantial reductions observed by 2037 (45.13%) due to greater RE penetration. A coal phase-out combined with 71% RE in the generation mix leads to a significant reduction by 2045, with emissions falling to 28.96 $MtCO_2$,76.3% below the reference level for that year.

However, more pronounced emission reduction is achieved both in the near term and throughout the transition pathway when regional power trade, demand-side interventions such as enhanced energy

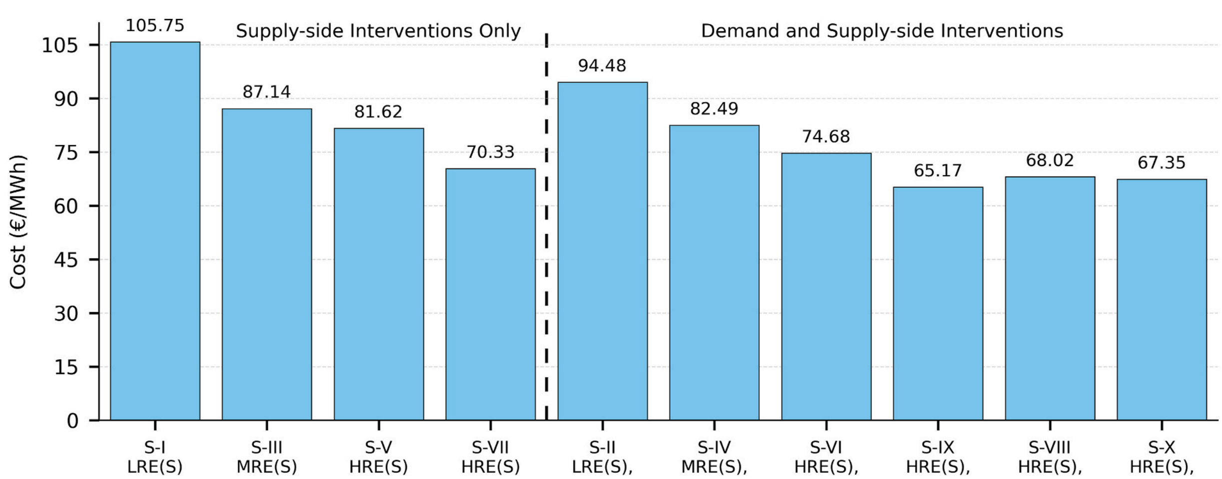

Fig. 10. Power generation cost across the scenarios: Model results.

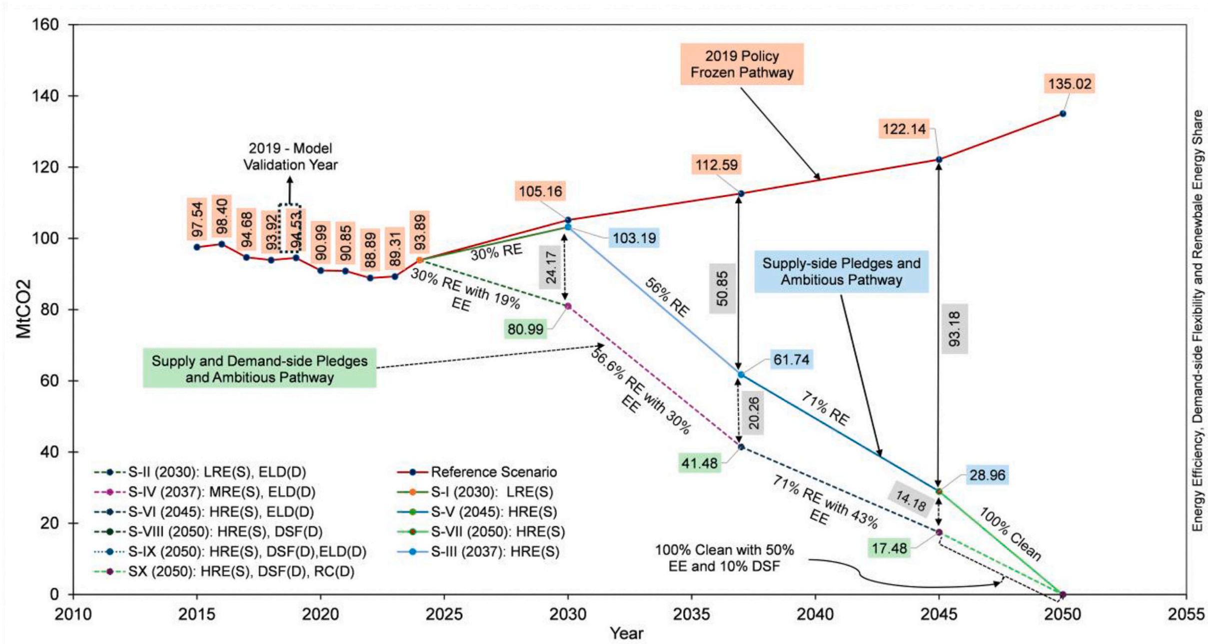

Fig. 11. Emissions pathways in pledged and higher ambition scenarios for Thailand.

efficiency (EE), and demand-side flexibility (DSF) are integrated with supply-side measures. Under this trajectory, emissions drop to 80.99 $MtCO_2$ in 2030 (22.3% below the reference), 41.48 $MtCO_2$ in 2037 (63.2% reduction), and 17.48 $MtCO_2$ in 2045 (85.7% reduction). These values represent 21.5%, 32.3%, and 39.6% additional reductions, respectively, compared to their supply-side-only counterparts, demonstrating the substantial contribution of demand-side measures. By 2050, both intervention pathways converge to zero emissions, indicating the technical feasibility of a fully decarbonized power sector.

The modeled results emphasize that achieving net-zero emissions by mid-century in Thailand is technically feasible and has multiple broad socio-economic benefits. While supply-side interventions are essential, the addition of demand-side strategies significantly accelerates decarbonization rate and at lower cost, providing evidence for implementation of the pledged policies and scope for higher ambition for enabling a low-carbon energy future.

6.8. Model inter-comparison of capacity expansion numbers

This section compares the PyPSA-TH model's power generation expansion numbers with existing literature (Table 2) on Thailand's clean energy transition by 2050. Table 9 shows that the PyPSA-TH model projects 523.5 TWh in S-VII (HRE, 2050), falling within the range of prior studies (410–620 TWh), supporting its validity. LEAP-NEMO in Ref. [19] estimates 577 TWh with 71% renewables and CCS, while AIM/CGE in Ref. [19] projects 440 TWh with 74% renewables, noting GDP losses due to high costs. AIM/End-use studies vary: one [22] reports 593 TWh with 65%–66% solar/wind and CCS; the second [23] shows 410 TWh, focusing on demand reduction and hydrogen; and in another study [24] ranges are between 580 and 620 TWh, emphasizing role for hydrogen and renewables (107 GW solar, 43 GW wind). Multi-period Linear Programming in Ref. [26] projects 515 TWh with PVBESS and hydrogen blending, and Switch in Ref. [32] estimates 441 TWh. PyPSA-TH's 523.5 TWh aligns with these, exceeding demand-focused studies [20] but below CCS-reliant studies [22,24], reflecting a practical balance for Thailand with high renewables (132.74 GW solar, 27.55 GW offshore wind in S-VII), DSF, and hydro imports, making it a credible tool for policy planning.

Table 9
Comparison of model-based power generation capacities for Thailand's 2050 clean energy transition.

REF	Model-Based Power Generation	Model Name	Target Year of Clean Energy Transition
[19]	577	LEAP NEMO	2050
[20]	440	AIM/CGE	2050
[22]	593	AIM/Enduse	2050
[24]	580 - 620 (Low and High Hydrogen)	AIM/Enduse	2050
[23]	410	AIM/Enduse	2050
[26]	515	Multi-period Linear Programming	250
[32]	441	Switch	2050
Proposed	523.5	PyPSA-TH	2050

Source: Authors' compilation

6.9. Policy implications and recommendations

Insights from the ten scenarios developed for Thailand power sector using the PyPSA-TH model strengthen the case for implementing the pledges and raising the ambition strategically in a phased manner for transitioning to a clean energy-based power sector. This shift as seen using evidence-based techno-economic feasibility analysis helps to understand need for financial mobilization to meet the targets in multiple policy documents. Given the long-term nature of power sector infrastructure and Thailand's commitment to a clean energy transition, strategic planning can help mitigate the risk of stranded assets, job losses, risk of rising injustice in transition, land use planning. The following are the key recommendations based on the modeling exercise:

Human Capacity Development: The rapid expansion of solar, offshore and onshore wind as well as biomass capacities highlights the need for capacity building in specific sectors for enhancing new skills, reskilling or upskilling of energy sector professionals for energy system integration, demand side and supply side intervention integration, grid expansion and management, and maintenance. Specialized training programs are critical to building a workforce adept at managing new technologies. Policies can prioritize targeted upskilling and reskilling initiatives, developing engineers and technicians proficient in solar, offshore wind, onshore wind, and energy storage systems. Educational institutions, in collaboration with industry leaders such as EGAT, PEA, MEA, and renewable energy developers, can offer technical courses tailored to these needs. Additionally, international collaborations, workshops, and training programs facilitate cross-border power trade and the mobility of skilled human capacity creating a regional human capability to help transition.

Institutional Coordination: Strong institutional coordination is crucial for managing land-use conflicts, streamlining project approvals, and ensuring inter-ministerial collaboration. A dedicated transition management task force, modeled after successful examples such as the Greater Mekong Subregion's energy initiatives [66] or Scotland's Just Transition Commission [67], could serve as a starting point.

Financial Framework: The transition's success hinges on a robust financial framework to de-risk investments to mobilize anything around €230.32 billion or less over a period of two and half decades. Securing green finance for large-scale projects and enhancing the bankability of renewable energy initiatives are paramount. The investment can be attracted by promoting Thailand's existing Feed-in Tariffs (FiT), Direct Power Purchase Agreements (PPAs), and green bonds policies [68] along with providing more grants and subsidies (like China and Germany [64] and Public-Private Partnerships (PPP) projects, which is successful in the US and EU [69].

Enabling Ecosystem for Renewable Integration: To support large-scale renewable energy integration, an enabling ecosystem comprising smart grids, system flexibility mechanisms, and storage technologies is essential [70]. Smart grids enable dynamic monitoring, automation, and control of electricity flows, which are critical in managing the variability and uncertainty of solar and wind generation. Flexibility measures such as demand-side response and flexible gas generation improve the system's ability to adapt to fluctuating supply and demand. Additionally, storage systems, including short-duration battery energy storage systems (BESS) and long-duration options like pumped hydro energy storage (PHES), play a pivotal role in absorbing excess renewable generation, reducing curtailment, and enhancing grid reliability [71]. The integration of these technologies ensures a more resilient and efficient power system, capable of supporting Thailand's long-term decarbonization targets.

Land-Use Management: To mitigate land-use conflicts, especially with solar requiring up to 2595.2 km^2 (0.50% of total land area) in S-VII, policies should incentivize rooftop solar installations in urban areas like Bangkok (served by MEA) and promote after feasibility studies of Agrivoltaic systems integrating agriculture and solar generation as successes found in China, France, Italy, South Korea and India [72]. Utilizing underutilized or degraded lands, estimated at 12,351 km^2 available in 2018, could support renewable projects while preserving arable land. Inter-ministerial coordination among the Ministry of Energy, the Ministry of Agriculture, and local governments is vital to align land-use policies with renewable energy expansion requirements. Geographic Information System (GIS) mapping should be utilized to generate detailed spatial data on land use, solar potential, and land availability, which can guide strategic solar deployment by locating optimal sites and minimizing competing demand for resources. Transparent stakeholder dialogue can balance environmental, economic, and social priorities, ensuring sustainable land allocation.

Focus on Hydrogen Storage Development: Considering Thailand's strong solar and offshore wind potential, and to enhance grid flexibility and support higher RE integration, Thailand can prioritize the development of green hydrogen storage systems recommended upon the modeled 6 GW hydrogen storage capacity and global trends of hydrogen fuel utilization in terms of market growth and technological innovation [73]. Lessons from Japan's hydrogen strategy [74] could guide Thailand in establishing the potential roadmap and scope for regional cooperation.

Strengthening Cybersecurity: As the power sector continues to digitize and decentralize, cybersecurity becomes a national priority. Recent outages in Europe [75] highlight systemic vulnerabilities. In Thailand, the National Cybersecurity Agency (NCSA) collaborates with EGAT to prevent cybersecurity threats in the energy sector. Strategic partnerships with global technology leaders and institutions such as the Office of Cybersecurity, Energy Security, and Emergency Response (CESER) in the USA [76] and the European Cyber Security Organization (ECSO) [77] can help in in knowledge transfer. Moreover, upskilling the energy workforce in cybersecurity is essential to ensure operational resilience and safeguard public trust during the energy transition.

6.10. Study limitations

Like any other research endeavor, this paper solves some specific research questions but also give rise to many others. This research offers novel and important insights into Thailand's transition to a clean and sustainable energy system using the PyPSA-TH model. Within the scope of this paper, it solves critical issues such as capacity expansion path and broad socio-economic effects. The following limitations highlight opportunities for future research, scope to enhance the modelling framework and applicability.

- **Storage technology:** The present model includes only battery and hydrogen storage technologies. Other storage options, such as Pumped-Hydro Energy Storage (PHES), Liquefied-Air Energy Storage (LAES), Compressed-Air Energy Storage (CAES), Thermal Energy Storage (TES), and Flywheel Energy Storage, are excluded. Future studies can assess their techno-economic feasibility to broaden scope of storage options.
- **Carbon removal technology:** The current model does not incorporate within its scope advanced or emerging technologies such as Carbon Capture and Storage (CCS), Carbon Capture, Utilization and Storage (CCUS), or cofiring technologies like with hydrogen or ammonia cofiring. As these technologies mature more, they will eventually become relevant in decarbonization strategies for Thailand although they are right now not in official action plans and pledges.
- **Sector-Specific Load Data:** The model relies on total hourly load data, but lacks breakdown for industrial, residential, and transport sectors due to data access limitation. Incorporating detailed sectoral load profiles would enable precise demand-side management modeling and sector coupling analysis, which can improve scenarios such as S-VIII (10% DSF). This could refine load-shifting potential and capacity expansion plans, offering deeper insights into structural energy shifts.
- **Demand-Side Flexibility (DSF):** While S-VIII incorporates a 10% DSF shift, reducing storage needs, broader DSF and sector coupling remain underexplored. In high renewable penetration scenarios (S-VII to S-X), IoT-enabled DSF strategies could optimize real-time load management, complementing storage systems. Future research can integrate these approaches to balance supply and demand dynamics more effectively.
- **Socio-Political-Economic Analysis of transition pathways:** The study attempts to quantify job creation but leaves room for further refinement to understand the quality of jobs, economy wide and sector specific analysis such as what kind of jobs will be lost, and how that can be compensated (in cases of coal and fossil fuel phase out). Different methods can be applied to understand economy-wide impacts with up-to-date disaggregated input-output tables. A detailed examination of workforce retraining, equitable job distribution, and micro-and macroeconomic impacts, especially with the phase-out of fossil fuels, is critical to delivering justice in the transition process. Future research can address these gaps to inform policies for a just transition.

7. Conclusions

This study presents PyPSA-TH, a customized open-source model designed to explore Thailand's electricity sector transition. Through ten strategic scenarios incorporating supply and demand-side interventions, augmented by supply-side capacity expansion, energy efficiency, demand-side flexibility and regional cooperation, the model derives evidence-based pathways for Thailand's 100% clean power sector transition. Power sector is currently dominated by fossil fuels. The findings underscore the technical and economic feasibility of achieving a 100% clean energy system by 2050, with solar emerging as the backbone, complemented by onshore wind, offshore wind, biomass, and storage facilities by mid-century. In the transition process, existing gas capacities in the near term play a crucial role, even though new capacities are not being added.

Modeled clean energy transition in Thailand promises transformative socio-economic benefits, although it demands strategic foresight and planning exercises. Scaling up supply-side capacity from 107.67 GW in 2030 (S-I) to 353.89 GW by 2050 (S-X) requires substantial investment, peaking at €230.31 billion in a high renewable scenario (S-VII). However, integrating demand-side measures such as energy efficiency and intraday load shifting can slash this cost by up to 48%, easing financial pressures on energy supply sector. Yet, as Akimoto et al. [78] highlight, the feasibility of such transitions can be impacted by hidden costs, particularly those associated with grid integration of variable RE sources like solar and wind, which may necessitate further adjustments in infrastructure planning. The transition also sparks significant job growth, reaching 9.43 million new jobs by 2050 (S-IX), with solar and battery storage leading the charge. Phasing out fossil fuels—coal by 2045 (S-V) and gas by 2050 (S-VII)—is assessed to impose a burden of €2.77 billion in the form of stranded asset costs, underscoring the need for careful planning in near term. Land requirement of maximum 5612.87 km^2 (S-VII), fits within Thailand's 12,351 km^2 of available unused land. However, given solar PV's dominant role, spatial constraints can be eased through solutions such as rooftop, floating, and agri-voltaic systems. The transition to clean energy also yields co-benefits, as reported in similar studies [47,79], including enhanced air quality, reduced health impacts from air pollution-related diseases, a decrease in fuel import expenditures, improved well-being, and increased resource efficiency.

To enable this ambitious shift over the next two and a half decades, a clear policy signal is required to build confidence among investors. Human capacity development is critical to support the technical demands of solar, offshore wind, and storage integration, requiring targeted upskilling programs (in sectors like construction, manufacturing, mining and extraction, wholesale trade, distribution, and transport, professional and business services [80]) and international collaboration. Strong institutional coordination, potentially through a dedicated task force, is essential to streamline approvals and manage land-use conflicts, while a robust financial framework, leveraging green bonds and Power Purchase Agreements (PPAs), can de-risk the investment needed. Policy in securing the critical minerals required in solar panel and battery storage manufacturing also require special attention.

PyPSA-TH demonstrates that Thailand, with a relative quite small current coal capacity, can achieve a clean energy transition in the power sector by 2050 through strategic supply side clean technology deployment integrated with EE, DSF, and regional cooperation. This transition, considering both supply and demand-side contributions, promises significant socio-economic benefits such as lower generation costs, substantial employment creation, and sustainable land use. As an open-source tool, PyPSA-TH invites global collaboration to refine its insights, offering a replicable model for developing nations navigating the complex interplay of energy, social, economic, and environmental goals in the pursuit of a net-zero future. Future work can extend the model to explore pathways for achieving Thailand's net-zero emissions target by 2065, incorporating strategies such as sector coupling, carbon capture, and scaling up green hydrogen production. Additionally, enhancing connectivity with the Association of Southeast Asian Nations (ASEAN) through regional power grid integration and cross-border clean energy trade, as envisioned in initiatives like the ASEAN Power Grid and explored in the studies by S. Endo et al., H. Phoumin et al., and K. Handayani et al. [81–83] will strengthen national and regional energy security and resilience.

CRediT authorship contribution statement

Firuz Ahamed Nahid: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Joyashree Roy:** Conceptualization, Formal Analysis, Funding acquisition, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Weerakorn Ongsakul:** Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix-A

8 Model Overview

The model uses linear optimization to minimize total annualized system costs, ensuring both supply-demand equilibrium and the operational reliability of the power network. Mathematical formulations and constraints are adapted from published sources [7,18,84].

8.1 Objective Function

The objective function is designed to minimize the total annual system cost (AC), encompassing capital investment (CAPEX) and operational expenditures (OPEX) related to generation, storage, and transmission infrastructure. This is mathematically represented in Equation (A.1), as adapted from Ref. [3]:

$$\min_{F_\ell, G_{n,r}, H_{n,s}, E_{n,s}, f_{\ell,t}, g_{n,r,t}, h_{n,s,t}, suc_{n,r,t}, sdc_{n,r,t}} \left[\sum_l C_\ell . F_\ell + \sum_{n,r} C_{n,r} . G_{n,r} + \sum_{n,r,t} \left(w_t . o_{n,r} . g_{n,r,t} + suc_{n,r,t} + sdc_{n,r,t} + \sum_{n,s} C_{n,s} . H_{n,s} + \sum_{n,r} \widehat{C}_{n,s} . E_{n,s} + \sum_{n,r,t} w_t . o_{n,s} . \left[h_{n,s,t}\right]^+ \right. \right] \quad (A.1)$$

Where F_ℓ defines the transmission capacity limit for each branch ℓ, with C_ℓ indicating the annualized capital cost per unit of that capacity, establishing the financial framework for expanding the grid. Meanwhile, $G_{n,r}$ represents the installed power generation capability of technology r at bus n, with $C_{n,r}$ as the annualized investment cost per unit, outlining the expense of building new generation infrastructure. The operational output of generator r at bus n during time step t is captured by $g_{n,r,t}$ paired with $o_{n,r}$ as the per-unit variable operating cost, and weighted by wt, a factor that adjusts for the temporal importance of each period, collectively determining the ongoing operational costs. Costs associated with starting up ($suc_{n,r,t}$) and shutting down ($sdc_{n,r,t}$) generation units are aggregated across all buses, technologies, and time steps, reflecting the expenses tied to cycling power production. On the storage front, $H_{n,s}$ and $E_{n,s}$ denotes the power output and energy storage capacities of technology s at bus n, with $C_{n,s}$ and $C_{n,s}$ as their respective annualized capital costs, setting the investment needed for storage solutions. The storage discharge at time t, marked by $H_{n,s}$ incurs a variable cost $o_{n,s}$ only during positive dispatch ($[h_{n,s,t}]^+$), which highlights the cost of releasing stored energy. In essence, this objective function aims to minimize the total of these diverse costs, effectively guiding the strategic expansion of capacity and operational dispatch across branches, technologies, storage units, buses, and time intervals to support Thailand's shift toward a sustainable energy future.

8.2 Demand-Supply Equilibrium Constraint

At each time step t, the electricity demand $d_{n,t}$ at bus n must be satisfied through local generation, storage discharge, or power transferred via network connections. This balance is represented in Equation (A.2).

$$\sum_r g_{n,r,t} + \sum_s h_{n,s,t} + \sum_\ell \alpha_{\ell,n,t} . F_{\ell,t} = d_{n,t} \leftrightarrow w_t . \lambda_{n,t} \ \forall n, t \quad (A.2)$$

Here, $\sum_r g_{n,r,t}$ represents the total power generated at bus n from all generation technologies r at time t, reflecting the aggregate output from local power sources. The term $\sum_s h_{n,s,t}$ indicates the net power contribution from all storage technologies s at bus n during time t, encompassing both charging and discharging activities. The expression $\sum_\ell \alpha_{\ell,n,t} . F_{\ell,t}$ calculates the net power inflow or outflow at bus n from all branches ℓ at time t, where the flow is adjusted by the network topology. On the demand-side, $d_{n,t}$ denotes the electricity consumption required at bus n at time t, setting the target that must be met. The term $w_t . \lambda_{n,t}$ introduces a weighted marginal price at bus n during time t, with w_t as a time-weighting factor and $\lambda_{n,t}$ as the marginal price, accounting for the economic value or cost of balancing supply and demand. Additionally, $\alpha_{\ell,n,t}$ is an element of the incidence matrix, equal to -1 if branch ℓ starts at bus n, $+1$ if it ends at bus n, or 0 otherwise, defining the connectivity of the network. The parameter $\eta_{\ell,t}$ represents the efficiency loss for branch ℓ, which may vary with time based on factors like outside temperature (e.g., for a heat pump), influencing transmission effectiveness. Together, these terms ensure a robust equilibrium between supply and demand across all buses and time steps in the model.

8.2.1 Storage Constraint: Energy Balance and Capacity Limit. The energy levels $e_{n,s,t}$ of each storage unit must follow a consistent temporal trajectory and remain within its designated energy capacity $E_{n,s}$. The storage energy balance is defined in Equation (A.3), while the storage capacity constraint is outlined in Equation (A.4).

$$e_{n,s,t} = \eta_{n,s,0} \ e_{n,s,t-1} + \eta_{n,s,+} \cdot w_t \left[h_{n,s,t}\right]^+ - \eta_{n,s,-} \cdot w_t \left[h_{n,s,t}\right]^- + w_t \cdot h_{n,s,t,inflow} - w_t \cdot h_{n,s,t,spillage} \quad (A.3)$$

$$\widetilde{e}_{n,s,t} \cdot E_{n,s} \le e_{n,s,t} \le \bar{e}_{n,s,t} \cdot E_{n,s} \quad \forall n, s, t \quad (A.4)$$

Here, $\eta_{n,s,0}$ defines the self-discharge or standing loss rate of the storage unit for technology r at bus n, representing the natural energy leakage over time. The parameter $\eta_{n,s,+}$ indicates the efficiency of charging for the storage unit, while $\eta_{n,s,-}$ reflects the efficiency during discharge, capturing the energy losses in each process. Additionally, $h_{n,s,t,inflow}$ accounts for external energy inputs into the storage system, such as natural water inflows into a hydro reservoir, and $h_{n,s,t,spillage}$ represents any surplus energy that must be discarded or spilled when storage exceeds capacity. The state of charge is constrained by $\widetilde{e}_{n,s,t}$, the lower bound typically set to 0 to avoid negative energy levels, and $\bar{e}_{n,s,t}$, the upper bound usually set to 1 to ensure the stored energy stays within the unit's rated capacity.

8.3 Power Flow Constraints

Kirchhoff's Current Law (KCL), represented in Equation (A.5) [7], ensures energy conservation by requiring that the net power flow into and out of each node (bus) is zero. Meanwhile, Kirchhoff's Voltage Law (KVL), shown in Equation (A.6) [18], enforces the physical consistency of power flows by mandating that the total voltage drop around any closed loop in the network equals zero.

$$\sum_r g_{n,r,t} + \sum_s h^+_{n,s,t} + \sum_s h^-_{n,s,t} + \sum_\ell \alpha_{\ell,n,t} . F_{\ell,t} = d_{n,t} \quad \forall n, t \quad (A.5)$$

$$\sum_\ell C_{\ell,c} \cdot x_\ell \cdot f_{\ell,t} = 0 \ \forall_{c,t} \quad (A.6)$$

The term $\sum_r g_{n,r,t}$ captures the combined electricity output at bus n from all generation technologies r during time t, reflecting the total power produced at that node. Meanwhile, $\sum_s h^+_{n,s,t}$ represents the aggregate energy being charged into storage units at bus n across all storage technologies s at time t, whereas $\sum_s h^-_{n,s,t}$ accounts for the total energy discharged from storage at the same bus and time, detailing the storage dynamics. The expression $\sum_\ell \alpha_{\ell,n,t} . F_{\ell,t}$ calculates the net power flow entering bus n from all connected branches at time t, illustrating the transmission contributions. On the demand-side, $d_{n,t}$ signifies the electricity consumption at bus n during time t, setting the benchmark for energy requirements. Additionally, $\sum_\ell C_{\ell,c}$ sums up specific parameters across all branches ℓ that belong to a cycle c within the network topology, providing a structural overview of the grid. The parameter x_ℓ denotes the series inductive reactance of branch ℓ, which influences the electrical behavior of the line, while $f_{\ell,t}$ indicates the power flow through branch ℓ at time t, tracking the movement of electricity across the network.

8.3.1 Generator Capacity Constraints. The generator capacity constraint limits each unit's power output to its maximum installed capacity. This relationship is mathematically defined in Equation (A.7).

$$0 \leq g_{n,r,t} \leq G_{n,r} \quad \forall_{n,r,t} \tag{A.7}$$

Where, $g_{n,r,t}$ represents the power output of the generator at bus n for all technologies r at time t, and $G_{n,r}$ represents the installed capacity of the generator at bus n for all technologies r at time t.

8.3.2 Storage Charging Constraint. This constraint ensures that the charging and discharging power for each storage technology at every bus remains within the allowable maximum limits. The respective conditions are expressed through Equation (A.8) and (A.9).

$$0 \leq h^{+}_{n,s,t} \leq H_{n,s} \quad \forall_{n,s,t} \tag{A.8}$$

$$0 \leq h^{-}_{n,s,t} \leq H_{n,s} \quad \forall_{n,s,t} \tag{A.9}$$

Where the term $h^{+}_{n,s,t}$ represents the charging power of storage technology s at bus n at time t, while $h^{-}_{n,s,t}$ denotes the discharging power of the same storage technology at the same bus and time. These terms distinguish between the two directions of energy flow in storage systems. The variable $H_{n,s}$ defines the maximum discharging capacity of storage technology s installed at bus n, which serves as an upper limit to ensure that the discharging rate does not exceed the physical capabilities of the storage system.

8.3.3 Energy Storage Constraints. The storage energy constraint guarantees that the energy stored at each bus remains within the defined capacity limits. This condition is formulated in Equation (A.10).

$$0 \leq e_{n,s,t} \leq E_{n,r} \quad \forall_{n,s,t} \tag{A.10}$$

Where the variable $e_{n,s,t}$ represents the stored energy of storage technology s at bus n at time t, indicating the state of charge of the storage unit at that specific point in time. The parameter $E_{n,r}$ denotes the maximum energy capacity of the storage technology s at bus n, which serves as the upper limit for how much energy can be stored in the system.

8.3.4 Power Flow Limits. This constraint represented by equation (A.11) ensures that the power flow $f_{\ell,t}$ through each branch ℓ at a given time t doesn't surpass its maximum allowable capacity f^{max}_{ℓ}.

$$-f^{max}_{\ell} \leq f_{\ell,t} \leq f^{max}_{\ell} \quad \forall \ell, t \tag{A.11}$$

8.3.5 Recovering Cyclic Energy Storage Constraint. This constraint requires that the stored energy levels at the end of the optimization horizon match their initial values, ensuring continuity over the modeled period, presented by equation A.12

$$z_{n,s,T} = z_{n,s,0} \quad \forall n, s \tag{A.12}$$

Where, T is the final time and $z_{n,s,0}$ is the initial stored energy.

8.3.6 Greenhouse Gas Reduction Constraint. This constraint limits the total greenhouse gas emissions to remain below a predefined target, as expressed in equation (A.13) [18].

$$\sum_{n,rt} Km_{n,r} \cdot g_{n,r,t} \leq EM^{max} \tag{A.13}$$

Where, $Km_{n,r}$ represents the emission factor for generation technology r at the bus *n, and* EM^{max} is the maximum allowable emissions.

Appendix-B

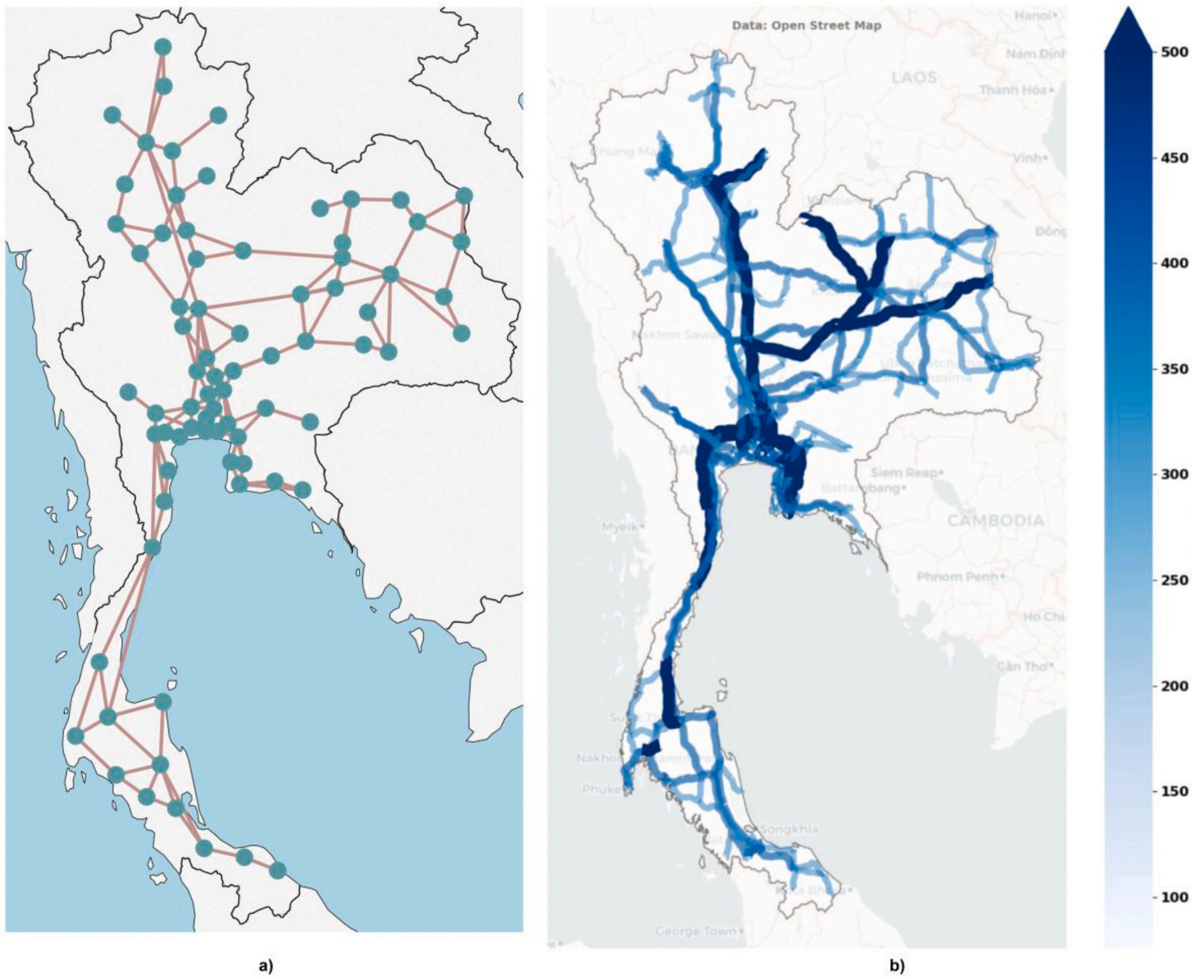

Fig. B1. a) Regions or load points of PyPSA-TH Model b) Transmission line map generated by PyPSA-TH

Table B1
Cost assumptions across the scenario years (2019–2050)

Year	Carrier	Coal	Oil	Gas	Solar	Onshore Wind	Offshore Wind	Biomass	Hydro	Hydrogen	Battery
	Operational Lifetime (years)	30	25	35	30	30	30	25	50	30	10
2019	Capital Expenditure (€/kW)	1183.74	748.86	820.5857	869.111	1401.792	2943.763	1671.225	1124.72	2162.492	624.7039
	Fixed O&M (% of capital cost)	3.52	3.5	2.5	1.67	2.8	2.22	2.77	2.5	5.97	0.11
	Variable O&M (€/MWh)	3.18	1.93	5.27	0.01	1.02	1.7	1.7	1.5		
2030	Capital Expenditure (€/kW)	1183.07	747.62	820.59	616.79	1196.2	2009.24	1537.53	903.53	1364.71	984.52
	Fixed O&M (% of capital cost)	3.51	3.74	2.5	1.52	2.81	1.95	42.52	2.65	5.97	0.11
	Variable O&M (€/MWh)	3.18	1.93	5.27	0.01	1.02	1.7	1.7	1.5		
2037	Capital Expenditure (€/kW)	1652.443	896.03	1146.885	490.625	1056.018	1693.835	1387.118	1196.03	1252.836	845.696
	Fixed O&M (% of capital cost)	3.52	0.99	2.5	1.58	2.71	2.1	2.77	2.72	5.97	0.11
	Variable O&M (€/MWh)	3.18	1.93	5.27	0.01	1.02	1.7	1.7	1.5		
2045	Capital Expenditure (€/kW)	1402.111	816.878	972.861	557.913	1130.782	1862.051	1467.338	1040.03	1124.98	687.04
	Fixed O&M (% of capital cost)	3.52	1	2.48	1.67	2.59	2.29	2.77	2.77	5.97	0.11
	Variable O&M (€/MWh)	3.18	1.93	5.27	0.01	1.02	1.7	1.7	1.5		
2050	Capital Expenditure (€/kW)	1808.907	954.5	1255.65	448.57	1009.29	1588.7	1336.98	1293.53	1045.07	587.88
	Fixed O&M (% of capital cost)	3.52	0.99	2.5	1.67	2.59	2.29	2.77	2.77	5.97	0.11
	Variable O&M (€/MWh)	3.18	1.93	5.27	0.01	1.02	1.7	1.7	1.5		

Note: The conversion rate used is 1 THB ~ 0.027 Euro [Dated May 18, 2025 [85]. 2019 Average rate is ~0.028 [86].
Source: Author compilation from sources in reference [47,48].

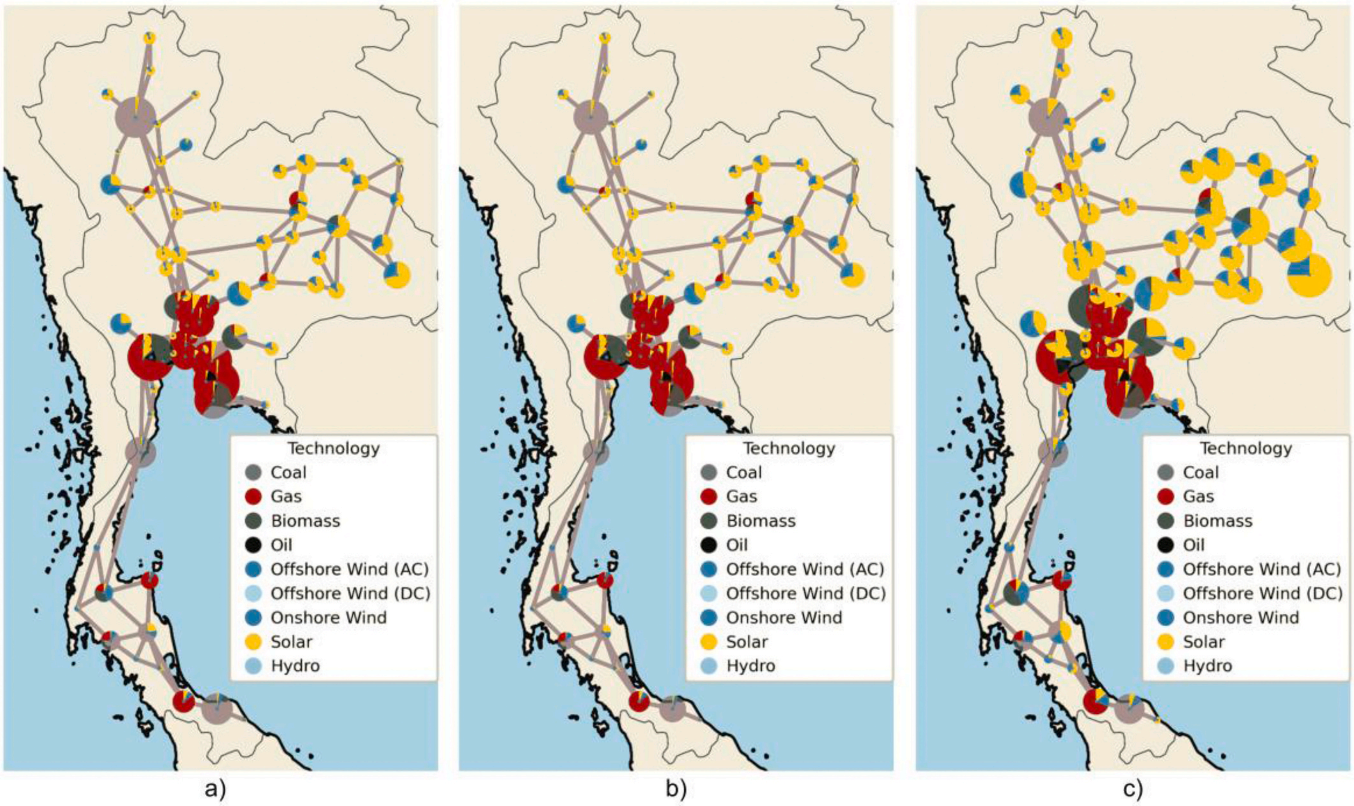

Fig. B2. Spatial distribution of installed capacity across the country: a) Scenario I, b) Scenario II and c) Scenario III

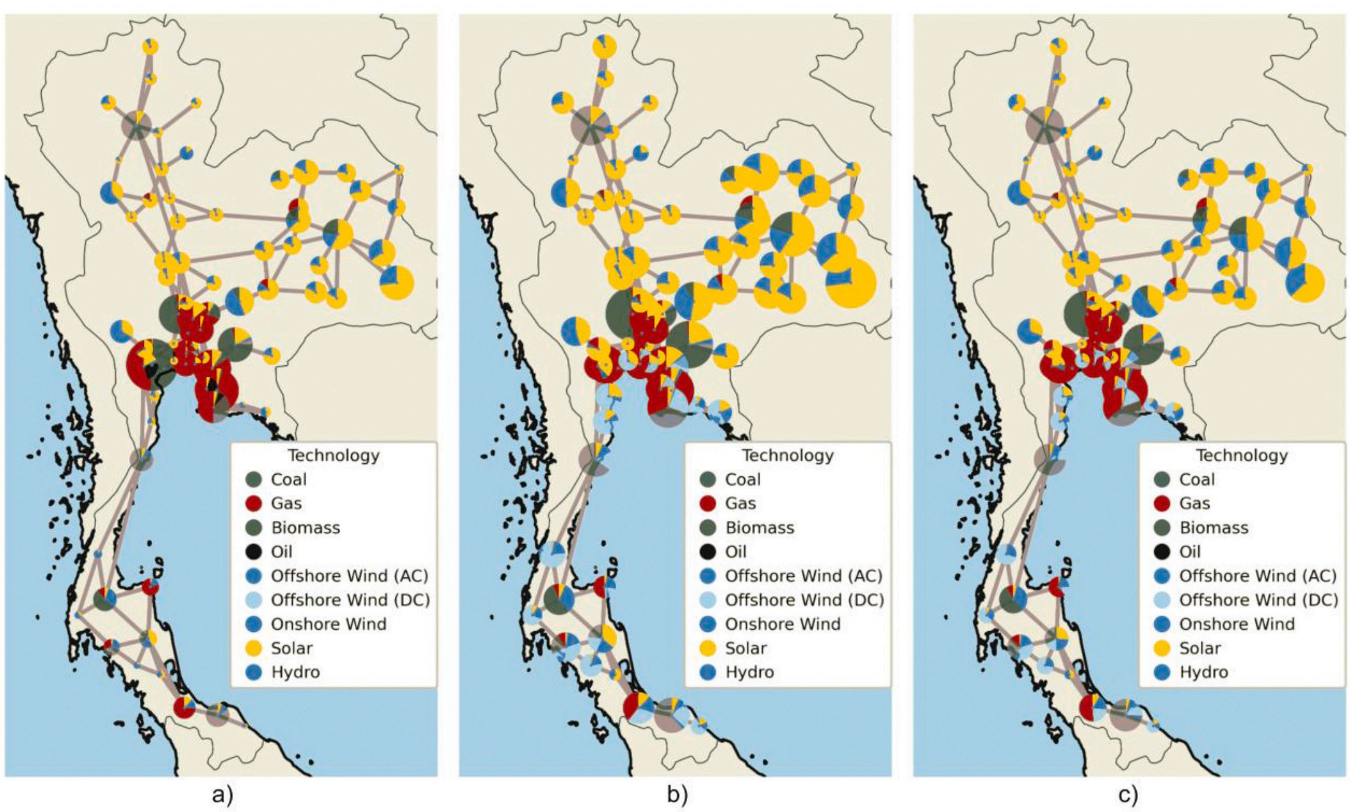

Fig. B3. Spatial distribution of installed capacity across the country: a) Scenario IV, b) Scenario V and c) Scenario VI

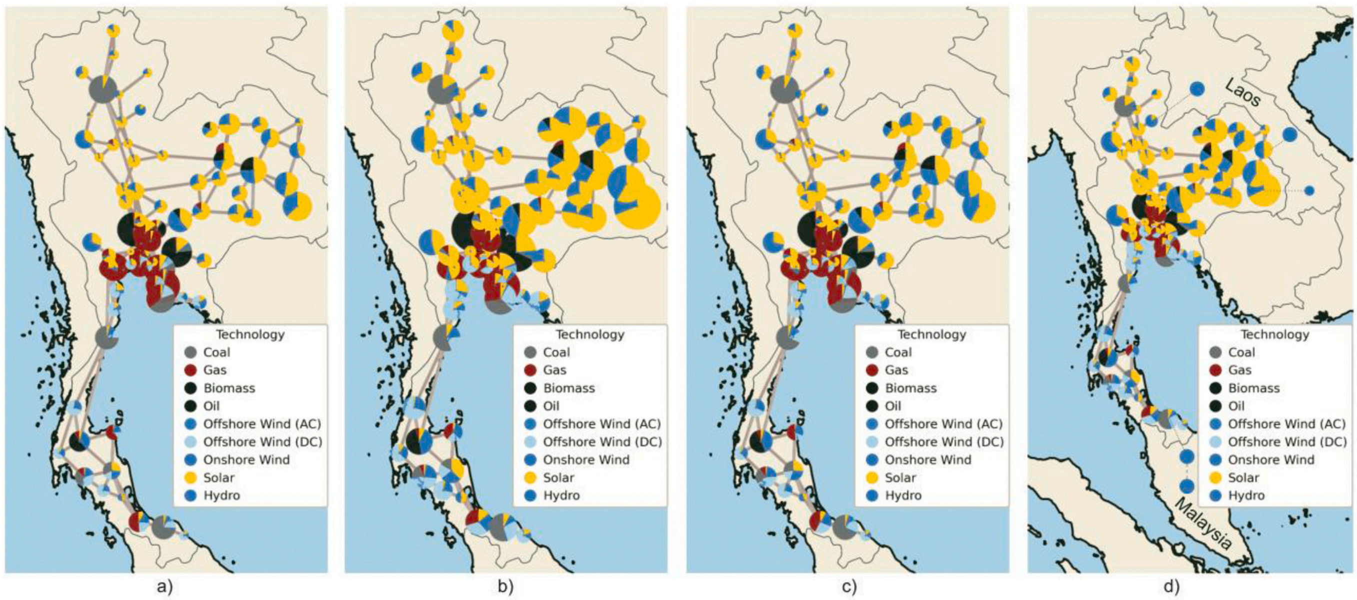

Fig. B4. Spatial distribution of installed capacity across the country: a) Scenario VII, b) Scenario VIII, c) Scenario IX, and d) Scenario X

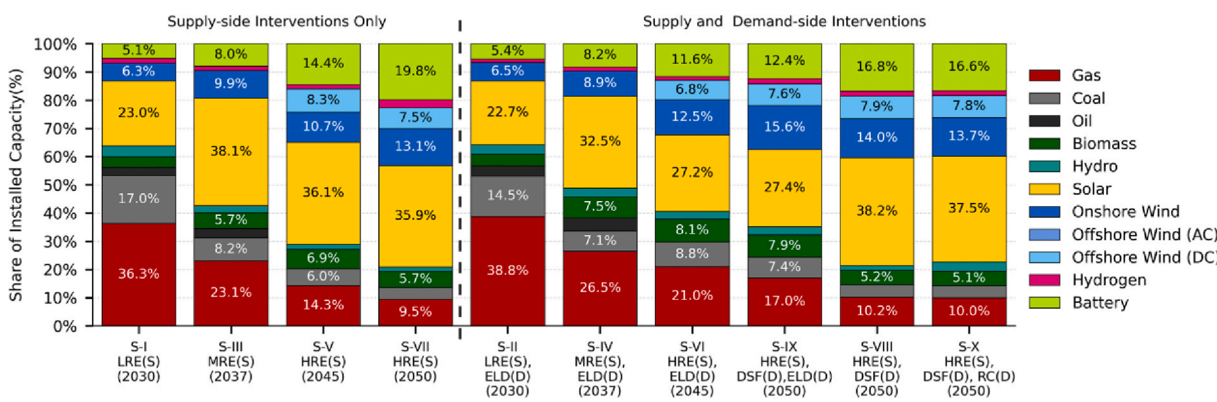

Fig. B5. Share of fuel types in the installed capacity requirement across the modeled scenarios

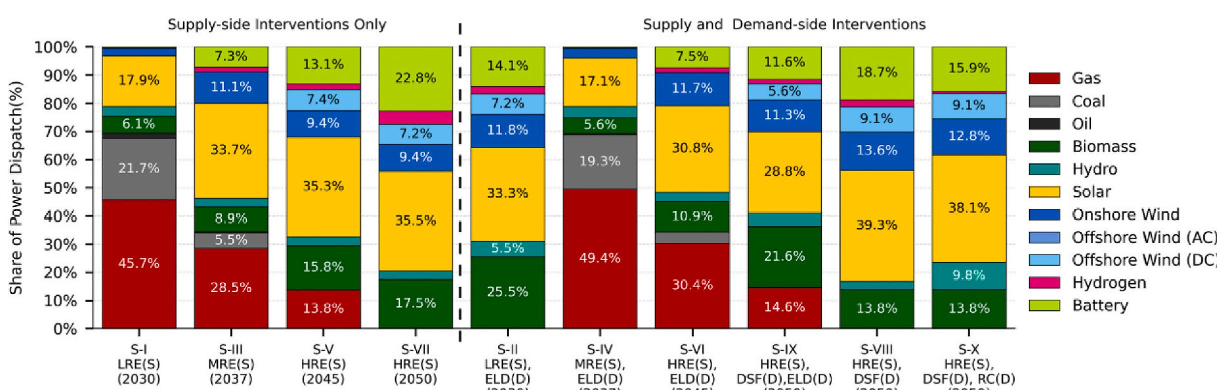

Fig. B6. Share of power dispatch across the modeled scenarios

Data availability

The data and code are availavle at https://github.com/FiruzAhamed/PyPSA-TH.

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