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Rethinking Thailand’s energy future: strategies for sustainable renewable solutions using the hybrid optimisation of multiple energy resources (HOMER) modelling approach

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Abstract

Purpose – This study aims to develop a sustainable renewable energy strategy for Nakhon Ratchasima (KORAT), Thailand, in response to growing energy demands driven by rapid population growth and industrialisation. The research explores the optimal mix of renewable energy sources to maximise energy efficiency and sustainability in the region.

Design/methodology/approach – The hybrid optimisation of multiple energy resources (HOMER) Software was employed to simulate a microgrid system tailored for KORAT. The model integrated local demand profiles and climatic data to evaluate the performance and cost-effectiveness of various renewable energy technologies, including solar, hydropower, wind and energy storage systems.

Findings – Simulation results indicated that solar power systems are the most effective and cost-efficient renewable option for the region, closely followed by hydropower systems. Wind power demonstrated lower performance and economic viability due to local wind speeds falling below the cut-in speed of the selected turbines. Similarly, battery storage did not significantly enhance the renewable energy fraction due to limited surplus energy, indicating lower cost-effectiveness.

Research limitations/implications – This study is limited to a single province – Nakhon Ratchasima – which may not fully represent the diverse geographic and climatic conditions across Thailand. Despite these limitations, the findings offer a replicable framework for regional energy planning and highlight the importance of site-specific data in designing cost-effective hybrid renewable systems for Thailand and similar developing regions.

Practical implications – This study provides a practical framework for designing region-specific hybrid renewable energy systems using real-world data and HOMER software. The findings support policymakers, utility providers and investors in making informed decisions about energy planning in Thailand.

Social implications – The transition to hybrid renewable energy systems in Thailand, as demonstrated in this study, can significantly improve energy access, affordability and reliability for local communities. Reducing

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dependence on fossil fuels helps lower greenhouse gas emissions and air pollution, contributing to better public health outcomes.

Originality/value – This study presents the first HOMER-based microgrid simulation specifically focused on KORAT, providing a replicable framework for integrating renewable energy in similar regions across Thailand. It contributes valuable insights for policymakers and energy planners aiming to advance renewable energy adoption through evidence-based system design.

Keywords HOMER, Thailand, Sustainable, Renewable energy, Hybrid, Energy generation systems

Paper type Research article

1. Introduction

The world is experiencing rapid population growth and industrialisation, contributing to the increasing global energy demand. Accordingly, energy security and environmental concerns are now being considered within the energy sector, with renewable energy systems becoming an alternative source of electricity generation in many countries. Thailand was chosen as the study area as a developing country due to its fast-growing economy, energy demand, and fossil fuel imports (International Energy Agency, 2019). Thailand also heavily depends on natural gas, coal, and lignite (Thepsaskul *et al.*, 2025). However, the situation has changed since the Ministry of Energy introduced a Power Development Plan (PDP) in 2018 to promote energy efficiency and security, decrease the proportion of coal in the electricity generation process, and forecast (Kiatfuengfoo, 2020). The updated PDP in 2020 set a goal of an overall power capacity of 56,431 MW, of which 18,833 MW was from renewable energy resources (Ministry of Energy Thailand, 2020a). Thailand generated renewable energy in 2018 from different resources, ranging from solar power (26%) and hydropower (26%), mini-hydro power (2%), biomass (30%), biogas (4%), Waste to Energy (3%) (Ministry of Energy Thailand, 2020a, 2020b). In 2015, all United Nations members adopted the 2030 Agenda for Sustainable Development, which outlines 17 Sustainable Development Goals – SDGs (United Nations, 2022). Energy efficiency and renewable energy resources are closely related to SDG 7, which aims to ensure access to affordable and clean energy. Unfortunately, due to the COVID-19 pandemic, progress towards achieving this goal has been delayed, and previous advancements have weakened (Poorisat *et al.*, 2024).

To progress towards Goal 7, policy support and collaboration between public and private organisations in developed and developing countries are necessary. It is projected that if current trends continue, 670 million people will still be without electricity by 2030, despite 92% of the world's population having access to it (United Nations, 2022). Additionally, international financial incentives for renewable energy in developing countries have decreased from 24.7 billion to 10.9 billion between 2017 and 2019 (United Nations, 2022). Improving energy efficiency is also crucial in reducing greenhouse gas emissions and meeting global climate goals. Accordingly, microgrids are essential to accelerate the process as they are networks of low-voltage distribution systems integrating power storage and flexible loads (Dagar *et al.*, 2021). They also ensure that the power grid provides sustainable, economical, and reliable electricity (Ahmad *et al.*, 2023). Since local generators are close to end users, demand and supply management is more favourable because minimal line losses result in an optimal voltage and frequency profile (Bjarghov *et al.*, 2021).

This study focuses on Nakhon Ratchasima, commonly known as KORAT, in northeastern Thailand, a region with high renewable energy potential. KORAT benefits from abundant solar irradiance and possesses wind, hydro, and solar farm infrastructures. Notably, it hosts the Huay Bong 2 and 3 wind farms, some of the country's largest, which supply electricity to the Electricity Generating Authority of Thailand – EGAT (Martosaputro and Murti, 2014). Additionally, it is home to the 1,000 MW Lam Ta Khong hydropower plant, generating 181 GWh annually (Electricity Generating Authority Thailand, 2023).

Despite KORAT's favourable renewable energy potential, there is a paucity of integrated assessments that jointly optimise cost, reliability, and technical feasibility across multiple renewable sources. Existing regional studies typically focus on a single energy type or lack comprehensive techno-economic comparisons (Niyomtham *et al.*, 2022). To address this gap, the present study employs the Hybrid Optimisation of Multiple Energy Resources (HOMER) platform to design and evaluate a hybrid renewable energy system tailored to KORAT's demand and resource profile. HOMER is particularly suitable for this purpose, as it enables simulation of hourly energy balances over a full annual cycle (8,760 h), assessment of multiple technology combinations, and sensitivity analyses to ensure robust decision-making (Singh and Rizwan, 2022). While the software does not model thermal loads or intra-hour variability (Ram *et al.*, 2022), it remains widely recognised for its capacity to capture key techno-economic trade-offs in hybrid renewable system design (Al Wahedi and Bicer, 2022).

Thailand's National Energy Plan (NEP) and PDP are central policy frameworks guiding the country's transition towards a sustainable and low-carbon future (Asean Centre for Energy, 2025). The NEP integrates multiple energy sub-plans, including the PDP, to achieve carbon neutrality by 2050 and net-zero greenhouse gas emissions by 2065 (EGAT, 2024). As of mid-2025, the NEP remains in draft form and has not been formally promulgated, while the draft PDP 2024–2037, which has undergone public hearings, is awaiting official approval, anticipated in late 2025 or early 2026 (Bangkok Post, 2025b; United Nations, 2025). Key proposed elements include increasing the renewable share to approximately 51% by 2037, integrating hydrogen technologies and Small Modular Reactors (SMRs), and setting targets for smart grid deployment and emissions reduction (Asean Centre for Energy, 2025; Ministry of Energy, 2025). In alignment with these strategic directions, this study advances the renewable energy planning literature by introducing a province-level, demand-aligned optimisation framework that integrates solar PV, hydropower, wind, and energy storage technologies under site-specific meteorological and demand conditions.

Moving beyond descriptive or technology-specific modelling, the framework quantifies system-level trade-offs, identifying the solar–hydro capacity combinations required to meet specified renewable energy fractions and Cost of Energy (COE) thresholds, determining the inflection points at which storage delivers net system benefits, and highlighting operational contexts in which wind power becomes economically unviable. Robustness is tested through sensitivity analyses incorporating near-term Thai cost trajectories, including fuel price and capital expenditure trends. By situating these findings within the evolving NEP and PDP policy landscape, the study provides a transferable, decision-oriented template for scaling renewable deployment across provinces while ensuring alignment with national decarbonisation objectives.

Accordingly, the study aims to answer the following research questions: *(RQ1):* What is the potential of key renewable energy resources in the region of KORAT, Thailand? *(RQ2):* What is the most cost-effective configuration of hybrid renewable energy systems in KORAT that can match regional energy demand with minimal capital investment?. By investigating these questions, this study proposes a practical renewable energy strategy that supports Thailand's national goals and contributes to broader efforts to achieve SDG 7 in similar developing contexts.

2. Review of existing microgrid systems

This section contextualises the microgrid system of renewable energy resources across Asia and Europe, with a focus on Thailand. The focus of this literature review will be on Asia and Europe because they possess extreme climate differences (Zohner *et al.*, 2020), including temperature (Vicedo-Cabrera *et al.*, 2021), wind speed (Tian *et al.*, 2019), and solar irradiation (Prăvălie *et al.*, 2019). In Asia, renewable energy resources are integrated on a smaller scale (Dulal *et al.*, 2013) compared to Europe, which is much larger (Tröndle *et al.*, 2020). For example, in Denmark, comprehensive renewable power generation methods are at the national level (Lund *et al.*, 2022). However, in countries such as Thailand, India, and Malaysia, the scale of power generation is smaller due to insufficient renewable energy frameworks, which are often hindered by economic conditions and high investment costs (Lau *et al.*, 2022). In contrast, Denmark’s smart energy systems exemplify an excellent energy system that can generate 100% renewable energy (Mathiesen *et al.*, 2015).

2.1 Existing microgrid systems in Asia

This paper selected Thailand (Smith *et al.*, 2015), Malaysia (Ashourian *et al.*, 2013), and India (Amutha and Rajini, 2016) as case studies for microgrid studies. HOMER software was employed in all studies to conduct electrical load assessment, cost estimation of grid extension, and identify available resources and feasibility studies regarding technical and financial perspectives (Amutha and Rajini, 2016; Ashourian *et al.*, 2013; Smith *et al.*, 2015), where all studies are located in rural areas and island settings. In Thailand, Jig Island, Poh Island, and Pu Island were selected due to high solar irradiance, wind speed harvesting opportunities, and isolation from the national grid (Smith *et al.*, 2015). The purpose of the studies in three countries was to observe the environmental impacts of the combined power systems and compare the benefits of traditional and microgrid technologies (Amutha and Rajini, 2016; Ashourian *et al.*, 2013; Smith *et al.*, 2015). Tsunami-prone remote locations in Thailand face challenges in connecting to the national grid due to limited electricity, as the underwater cable is not economically viable (Peerapong and Limmeechokchai, 2017).

The study in the Thailand setting revealed that the optimised designed microgrid scenario in Koh Jig with the combination of 65 kW diesel generators, 5 kW wind turbines, 75 kW PV panels, and lead acid batteries created lower environmental impacts regarding global warming and resource depletion which was revealed to be more favourable for rural electricity generation than the national grid (Smith *et al.*, 2015). The optimised hybrid system in Thailand consumes 19% of renewable energy, costing 0.422 USD/kWh, which is economically viable (Smith *et al.*, 2015). The energy cost increased dramatically with the addition of the wind power system, making it impossible. Therefore, the sustainability of the Koh Pu and Koh Po hybrid systems depends on their management and operational capabilities (Greacen *et al.*, 2007).

Malaysia shares similar climatic conditions to Thailand and other countries in tropical zones (Phanprasit *et al.*, 2021; Shaikh *et al.*, 2017). It is noteworthy that Thailand, Malaysia and India have an all-year abundance of solar resources and a lesser abundance of wind resources (Amutha and Rajini, 2016; Ashourian *et al.*, 2013; Smith *et al.*, 2015) and that the governments of Malaysia (Suruhanjaya Tenaga, 2020) and Thailand (Ministry of Energy Thailand, 2020b) are promoting increased electricity generation from renewable energy resources. Since most Malaysian islands rely on diesel generators, electricity shortages are a significant issue (See *et al.*, 2022). Malaysia mainly relies on natural gas, coal, hydropower, and other forms of energy fuel (Chong *et al.*, 2015). Resort islands in Malaysia were used as case studies, and the simulation strategy was configured with two cases of load profiles (with and without tourists) to observe the difference, which revealed that 200 kW of solar panels and a 40 kW wind power system with an inverter could supply the electrical demand with zero pollutants (Ashourian *et al.*, 2013).

A feasibility study of Microgrids in India was conducted in Kadayam, Tamil Nadu, with the existing hydropower plants (Amutha and Rajini, 2016). The simulation results revealed the most optimal combination as the integration of a 22.5 kW solar panel, a 10 kW generic wind turbine, Surrette S460 48V batteries, a 140 L/s design flow rate hydro-reservoir, and a 30 kW rectifier, with a dispatch strategy of cycle charging (Amutha and Rajini, 2016). In the selected countries, the national grid extension is not always economically viable compared to the microgrid (Amutha and Rajini, 2016; Ashourian *et al.*, 2013; Smith *et al.*, 2015; Surur *et al.*, 2020). In conclusion, the Asian microgrid systems with solar panels effectively matched site load demand, reducing energy costs and environmental impacts in all case studies (Amutha and Rajini, 2016; Smith *et al*., 2015; Surur *et al*., 2020). To conclude, renewable electricity generation costs less than installing a cable connection system from rural areas and islands to the national grid (Gesellschaft fur Internationale Zusammenarbeit, 2018).

2.1.1 Review of existing renewable energy systems in KORAT. This subsection reviews the renewable energy resources currently available in KORAT to establish their suitability for hybrid microgrid modelling in HOMER software.

(1) Wind power system.

As of 2015, two main wind power sites were operating in the province: the Lam Ta Khong wind farm (2.5 MW) and the Huay Bong 2 and Huay Bong 3 farms (103.5 MW each). EGAT developed the first project, while Wind Energy Holding Company Limited developed Huay Bong 2 and 3 under 25-year power purchase agreements with EGAT. Wind turbine specifications and power curves from these projects were incorporated as input data for the simulation (Electricity Generating Authority of Thailand, 2016b; SIEMENS Energy, 2012; WINDPOWER, 2016).

(2) Hydropower system.

The Lam Ta Khong Dam was modelled with an installed capacity of 1,000 MW, using Alstom pump-storage turbine specifications (ALSTOM, 2011) because HOMER cannot simulate pumped storage; only the turbine mode was modelled. The project is divided into two phases, with generating units installed sequentially; however, only one turbine typically operates at a time. Consequently, the plant does not consistently reach full capacity, as generation depends on electricity demand, power system management, and reservoir levels. Reservoir water availability is further constrained by rainfall variability and agricultural irrigation demands. The dam has a total volume of 10.3 million m^3, an average annual inflow of 71,839 m^3/s, and a maximum elevation of 600 m above Mean Sea Level (MSL). In 2015, the reservoir averaged 646 m MSL, indicating that generation was technically feasible under alternative management strategies.

(3) Solar power system.

In 2015, KORAT recorded a peak solar generation capacity of 7.5 MW, supplying electricity to more than 5,100 households. With 923,467 households in the province (Thai Official Statistics Registration Systems, 2016), the potential for widespread rooftop solar PV deployment is significant. Thailand continues to expand its solar sector, including the 45 MW hydro-floating solar hybrid at Sirindhorn Dam in Ubon Ratchathani—the largest of its kind globally (Electricity Generating Authority of Thailand, 2021). These resources underscore Thailand's attractiveness to energy investors, particularly given the abundance of solar potential.

2.2 Existing microgrid systems for sustainable cities

Cities are responsible for a significant portion of global greenhouse gas emissions, accounting for approximately 60% of total emissions (Wiedmann *et al*., 2021). Hence, addressing the impacts of climate change and accelerating the transition to a green economy requires reducing potential emissions by integrating renewable energy sources (Bagheri *et al*., 2018). Denmark, for instance, has set a target to achieve 100% renewable energy and become climate-neutral by 2050, which involves implementing large-scale renewable power systems (Lund *et al*., 2022; Mathiesen *et al*., 2017). Aalborg, Denmark, has been studied as a case for transitioning to renewable energy sources, with a focus on heavy transport fuels, industrial demand, transport demand, access to national variable energy sources, and electricity export and import (Thellufsen *et al*., 2020). Also, the use of biomass has been identified as a key strategy for decarbonising local regions, and Aalborg has been found to have adequate rooftops for solar panel installation and sufficient land area for wind turbines (Mathiesen *et al*., 2017). Accordingly, energy analysis tools, such as EnergyPLAN, have been employed to evaluate the feasibility of 100% renewable energy by 2050 in Aalborg, which would make Denmark independent from traditional fuels, benefiting the environment, climate, and economy (Lund *et al.*, 2022).

Previous studies have analysed the feasibility and environmental efficiency of hybrid renewable systems in rural areas, specifically focusing on the impact of economies of scale. For example, studies conducted in Canada (Bagheri *et al.*, 2018) and South Korea (Baek *et al.*, 2016) have employed the HOMER software to investigate this issue. Accordingly, Bagheri *et al.* (2018) conducted their study in Vancouver, Canada, using electrical load data from 2016 and inputting PV output, wind turbines, biomass gasifiers, power converters, and energy storage into the HOMER software. Their findings showed that the energy cost ranged from 0.3 to 0.307 USD/kWh. Furthermore, the study indicated that wind power is not economically feasible in Vancouver, while biomass is the most efficient renewable energy source (Bagheri *et al.*, 2018). It is worth noting that solar energy constituted a significantly more significant proportion, exceeding 50%, than biomass during April and May (Bagheri *et al.*, 2018). Similarly, Baek *et al.* (2016) employed electricity usage data from 2013 in Busan, South Korea, to simulate the most efficient configuration of PV panels, wind turbines, converters, and batteries. Their results showed that the optimal configuration has an energy cost of 0.399 kWh/USD and utilises 100% renewable energy fractions comprising 4,130 kW PV panels, a 1,482 kW converter, and 5,525 batteries (Baek *et al.*, 2016). It is worth noting that Vancouver and Busan have high population levels of 630,000 and 3,500,000, respectively. Implementing microgrid systems within urban settings has significant implications for establishing sustainable cities (Sami *et al.*, 2021). On-site renewable energy generation and microgrids reduce GHG emissions potential, critical for energy-intensive sectors like buildings and transport and promote energy reliability and security (Kiehbadroudinezhad *et al.*, 2023), which is crucial for sustainable development (United Nations, 2022). Adopting microgrid systems facilitates the development of a more self-sufficient and inclusive urban infrastructure while reducing environmental impact and contributing to a more sustainable future (Isanbaev *et al.*, 2023).

2.3 Methodological evolution: from HOMER to Artificial Intelligence

Most existing hybrid energy system studies have relied heavily on HOMER software for optimisation, owing to its accessibility, transparent structure, and ability to simulate hourly energy balances over extended periods (Poorisat *et al.*, 2024). Although HOMER has been instrumental in advancing techno-economic feasibility analysis, it remains constrained by simplified dispatch strategies and its dependence on single-objective cost minimisation. These limitations restrict its capacity to capture the inherently non-linear and multi-objective trade-offs that characterise hybrid energy systems (Hoummadi *et al.*, 2025). Recognising these shortcomings, recent research has increasingly shifted toward Artificial Intelligence (AI) and metaheuristic optimisation algorithms such as Genetic Algorithms (GA), Artificial Bee Colony (ABC), Ant Colony Optimisation (ACO), Grey Wolf Optimisation (GWO), and Harris Hawks Optimisation (HHO). Unlike HOMER, these methods can explore global solution spaces more effectively, achieving an optimal balance between multiple objectives, including cost, emissions, reliability, and resilience, within complex, dynamic systems (Zulu *et al.*, 2023).

Comparative studies have underscored the advantages of this methodological transition. Hoummadi *et al.* (2025), for instance, compared HOMER-generated results with AI-based optimisation outcomes and found that AI consistently produced a lower COE, reaching as little as 0.035–0.037 USD/kWh, compared to HOMER’s 0.06 USD/kWh and prevailing retail tariffs of 0.115 USD/kWh. Similarly, Ouederni and Davidson (2025) combined HOMER with metaheuristic techniques such as GWO and HHO, demonstrating that GWO achieved the most competitive results with a minimum energy cost of 0.268 USD/kWh. These findings reveal how advanced algorithms can substantially reduce system costs while improving performance, particularly in isolated rural communities.

Despite these advancements, much of the AI-driven literature still emphasises cost minimisation, with limited integration of broader sustainability dimensions such as emissions reduction, storage optimisation, and system resilience under fluctuating renewable and demand conditions (Zulu *et al.*, 2023). For example, Tahir (2025), through a Systematic Literature Review, confirmed that AI and metaheuristic techniques, for example, GA, PSO, ACO, now dominate hybrid microgrid optimisation studies, outperforming traditional tools like HOMER in managing real-time uncertainty and multi-objective decision-making. AI-enabled systems further enhance predictive maintenance, reliability, and renewable utilisation, especially in remote contexts where HOMER's static control logic becomes a major constraint (Ahmed *et al.*, 2025). Collectively, post-2024 evidence indicates that AI-based optimisation methods outperform HOMER in cost efficiency, adaptability, and multi-objective control (Tahir, 2025). Nevertheless, HOMER continues to serve as a foundational techno-economic tool, especially for policy-aligned energy planning. The emerging research frontier lies in hybridising AI with HOMER, combining HOMER's transparency and economic insight with AI's adaptive learning and optimisation capacity to meet national energy transition targets.

However, few studies have explicitly aligned these AI-driven frameworks with Thailand's national energy policy trajectories, such as the Power Development Plan (PDP, 2024) and National Energy Plan (NEP, 2023), both targeting over 50% renewable penetration by the 2040s (Asean Centre for Energy, 2025). For example, Ngao-det *et al.* (2025) modelled a 100% renewable rural microgrid in Thailand using HOMER Pro, achieving impressive sustainability metrics (COE = 0.19 USD/kWh vs 1.85 USD/kWh for diesel). However, the absence of AI integration highlighted HOMER's role as a baseline platform rather than a complete optimisation environment. Therefore, bridging this methodological gap requires not only technical innovation but also a stronger policy-oriented perspective, ensuring that AI-based models are both technically robust and strategically relevant to national and regional energy transition planning.

2.4 Lessons from the reviewed microgrid systems and study justification

The literature reviews described in this section cover several world areas on both small and regional scales. The case studies were selected because they have different configurations and demographic information, such as hot and cold climates. Some areas have high solar potential, while others have high wind or hydropower potential. In Asia, renewable energy resources are integrated on a smaller scale compared to those in Europe, which have a much larger scale. The barriers to renewable energy in Asia include a lack of skilled training facilities and standards, high initial costs, an insufficient renewable energy policy framework, and unfavourable economic situations (Dulal *et al.*, 2013). In some countries, such as Japan, South Korea, and Taiwan, the primary barrier to the adoption of renewable energy is resistance to change in renewable energy technologies (Chen *et al.*, 2014). For example, in Thailand, 100 million USD were invested in biofuels and solar technology (Dulal *et al.*, 2013), but the national scale of renewable energy integration is still not possible due to several barriers, including economics, renewable energy policies, financial barriers, and subsidies for conventional energy (Kardooni, 2012).

Addressing this need, the present study leverages actual electricity consumption data to develop an optimised, holistic hybrid renewable energy model for KORAT, which is the second-largest province in Thailand. Uniquely, the study proposes a hybrid energy system that combines solar, wind, hydropower, and battery storage tailored to both local climatic conditions and usage patterns. It is further aligned with Thailand's strategic energy objectives, including the PDP 2024, which envisions adding approximately 43 GW of generation by 2037 of which around 24 GW is projected to be obtained solar power and increasing renewables to roughly 51% of electricity generation; and the NEP 2023, which targets even higher renewable shares in the 2040s (Bangkok Post, 2025b), all in service of achieving climate and energy resilience goals (Asean Centre for Energy, 2025).

This alignment significantly enhances the study's relevance for national and regional policymakers such as the Energy Policy and Planning Office (EPPO), EGAT, Provincial Electricity Authority (PEA), and the Ministry of Energy of Thailand, by providing a replicable framework for scale-up across other provinces and other Southeast Asian countries with similar climates. It also offers critical insights for investment prioritisation, strategic energy planning, and policy formulation, thereby facilitating Thailand's transition to a more resilient and sustainable energy future. Importantly, the study emphasises the necessity of site-specific data preparation, recognising that each region's unique demand structure and resource endowments require customised energy management strategies to ensure optimal performance, feasibility, and alignment with national policy trajectories.

3. Material and methods

3.1 Data collection and pre-processing

To ensure that the simulations reflect real operating conditions, the study collected high-resolution, site-specific datasets and verified their accuracy and completeness. The electrical-load profiles for 2015 were obtained from PEA, covering both residential and commercial consumption (Provincial Electricity Authority Thailand, 2016). This year was selected as the baseline, representing the most recent period with complete demand data and reflecting a regional peak load of approximately 2.908 GW in May 2015. All cost inputs were normalised to 2015 USD to maintain consistency. The Liquefied Natural Gas (LNG) price was set at 0.162 USD per litre based on EGAT's 2015 market value, while technology-specific capital costs were drawn from IRENA (2015–2020) and national energy reports. Streamflow data for the Lam Ta Khong Dam were sourced from EGAT to capture seasonal hydropower variation, and meteorological inputs (ambient temperature, wind speed, and solar irradiance) for KORAT were retrieved from the US Department of Energy's National Renewable Energy Laboratory (2025), which is a typical meteorological year database cross-checked against regional weather records from the Thai Meteorological Department (2025). For energy storage, the CellCube FB 200-1,600 vanadium-redox flow battery was modelled for its high capacity and deep-discharge capability (Mardilovich and Harrer, 2023). Although HOMER allows users to set replacement intervals, it assumes a fixed lifetime and does not capture degradation effects, an acknowledged software limitation (Kafando *et al.*, 2024). These baseline inputs together form the "Conventional grid-only" reference case, yielding a Cost of Energy (COE) of ≈0.242 USD/kWh and a Net Present Cost (NPC) of ≈51.9 billion USD with 0% renewable penetration. All subsequent hybrid configurations and sensitivity analyses are evaluated relative to this 2015 baseline to quantify economic and technical improvements. The data-collection workflow is summarised in Figure 1.

3.2 Modelling tools and rationale

Hybrid Renewable Energy Systems can be simulated using various software, including HOMER, EnergyPLAN, and RETScreen (Roma *et al.*, 2024). Among these, HOMER has been extensively validated for techno-economic optimisation of decentralised hybrid systems, with advantages such as high temporal resolution, flexible system configuration, and user accessibility (Bagheri *et al.*, 2018). While RETScreen provides high-level feasibility analyses based on annual averages, it does not capture hourly dispatch dynamics critical for systems with intermittent sources such as solar and wind power (Iweh *et al.*, 2023). In contrast, EnergyPLAN is more suitable for national-level policy simulations rather than sub-regional microgrids (Roma *et al.*, 2024). HOMER was therefore chosen for this study, given its ability to conduct hour-by-hour energy balance simulations and integrate technical and economic optimisation (Zhang *et al.*, 2022). Its capabilities allow for detailed assessment of renewable

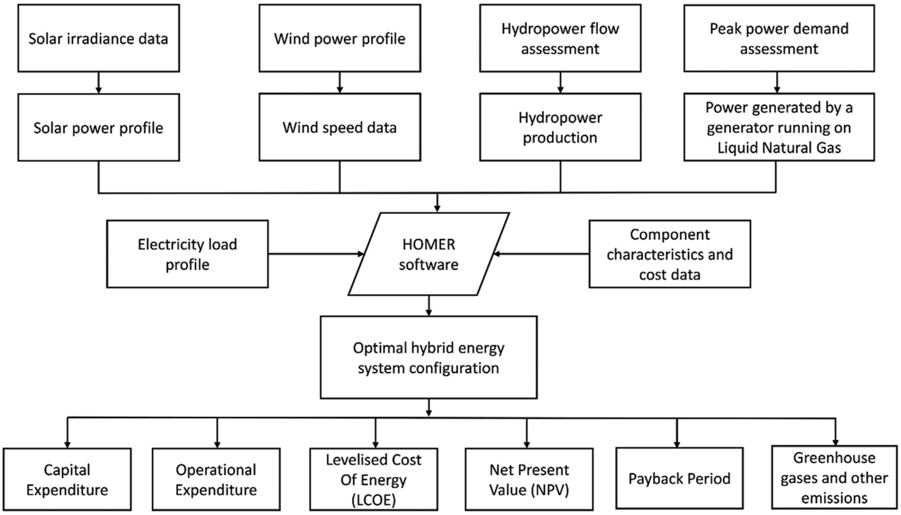

Figure 1. Schematic flow chart of the study process. Source: Authors' own work

penetration, COE, NPC, and demand–supply matching. The NPC is the key financial indicator used by HOMER to rank system configurations. Also, NPC represents the total cost of installing and operating the system over its lifetime, discounted to present value, minus all revenues. Moreover, its sensitivity analysis module supports robustness testing against variations in fuel prices, resource availability, and technology costs (Buonomano *et al.*, 2023). These features make HOMER particularly well-suited for provincial-scale energy planning in Thailand, where climatic variability and decentralised demand must be considered (Asean Centre for Energy, 2025).

Nonetheless, HOMER has limitations that warrant acknowledgement. It primarily employs single-objective optimisation, minimising NPC, without the ability to simultaneously incorporate multi-objective criteria such as emissions reduction or resilience enhancement (Hoummadi *et al.*, 2025). Furthermore, it does not capture intra-hour variability, voltage fluctuations, or depth-of-discharge dynamics, which are increasingly addressed by emerging multi-objective and AI-based optimisation approaches (Khan *et al.*, 2024). These limitations imply that while HOMER provides robust baseline insights into techno-economic trade-offs, complementary modelling tools may be required for more comprehensive evaluations (US Department of Energy's National Renewable Energy Laboratory, 2025).

3.3 Study area

KORAT is Thailand's largest province by population and second-largest by area, covering a total area of 20,494 km^2. The centre is located at 14° 58′ 12″ N, 102° 6′ 0″ E (see Figure 2), in Northeastern Thailand (Duangkrayom *et al.*, 2022). The province has quickly emerged as a hotspot of economic growth and urbanisation (Dutta and Chavalparit, 2023). KORAT was selected as the study area because of its high electrical load profile (Provincial Electricity Authority Thailand, 2016), as it is one of the most popular tourist destinations and has a high population level. The province has a population of 2.6 million (Board of Investment Thailand, 2022) and uses small-scale and national-scale generation (Deepo *et al.*, 2021; Kosa *et al.*, 2011). The province's total provincial product was 5,280 USD per capita per year, with the agricultural sector contributing the highest proportion in 2018 (Nakhon Ratchasima Provincial Hall, 2018).

Figure 2. Map of Thailand with the study area. Source: Google Maps (2025)

3.4 Electrical load estimation

The hourly load profile of KORAT was obtained from the Provincial Electricity Authority Thailand (2016) based on commercial and residential metering data from 2015. This dataset was used to generate representative daily and seasonal load curves within HOMER. The demand profile is strongly influenced by the high and persistent cooling loads arising from Thailand's tropical climate. In particular, electricity consumption peaks during April and May, coinciding with elevated summer temperatures. The 2015 average daily electricity demand was 45,354,024 kWh, with an average power demand of 1,889,751 kW and a peak of 2,908,821 kW, corresponding to a load factor of 0.65 (Provincial Electricity Authority Thailand, 2016). This high and relatively stable demand underscores the necessity of hybrid systems capable of reliably addressing base load while accommodating seasonal fluctuations.

3.5 Methodological alignment with research objectives

The methodological framework adopted in this study was deliberately aligned with the overarching objective of identifying cost-effective, reliable, and context-appropriate hybrid renewable energy configurations for KORAT. The use of HOMER as the principal modelling tool reflects a strategic emphasis on techno-economic optimisation, where minimisation of the NPC provides a robust and widely accepted baseline for assessing system feasibility in the context of developing countries (Poorisat *et al*., 2024). By incorporating hourly simulation, HOMER captures the temporal variability of renewable resources and demand patterns that annual-average models would overlook, thereby ensuring a realistic representation of operational dynamics (Ouederni and Davidson, 2025).

Equally important, the reliance on HOMER's sensitivity analysis enables the evaluation of system robustness under fluctuating conditions of fuel prices, renewable availability, and technology cost factors of particular relevance to Thailand's volatile energy market (Bangkok Post, 2025b; Zhang *et al*., 2022). At the same time, the model does not accommodate multi-objective optimisation or intra-hour dispatch variability (Nebey, 2021). Accordingly, these limitations do not undermine the main objective of the study. Instead, they delineate the scope of the findings because the results are best interpreted as a techno-economic baseline, rather than a comprehensive environmental or resilience-oriented assessment (Poorisat *et al*., 2024). This methodological positioning strengthens the study's contribution to the literature and policy discourse. It provides actionable insights for provincial and national planners by demonstrating which technology mixes are most economically viable under current conditions, while also identifying the extent to which further refinements, such as AI-based multi-objective optimisation or resilience modelling, may be required in future research (Hoummadi *et al*., 2025). In this manner, the chosen methods strike a balance between analytical rigour, contextual relevance, and practical applicability to Thailand's provincial energy planning challenges.

4. Results and modelling of hybrid renewable energy systems

This section presents the results of modelling hybrid renewable energy systems involving three renewable energy resources in Thailand: solar power, wind power, and hydropower. The data of existing renewable energy systems in KORAT were input into the HOMER software. The modelling outcome of this study is discussed in the section below.

4.1 Simulation approaches

The renewable resource base of the KORAT region was assessed using solar irradiance, wind speed, hydrological inflows, and temperature profiles. Climate data, including daily solar radiation, clearness index, wind speed, and temperature, were obtained from the HOMER software (US Department of Energy's National Renewable Energy Laboratory, 2025). HOMER compiles long-term monthly averages from global datasets such as NASA Surface Meteorology, Solar Energy, and MERRA-2, providing Typical Meteorological Year (TMY) data that reflect representative climate conditions rather than a single year (Nebey, 2021). As summarised in Table 1, solar radiation and clearness index values peak in the summer months of April–June, highlighting a strong seasonal solar energy potential. Table 1 also reports monthly averages for wind speed, temperature, and hydrological inflows at Lam Ta Khong Dam. Flow rate data were derived from EGAT records, ensuring accurate, location-specific inputs for evaluating the feasibility of hybrid renewable energy deployment in the province.

The hydropower resource data (Table 1) were obtained from the Lam Ta Khong Dam database (Electricity Generating Authority of Thailand, 2016a). Because the organisation did not provide flow rate data directly, it was calculated using Equation (1). According to the records, electricity generation was primarily from a single turbine, with additional turbines operating only during peak demand and functioning as pumps during off-peak periods. The dam's total installed capacity is 1,000 MW. Generation and pumping modes were modelled in the software, while turbine efficiency values were sourced from the manufacturer (ALSTOM, 2011).

Table 1. Daily Solar radiation, clearness index, wind speed, temperature, and monthly flow rate in Nakhon Ratchasima

Month	Daily solar radiation (kWh/ m^2/day)	Clearness index	Wind speed (m/s)	Temperature (°C)	Monthly flow rate (L/s)
January	5.11	0.622	3.41	24.61	72,900
February	5.44	0.6	3.1	26.12	66,500
March	5.66	0.566	3.1	26.67	76,800
April	5.81	0.55	2.81	26.76	75,400
May	5.28	0.493	2.45	26.85	61,600
June	4.98	0.493	3	26.43	69,000
July	4.84	0.455	2.91	26.09	69,700
August	4.66	0.442	2.97	26.01	73,400
September	4.63	0.458	2.09	25.71	71,600
October	4.53	0.489	3.01	24.81	68,600
November	4.62	0.553	3.36	23.54	70,900
December	4.77	0.603	3.66	22.99	72,200

Source(s): Electricity Generating Authority of Thailand (2016a), US Department of Energy's National Renewable Energy Laboratory (2025)

Equation (1): Flow rate of a hydropower system (Q)

$$Q = \frac{P_{Hydro}}{\eta x H_{turbine} x g x \rho_{water}} \tag{1}$$

Where;

P_{Hydro} = Power generated by the hydropower plant (W)

$H_{turbine}$ = Head of the turbine (m)

g = Gravitational acceleration (m/ s^2)

ρ_{water} = Density of water (kg/ m^3)

4.2 Simulation

The procedure in section 4 was performed step-by-step to ensure that the demand profile created by HOMER corresponded with the input data. The simulation strategies and results are listed below.

4.2.1 Demand verification and calibration. The hybrid renewable energy model for this study was developed and calibrated using HOMER software, incorporating a detailed 8,760-h load profile obtained from PEA. Initially, daily, weekly, and monthly electrical load data were input into the model and cross-checked with values provided by the PEA to ensure accuracy. The peak load of 2,908,821 kW in May was confirmed, aligning with the highest recorded temperature of 40.1 °C in 2015, which reflected increased cooling demand from air conditioners and lighting, common energy uses in KORAT (Thai Meteorological Department, 2025). This alignment between demand and climatic conditions validated the demand profile. Climatic inputs such as solar irradiation, wind speed, and temperature were sourced from HOMER's database and verified against regional datasets, while hydropower inputs were calibrated using real operational data from the Lam Ta Khong Dam. Energy components were defined based on real-world technical specifications and cost data from EGAT, private providers, and reliable guidelines (IRENA, 2023). Multiple system configurations were simulated, and key performance metrics, including COE, NPC, renewable energy fraction, and surplus energy, were analysed. Sensitivity analyses were conducted to address future cost trends and potential changes in fuel prices. Overall, the model was rigorously validated to ensure transparency, reliability, and reproducibility.

4.2.2 Validation of renewable energy system models. The individual components' cost analysis was completed before the simulation to calculate the COE and NPC. EGAT provided most of the components; the rest were supplied by private organisations that sell electricity to EGAT. The pricing criterion of each element was assumed as follows:

1. The capital cost of components provided by EGAT (government fund) was set as zero in HOMER software because the study aims to develop the existing models, which include (1) Lam Ta Khong Hydropower plant, (2) Lam Ta Khong wind turbines, and (3) the KORAT grid (Normally power is transported from the national grid, and only fuel consumption and operation cost are included in the simulation).
2. The replacement cost was assumed to be 10% of the capital cost.
3. The capital cost of the components provided by private companies was determined based on standard prices, including those for Huay Bong 2 and Huay Bong 3 wind turbines, solar cell panels, and converters.

4.2.3 Simulation results. In each case, simulations were performed using single-mode and hybrid power generation systems to outline the potential of renewable energy systems.

4.2.3.1 Generator running on liquid natural gas (KORAT grid). The generator, labelled KORAT, was modelled as the primary electricity supplier. In practice, electricity in KORAT is imported from the national grid operated by the PEA. To represent this supply, a virtual generator with a capacity of 6,000,000 kW, twice the peak load, was created in HOMER to ensure reliability and avoid shortages during periods of high demand. A minimum load ratio of 1% was applied, with the assumption that no energy was exported back to the grid. In Thailand, Liquid Natural Gas (LNG) is the predominant fuel source. For the simulation, the model assumed full demand coverage through grid-based generation. In 2015, the price of LNG was 0.162 USD/L (PTT Public Company Limited, 2016). Based on this input, the COE for conventional generation was calculated as 0.292 USD/kWh using Equation (2). In HOMER, the levelised COE is defined as the average cost per kilowatt-hour of useful electricity produced by the system.

Equation (2): Levelised COE

$$COE = \frac{C_{annualise,total-}H_{served}C_{boiler}}{E_{served}} \tag{2}$$

Where;

$C_{annualised}$ = Total annualised cost (USD/year)

H_{Served} = Total thermal load reserved (kWh/year)

C_{boiler} = Boiler marginal cost (USD/kWh)

E_{served} = Total electrical load served (kWh/year)

In this case, the total thermal load served is zero, meaning that COE is only calculated by Equation (3). Hence, the total annualised COE is calculated from the annual NPC, real discount rate, project lifetime, and capital recovery factor.

Equation (3): Levelised COE without thermal load

$$COE = \frac{C_{annualised,total}}{E_{served}} \tag{3}$$

A system's NPC is the total expense incurred over its lifetime, subtracted from all revenue gained by the project. Replacement costs, capital costs, operation and maintenance costs, fuel costs, emission penalties, and the cost of purchasing electricity from the grid are included. Savage value and grid sales are included in revenues. NPC is the most critical measure for ranking the system in the HOMER simulation. Equation (4) is used to calculate annualised costs. The project lifetime is 25 years with an 8% discount rate.

Equation (4): Annualised cost

$$C_{annualised,total} = CRF\left(i, R_{project}\right) \cdot C_{NPC,total} \tag{4}$$

Where;

$C_{annualized,total}$ = Total annualised cost (USD/year)

i = The annual discount rate (%)

R_{proj} = The project lifetime (year)

$C_{NPC,total}$ = Total Net Present Cost (USD)

As a result, a power system with a 6,000,000 kW generator running on liquid natural gas has a levelised energy cost equivalent to 0.242 USD/kWh with 51.9 billion USD and a 0% renewable energy fraction.

4.2.3.2 Generator running on the KORAT grid and solar power system. In a solar energy system, the quantity of panels required is determined by the available solar intensity and the electrical load requirement. In this case, a solar power system was installed to increase renewable energy penetration, leveraging KORAT's abundant solar resources. The generator's capacity remains constant at 6,000,000 kW. The initial size of solar cell panels is set to be 7,500 kW based on the existing technology in the province. After considering the variations in solar capacity, the system with 90,000 kW of solar power is the most realistic in terms of capital cost and the area required for rooftop installation. The energy cost is 0.244 USD/kWh with NPC of 52.1 billion USD. The simulation results reveal that 90,000 kW solar panels can provide 88,245 kW. The renewable energy fraction is 0.78% with 0% of surplus energy. April was selected as a representative month for solar power due to its highest solar radiation values compared to the other months.

4.2.3.3 Generator running on the KORAT grid and a wind energy system. The electrical power from wind turbines depends on the wind speed in the area of interest. For this study, DeWind D6 and SIEMENS 2.3 MW wind turbines were inputs to HOMER software. The 2015 wind power system configuration in KORAT was used as the baseline model, which includes 90 wind turbines generating 207 MW and two additional turbines with 2.5 MW capacity. Although the electricity demand is consistent, the existing system produces low renewable energy with a high NPC of 52 billion USD. According to HOMER's analysis, wind speeds often do not reach the cut-in speed of the turbines, which is the point at which they begin generating electricity. December was chosen as the representative month for wind power generation because it has the highest renewable energy penetration and wind speeds compared to other months, verified by simulation output. Despite the high installed capacity of the wind power system, the fraction of renewable energy and the amount of electricity generated by the system are relatively low, as the power produced by wind power accounts for only 0.43% of the total, with an installed capacity of 209.5 MW. In comparison, solar power accounted for 0.87% with an installed capacity of 90 MW. Therefore, solar power can generate more power than wind power systems despite having a lower installed capacity.

4.2.3.4 Generator running on the KORAT grid and a hydropower energy system. The Lam Ta Khong hydropower plant has four turbines capable of generating up to 1,000 MW of power during peak demand. Still, only one turbine was operating due to the 2015 drought crisis. The simulations conducted using run-of-river hydropower ranged from one to four turbines in operation. It was discovered that the plant could contribute up to 36.28% of the total electricity generated from renewable sources with all four turbines in operation. Nevertheless, two turbines were used as a baseline to prevent a water shortage in case of peak demand for other purposes. It is noteworthy that this approach was realistic, given the drought crisis in Thailand, which necessitated the reservation of a significant amount of water for irrigation and other purposes. The hydropower plant's energy cost was 0.235 USD/kWh, contributing 18.14% of the total electricity generated, which is comparatively low compared to solar and wind power, as hydropower plants have high efficiency and stability. Additionally, the relationship between stream flow and power generated revealed that the hydropower plant could generate power constantly throughout the year.

4.2.3.5 Generator running on KORAT grid, solar, wind, and hydropower energy systems. In the previous tasks, each component was simulated individually to observe the trend of renewable outputs, COE, and NPC. This simulation integrated every component into one system. Table 2 presents the installed capacity, annual electricity production, and electricity generated by each component.

The energy cost in this case is 0.237 USD/kWh, with a renewable energy fraction of 19% and NPC of 50.7 billion USD. The value of surplus energy is the highest compared to the other cases, at 191.5 kWh per year.

4.2.4 Simulation with increased renewable capacity. The COE of the third system (0.241 USD/kWh) presented in Section 4 was adopted as the upper threshold for integrating additional PV panels and hydropower capacity. This approach aimed to design an energy system that remains economically viable in terms of both COE and NPC while increasing the share of renewable generation. In contrast, the second system in Table 3 achieved only a 19.4% renewable energy fraction, which is relatively low and not representative of the national electricity demand since the analysis focused solely on a single province.

(1) Addition of hydropower capacity by a mini-hydropower plant

In Section 4, only two turbines were in operation. Due to its large-scale generation, power management at Lam Ta Khong Dam is complex, as it involves several authorities in Thailand, including the Royal Irrigation Department and the Meteorological Department. Micro-hydro power sites in KORAT were examined. Accordingly, 17 sites were identified with the potential for electricity generation, of which 11 are run-of-river hydropower plants, while the rest are suitable for reservoir schemes. It was determined that the run-of-river model is more appropriate due to the area's mountainous terrain. Due to HOMER software limitations, only one turbine could be modelled, and several values had to be assumed and calculated. The total

Table 2. Electricity generation by each component

Production component	Installed capacity (MW)	Electricity produced (kWh/year)	Electricity generated (%)
Generic flat plate PV	90	143,427,760	0.87
KORAT grid	6,000	13,350,359,040	80.58
SIEMENS wind turbine	270	70,942,784	0.43
DeWind D6	5	648,128	0.00
Hydropower plant	520	3,003,390,208	18.13
Total	*6,825*	*16,568,767,488*	*100.00*

Source(s): Authors' HOMER software simulation results

Table 3. Comparison of each configuration

Item	Type of system	Cost of energy (USD/kWh)	NPC (Billion USD)	Electricity produced from renewable resources (%)
1	KORAT grid	0.242	51.9	0.00
2	KORAT grid + Solar power system	0.244	52.1	0.78
3	KORAT grid + Wind power system	0.243	52.6	0.43
4	KORAT grid + Hydropower plant (2 turbines)	0.235	50.3	18.4
5	KORAT grid + Solar power system + Wind power system + Hydropower plant	0.237	50.7	19.4

Source(s): Authors' HOMER simulation results

capacity for the new virtual turbine, obtained by adding the capacity of mini-hydro sources expected to be installed, is 4,540 kW (Kosa *et al.*, 2011). As the individual-designed head differs, the mean value of generation and efficiency was calculated for the virtual turbine.

The assumptions for calculation made for the suitability of input to HOMER software include:

(1) The efficiency value for the virtual turbine was assumed to be 0.7.

(2) The head of the turbine remains constant at 360 m.

(3) The flow rate was added to hydropower resources. Equation (1) was used to calculate the flow rates.

(4) Cost analysis was based on the data from the International Renewable Energy Agency (IRENA, 2012). The average cost is 2,300 USD per kW, referring to the average value.

After recalculation, the turbines generated 4,540 kW while the water flow rate was 219,791 L/s, accounting for all the turbines. The initial cost of the additional hydropower plant was 19,442,000 USD, with an assumed efficiency of 0.7, as most power production is sourced from the Lam Ta Khong hydropower plant. The monthly flow rate introduced to the system was calculated to be 35,539 L/s. The findings indicated that with the increased capacity, the energy cost was at 0.237 USD/kWh, with an NPC of 50.7 billion USD. With this increase, the renewable energy fraction rose to 21%, a positive outcome.

(1) Addition of PV panels

As per Thailand's PDP, the solar power system was anticipated to have the highest capacity proportion and more solar panel capacities were added to the simulation. This simulation aimed to maximise solar power capacity while keeping costs in check, with the cost limit of 0.242 USD/kWh. As a result, 470 MW was selected, representing 25% of the renewable energy fraction. The NPC of this system was lower than that of a generator running on natural gas, leading to 3% of annual electricity generation. The area required for solar panel installation was 7.285 km^2, based on the area needed for a megawatt-scale power plant (IFC, 2015).

4.2.5 Simulation with an overall increase in renewable penetration. Thailand experiences three distinct seasons: winter, rainy season, and summer. As the country's Air conditioning (AC) loads are directly linked to temperature, May was chosen first for this simulation due to its peak demand. The solar power system generated a maximum power output of 398,047 kW at noon. The SIEMENS wind turbine generated a peak power of 785 kW on the same day, while the DeWind D6 produced no power. The study confirms that wind power plays a minimal role in daily power generation, while hydropower plants offer the most consistent output throughout the year. December was chosen as a representative month due to the significant difference in wind power generation. The peak power generated by wind turbines during this month was 1,824 kW, nearly twice the amount generated in May. However, solar power generation remained consistent throughout the year, as it was high every month. In summary, power generation from solar power systems is available year-round, whereas wind systems generate a significant amount of power but with fluctuations (see Figure 3).

4.2.6 Hybrid energy system with storage. Adding an energy storage system to a power generation network was examined to minimise energy waste. A Cell-cube FB 200-1,600 battery model was used in the simulation to represent a large-scale electrical network. The system's schematic and the relationship between power generation, AC loads, and surplus energy were analysed. The results showed that excess energy was low compared to the electricity demand and generation, with only three days a year having excess power generation. After adding 1,000 and 3,000 batteries, the system provided an identical renewable energy fraction of 24.4%, indicating that the battery addition was unnecessary and resulted in unnecessary increases in energy costs. Figure 4 illustrates a comprehensive system schematic incorporating energy storage.

In addition, the state of charge was almost always below 100%, indicating that energy was being used up. It was concluded that energy storage is not essential for the system due to the low frequency of surplus energy generation and its minimal contribution to the increase in the renewable energy fraction. It is worth noting that in Thailand, the electrical systems are not autonomous and are controlled by organisations such as the PEA, EGAT, and Metropolitan Electricity Authority (MEA). Furthermore, the capital cost of the batteries is higher than that of running generators, making the addition of batteries unnecessary.

4.2.7 Estimating the future COE using HOMER simulation. After conducting simulations with various future cost scenarios, it was determined that most components involved in energy production are expected to become less expensive in the future. The analysis focused on nine years and concluded that by 2025, the average cost of producing electricity by solar PV could be reduced by 59%, offshore wind turbines by 35%, and onshore wind turbines by 26%, when compared to the benchmark costs of the IRENA 2015 report (IRENA, 2016).

(1) Cost of fossil fuels

The Department of Energy and Climate Change data was utilised to forecast fuel prices. The prediction was based on the average price derived from the forward price curve. The high price was also considered to account for the worst-case scenario. Notably, the cost per barrel exceeded 185 USD and 120 USD per barrel in the central price.

(2) Cost of natural gas

Natural gas prices experienced a steady increase over twenty years, starting in 2015 and ending in 2035. The highest price is recorded at 0.236 USD, where 1 litre of LNG provides 18,179 Btu.

(3) Cost of solar panels

Solar panel prices decreased over time, including all necessary hardware and expenses, resulting in an exponential decrease in the cost curve of solar systems. From 2015 to 2025, solar power system costs were expected to decrease by 27% in USD per watt. In Thailand, both monocrystalline and multicrystalline panels were widely used. It had been predicted that by 2050, the price per kW would reach 1,750 USD per kW (Black and Veatch, 2012). The inverter costs were also considered. For central inverters, string inverters, and micro inverters, the cost of each type of inverter was expected to decrease by 39%, 33%, and 30%, respectively.

(4) Cost of wind turbines

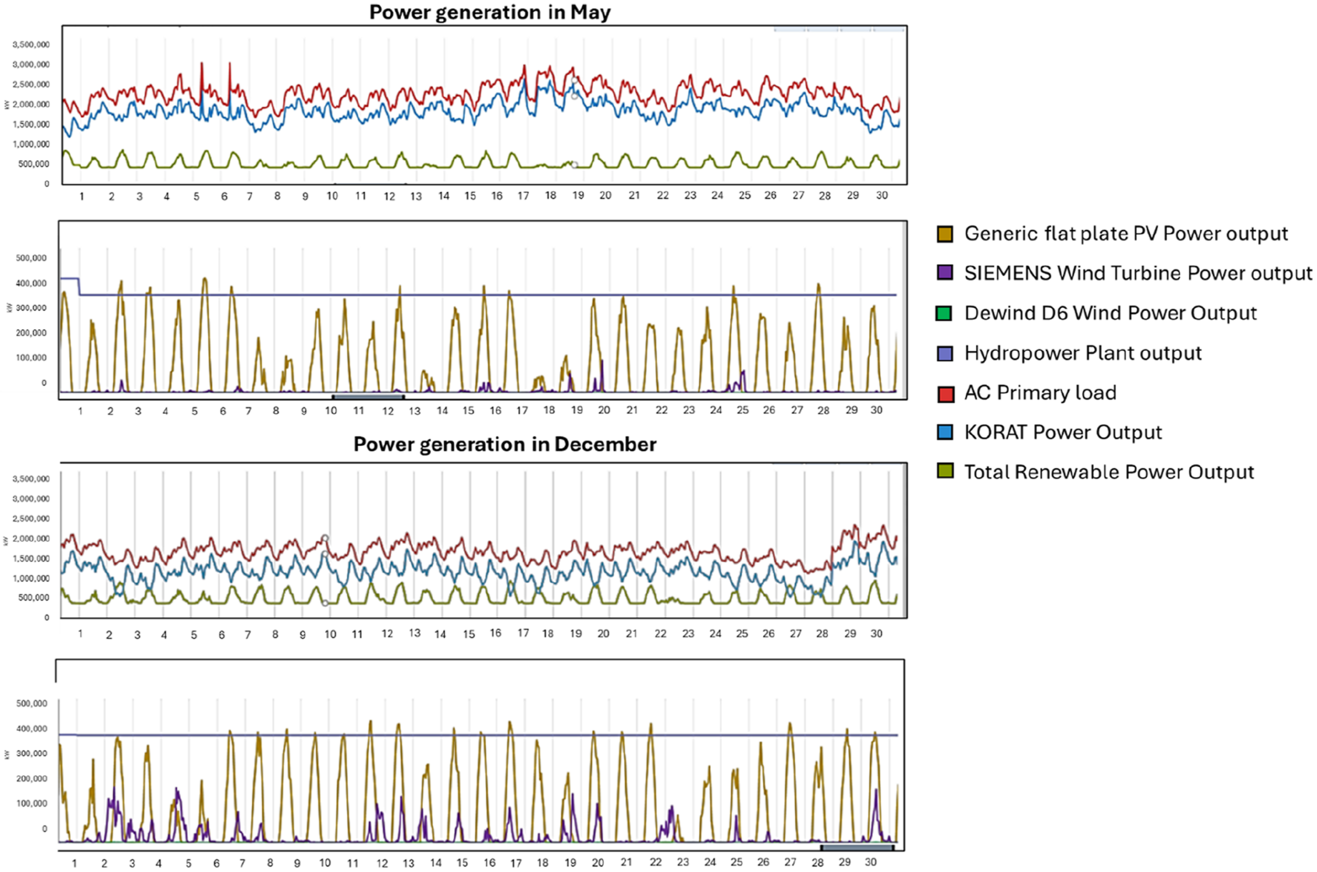

Figure 3. The relationship between AC loads, KORAT grid power output and renewable power in May and December. Source: Authors' HOMER simulation results

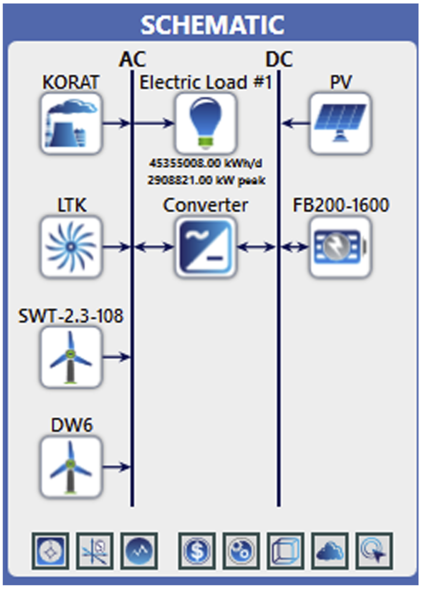

Figure 4. Complete system schematic with energy storage

Onshore wind turbines dominate the wind energy market in Thailand. The cost of wind turbines is directly linked to the prices of steel and copper. However, wind turbine costs have decreased since they peaked in 2008 and 2009 (IRENA, 2016). Between 2015 and 2025, cost reduction is expected to be around 12% for larger turbines with higher hub heights and more significant swept areas. The levelised COE is also predicted to decline by 26% by 2025, while wind turbine prices are expected to remain fixed at USD 1,980 per kW from 2010 to 2050. Given the low wind speeds in Thailand, the cost of wind power is estimated to be 927,893.75 USD per MW in 2025 (Valpy *et al.*, 2014).

(5) Cost of hydropower plant

The capital cost of hydropower plants is expected to remain steady at 3,500 USD per kW from 2010 to 2050 because hydropower plant technology has matured, making cost reduction difficult (Black and Veatch, 2012). The operation and maintenance cost is also fixed at 15 USD per kW/year.

(6) Future cost of energy

A simulation was conducted to assess the system's functionality without storage. The simulation input was based on the energy cost of 2025, and a sensitivity analysis was conducted to compare the current and future energy costs. Thailand, which heavily relies on natural gas, was used as the basis for the simulation. The simulation used natural gas prices and properties to make predictions. According to IRENA (2012), the world price of natural gas is projected to be 0.236 USD per litre in 2025 for the worst-case scenario. Accordingly, the cost of solar power systems is expected to decrease exponentially (IRENA, 2016). In the previous section, the cost of a solar panel was estimated to be 3,000 USD per kW. The simulation assumed the capital cost would be 800 USD per kW in 2025, while the inverter price would be 0.09 per watt. Conversely, the cost of wind power systems is not expected to decrease as drastically as that of solar power systems in the 2025 cost prediction. The simulation used the cost of a wind turbine manufactured in Europe, which is 477,068 USD per MW (Valpy *et al.*, 2014). Similarly, the cost of hydropower technology is not expected to change significantly. The simulation assumed a cost of 2,300 USD per kW, the same as in the previous simulation.

Regarding the energy cost comparison in 2016 and 2015, natural gas was expected to rise from 0.162 to 0.236 USD per litre; solar power was expected to decrease from 3,000 to 800 USD per kW. Wind power was expected to decrease from 660,000 to 477,068 USD per MW, inverters were expected to increase from 300 to 900 USD per unit, and hydropower was expected to remain constant at 2,300 USD per kW (PTT Public Company Limited, 2016). The values were used as inputs in the simulation to observe the changes in the system's COE, NPC, and capital cost with the cost of each technology in 2025.

4.2.8 Future cost of energy. The rise in natural gas prices led to increased energy costs, with the generator responsible for 75.31% of energy generation in the previous simulation. The findings underscore the significance of renewable energy sources in the context of increasing fossil fuel costs. The preceding section also demonstrates that renewable energy can help reduce capital costs. Interestingly, the levelised energy cost for wind power remains unchanged despite cost reductions, while solar power provides a cheaper alternative.

By 2024, the cost of solar power generation is expected to be cheaper than the marginal cost of generation from the generator. Solar power, combined with the stable price of hydropower plant technology and fluctuations in the prices of solar cell panels, wind turbines, and fossil fuels, makes the solar power system the most suitable option for Thailand's climate and natural resources. In summary, renewable energy is vital for the future, and solar power is a promising solution.

4.3 Seasonal variability and hydropower constraints in the context of simulation outcomes

The HOMER-based simulations for KORAT highlight both the opportunities and vulnerabilities of hybrid renewable energy systems that rely predominantly on solar and hydropower. When evaluated against regional climatic patterns, three critical insights emerge, including (1) the natural alignment of solar generation with peak seasonal demand, (2) the limited year-round reliability of hydropower under hydrological constraints, and (3) the need for adaptive policy and planning strategies to strengthen system resilience.

4.3.1 Demand–supply alignment. The simulated demand–supply matching highlights the contrasting seasonal dynamics of solar and hydropower generation in KORAT. Solar PV output remains relatively stable year-round, with peak production during the hot pre-monsoon months of April and May. These months also correspond with the highest electricity demand, primarily driven by intensive AC cooling loads, resulting in a natural synergy between solar generation and seasonal demand peaks (Poorisat *et al.*, 2024). In contrast, the hydropower module, calibrated using inflow data from the Lam Ta Khong Dam, revealed some declines in output during the late dry season (Electricity Generating Authority of Thailand, 2016a). This reduction reflects broader hydrological constraints in Southeast Asia, where reservoirs experience consistently reduced inflows before the onset of the monsoon. Consequently, hydropower becomes less reliable as a baseload supply during the critical pre-monsoon demand period, thereby exposing the energy system to seasonal vulnerabilities (Samjhana and Manan, 2025). Recent studies further emphasise that climate change compounds these hydrological uncertainties. For instance, Samjhana and Manan (2025) note that Southeast Asia exhibits mixed capacity factor trends under warming scenarios, with potential rebound effects but heightened variability in dry-season generation. To mitigate such risks, three adaptive strategies were proposed, including integrating hydropower with floating solar PV, which can reduce evaporation losses and offset seasonal inflow variability, and the use of AI-driven forecasting and reservoir optimisation to enhance the efficiency and reliability of water–energy operations the development of transboundary water–energy governance frameworks that align energy security with regional hydrological realities (Samjhana and Manan, 2025). Collectively, these strategies can strengthen grid resilience, support decarbonisation pathways, and ensure energy security in climate-vulnerable zones such as Thailand and the wider Southeast Asian region.

4.3.2 Seasonal reliability gaps. The simulations further reveal that months with reduced water inflow force curtailment of hydropower generation, thereby increasing reliance on solar PV and, where available, storage solutions, which is supported by Ali and Sridhar (2019), who provided the empirical evidence from the Mekong Basin, where remote-sensing studies of Lam Pao, Sirindhorn, and Ubol Ratana dams show that reservoir regulation amplifies dry-season releases by up to 94% while reducing wet-season outflows by 55–70% (Ali and Sridhar, 2019). Such variability underscores hydropower's limited reliability as a year-round supply source under changing climatic and hydrological conditions. Accordingly, these findings affirmed that hydropower is inherently vulnerable to changing climatic and hydrological conditions. In contrast, solar PV demonstrates greater temporal consistency and alignment with demand peaks, positioning it as the more reliable backbone technology within KORAT's energy portfolio.

4.3.3 Policy and planning implications for KORAT. By triangulating the KORAT simulation outputs with Thailand's evolving policy architecture, this study underscores the need to co-design technology choices with hydrological realities and governance arrangements (Asean Centre for Energy, 2025). In monsoon climates, when cooling demand peaks ahead of the wet season, solar PV aligns naturally with seasonal load. In contrast, intra-annual inflow variability constrains the reliability of hydropower, warranting a shift from baseload service to flexible, reserve-oriented operation (Samjhana and Manan, 2025). Additionally, the current drought conditions in KORAT, evidenced by alarmingly low storage at Lam Ta Khong, reinforce this vulnerability and highlight hydropower's comparative advantage as a balancing energy resource (The Nation, 2025). These dynamics align with Thailand's planning framework; for example, the draft PDP 2024 targets 51% renewables by 2037, an outcome that demands system-level integration across generation, storage, and grid operations rather than independent deployments of renewable energy technologies (Asean Centre for Energy, 2025). This approach is consistent with this logic, as PDP 2024 anticipates approximately 3.5 GW of additional Lao PDR hydropower imports by 2035–2037 and around 2,472 MW of domestic pumped-storage, explicitly repositioning hydro to firm variable supply rather than anchor baseload (Asean Centre for Energy, 2025; Bangkok Post, 2025b).

The broader significance is a climate-informed, multi-scalar governance model. Firstly, hybrid solar–hydro operation, especially floating PV co-located on reservoirs with optimised water management, can offer a near-term pathway to mitigate seasonal shortfalls and reduce evaporative losses. The most representative example is Thailand's hydro-floating PV program, which is 45 MW Sirindhorn Dam with 15 more projects nationwide, totalling 2,725 MW, providing institutional stability for such integration (Electricity Generating Authority of Thailand, 2021). Secondly, electrochemical Long-Duration Energy Storage (LDES) should complement daily-cycling batteries and pumped storage to bridge multi-day monsoon cloudiness and dry-season energy deficits (Twitchell *et al.*, 2023). Thirdly, transboundary water–energy coordination is essential because drought-driven variability in the Mekong basin can curtail Lao hydro exports to Thailand, so power-sector objectives must be harmonised with basin-level water priorities and social safeguards (Bangkok Post, 2025a).

In essence, KORAT serves as a policy-relevant small-scale case study of Thailand's transition. The study offers provincial-scale modelling that underpins a framework where solar energy constitutes the foundation, hydropower offers flexibility, and storage combined with multi-level governance ensures resilience amid increasing hydro-climatic variability, converting national objectives into actionable, climate-credible pathways.

5. Discussion

This section critically evaluates the economic and technical performance of the four simulated energy system configurations for KORAT. The discussion focuses on the interrelationships among the COE, NPC, capital cost, and renewable energy penetration, illustrating how different levels of fossil-fuel dependency, particularly on natural gas and the integration of renewable technologies, shape overall system costs and financial feasibility. Across all configurations, natural gas remained the primary energy source, and reductions in its consumption consistently translated into lower total energy costs. The COE, representing the average cost of generating one kilowatt-hour of electricity over the system's lifetime, was used as the key metric for assessing cost-effectiveness. Although Systems 1, 2, and 3 displayed similar COE values, their underlying economic structures varied considerably, especially in terms of renewable energy contribution and capital investment. Sensitivity analyses were undertaken to further investigate the implications of fluctuating fuel prices and declining renewable technology costs on these dynamics.

The results revealed that System 2 achieved the lowest COE (0.237 USD/kWh), primarily due to a 16.37% reduction in natural gas consumption compared to the baseline. This improvement resulted from the integration of hydropower, solar PV, and wind resources. However, the total cost of System 2 was higher than the baseline because renewable energy technologies required significant upfront capital investment. In contrast, System 4 exhibited the highest COE (0.25 USD/kWh), largely as a result of a near twofold increase in natural gas prices, despite capital costs being reduced by 68.6% compared to System 3. To isolate the influence of fuel prices, a sensitivity scenario was simulated using the 2016 gas price alongside reduced renewable capital costs. Under these conditions, the COE fell to 0.2358 USD/kWh, the lowest across all scenarios, and the NPC decreased to 50.5 billion USD. These findings clearly indicate that natural gas price levels play a decisive role in shaping system-wide energy costs and long-term financial viability. The NPC results further highlight these relationships. System 2 recorded the lowest NPC (50.7 billion USD), mainly because reduced fuel expenditures offset the additional capital investments in renewable energy. System 3, despite increasing the renewable energy fraction to 24.0%, had the second-highest NPC (51.7 billion USD) due to its large capital investment in expanded hydropower capacity and 470 MW of PV installations. System 4 recorded the highest NPC (54.1 billion USD) as a direct consequence of elevated fuel prices. Collectively, these outcomes underscore that both natural gas prices and renewable technology capital costs critically determine the financial performance of hybrid energy systems. While the integration of renewable energy can reduce dependency on fossil fuels, the economic benefits depend heavily on the balance between fuel price trajectories and the scale of capital investment required (see Table 4).

Moreover, the simulation results also demonstrate that solar PV systems consistently achieved the lowest COE among all renewable options, outperforming hydropower and wind energy. This superior performance can be attributed to a combination of technological, geographic, economic, and demand-related factors that collectively enhance the viability of solar energy in the region. Firstly, the declining cost trajectory of solar PV technology has

Table 4. Comparison between each system

Item	Renewable energy system	COE (USD/kWh)	NPC (Billion USD)	Capital cost (million USD)	Renewable penetration (%)
1	KORAT generator	0.242	51.9	0	0
2	KORAT generator with hydropower plant, 0.09 MW PV system, and wind power	0.237	50.7	433.62	19.4
3	KORAT generator with added hydropower capacity, 470 MW PV system, and wind power	0.241	51.7	1707.062	24
4	KORAT 2025 (Based on system five in section 4)	0.253	54.1	536.495	24

Source(s): Authors' HOMER simulation results significantly improved its affordability. Between 2009 and 2017, global solar panel prices dropped by approximately 76%, driven by economies of scale, technological advancements, and increased market competition (IMF, 2019). As a result, solar power has become highly competitive, surpassing even newly constructed fossil-fuel plants in cost per kWh in Thailand since around 2022 (BloombergNEF, 2025). Secondly, KORAT benefits from abundant solar resources, with average daily solar irradiation ranging from 4.5 to 5.5 kWh/m^2 (Narkwatchara *et al.*, 2021). This high solar potential enables PV systems to operate with strong capacity factors, facilitating consistent annual energy generation and driving down the COE. To leverage this resource, the study incorporated up to 90 MW of solar capacity in hybrid simulations, resulting in substantial reductions in COE. Third, solar PV systems offer greater scalability, shorter deployment timelines, and lower capital investment per kilowatt installed compared to hydropower. According to IRENA (2023), in Asia, the COE of solar power was 0.044 USD/kWh, while the COE of hydropower was 0.10 USD/kWh. Unlike large dams, which often require land transformation, community relocation, and prolonged permitting processes, solar installations can be implemented with minimal disruption (Zhao *et al.*, 2024). This logistical simplicity further strengthens the financial and operational case for solar. Another critical factor is the temporal alignment between solar energy generation and peak electricity demand.

In Thailand, energy consumption typically peaks during sunny daytime hours due to widespread use of air conditioning (Tipasri *et al.*, 2022). Also, solar PV systems can directly serve these peak loads, reducing reliance on expensive fossil-fuel generation. While solar is inherently intermittent, its predictable generation profile complements dispatchable resources such as hydropower, reducing the need for extensive energy storage solutions. Collectively, these advantages make solar PV the most cost-effective renewable energy option for KORAT. The simulation results confirm this, with solar-dominated configurations consistently yielding the lowest levelized costs. These findings align with broader national and regional trends. For instance, Komrit and Zabihian (2023) found that solar PV was the most economically viable option in six of the seven regions studied across Thailand. In addition, Tongsopit *et al.* (2024) emphasised the maturity of the Thai solar market and its potential for a rapid return on investment when systems are well-designed.

Following closely, hydropower emerged as the second-most cost-effective option, narrowly trailing solar due to its low operating costs, high reliability, and dispatchable nature (Niyomtham *et al.*, 2022). The presence of existing infrastructure, such as the Lam Ta Khong dam, provided a stable energy source with minimal emissions and strong capacity factors (Almeida *et al.*, 2022). However, the high upfront capital costs and site-specific limitations of hydropower constrained its scalability and overall cost competitiveness compared to solar. In contrast, wind power significantly underperformed in the study, primarily due to the region's insufficient and inconsistent wind resource. Average wind speeds of 2.8–4.0 m/s at 10 m height placed the area within wind classes 1–2, which is unsuitable for viable power generation (Tong *et al.*, 2021). The selected wind turbine model frequently failed to reach its cut-in speed, resulting in extended periods of negligible output and a capacity factor estimated at only 5–15%, far below the 30–40% typical of well-sited wind farms. This underutilisation inflated the COE of wind energy, diminishing its economic viability despite O&M costs. Moreover, wind generation showed poor alignment with demand and contributed little surplus energy, limiting its ability to displace fossil fuels or contribute meaningfully to grid stability. Even though wind technology has seen global cost reductions (IRENA, 2023). Thailand's inland regions, including KORAT, lack the wind resources needed to capitalise on these advances. Effective wind power development in the country remains confined to specific coastal or high-altitude zones. These findings are consistent with national trends, where wind contributes minimally due to similar resource constraints (Niyomtham *et al.*, 2022). Accordingly, the study concludes that wind energy is currently not a feasible option for this province, highlighting the critical importance of site-specific assessments in renewable energy planning.

6. Environmental and policy implications for Thailand's energy transition

The integration of renewable energy resources plays a critical role in reducing GHG emissions and other harmful pollutants, such as particulate matter. Prior to the implementation of renewable energy systems, the levels of these emissions can be substantial, posing significant risks to both environmental and human health. Conventional power generation relying on fossil fuels releases a range of pollutants, including carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2), particulate matter (PM), and unburned hydrocarbons, all of which contribute to air pollution, climate change, and adverse health outcomes. Simulation results from this study confirm that increasing renewable energy penetration leads to substantial emission reductions across all categories.

In particular, the configuration with the highest renewable energy share exhibited the lowest emissions, with total harmful gas and particulate matter outputs reduced by approximately 20.6%, while meeting the same level of AC electrical demand. This demonstrates the potential for solar- and hydro-based hybrid systems to not only deliver cost and reliability benefits but also significantly reduce environmental impacts. These outcomes align with Thailand's broader commitments under its PDP, which target reductions in carbon intensity and a greater share of renewables in the national energy mix. The findings therefore provide an evidence base for linking provincial-scale energy planning with national decarbonisation objectives, particularly in regions such as KORAT that benefit from strong solar resources and existing hydropower infrastructure. To build on these environmental benefits, it is recommended that Thailand's key energy planning and regulatory bodies, including EPPO, the EGAT, the PEA, and the Department of Alternative Energy Development and Efficiency (DEDE), actively integrate PV-first, hydro-supported hybrid energy systems into provincial-level power development plans (Asean Centre for Energy, 2025; EGAT, 2024). Positioning solar PV as the primary renewable resource, complemented by hydropower for firming and dispatchability, provides a practical and cost-effective pathway to reduce emissions while enhancing energy security. These configurations should serve as technical baselines and planning models for coordinated action between national and provincial agencies. However, to make these insights actionable for policy and investment decision-making, further analytical refinement is required. Specifically, these organisations should undertake expanded scenario and sensitivity analyses incorporating fuel price volatility, renewable technology cost trajectories, and dynamic electricity demand growth. Developing such decision-grade evidence would strengthen the robustness of power sector planning, tariff design, and investment prioritisation under Thailand's PDP framework. In particular, collaboration between EPPO, EGAT, and DEDE will be essential to align provincial renewable energy strategies with national energy security and decarbonisation goals (United Nations, 2025). By expanding the analytical foundation through broader parametric testing and integrated modelling, policymakers and planners can craft more targeted, locally adapted strategies to accelerate Thailand's transition toward a low-carbon, sustainable energy future.

7. Conclusion

This study developed a Sustainable Renewable-Energy Strategy for KORAT, Thailand, using HOMER to simulate and optimise hybrid systems comprising solar, hydropower, wind, and energy storage. The simulations indicate that solar PV delivers the most favourable cost–yield profile for the province, followed by hydropower, where wind performs poorly under intermittent resource conditions, with average speeds frequently below turbine cut-in thresholds. In this case, energy storage, which was added to the system, provided a low proportion of surplus energy and the non-autonomous nature of Thailand's grid, though it may become more useful as variable renewables scale. Additionally, under 2025 cost trajectories, solar and hydropower remain the principal contributors to Thailand's renewable mix. Solar's advantages include lower capital intensity relative to large hydro and minimal ecological or social disruption, while hydropower remains a reliable, cost-efficient and dispatchable technology. However, biomass shows potential but requires careful supply-chain governance to avoid mismatches and land-use conflicts. Onshore wind is not economically viable for KORAT, though offshore prospects may benefit future investigation.

Beyond these findings, the results translate into practical strategic and policy directions. Firstly, distributed and utility-scale PV should be prioritised as the backbone of provincial supply, for example, by promoting rooftop PV panel installation, through feed-in-tariff schemes and performance-based incentives for high-load sites, including malls, campuses, and industrial estates. Secondly, hydropower should be operationally repositioned from baseload to flexible balancing, by implementing turbine dispatch strategies tied to seasonal inflows, coordinating closely with water agencies, and pursuing PV–hydro co-location, for example, floating PV on reservoirs, to reduce evaporation and firm dry-season output. Thirdly, energy storage should be managed effectively, which can be done by utilising retained pumped storage and short-duration batteries for daily cycling, while considering LDES options to cover multi-day monsoon cloudiness and dry-season deficits as renewable penetration rises. Fourthly, demand-side measures, time-of-use tariffs, automated demand response for cooling loads, and smart metering should be used to align consumption with PV-rich midday profiles, lowering curtailment risk and capacity needs. Finally, grid and market reforms that reward flexibility will help integrate higher variable shares in line with national targets.

These pathways imply differentiated roles for stakeholders. National ministries and regulators should align PDP and NEP instruments with provincial deployment programs and adopt stable, transparent tariff frameworks. The authorities, including EGAT, PEA, and MEA, should co-plan substation upgrades, feeder-level PV hosting capacity, and inter-provincial transfer corridors. Also, hydropower operations should be jointly scheduled with irrigation and disaster-risk agencies. Private developers and investors can de-risk project pipelines through standardised procurement and credit enhancements, while local governments and communities can aggregate rooftop schemes and ensure equitable access for low-income households, for example, social solar and on-bill financing. Moreover, due to the fact that Thailand relies on regional hydropower imports, energy planning should also monitor transboundary hydrology to mitigate exposure to drought-related supply volatility. Regarding societal and economic co-benefits, a PV-led, hydro-firmed pathway reduces exposure to imported fuel price shocks, creates local employment in installation and O&M, improves air quality, and enhances resilience of critical services during heat waves. Additionally, well-designed tariffs and community programs can distribute benefits more evenly, supporting a just transition in fast-growing provincial economies such as KORAT. From a theoretical perspective, the study contributes a province-scale, data-aligned modelling framework that demonstrates how hourly climatic and load profiles can be operationalised into policy-relevant portfolios. The framework is replicable for other Thai provinces and comparable monsoon regions, offering a practical bridge between techno-economic optimisation and planning decisions.

However, the study’s limitations should be acknowledged as the results are mainly based on KORAT-specific assumptions. Equally important, HOMER’s single-objective optimisation and hourly resolution do not capture intra-hour dynamics, market behaviour, or real-time grid stability constraints. Accordingly, future work should couple the present framework with multi-objective and AI optimisation, real-time pricing and dispatch models, richer socio-economic datasets, and resilience metrics. Extending the analysis to metropolitan contexts, such as Bangkok and other provinces, would test generalisability and refine siting and sequencing recommendations.

When compared with previous studies, the present findings reinforce but also extend Thailand’s renewable energy discourse. For instance, similar studies in Vietnam and Malaysia also identified solar PV and hydropower as dominant pillars in tropical hybrid systems, confirming the regional robustness of these resources under monsoon variability. However, unlike these contexts, the KORAT model emphasises the operational flexibility of hydropower and the strategic sequencing of storage deployment, which are critical for Thailand’s decentralised grid architecture. Nationally, this framework demonstrates strong potential for replication across other provinces with comparable resource endowments, supporting the renewable targets outlined in the PDP 2024; NEP 2023. By aligning techno-economic optimisation with policy implementation, the study offers a scalable model that bridges provincial planning with national energy transition objectives. In conclusion, the study provides an analytically grounded and implementation-ready case study, where distributed and utility-scale PV should be taken into account as the foundational resource while operating hydropower for flexibility. Further, phase in storage as renewable penetration increases, and align tariffs, permitting, and grid operations to reward demand–supply synchronisation. Collectively, these steps translate the simulations into actionable policy and investment decisions, advancing Thailand's energy-transition objectives at both provincial and national levels.

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Abbreviation	**Full Form**
AC	Alternating Current
COE	Cost of Energy
EGAT	Electricity Generating Authority of Thailand
GWh	Gigawatt-hour
HOMER	Hybrid Optimization of Multiple Energy Resources
IFC	International Finance Corporation
IRENA	International Renewable Energy Agency
kWh	Kilowatt-hour
LNG	Liquefied Natural Gas
MEA	Metropolitan Electricity Authority
MMUSD	Million US Dollars (inferred)
MSL	Mean Sea Level
MW	Megawatt
NREL	National Renewable Energy Laboratory
NPC	Net Present Cost
PEA	Provincial Electricity Authority
PDP	Power Development Plan
PV	Photovoltaic
SDGs	Sustainable Development Goals
TMD	Thai Meteorological Department
USD	United States Dollar

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